2002-01-2392

Low Pressure Greenhouse Concepts for Mars: Atmospheric Composition

Vadim Ye. Rygalov and Ray A. Bucklin
University of Florida

Alan E. Drysdale
Boeing

Philip A. Fowler
Dynamac Inc.

Raymond M. Wheeler
KSC NASA

ABSTRACT

The main principles of artificial atmospheric design for a Martian Greenhouse (MG) are described based on:

1. Cost-effective approach to MG realization;
2. Using in situ resources (e.g. CO_2, O_2, water);
3. Controlled greenhouse gas exchange by using independent pump in and pump out technologies.

We show by mathematical modeling and numerical estimates based on reasonable assumptions that this approach for Martian deployable greenhouse (DG) implementation could be viable. A scenario of MG realization (in terms of plant biomass/photosynthesis, atmospheric composition, and time) is developed. A list is given of technologies (natural water collection, MG inflation, oxygen collection and storage, etc.) that are used in the design. The conclusions we reached are:

1. Initial stocks of oxygen and water probably would be required to initiate plant germination and growth;
2. Active control of MG ventilation could provide proper atmospheric composition for each period of plant growth;
3. MG operation based on simplest technological solutions could provide for oxygen accumulation for people arriving on Mars.

There is a reasonable prospect of achieving cost effectiveness during a single 600-day mission. A short description of future development of a Mars Greenhouse-project is presented.

INTRODUCTION: GREENHOUSE ATMOSPHERIC COMPOSITION BASED ON THE NATURAL RESOURCES OF THE PLANET

Terrestrial plants need a balanced composition of atmospheric gases to be maintained within certain limits for growth (Wheeler et al., 2000). Carbon dioxide and oxygen are the basic gases used in the processes of photosynthesis and respiration: $CO_2 + H_2O \Leftrightarrow CH_2O + O_2$. During plant growth, carbon dioxide is used in greater amounts than oxygen, but oxygen is particularly critical during germination and for respiration at dark period. Presence of some trace organic gases in a closed volume (ethylene and etc.) is also important for plant growth regulation (Devlin, 1975; Chernigovsky, 1975; Lisovsky, 1979).
The average composition of the Earth's atmosphere compared to the atmosphere of Mars is presented in Table. 1 (APPENDIX, III).
From the analysis of this table the following conclusions could be formulated:

- There are considerable differences in atmospheric composition between Mars and Earth;
- Carbon dioxide is presented in the Martian atmosphere in significant amounts;
- Oxygen and water are not common in the Martian atmosphere;

- The existing Martian atmospheric composition is probably not suitable for Earth's plants growth; (other environmental parameters: temperatures, high UV – radiation, toxic gases and dust, etc., may also be a problem)
- Growing plants on Mars will require artificial growth conditions inside a closed environment.

An analytical model can be used to simplify analysis of the minimal greenhouse atmosphere for plant growth and development. This minimal, most cost effective, atmosphere (Rygalov et al., 2001) should include CO_2, O_2, and water vapor at sufficient concentrations to support vigorous plant growth. We need to determine by experimentation the cost of maintaining particular conditions, and what effect different conditions would have on plant productivity. This atmosphere could probably be maintained by controlled gas exchange between the greenhouse and outside Martian air during all period of plants growth. However, due to the low concentration of oxygen and water vapor, other sources of these commodities might be more cost effective. The rate of gas exchange should be regulated to account for plant growth (photosynthesis rate changes). It is expected that any gas mixture dense enough to support plants will be adequate to maintain the mechanical pressure needed to keep the soft Deployable Greenhouse (DG) covering inflated. If the most cost effective pressure is found to be near Earth-normal pressure, there might be a problem in designing a cover that is both strong enough and transparent. Both composition of the atmosphere & DG mechanical design are closely connected through the desired exchange of air inside a greenhouse and with outside atmosphere. So, this becomes the task of Artificial Atmosphere Design (AAD). This design issue can be solved in different ways. The cheapest and most cost effective design approach is probably using of indigenous Martian resources (carbon dioxide, oxygen, water, etc.), and the lowest pressure that is suitable for vigorous plant growth.

COMBINING ELEMENTS OF ARTIFICIAL ATMOSPHERE DESIGN

The basic description of the atmospheric constituents dynamic inside enclosure could be presented as:

Velocity of changes in atmospheric concentration (or partial pressure) of the gas =
Initial atmosphere
+ Input from outside (provided by controlled pumping-in process)
- Losses to outside (provided by controlled pumping-out process or regulated venting, and unregulated leakage)
+ Influence of system's closure (conversion or modification by plants and microbes, physical sorption, chemical reactions, etc.).

Assumptions:

- an elevated pressure is required for mechanical stabilization of DG, so greenhouse ventilation is realized by forced pumping-in and pumping-out or controlled passive venting and unavoidable leakage;
- plants inside the greenhouse take in carbon dioxide and release oxygen;
- relative humidity is maintained by evapotranspiration and condensation;
- neutral gases go through the DG without any modification; however, they may need to be purged at intervals if they result in excessive pressure.

Partial and total pressure changes are due to the following:

- gas pumped in
- gas removed
- photosynthesis and respiration
- leakage
- transpiration

This qualitative description is represented in the following mathematical description:

$$dPi/dt = (F/V)*Pio + fiX/V + ((K_L G)/V)*(Pis – Pi) – (K_C G_C/V)*(Pi – Pic) – (L/V)*(Pi – Pio) – (R/V)*Pi$$

; where: Pi = partial pressure of certain gas inside greenhouse;
Pio = partial pressure of certain gas in outside atmosphere;
Pis = saturated partial pressure of the gas at system temperature (included in water vapor dynamic description only; Rygalov et al., 2002);
Pic = saturated partial pressure of the gas at cooling unit temperature (included in water vapor dynamic description only; Rygalov et al., 2002);
F = outside air flow rate into greenhouse;
R = inside air flow rate out from greenhouse (or in other words forced leaks);
L = total free leaks flow rate;
(*Note*: parameters F, R and L characterize the regime of greenhouse ventilation);
V = total volume of greenhouse;
X = plants biomass;
fi = specific rate of gas conversion in photosynthetic processes (can be positive, for example for O_2, or negative, for example for CO_2);

G = area of the gas evaporation (included in vapor dynamic description only; Rygalov et al., 2002);

G_C= area of gas condensation (included in vapor dynamic description only; Rygalov et al., 2002);

K_L = specific rate of gas evaporation (included in vapor dynamic description only; Rygalov et al., 2002);

K_C = specific rate of gas condensation (included in vapor dynamic description only; Rygalov et al., 2002);

t = time.

This mathematical description is not specified for certain physical unites.

The total dynamic pressure in the system is equal to the sum of the individual dynamic pressures for all gases in the system. It is assumed in the equation presented that DG operation is developing with a constant system temperature. Any changes in temperature could be taken into account through changes of numerical values parameters of the model, but wide temperature swings are generally detrimental to plants.

The mathematical model presented includes the most general processes determining gaseous dynamic of the greenhouse (Henderson et al., 1997; Johnson, 1999). Any other components of DG atmospheric composition dynamic (trace contaminants, or some specific sources and sinks of gases) could be easily introduced in further specific development of this model.

For calculation of DG atmospheric composition this mathematical approach is applied to each constituent gas, including:

1. CO_2;
2. O_2;
3. H_2O;
4. Neutral gases;
5. Ethylene and trace gases (neglected in the approach developed in the paper);
6. Total pressure.

The solution of the differential equation for each atmospheric gas was obtained by standard well - known methods, and is presented in the (APPENDIX, I). We are going to use the steady - state part of this solution only in further consideration.

EXPERIMENTAL REALIZATION

Some of the equation parameters that characterize a greenhouse enclosure can be more easily measured experimentally (for example: K_L, K_C, F, L, R) than calculated directly. For these experimental measurements a Martian Greenhouse prototype was developed. The prototype, shown in Fig. 1, has a hemispheric Lexan cover installed on a stainless steel base. The prototype had a diameter of ~ 1 m, and a total volume of ~ 0.417 m^3. We envisage the top being made of soft transparent materials for operational use. Soft materials are planned to take a test in later works. The prototype includes the following internal environmental controls:

- a cold coil with an external chilled water source;
- resistance heating elements;
- an air circulation fan;

A pump with rate ~ 5 L/min air under 101.3 kPa is provided for gas exchange between the system and the outside air of Thermotron. This system allows us to realize a closed water cycle and provides atmospheric gases from outside.

Fig. 1. Martian Greenhouse Prototype (MGP).
(In the center of the Dome there is system climate control tower that includes a coolant coil and a water distribution unit.)

This MG prototype was designed to be installed inside another vacuum chamber that allows us to imitate Martian surface conditions. The vacuum chamber (Thermotron, Fig.2) has the following internal dimensions: 1.22 m-width, 1.22 m-height, and 1.62 m-depth. It provides environmental control that ranges from terrestrial to Martian conditions:

- temperature ~ -72 to +177 °C:
- pressure ~ 0.1 kPa (~ 1 mm Hg) to ~ 101.3 kPa (~ 768 mm Hg, atmospheric pressure on Earth).

The chamber was equipped with three high-pressure sodium lamps which provided illumination from ~ 85 to 135 W/m^2 for plants. These light conditions are assumed closely imitate Martian.

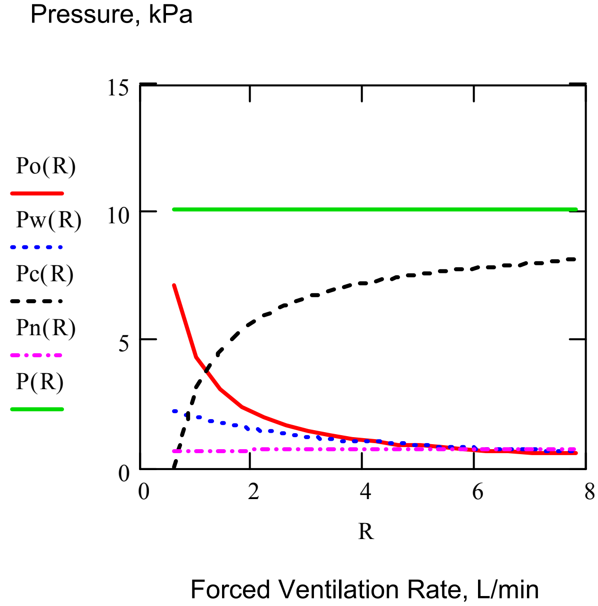
This equipment provides the ability to simulate a wide range of conditions expected to be encountered on Mars. Results of preliminary tests performed to obtain numerical values of constants for further calculations are shown in Table 2.

Fig. 2. Thermotron – set up for plant growth simulation under Martian conditions (KSC NASA).

These preliminary numerical values (presented in Table. 2, APPENDIX, IV) were used for direct application or calculation of the mathematical model constants.

NUMERICAL ESTIMATES

Changes in the MG atmospheric composition were calculated using the mathematical theory developed above and the standard version of MathCAD 2000 for this greenhouse configuration (APPENDIX, II).
Results of the calculation are presented on the graphs below.



Proper region of ventilation parameters obtained on the basis of steady-state calculation cycle (Atmospheric Management Cycle, APPENDIX, V):

Po(0.63)	6.825	kPa
Pw(0.63)	2.233	kPa
Pc(0.63)	0.387	kPa
Pn(0.63)	0.647	kPa
P(0.63)	10.092	kPa

Fig. 3. MG prototype atmospheric composition with developed plant biomass under different gas exchange rates (forced ventilation).

The initial atmospheric composition was chosen on the basis of the following assumptions:

1. Partial oxygen pressure > ~3 kPa at least (Wheeler R. M. et al., 2000)
2. Partial carbon dioxide pressure > 0.05 kPa, but < ~2 kPa (Wheeler R. M. et al., 2000);
3. Water vapor pressure should create RH ~ 60 to 70 % (Wheeler R. M. et al., 2000);
4. Neutral gases do not influence plant growth at any anticipated pressures;
5. Steady-state calculation cycle (APPENDIX, II & V);
6. 10 kPa is assumed for this model total pressure value (pressure differential in this case is ~ 9 kPa for Mars and Thermotron experimentation).

For another assumed DG total pressure atmospheric composition could be recalculated on the basis of algorithm suggested.

Here: Po(R) = partial pressure of oxygen in DG atmosphere, kPa;

Pc(R) = partial pressure carbon dioxide, kPa;

Pn(R) = partial pressure of neutral gaseous, kPa;

Pw(R) = partial pressure of water vapor, kPa;

P(R) = total Martian DG atmospheric pressure, kPa;

R = total gas exchange rate, L/min.

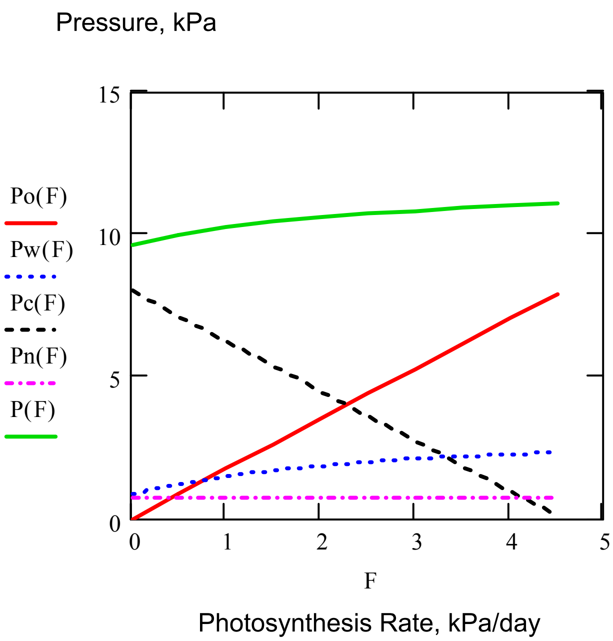


Fig. 4. MG prototype atmospheric composition with plant biomass (photosynthesis rate) changing from seeds to developed plant.

(Partial pressures of atmospheric constituents are marked as for the previous graphs:

Po(F) = partial pressure of oxygen in DG atmosphere, kPa;

Pc(F) = partial pressure carbon dioxide, kPa;

Pn(F) = partial pressure of neutral gaseous, kPa;

Pw(F) = partial pressure of water vapor, kPa;

P(F) = total Martian DG atmospheric pressure, kPa;

F = photosynthesis rate in kPa/day.)

This graph shows the transition process of biomass growth (and consequently photosynthesis rate increasing), which is assumed not to be limited by the system design. The ventilation rate is the rate of changes of air inside enclosure during the process of plant cultivation. Total pressure rises because the rates of photosynthesis and plant transpiration increase during the process of plant biomass growth.

It is seen that at the stage of germination, the partial pressure of oxygen is not enough for plants root respiration, which requires at least ~ 3 kPa, (Wheeler et al,, 2000). To ensure that the roots have adequate oxygen, the partial pressure of oxygen in the air might need to be elevated. Thus, we assume that the partial pressure of oxygen required in the air to be about 6 kPa. To achieve this, an additional stock of oxygen will need to be provided during the early stages of plant growth. An example of enriching with oxygen is presented in Fig. 5. In this case, oxygen is added at a continual rate. For a real system, it would be simpler to add a fixed quantity of oxygen, if this can be done without generating excessive pressures.

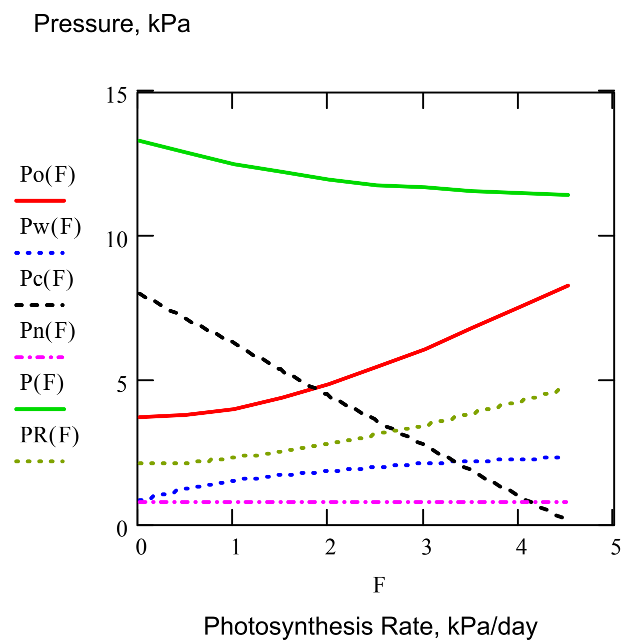


Fig. 5. Corrected with additional stock of oxygen version of MG atmospheric composition.

(Po = partial pressure of oxygen in DG atmosphere, kPa;

Pc = partial pressure of carbon dioxide, kPa;

Pn = partial pressure of neutral gaseous, kPa;

Pw = partial pressure of water vapor, kPa;

P = total Martian DG atmospheric pressure, kPa;

R = total gas exchange rate, L/min;

PR(F) = oxygen accumulation rate, kPa/day.)

The change of Martian Greenhouse atmospheric composition over time is shown in Fig. 6 for 180 days of plant biomass development.

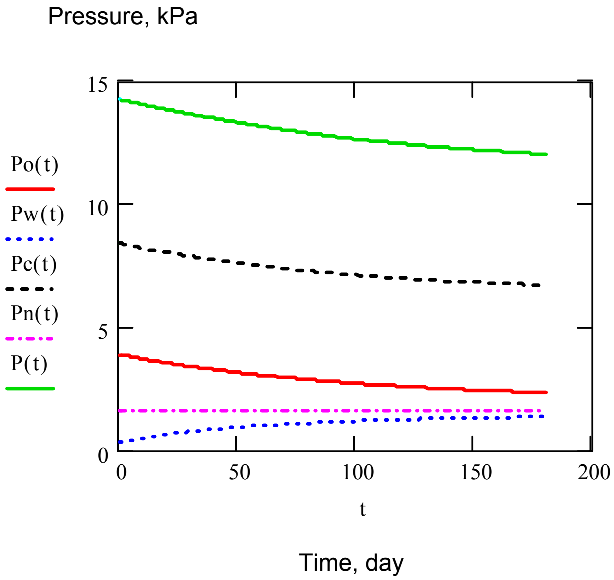


Fig. 6. Martian DG atmospheric composition during 180-days plant biomass production cycle.

It is seen from Figure 6 that a regime of Martian DG gas exchange exists that could provide more or less constant atmospheric conditions for plant cultivation during a relatively long period of time.
So, from analysis of the results of calculations, the following preliminary conclusions were derived:

- Martian carbon dioxide could be used for inflation and further ventilation of a MG while maintaining concentrations of the main atmospheric gases at levels acceptable for plant growth;
- Initial stages of MG implementation require a preliminary stock of oxygen that could be used during plant germination;
- The main constituents of MG atmospheric composition are expected to be: carbon dioxide ~ 1.0 kPa; oxygen ~ 6.0 kPa; water vapor ~ 3.0 kPa. (These conditions are assumed to be acceptable for plants and should be tested in long - term experiments).

These results allow us to formulate in general terms the scheme of Atmospheric Management Cycle (AMC) for MG (Table. 3, APPENDIX, V).

CONCLUSIONS

From our theoretical estimates using reasonable assumptions and some preliminary measurements of a MG prototype operating in simulated Martian conditions we can conclude:

1. It is possible to create and maintain an artificial atmosphere of suitable for plant growth by using the Martian atmosphere with minor additions (initial oxygen, and may be liquid water);
2. This initial oxygen what could be transported from Earth or collected on Mars for 3 crew members is about 16 kg;
3. The initial amount of liquid water for proper level of humidity what could be collected on the Mars (not transported from the Earth) for 3 members of the crew (Rygalov et al., 2001) is about 300 kg (sanitary needs are not included).
4. This water could be maintained without losses during a long period of time within closed water cycle (with small periodical additions from outside to compensate unavoidable losses).
5. The amount of oxygen what could be collected during period of MG automatic operation together with initial amount for plant germination could be about 120 kg and can be considered as emergency stock (for 3 person it provides ~ 45 days, ~ 1.5 Earth's months survival in the case of some accidents).

The approach presented for growing plants on Mars may make bio-regeneration more cost effective by using in-situ resources (Table. 4, APPENDIX, VI). We expect that further improvements might include use of Martian soil as a substrate, and use of Martian water, particularly if it is readily available as is suggested on the basis of early data from the Mars Odyssey mission (Wheeler et al., 2000).

SCENARIO OF MARTIAN DG DEVELOPMENT AND IMPLEMENTATION

From Table 1 (APPENDIX, III) it is seen that the main gases for maintaining biological processes (CO_2, O_2, H_2O as vapor) are present in the atmosphere of Mars but in undesirable amounts and proportions for terrestrial plant growth. So, there is, probably, no need to transport these gases to Mars from the Earth. The technological task is to collect the gases that are lacking (oxygen, mainly) in the required amounts on the Martian surface and then to start plant cultivation. Water vapor will appear in the process of evaporation in a proper amount (Wiederhold, 1997; Rygalov et al., 2002) once liquid water for plant cultivation will be collected (Levin et al., 2000). (But all these planning actions require producing the estimates for mass of the technological equipment in comparison to the mass of resources collected.) Hence, the approximate scenario of MG implementation on Mars could be as shown in Table 5 (APPENDIX, VII).
It is seen from the Table. 3 (APPENDIX, V), that technologies for the creation and maintenance of artificial atmospheres on the basis of the Martian atmosphere are important. These technologies are not yet completely

available, so there is a need for their development. This approach will depend on:

- optimal environmental requirements for plant cultivation (illumination, CO_2 level, temperature, O_2 level , relative humidity, etc.) that must be achieved;
- natural environmental composition of the planet.

FUTURE WORK

The approach presented for growing plants on Mars may make bio-regeneration more cost effective by using in-situ resources. We expect that further improvements might include use of Martian soil as a substrate, and use of Martian water, particularly if it is readily available as is suggested by early data from the Mars Odyssey mission (Wheeler R. M. et al., 2000). Validation of this approach will require that we:

1. Determine the optimal environmental requirements for growing terrestrial plants using Martian resources; time of testing ~ 1 year, including period of experimental preparation (with proper funding). This will require both literature search and further experimentation.
2. Testing of the technologies of maintaining the MG internal environment using the simulated Martian environment; approximate time of testing ~ 3 year, including period of preparation (with proper funding).

ACKNOWLEDGMENTS

Thanks to:

- University of Florida Agricultural and Biological Engineering Department (theoretical and psychological support);
- BOEING Corp. (theoretical and psychological support);
- NASA KSC Life Sciences Department (theoretical, experimental, psychological support);
- Dynamac Corporation (experimental, financial, psychological support);
- INS USA (organizational and psychological support);
- All colleagues and friends around the world (general support).

REFERENCES

1. Closed System: Man-Higher Plants (4-th Munths Experiment). Edit. by prof. G. M. Lisovsky. Novosibirsk: Nauka, 1979, 160 p.
2. Devlin R. M. Plant Physiology. D. Van Nostrand Company, 1975, 600 p.
3. Experimental Ecological Systems Including Men. Edit. by Ac. V. N. Chernigovsky. The Problems of Space Biology, V. 28. Moscow: Nauka,1975, 312 p.
4. Henderson S. M. , Perry R. L. , Young J. H. Principles of Process Engineering. ASAE. The Society for Engineering in Agricultural, Food and Biological Systems, 1997, 353 p.
5. Hiscox J. A. Biology and the Planetary Engineering of Mars.http://spot.colorado.edu/~marscase/cfm/articles/biorev3.htr, 2000, 22 p.
6. Hodgman C. D. Handbook of Chemistry and Physics, A Ready – Reference book of Chemical and Physical Data. Chemical Rubber Publishing Co., Cleveland, Ohio, 1949, 2737 p.
7. Johnson A. T. Biological Process Engineering. John Wiley & Sons, Inc. 1999, 732 p.
8. Ksanfomality L. V. The planets rediscovered. Moscow: Nauka, 1978, 152 p.
9. Levin G. V. and Levin R. L. Liquid Water and Life on Mars.http://www.biospherics.com/mars/spie2/spie98.htm, 2000, 14 p.
10. Rygalov V. Ye., Bucklin R. A., Drysdale A. E., Fowler P. A., Wheeler R. M. The Potential for Reducing the Weight of a Martian Greenhouse. Proceedings of the 31st International Conference on Environmental Systems, ICES2001, 2001-01-2360, SAE, 2001, 14 P.
11. Rygalov V. Ye., Fowler P. A., Metz J. M., Wheeler R. M., and Bucklin R. A. Water Cycles in Closed Ecological Systems: Effects of Atmospheric Pressure. Life Support & Biosphere Sciences, Vol. 8, No. 2, Part 2, 2002 a, (in press).
12. Wallace J. M. and Hobbs P. V. Atmospheric Science (An Introductory Survey).University of Washington, Academic press, 1977, 469 p.
13. Wiederhold P. R. Water Vapor Measurement. Marcel Dekker,Inc. 1997, 357 p.
14. Wheeler R. M. and Martin – Brennan C., Mars Greenhouses: Concepts and Challenges, Proceedings From a 1999 Workshop, NASA Technical Memorandum 2000 – 208577, NASA KSC, 2000, 141 p.

APPENDIX

I. SOLUTIONS FOR MAIN GASEOUS DYNAMIC COMPONENTS OF MG ATMOSPHERE

1. Inflation & maintaining of pressure.

Inflation could be described by formula:

$P = Po*(1 + F/L) + (Pi – Po*(1 + F/L))*exp(- (L/V)*t)$

Where: P = total pressure inside inflatable structure, kPa;
Po = total pressure of original Martian atmosphere, kPa:
Pi = initial pressure inside inflatable structure created by stock of oxygen and water vapor, kPa;
F = rate of inflation, m3/sec;
L = leaks rate, m3/sec;
V = volume of enclosure, m3;
t = time, sec.

Leaks could be described by formula:

$P = Po + (Pm – Po)*exp(- (L/V)*t)$

Where: Pm = up limit of pressure inside enclosure, kPa;
Other signs are the same as in basic equation.

2. Photosynthesis of plants.

Partial pressure of the main gaseous constituents could be described by the following formulas:

$Pc = (Poc – PH/L) + (Pcm – (Poc – PH/L))*exp(- (L/V)*t)$

$Ps = (Pos + PH/L) + (Psl – (Pos + PH/L))*exp(- (L/V)*t)$

Where: Pc = partial pressure of CO_2, kPa;
Ps = partial pressure of O_2, kPa;
PH = rate of photosynthesis, m3/sec;
Pcm = maximum limit of partial CO_2 pressure, kPa;
Psl = low limit of O_2 pressure, kPa;
Poc = outside pressure of CO_2, kPa.
Other signs are the same as in basic equation.

3. – 4. CO2 supplying & O2 removing.

Ventilation process could be described by formulas:

$Pc = F*Poc/R + (Pcl – F*Poc/R)*exp(- (R/V)*t)$

$Ps = Psm*exp(- (R/V)*t)$

Where: Poc = outside CO_2 pressure, kPa;
Pcl = low limit of CO_2 pressure inside greenhouse, kPa;
Psm = up limit of O_2 pressure inside greenhouse, kPa.

II. NUMERICAL CALCULATIONS FOR MG ATMOSPHERIC COMPOSITION MANAGEMENT ALGORITHM (Continuous cultivation during period 180 days, Fig. 6)

MG Atmospheric Composition vs Ventilation Rate (under ~ 10 kPa of total pressure)
(growing plants, arising photosynthesis)

PNe 0.05 kPa   PCe 0.35 kPa   R 2.3 L/min   P 10.0 kPa

Psw 3.1 kPa   Pcw 1.4 kPa   A 0.37 m3/min   B 0.13 m3/min

a 0.43

t 0 1 180

$$Po(t)\quad \frac{4.7\,(1\quad 1\,\exp(\quad 0.01\,t))}{R}\quad 3.9\,\exp(\quad 0.01\,t)$$

$$Pw(t)\quad Psw\,\frac{1\quad \dfrac{A\;Pcw}{[\,B\quad a\,[4.7\,(1\quad 1\,\exp(\quad 0.01\,t))]\,]\;Psw}}{1\quad \dfrac{A}{B\quad a\,[4.7\,(1\quad 1\,\exp(\quad 0.01\,t))]}\quad \dfrac{R}{B\quad a\,[4.7\,(1\quad 1\,\exp(\quad 0.01\,t))]}}$$

$$Pc(t)\quad \frac{P\quad Pw(R)}{PCe\quad PNe}\,PCe\quad \frac{4.7\,(1\quad 1\,\exp(\quad 0.01\,t))}{R}$$

$$Pn(t)\quad \frac{P\quad Pw(R)}{PCe\quad PNe}\,PNe$$

$$P(t)\quad Po(t)\quad Pw(t)\quad Pc(t)\quad Pn(t)$$

Notes:

1. **Symbols:**

PNe = outside pressure of neutral gases, kPa;
PCe = outside pressure of carbon dioxide, kPa;
Psw = saturated vapor pressure at ~ 23 ^{o}C, kPa;
Pcw = saturated vapor pressure at the temperature of the coolant unit ~ 14 C, kPa;
R = DG model gas exchange rate, L/m2/min;
P = total pressure in the greenhouse model, nominally ~ 10 to 15 kPa;
A = condensation constant for DG model, measured in experiments, m3/min;
B = evaporation constant for DG model, measured in experiments, m3/min;
a = conversion factor between photosynthesis rate and transpiration rate, dimensionless;
t = time, days;
Po(t) = oxygen partial pressure;
Pc(t) = carbon dioxide partial pressure;
Pw(t) = water vapor partial pressure;
Pn(t) = neutral gases partial pressure;
P(t) = total pressure.

2. **Assumptions for algorithm:**

- There is no water vapor or oxygen outside the DG structure;
- Oxygen is supplied initially;
- Specific rate of plant biomass growth is ~ 0.01 (g/g/day) (equal to the specific rate of oxygen supply at initial stages of MG operation: germination). This should be determined directly and more accurate in further tests;
- Initial values of system constants and outside atmospheric composition could be changed, depending on the DG design, planetary location and further system improvements;
- Temperature value is assumed about 20 ^{o}C, which should be provided by proper MG systems and functional unites.

III. *TABLE. 1.* COMPARISON OF ATMOSPHERIC COMPOSITIONS OF MARS AND EARTH.

Species	Mars (surface)	Earth (sea level)	Comments
CO_2	~ 0.667 kPa (953,200 ppm)	~ 0.0334 kPa (330 ppm, minor)	Hodgman, 1949; Wallace et al., 1977; Hiscox, 2000
N_2	~ 0.02 kPa (27,000 ppm)	~ 79.17 kPa (780,000 ppm)	Hodgman, 1949; Hiscox, 2000
Ar	0.0112 kPa (16,000 ppm)	~ 0.95 kPa (9,400 ppm)	Hodgman, 1949; Hiscox, 2000
O_2	0.00091 kPa (1,300 ppm, minor)	~ 21.32 kPa (210,000 ppm)	Hodgman, 1949; Hiscox, 2000
CO	0.00049 kPa (700 ppm, minor)	0.0012 kPa (~ 12 ppm, very minor)	Nitta et al., 1996; Hiscox, 2000
H2O, Vapor	0.00021 kPa (300 ppm, minor)	0 to ~ 4.3 kPa (~ 3.2 kPa, ~ 31500 ppm, saturated vapor at ~ 25 °C)	Hodgman, 1949; Wallace et al., 1977; Hiscox, 2000; Levin et al., 2000
Ne	$1.75*10^{-6}$ kPa (2.5 ppm, very minor)	0.0012 to 0.0018 kPa (12.0 to 18.0 ppm, very minor)	Hodgman, 1949; Hiscox, 2000
Kr	$0.21*10^{-6}$ kPa (0.3 ppm, very minor)	0.0001 kPa (1.0 ppm, very minor)	Wallace et al., 1977; Hiscox, 2000
Xe	$0.56*10^{-6}$ kPa (0.8 ppm, very minor)	-	Hogdman, 1949; Hiscox, 2000
O_3, Ozone	$0.028*10^{-6}$ to $0.14*10^{-6}$ kPa (0.04 to 0.2 ppm, extremely minor)	~ 0.0012 kPa (0 to 12 ppm, very minor)	(Ozone's layer protecting the Biosphere of the Earth.) Wallace et al., 1977; Ksanfomality, 1978; Hiscox, 2000
H_2	-	0.0051 to 0.01 kPa (50 to 100 ppm, minor)	Hodgman, 1949; Hiscox, 2000
He	-	0.00041 to 0.00051 kPa (~4.0 to 5.0 ppm, very minor)	Hodgman, 1949; Hiscox, 2000
Total pressure	~ 0.7 kPa (variable)	~ 101.5 kPa (variable)	

IV. *TABLE. 2.* PRELIMINARY NUMERICAL VALUES OF THE EXPERIMENTAL DG SYSTEM PARAMETERS MEASURED IN THE PROTOTYPE.

##	Parameter	Numerical value	Comments
1	Level of illumination	~ 85 to 135 W/m^2 PAR	Measured in Thermotron
2.	Soil evaporation rate	~ 0.13 to 0.19 L/m^2/day	Measured inside Dome
3	Plant transpiration rate	~ 2.3 L/m^2/day	Measured inside the Dome
4	Condensation rate (variable)	~ 0.37 to 0.53 L/m^2/day	Measured inside the Dome
5	Ventilation rate (variable)	~ 0 to 5.3 L/min (average	Measured inside the Dome
6	Plant photosynthesis rate	~ 4.7 L/m^2/day (max)	Measured approximately
7	Plant growth rate	~ 0.01 g/(g*day)	Measured approximately

V. MARTIAN GREENHOUSE ATMOSPHERIC MANAGEMENT CYCLE

TABLE. 3. SCENARIO OF MARTIAN GREENHOUSE ATMOSPHERIC MANAGEMENT CYCLE.

##	Stage of implementation	Combining elements	Description of stage
1	Initiation: inflation (pump in CO_2); preparation (add O_2 and water, brought from the Earth or collected on Mars); and germination (maintain pO_2 in the root zone)	Initiation (including inflation)	Inflation of deployable structure by using Martian CO_2, and an internal source of O_2 and water for achieving the appropriate pressures and atmospheric composition.
2	Atmospheric management cycle	Plants photosynthesis	Decreasing of CO2 content due to the process of photosynthesis until a certain level, ~ 0.1 kPa, is reached Increasing of O2 content in the process of photosynthesis of plants till a certain level, ~ 5 kPa, is reached
3		Removing excess oxygen (Some O_2 will be continuously required for plant respiration).	Pumping of atmosphere of greenhouse to outside atmosphere or storage tank (with using of oxygen separator).
4		Supplying carbon dioxide	Pumping outside atmosphere into the Greenhouse.
5	Ethylene & Trace gases removal	Elimination of toxic gases	Filtration and catalytic oxidation technologies

VI. ECONOMICAL BENEFITS FROM USING OF NATIVE MARTIAN ATMOSPHERIC RESOURCES

TABLE. 4. COMPARISON BENEFITS FROM ISRU - ORIENTED MG (for 3 crew – members).

##	Main Atmospheric Constituents	Mass of constituents in the case of MG Complete Closure, kg	Mass for ISRU oriented MG, kg	Estimates for expenditures during automatic MG operation, kg	Comments
1	Carbon Dioxide	~ 146	0	- ~ 146 (collected in biomass from outside atmosphere)	
2	Oxygen	~ 78.8	~ 15.8	+ ~101.6 (accumulation in the plants photosynthesis)	Initial stock of oxygen to start plant germination
3	Water	~ 300 (liquid water)	0	~ 0 (because of Closed Water Cycle)	
4	Total mass of constituents	~ 524.8	~ 15.8		Significant decreasing of initial stock of substances for ISRU oriented MG

VII. SCENARIO OF MARTIAN DG DEVELOPMENT AND IMPLEMENTATION

TABLE. 5. SCENARIO OF DG IMPLEMENTATION ON MARTIAN SURFACE.

Number of stage	Stage description	Required technologies	Approximate time of the stage development, days
1	Arrival on the planet, installation and inflation of the physical shell, mounting and startup of engineering equipment,	Engineering technologies developed for Earth, inflation of elastic shell in rarified atmosphere, etc.	Up to ~ 7 (Earth's), depends on DG sizes and level of technical & technological development
2	Collection of resources, creation and start of artificial climate and environment functioning including water cycle, etc.	Collection of biologically active gases and water from the outside atmosphere, collection and correction & enrichment of native soil, etc.	~ n*30(Earth's), where n ~ 1; could take a month
3	Initiation of plant growth: planting and cultivation of different crops, accumulation and extraction of oxygen, etc.	Technologies developed for Earth's greenhouses, technologies of concentration of atmospheres enriched by oxygen, etc.	~ 90 to 100, depends on the time of development of the slowest crop and artificial environment & regime cultivation
4	Arrival of personnel, extension of area of MG, improvement of technologies requiring human control, etc.	Technologies of isolation of native areas of soil and its treatment, etc.	Up to ~ n*30(Earth's), where n = 1, 2, …; depends on technical & technological development
5	Initiation of closed cycle of air exchange, nutrient supply and water recycling; and of harvesting, processing and transportation of solid plant matter, etc.	Technologies developed for Controlled Ecological Life Support Systems (Chernigovsky, 1975;Lisovsky, 1979), etc	Up to ~180 and longer (Chernigovsky, 1975;Lisovsky, 1979)
6	Possible decreasing of MG functioning and conservation due to leaving a base by crew.	Conservation technologies, including long-terms seeds maintenance	~ 30, depends on degree of DG development