Available online at www.sciencedirect.com

Advances in Space Research 34 (2004) 1546–1551

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Engineering concepts for inflatable Mars surface greenhouses

I. Hublitz [a,*], D.L. Henninger [b], B.G. Drake [b], P. Eckart [c]

[a] Agricultural and Biological Engineering Department, University of Florida, P.O. Box 110570, Gainesville, FL 32611-0570, USA
[b] NASA-Johnson Space Center, 2101 NASA Road 1, Houston, TX 77058, USA
[c] McKinsey & Co. Inc., Prinzregentenstr. 22, 80538 Munich, Germany

Received 19 October 2002; received in revised form 16 June 2004; accepted 18 June 2004

Abstract

A major challenge of designing a bioregenerative life support system for Mars is the reduction of the mass, volume, power, thermal and crew-time requirements. Structural mass of the greenhouse could be saved by operating the greenhouse at low atmospheric pressure. This paper investigates the feasibility of this concept. The method of equivalent system mass is used to compare greenhouses operated at high atmospheric pressure to greenhouses operated at low pressure for three different lighting methods: natural, artificial and hybrid lighting.

Keywords: Mars surface greenhouse; Life support systems; Bioregenerative life support systems; Space life science

1. Introduction

An inflatable greenhouse is an important component of the Mars mission infrastructure as plant-based life support systems offer self-sufficiency and possibly cost reduction. Resupply is prohibitive for long duration Mars missions as it increases the launch mass and consequently the launch costs. Risk to the astronauts is also increased by relying on frequent resupply from Earth. Greenhouses cannot only be used for the production of edible biomass but also as air and water regeneration processors.

Engineering considerations for inflatable Mars greenhouses include architecture, materials, thermal control system, lighting method, operation and maintenance, equipment, packaging and deployment, in situ resource utilization and power sources. This paper concentrates on the structural, material, lighting method and thermal aspects of the greenhouse.

Table 1 shows how expensive Mars infrastructure systems can become in the form of mass penalties for volume, power, thermal and crew-time requirements.

The goal of this study was to evaluate the impact of the lighting method and the atmospheric pressure level of the greenhouse on the equivalent system mass (ESM), especially the possibility of mass savings by operating the greenhouse at a lower pressure.

2. Greenhouse atmosphere

This paper compares the feasibility of a high-pressure greenhouse to that of a low-pressure greenhouse. For the high-pressure greenhouse, a pressure of 59.2 kPa is chosen with a gas composition equal to that of the surface habitat proposed in NASA's Design Reference Mission. The high pressure of 59.2 kPa provides a habitable environment for the crew and the crop. An atmosphere

---

[*] Corresponding author. Tel.: +1 352 392 1864x265; fax: +1 352 392 4092.

E-mail address: inka@ufl.edu (I. Hublitz).

0273-1177/$30 © 2004 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2004.06.002

Table 1
Mars mission infrastructure equivalencies (Drysdale et al., 1999; Hanford, 2002)

Equivalency	Minimum	Nominal	Maximum
Volume (kg/m^3)	2.08	2.08	66.7
Power (*nuclear, **photovoltaic) (kg/kW)	54*	87*	226**
Thermal (kg/kW)	58.8	66.7	76.9
Crew-time (kg/crew-hours)	1.25	1.25	1.5

pressure of 30 kPa is chosen for the low-pressure greenhouse because this pressure is considered to be the lower limit where plant growth is still feasible (Wheeler, 1999).

3. Structure and material

For the inflatable greenhouse an air-inflated structure is chosen. Gas retention is achieved with a redundant impermeable bladder assembly, while structural restraint is provided by Kevlar webbings. For radiation protection a dome could be deployed. This shell concept is depicted in Fig. 1 (Kennedy, 1999).

The type of shell assembly depends mainly on the lighting method. If natural sunlight is used, the shell assembly has to be highly translucent. If artificial lighting is used, an opaque multi-layer insulation can be installed to prevent heat loss during the night. The bladder is triply redundant with vacuum between the individual layers. If the innermost layer leaks there are still two layers left to ensure gas retention. Vacuum sensors installed between the layers detect possible leakage. The greenhouse shell assembly in relation to the lighting method is shown in Fig. 2.

The same bladder assembly will be used for the high-pressure (59.2 kPa) and the low-pressure (30 kPa) greenhouses since the bladder is responsible for gas enclosure. 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 2 the mass of the bladder and the restraint layer is given for both the high-pressure (59.2 kPa) and the low-pressure (30 kPa) greenhouse (Kennedy, 1999).

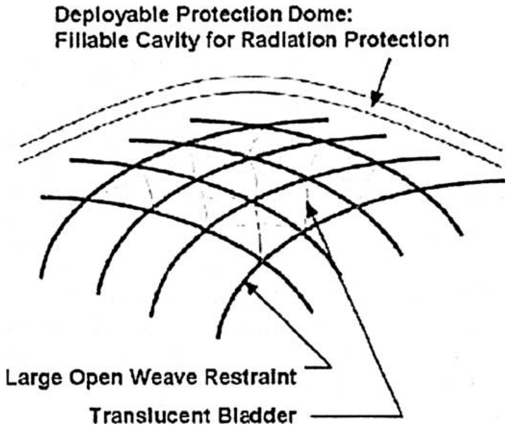

Fig. 1. Inflatable greenhouse shell concept (Kennedy, 1999).

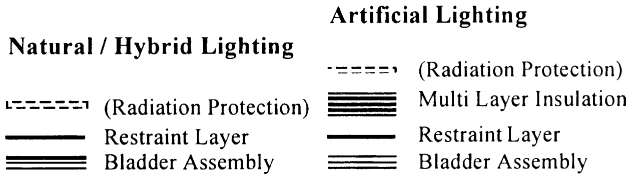

Fig. 2. Greenhouse shell assembly in relation to the lighting method.

The inflatable greenhouse discussed in this document is a horizontally orientated, semi-cylindrical, air-inflated pneumatic structure as depicted in Fig. 3. All edges are rounded in order to avoid high bending stresses in the structure. The end is shaped in the form of a quarter sphere. This volume can be used for storage of equipment, crops, regenerative life support systems and the thermal control system. Additional storage volume is available under the plant trays. A floor scuff pad has to be used to avoid damage of the bladder and restraint layer. A tunnel connects the individual greenhouses. The number of greenhouses connected to this tunnel depends on the amount of required in situ food production. The greenhouse is anchored to the Martian surface by a web of cables in order to avoid the greenhouse floor bulging down and lifting the greenhouse up due to its internal pressure (Kennedy, 2000).

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 unit growth area. Fig. 4 shows the mass per unit growth area for high and low pressure greenhouses depending on the required growth area and the lighting method.

The mass savings are depicted in Fig. 5. If the greenhouse is operated with low pressure (30 kPa) instead of high pressure (59.2 kPa) the mass of the greenhouse shell

Table 2
Mass per area of the greenhouse shell materials (Kennedy, 1999)

Material	High pressure (59.2 kPa) greenhouse (kg/m^2)	Low pressure (30.0 kPa) greenhouse (kg/m^2)
Bladder (Polyethylene)	1.22	1.22
Restraint layer (Kevlar)	1.31	0.66
Multi-layer insulation (Mylar, β-cloth)	1.22	1.22

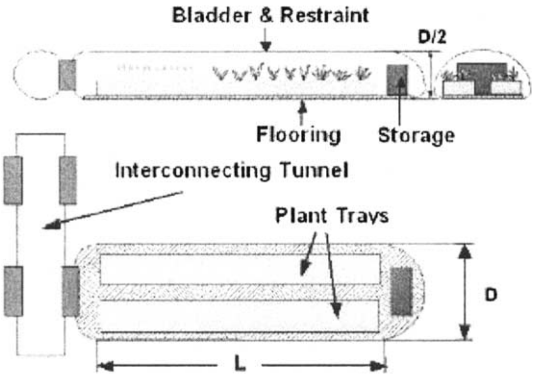

Fig. 3. Greenhouse architecture overview.

can be reduced by 17.4% for artificial lighting and by 25.7% for natural/hybrid lighting. The change of the lighting method from artificial to natural/hybrid lighting would reduce the shell mass by 32.5% for a high-pressure greenhouse and 39.9% for a low-pressure greenhouse. The mass of the greenhouse shell of a low-pressure greenhouse using natural/hybrid lighting is only 50.1% of that of a high pressure greenhouse using artificial lighting.

4. Lighting

Lighting is an important environmental factor for plant production, as it is required for the photosynthesis process which transforms carbon dioxide into oxygen while producing new biomass. For a plant production system basically four options of lighting methods can be considered:

- 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).

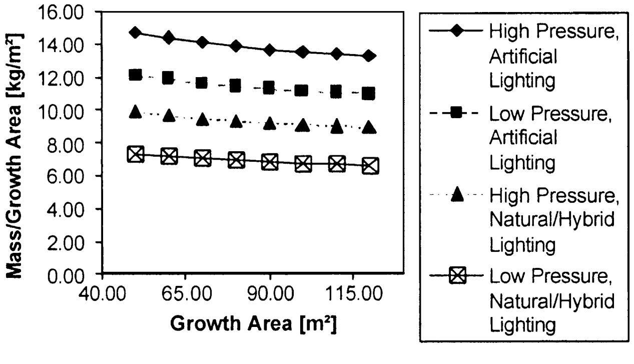

Fig. 4. Comparison of mass per growth area depending on growth area, lighting method and pressure level.

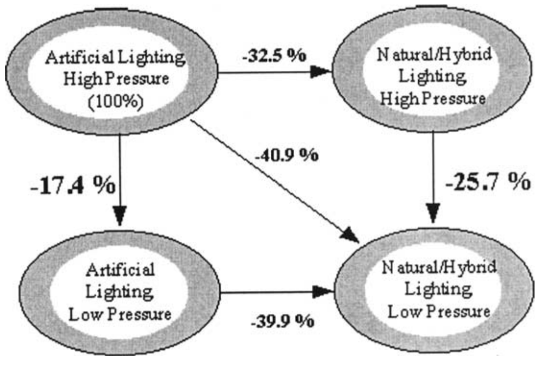

Fig. 5. Greenhouse shell mass savings depending on lighting method and pressure level.

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. For this study, the average photo-synthetically active radiation (PAR) level on Mars is estimated to be 20.8 mol/(m^2 day). A lighting period of 12 h during the day is assumed. High PAR levels can be achieved by using electrical light. For this study efficient high- pressure sodium (HPS) lights are selected. The PAR levels inside of the greenhouse depend on the lighting methods:

Natural lighting:
- high pressure ($t = 0.55$): PAR = 11.4 mol/(m^2 day)
- low pressure ($t = 0.65$): PAR = 13.5 mol/(m^2 day)

Hybrid lighting (HPS: 400 μmol/(m^2 s)):
- high pressure ($t = 0.55$): PAR = 28.6 mol/(m^2 day)
- low pressure ($t = 0.65$): PAR = 30.7 mol/(m^2 day)

Artificial lighting (HPS: 1000 μmol/(m^2 s)):
- high/low/ pressure: PAR = 43 mol/(m^2 day)

5. Thermal control system

The thermal properties of the greenhouse shell depend on the shell assembly (see Fig. 2). 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 inflatable greenhouse bladder material is 75%. The restraint webbings reduce the transmittance of the shell to 55% for high pressure and, 65% for low pressure. The emissivity of the greenhouse shell is 1.0 for heating requirement calculations and 0.8 for cooling requirement calculations. Heat gain and loss of the greenhouse are calculated by the energy balance equation considering solar radiation and internal waste heat as heat sources and radiation to the Mars

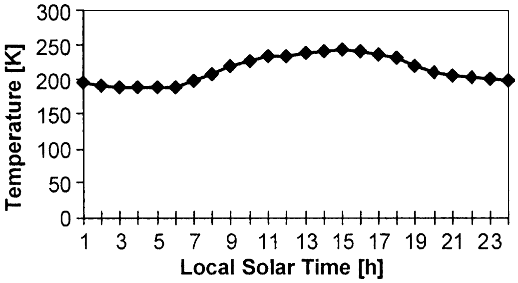

Fig. 6. Daily diurnal temperature cycle at Viking 1 landing site (22° north latitude) during mid-summer (Rapp, 1997).

environment as a heat sink. Conductive heat transfer through the greenhouse floor and convective heat transfer to the Mars atmosphere are regarded to be negligible (Ortiz, 2000; Ewert, 2000).

The Mars diurnal temperature change depends mainly on the season and latitude. Fig. 6 shows the diurnal temperature data of the Viking 1 landing site.

5.1. Natural lighting

The heat gain/loss of the natural greenhouse is calculated by subtracting the outgoing from the incoming energy flux (Schwarzkopf, 1990):

$$Q_s = I_{dn}\tau A_{in} - \varepsilon b(T_i^4 - T_s^4)A_{out}, \quad (1)$$

where Q_s is the solar heat gain/loss (W); I_{dn} the incident direct normal solar radiation per unit area (590 W/m^2); τ the transmittance (0.55 high pressure, 0.65 low pressure); ε the emissivity (0.8 day, 1.0 night); b the Stefan–Boltzmann constant [5.67×10^{-8} W/(m^2 K^4)]; T_i the interior temperature (assumed to be 298 K); T_s the Mars environment temperature (187–242 K Viking 1 landing site data); A_{in} the projected floor area; A_{out} is the greenhouse hull area (hatch area excluded).

Calculations of the greenhouse heat balance during the Martian day show that the maximum heat gain is at 13 h 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 h local solar time (see Fig. 7). In Tables 1 and 2, the minimum, maximum and average solar heat gain/loss of a high-pressure (59.2 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 because the transmittance of the high pressure greenhouse is lower compared to the low-pressure greenhouse.

An option to avoid the immense heat loss during the Martian night would be to cover the entire greenhouse with multi-layer insulation (MLI). Fig. 8 shows the solar heat gain/loss for a low and a high-pressure transparent greenhouse covered with MLI at night.

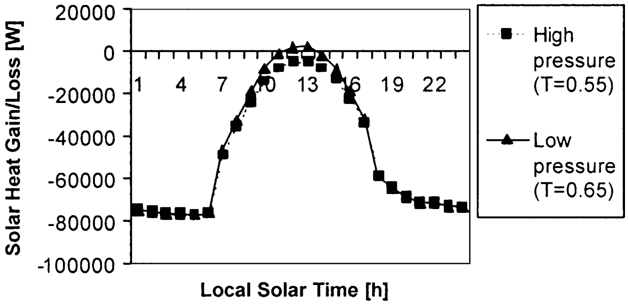

Fig. 7. Solar heat gain/loss for a low and a high pressure transparent greenhouse (90 m^2 growth area).

5.2. Artificial lighting

The heat gain/loss of the opaque greenhouse with artificial lighting is calculated by subtracting the outgoing energy flux from the generated internal energy (Schwarzkopf, 1990):

$$Q_s = -\varepsilon b(T_i^4 - T_s^4)A_{out} + Q_L, \quad (2)$$

where ε is the emissivity (0.8 day, 1.0 night); b the Stefan–Boltzmann constant [5.67×10^{-8} W/(m^2 K^4)]; T_i the interior temperature (assumed to be 298 K); T_s the Mars environment temperature (187–242 K Viking 1 landing site data); A_{out} the greenhouse hull area (hatch area excluded); Q_L is the waste heat lamps.

The waste heat is generated by the high pressure sodium lights required for a lighting level of 1000 mol/m^2 s:

$$Q_L = A_{grow}(Q_{P,L} + Q_{B,L})(N_{Lamp}/A_{grow}), \quad (3)$$

where A_{grow} is the required growth area (90 m^2); $Q_{P,L}$ the power requirement per lamp (400 W); $Q_{B,L}$ the ballast power requirement/lamp (60 W); (N_L/A_{grow}) is the lamps per growth area for a lighting level of 1000 mol/m^2 s (5.1 m^{-2}).

Fig. 9 shows the total heat gain/loss of the inflatable greenhouse for a 12-h lighting period with a lighting level of 1000 μmol/(m^2 s) from 6 to 18 h local solar time. The artificial lights are considered to be an additional internal heat source since they produce a large amount of waste heat when on. As the emissivity of the opaque

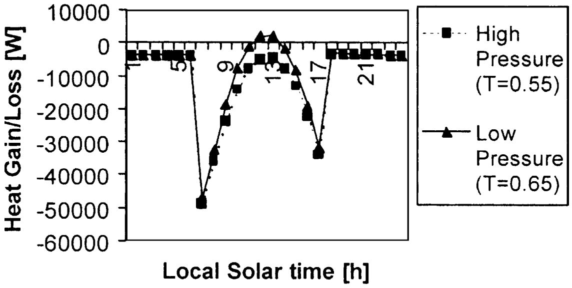

Fig. 8. Solar heat gain/loss for a low and a high pressure transparent greenhouse covered with multilayer insulation at night (90 m^2 growth area).

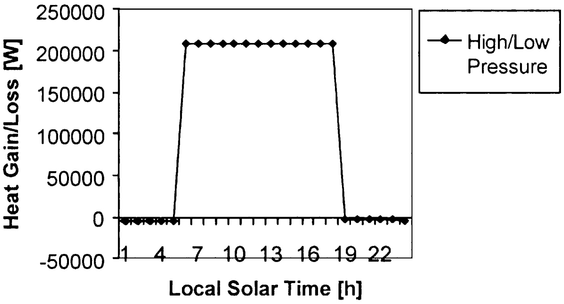

Fig. 9. Heat gain/loss for an opaque greenhouse with artificial lighting during the day (90 m^2 growth area).

greenhouse is very low due to the installed MLI, the heat loss during the night is almost nil.

5.3. Hybrid lighting

The energy balance for the hybrid lighting greenhouse is the combination of artificial and natural lighting greenhouse. Since a lighting level of 400 mol/m^2 s is assumed, the waste heat generated by the lamps is reduced to 40% of the value for 1000 mol/m^2 s,

$$Q_s = I_{dn}\tau A_{in} - \varepsilon b(T_i^4 - T_s^4)A_{out} + Q_L. \tag{4}$$

Fig. 10 shows the total heat gain/loss of a transparent low-pressure greenhouse with an artificial lighting level of 400 μmol/(m^2 s) added to natural lighting during the Martian day from 6 to 18 h local solar time. This concept leads to immense thermal requirements during the Martian day and immense heating requirements during the Martian night.

Because of 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 balanced by the waste heat of the lamps. This can be achieved by providing an additional artificial lighting level of, e.g., 400 μmol/(m^2 s) during the Martian night from 18 to 6 h local solar time. The diurnal heat gain/loss of this greenhouse concept is shown in Fig. 11. The condition required to make this greenhouse concept practical would be the selection of plants that need a 24-h lighting, period, e.g., wheat.

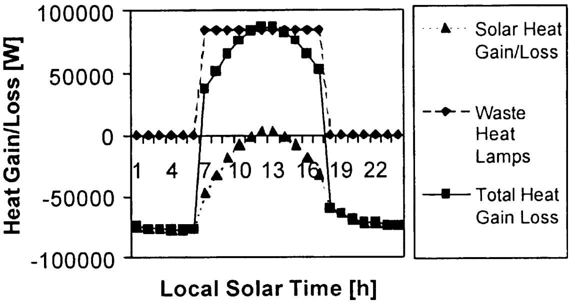

Fig. 10. Heat gain/loss for a transparent low pressure greenhouse with artificial lighting during the day (90 m^2 growth area).

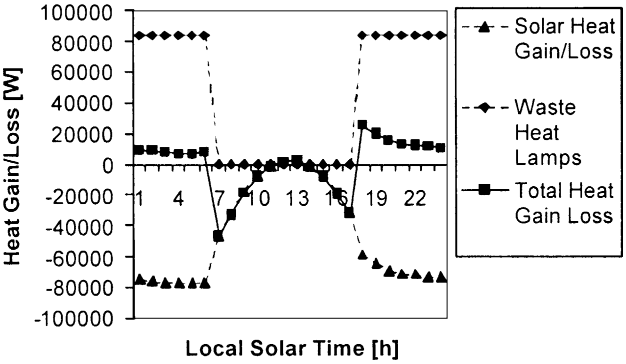

Fig. 11. Heat gain/loss for a transparent low pressure greenhouse covered with a MLI during the night with artificial lighting during the day.

6. Growth area

A preliminary study defined the relationship between the amount of edible plant mass grown and the amount of natural light available as (Gertner, 1999):

$$\text{Edible} = 0.77\text{PAR} - 6.1, \tag{5}$$

where Edible is the amount of edible plant mass produced [g/(m^2 day)]; PAR the lighting level of photo-synthetically active radiation inside of greenhouse (PAR) [mol/(m^2 day)].

Assuming six crew members and 0.89 kg food-dry-weight/(crew day) the total amount of in situ produced food in one Martian year is 3995.4 kg if 100% of the required food is grown locally. Fig. 12 shows the required

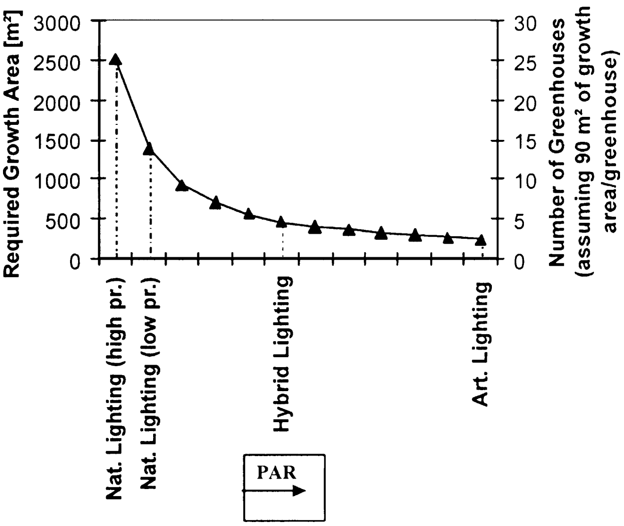

Fig. 12. Relation of lighting method, growth area and number of greenhouses.

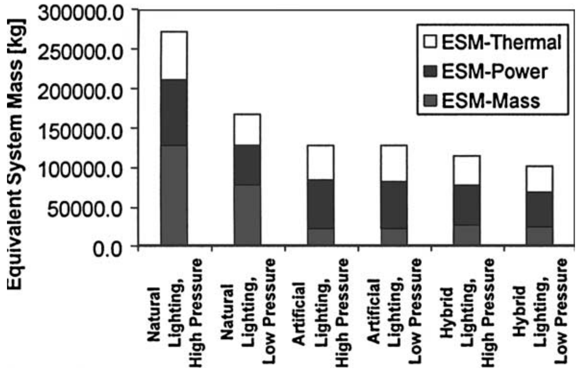

Fig. 13. Contribution of mass, power and thermal to equivalent system mass of a greenhouse assembly.

growth area and the number of greenhouses (assuming 90 m^2 growth area) in relation to the PAR level, and therefore to the lighting method (Eckart, 1996).

7. Results

The equivalent system mass analysis allows comparison of different greenhouse options with different parameters using a single scale. The total ESM value is the sum of the mass, volume, power, thermal and crew time requirements of the greenhouse subsystems (Levri et al., 2000):

$$\begin{aligned} \mathrm{ESM_{total}} &= \sum \mathrm{ESM_i}, \\ \mathrm{ESM_i} &= M_\mathrm{i} + \gamma_\mathrm{V} V_\mathrm{i} + \gamma_\mathrm{P} P_\mathrm{i} + \gamma_\mathrm{T} T_\mathrm{i} + (CTD\gamma_\mathrm{CT}), \end{aligned} \tag{6}$$

where $\mathrm{ESM_{total}}$ is the ESM of entire greenhouse (kg); $\mathrm{ESM_i}$ the ESM of subsystem i (kg); M_i the mass of subsystem i (kg); V_i the volume requirement for subsystem i (kW); P_i the power requirement for subsystem i (kW); T_i the thermal requirement for subsystem i (kW); γ_V the volume infrastructure cost factor (2.08 kg/kW); γ_p the power infrastructure cost factor (87 kg/kW); γ_T the thermal infrastructure cost factor (66.7 kg/kW); γ_CT the crew-time infrastructure cost factor (1.25 kg/kW); *CT* the total crew-time requirement of subsystem i (CM-h/y); *D* is the duration of the mission segment of interest (y).

In this study a simplified version of the ESM method was used, including mass, power and thermal requirements. Those values were calculated for greenhouses operated at high pressure and greenhouses operated at low pressure for three different lighting methods: natural, artificial and hybrid lighting.

Fig. 13 shows the results of the ESM analysis. 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.

8. Definitions, acronyms, abbreviations

ESM	Equivalent system mass
HPS	High pressure sodium lights
MLI	Multi-layer insulation
PAR	Photo-synthetically active radiation

Acknowledgements

The authors of this paper thank Michael Ewert, Kriss Kennedy and Ray Wheeler from NASA for providing useful information and a huge amount of support.

References

Drysdale, A.E., Hanford, A.J. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371. Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX, June 1999.

Eckart, P. Spaceflight Life Support and Biospherics. Space Technology Library, Microcosm Press, California, 1996.

Ewert, M.K. Personal Communication. NASA Johnson Space Center, Houston, TX, 2000.

Gertner, B. Mars Greenhouse Study: Natural vs. Artificial Lighting. Advanced Life Support Status Telecon, November 18, 1999, NASA Johnson Space Center, Houston, TX, 1999.

Hanford, A.J. Advanced Life Support Baseline Values and Assumptions Document, CTSD-ADV-484. Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX, 2002.

Kennedy, K.J. Inflatable Habitats and Greenhouse Design: Technology and Development for Mars Implementation. Inflatable Mars Greenhouse Workshop, Kennedy Space Center, Florida, December 9–10, 1999.

Kennedy, K.J. Personal Communication. NASA Johnson Space Center, Houston, TX, 2000.

Levri, A.J., Vaccari, D.A., Drysdale A.E. Theory and application of the equivalent system mass metric, in: Proceedings of the 30th International Conference on Environmental Systems. Toulouse, France, July 10–13, 2000.

Ortiz-Longo, C.R. Personal Communication. NASA Johnson Space Center, Houston, TX, 2000.

Rapp, D. The Mars Environment. JPL, California, December 4, 1997.

Schwarzkopf, S. Lunar Based Controlled Ecological Life Support System (LCELLS). Lockheed Missiles and Space Company, LMSC/F369717, NAS9-18069, October 1990.

Wheeler, R.M. High CO_2 Considerations for Plants. Inflatable Mars Greenhouse Workshop, Kennedy Space Center, Florida, December 9–10, 1999.