NASA MarsPort Engineering Design Student Competition 2001

Supporting Oasis Life (SOL)

MCCS/MAV

by

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Detailed Design Review Report

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Abstract

Manned missions to Mars will require the development of new technologies that will minimize payload launch from Earth. Utilizing the martian atmosphere to produce propellants and consumables on the surface of Mars can significantly reduce the amount of payload transported from Earth for a manned mission to Mars. One such method requires a reaction of feedstock hydrogen from Earth with the abundant carbon dioxide in the atmosphere of Mars to produce methane, oxygen, and water. Production of consumables (breathable air and water) and propellants (methane and oxygen) on the martian surface also requires reliable long-term storage. Therefore, the task of designing both cryogenic and non-cryogenic storage tanks necessitates a thorough understanding of the surface conditions on Mars, characteristics of cryogenic storage, and effective methods of propellant transfer. System reliability, minimal mass, and minimal power consumption are design constraints on which a Mars Cryogenic and Consumables Station (MCCS) are based.

Using current technologies a realizable MCCS was designed that has an approximate mass of 8.4 metric tons and a maximum power consumption of 28.2 kW for normal operations. The MCCS consists of nine thermally controlled tanks. The tanks are cylindrical with spherical end caps and are constructed of anodized aluminum alloy 6210. Cryogens are maintained on the surface using an MLI system and cryocoolers. H_2O is stored as a liquid in a heated tank. An Air Mixing Station was designed that provides quality breathing air to the crew. The breathable air and water are transferred to the habitat using Teflon® hoses. The Mars Ascent Vehicle (MAV) propellant tanks are equipped with a thermal control system and serve as backup tanks to the MCCS propellant tanks. The system described in this study was designed with primary and secondary systems for complete redundancy.

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Nomenclature

AMS: Air Mixing Station

BA: Breathable Air

BG: Buffer Gas

C-8: Cerachrome-8®

CM: Center of Mass

CTS: Cooling-Transfer System

DRM: Design Reference Mission [14]

ERV: Earth Return Vehicle

EVA: Extra Vehicular Activity

G\E: Graphite Epoxy

HU: Head Unit

ISRU: In-Situ Resource Utilization

k: Thermal Conductivity

MAV: Mars Ascent Vehicle

MCCS: MarsPort Cryogenics Consumables Station

MLI: Multi-Layer-Insulation

mt: metric ton

Q: Heat removed or gained

ρ: Density

TCS: Thermal Control System

UTS: Ultimate Tensile Strength

VJ: Vacuum Jacketed

1. Introduction

Scientific information gathered about Mars in the last fifty years from the Mariner, Viking Pathfinder, and Mars Global Surveyor missions has increased curiosity about the planet. Mars, the planet most like the Earth, has seasons and days similar in length, polar caps that change with season, and is the only other planet in the solar system where liquid water is believed to have flowed across its surface [24]. Liquid water is a prerequisite for life as we know it, and many humans wonder if we are alone in the universe. With Mars the likely candidate for life, humans are eager to make the 300 million mile voyage to search for the answers to this query and to investigate its geological history in hopes of learning more about our own planet.

One obstacle that prevents immediate human exploration of Mars is the large amount of consumables and propellant payload that is required to support a crew of six for the 500-day surface mission. Therefore, identification and utilization of the resources available on Mars is essential to the success of human exploration of the planet. To that end, one of the most abundant resources on the planet is atmospheric carbon dioxide. To reduce payload to Mars, it is proposed that a feedstock of hydrogen (H_2) be sent to the planet to produce consumables and propellants. Reacting the H_2 with the atmospheric carbon dioxide (CO_2) can produce crew consumables (breathable air and water) and the propellants (methane and oxygen) needed for the return to Earth. The storage of these consumables and propellants on the surface of Mars is the focus of this study. Sections 2 through 6 provide a detailed overview of the system that was designed to store these consumables and propellants. The sections that follow these give details on the design of each subsystem.

2. Mission Overview

Manned missions to Mars will occur in a series of launches due to the large payload requirements. The Reference Mission Version 3.0 Addendum outlines the first three launches: the Cargo-1 Lander, an Earth Return Vehicle (ERV), and the Crew Habitat [10]. The Cargo-1 Lander includes a nuclear power plant, the Mars Ascent Vehicle #1 (MAV #1 henceforth referred to as MAV), the In-Situ Resource Utilization (ISRU) plant, a feedstock of H_2, and the MarsPort Cryogenic and Consumables Station (MCCS). The Earth Return Vehicle (ERV) will remain in orbit around Mars until the crew returns to Earth. Two years later the Crew Habitat will arrive, carrying another MAV (MAV #2) and surface operations will begin. A complete mission timeline is provided in Appendix A.

The ISRU plant in the Cargo-1 Lander must produce consumables and propellants prior to crew liftoff from Earth. Therefore, once on the surface, the ISRU plant will react the feedstock H_2 with the CO_2 in the atmosphere to produce methane (CH_4) for use in the MAV as a propellant and water (H_2O) for the crew. Part of the H_2O will be electrolyzed to produce liquid oxygen (O_2) for breathable air (BA) and propellant. Also, argon (Ar) and nitrogen (N_2) will be extracted from the atmosphere to be used as buffer gases in BA and pneumatic tools [34].

A mission of this type will require an effective and efficient storage facility for the propellants and consumables produced by the ISRU plant. The MCCS will serve as this facility. The design of the MCCS is the focus of this study. Design objectives for the MCCS have been outlined and are presented here.

3. Design Objectives

The ISRU plant is assumed to be a black box from which the outputs are assumed constant per day. The production rates from the ISRU plant, the required mass, and production time of each constituent are shown in Table 1.

Table 1: Constituent Output Conditions from the ISRU and Desired Quantities.

Constituent	Purpose	Rate [kg/day]	Output Temperature [K]	Output Pressure [kPa]	Required Mass [kg]	Production time [days]
CH_4	Propellant	22.9	525	152	5800	253
O_2	Propellant	53.2	300	3040	20200	380
H_2O	Consumable	27.8	525	152	10000	360
O_2	Consumable	53.2	300	3040	4500	85
N_2/Ar	Consumable	8.7	240	30.4	3900	448

Having identified the production rates and required mass of each ISRU plant output a MCCS must satisfy specific design objectives. The MCCS must:

- **Liquefy** CH_4, O_2, and N_2/Ar
- **Store** consumables and propellants for six years
- **Distribute** consumables to the habitat and propellants to the MAV
- Utilize an effective **thermal management system**

Additionally, the following criteria are used in the design the MCCS:

- Store H_2O in solid or liquid phase
- Minimize liftoff mass and volume
- Minimize power consumption
- Ensure crew safety
- Capture and liquefy all boil-off gases
- Use rigid tanks on the MAV
- Recycle as much H_2 as possible
- Complete propellant production in 18 months
- Allow for rover access and Extra-Vehicular Activity (EVA) servicing
- Determine the "most thermally efficient use of resources"
- Land between +/- 15^o degrees of the equator

The landing site requirement stated above provides additional design constraints. Temperature, pressure, and dust storms are primary factors that affect the surface of Mars. Daily temperature variations recorded on the Viking landing (1976) and Pathfinder (1997) missions ranged from 184 to 242 K and 200 to 259 K respectively [3, 24]. However, these measurements were taken near 40°N latitude. It is assumed that the temperature experienced by the MCCS will be slightly higher at the lower latitudes and will not vary significantly with season. Considering the temperature variations detailed above, the expected daily temperature range selected for design purposes is 150 to 300 K. This temperature range is conservative but will ensure a robust design. Pathfinder and Viking Landers also recorded atmospheric pressure measurements from 6 to 9 mbar [24]. However, depending on surface elevation the pressure can range from 2 to 10 mbar. For design purposes the atmospheric pressure is considered a near vacuum. Recommended landing sites with similar surface conditions and desirable characteristics are given in Appendix B.

Noting the design objectives for a MCCS and the surface conditions detailed here, a MCCS is now presented. Additional assumptions made in the design of the MCCS are detailed in Appendix C.

4. MarsPort Cryogenics and Consumables Station Overview

The MCCS consists of four subsystems: the thermally controlled tanks, Cooling-Transfer System (CTS), Air Mixing Station (AMS), and the consumables and propellant transfer hoses. Table 2 illustrates how each subsystem of the MCCS alone satisfies at least one of the design objectives stated in Section 3. Details of each subsystem are provided below.

Table 2: MCCS Design Objectives Satisfied.

	Design Objectives			
MCCS Subsystems	Liquefaction	Storage	Distribution	Thermal Management
Cooling-Transfer System	X		X	X
Thermally Controlled Tanks	X	X		X
Air Mixing Station		X	X	
Transfer Hoses			X	

To effectively store the ISRU plant outputs, the O_2, CH_4, and buffer gas (BG) mixture (N_2/Ar) are stored cryogenically and the H_2O is maintained as a liquid in a heated tank, which is discussed in Section 9. The desired storage conditions of each are shown in Table 3. To achieve these conditions all ISRU output conditions must be liquefied.

Table 3: Storage Conditions.

	Storage Conditions		
Constituent	Temperature [K]	Pressure [kPa]	Phase
CH_4	100	132	Liquid
O_2	80	132	Liquid
H_2O	285	100	Liquid
N_2/Ar	90	690	Liquid

The liquefaction and distribution of the ISRU plant outputs will be accomplished using a Cooling-Transfer System (CTS). The CTS consists of specially designed transfer pipes for each ISRU plant output, condensers, and associated valves. These pipes route the fluid from the ISRU plant to the respective storage tank. The pipes for the cryogens are sized to maximize heat dissipation of the ISRU plant output gas prior to entering the condenser, reducing condenser workload. The H_2O pipes are designed to retain the heat to aid in the warming of the water. Redundant CTS's for each tank ensure that the fluid is transferred to the storage tank.

The MCCS consists of nine thermally controlled storage tanks. There are three O_2 tanks, two CH_4 tanks, two H_2O tanks, and one BG tank, all cylindrical in shape. There is one spherical Ar tank. This tank is a component of the AMS. The tanks are constructed of anodized aluminum alloy AA 6201. The number of tanks and arrangement was determined by the ISRU plant production rates to maintain a centrally located CM. Figure 1 shows the tank arrangement on the MCCS.

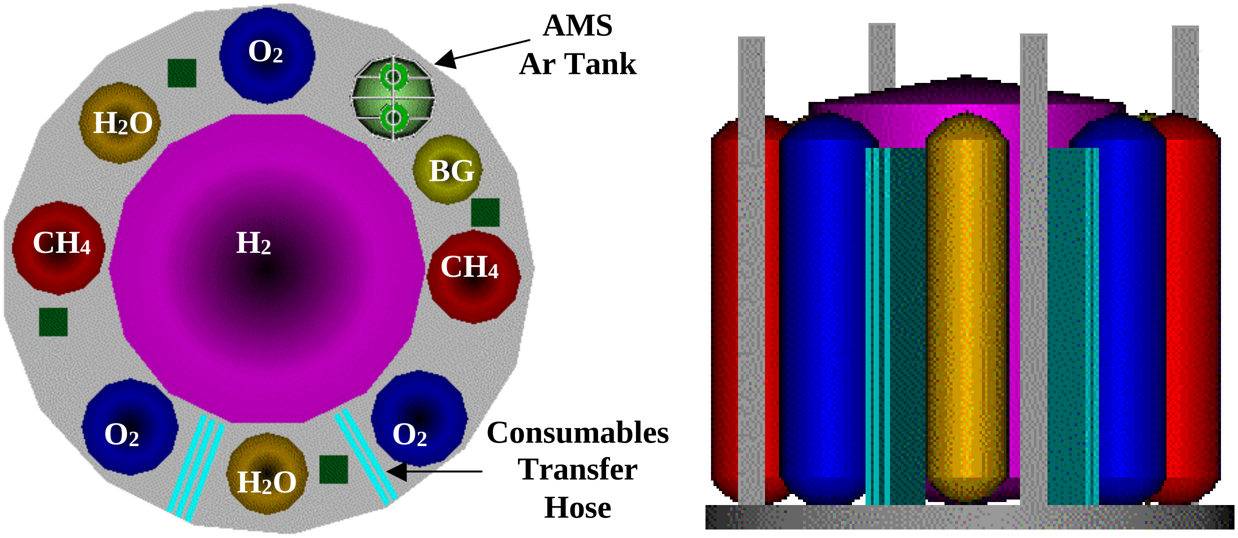


Figure 1: MCCS tank arrangement with AMS and consumables transfer hoses.

The thermal control system (TCS) of each tank maintains the desired storage conditions. The TCS consists of a Multi-Layer-Insulation (MLI) system and cryocoolers or heaters. Cryocoolers are used to maintain the cryogens. The water tanks are equipped with heating elements to prevent freezing.

The Air Mixing Station (AMS) produces breathable air by mixing O_2 and BG. The AMS separates the BG into gaseous N_2 and liquid Ar in a separation chamber. The separated N_2 and Ar are mixed with gaseous O_2 in a regulated manner producing safe BA in the following concentrations: 21% O_2, 71% N_2, 4% Ar. As a result of the separation process, excess Ar is diverted to a spherical tank for use in pneumatic tools and other mechanical processes. A second AMS is included for redundancy. The AMS is shown in figure 2 below.

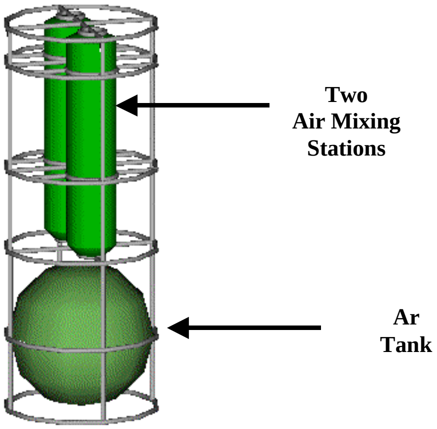


Figure 2: AMS with argon tank.

Distribution of the consumables to the habitat is done via hoses. The air and water hoses are made of Teflon® providing superior strength and durability at martian ambient conditions. There is one primary and one secondary hose for each consumable, a total of four transfer hoses each 500 m in length. The hoses are constructed of 100 five-meter lengths. This allows for leak detection and isolation. A Head Unit (HU) is located every 25 m, which contains a pump, flow meters and flow control devices. If a primary transfer line experiences a mechanical or material failure the secondary hose is used.

The consumables stored by the MCCS are secondary caches for the crew since the crew will bring with them enough H_2O and BA for the entire 500-day surface mission [14]. Thus, the primary function of the MCCS is to store propellants. To ensure mission success and crew safety, the MAV propellant tanks serve as the MCCS backup propellant tanks. There are five thermally controlled MAV tanks, four O_2 tanks and one CH_4 tank. In the event of a MCCS tank failure the propellants are transferred autonomously to the MAV propellant tanks with hoses.

The transfer of propellants to the MAV in an emergency situation or for MAV liftoff is accomplished using flexible vacuum jacketed (VJ) hoses. The ability to control the boil-off of the cryogen using variable temperature cryocoolers enables the transfer of the propellant to the MAV tanks without using pumps. To reduce MAV liftoff mass the cryocoolers, condensers, and transfer hoses are deployed prior to MAV launch. The MAV and the deployment of the transfer and cooling system are shown in figure 3.

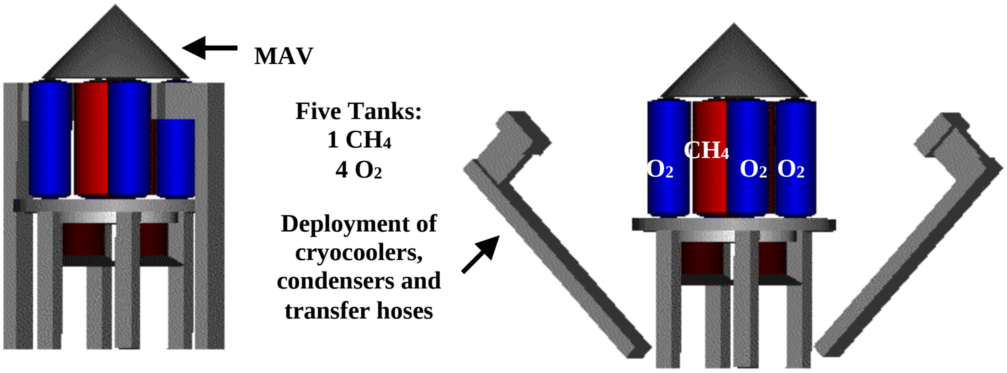


Figure 3: MAV with deployable components.

For the MCCS described here there are 14 thermally controlled tanks (nine on the MCCS and five on the MAV), two AMS's, a CTS for each tank, and consumables and propellant transfer hoses. Maximum mass and power totals for this design are given in Table 4.

Table 4: MCCS Mass and Maximum Power Consumption.

MCCS Subsystems	Mass [mt]	Power [kW]
Cooling-Transfer System	0.6	8.5
MCCS and MAV Thermally Controlled Tanks	6.8	1.1
Air Mixing Station	0.4	0.3
Transfer Hoses	0.6	18.3
MCCS Totals	8.4	28.2

5. Payload Arrangement

The Cargo–1 Lander consists of several surface components detailed in the Design Reference Mission (DRM) 3.0. The components considered in the design of the MCCS are listed below:

1. Mars Ascent Vehicle (MAV)
2. Feedstock Hydrogen
3. ISRU Plant
4. Habitat Transfer Hose

Figure 4 illustrates the tri-level payload arrangement for all of these components. This arrangement consists of three distinct levels. Level one consists of the MCCS storage tanks, H_2 feedstock tank, AMS's, CTS for each tank and consumables transfer hoses. The hoses are packed in five bundles of 50 (25 air hoses and 25 H_2O hoses) and are located between the storage tanks. Level two consists of the ISRU and blast shield. Level three is comprised of the MAV, MAV propellant tanks, and deployable MAV components.

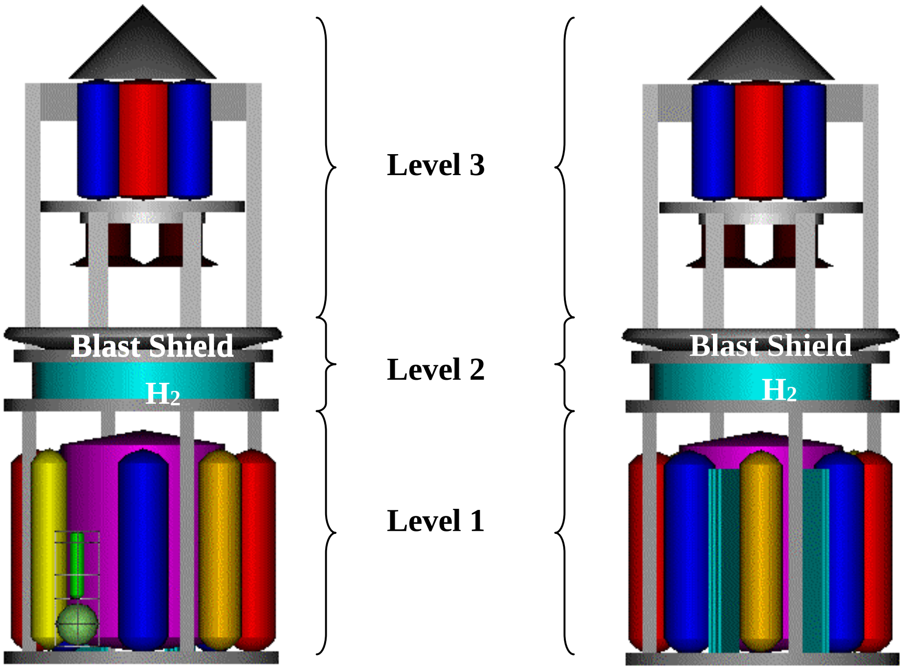


Figure 4: Payload arrangement with MCCS.

The payload arrangement shown here was obtained using thermal, mass, and function considerations. An explanation of the determination of the arrangement is given in Section 8.

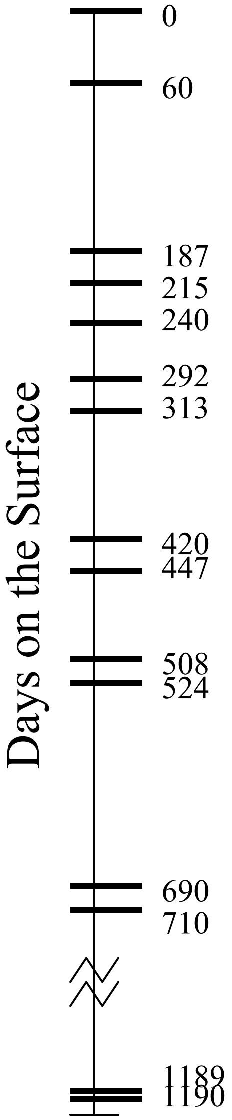
The payload arrangement presented here is 18.3 m in height and 7.5 m in diameter. The volume, mass, and power totals for the payload arrangement are shown in Table 5. These totals are compared to the maximum allowed payload for the Cargo-1 launch [10]. Details on the design of each MCCS subsystem are found in the following sections of this report.

Table 5: Volume, Mass, and Power Summary.

Payload	Arrangement	Allowed	% Difference
Volume [m^3]	808.5	1224.0	66
Mass [mt]	8.4	31.1	27
Power [kW]	28.2	160.0	17

6. Concept of Operations

The production, storage, and distribution of consumables and propellants on the surface of Mars will take place in two phases. Phase 1 is the Pre-Crew Arrival Operations. Deployment of surface components and MCCS operations will be conducted autonomously during this phase. Phase 2 is the Post-Crew Arrival Operations. This phase will consist of MCCS system checks, assembly of the consumables transfer hose, and filling of the MAV propellant tanks. Phase 1 will last 690 days, while Phase 2 is 500 days for a total of 1190 days. A detailed chronology of the events in each phase is provided in figure 5.



	DAY	EVENT
Phase 1	0	Cargo-1 Lander touches down on the surface of Mars Establish communications with Earth MCCS systems check Nuclear power plant deployed
	60	Release filler gas from all tanks ISRU plant begins producing CH_4, LOX, H_2O and BG Begin filling tank 1st CH_4, LOX, H_2O and BG tanks Turn on cryocoolers and heaters in these tanks
	187	1st CH_4 tank full; Begin filling 2nd CH_4 tank Turn on cryocooler in 2nd CH_4 tank
	215	1st LOX tank full; Begin filling 2nd LOX tank Turn on cryocooler in 2nd LOX tank
	240	1st H_2O tank full; Begin filling 2nd H_2O Turn on heater in 2nd H_2O tank
	292	Half of 2nd LOX tank full; begin filling 3rd for balance Turn on cryocooler in 3rd LOX tank
	313	CH_4 production complete
	420	H_2O production complete
	447	3rd LOX tank full; Switch back to 2nd LOX tank
	508	BG production complete
	524	LOX production complete End of constituent production Crew leaves Earth
Phase 2	690	Crew arrives at Mars MCCS system check
	710	Allow up to 20 days to lay the consumable hose
	1189	Initiate propellant transfer to MAV
	1190	MAV launch

Note: All "days" are 24 hours in length
Total number of days complied in the following manner:
540 days from landing to crew arrival
150 day crew transit
\+ <u>500 day crew surface mission</u>
1190 days of operation

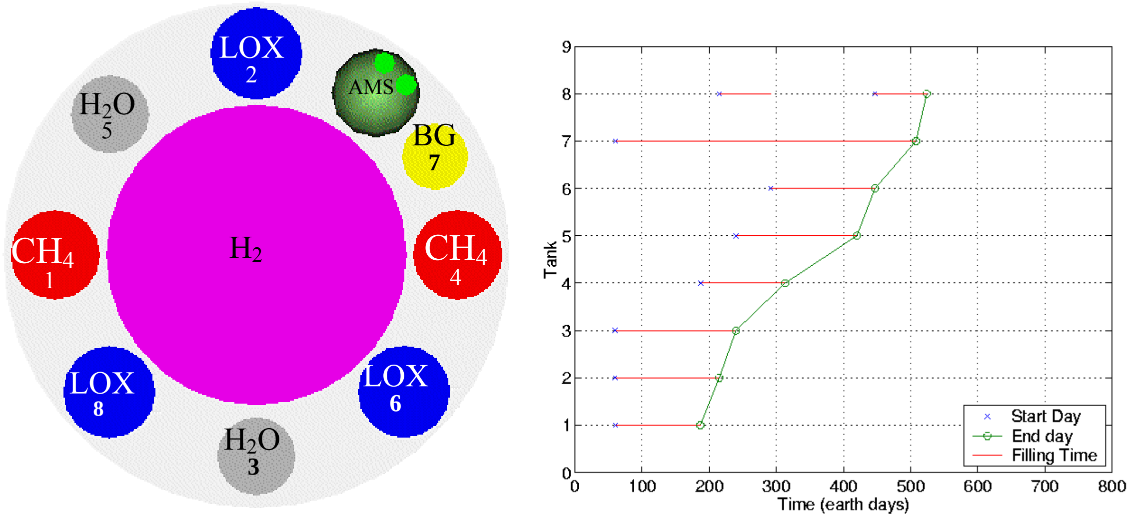
Figure 5: Concept of operations.

6.1 Phase 1: Pre-Crew Arrival Operations

Following touch-down of the surface components, time is allotted to establish communications with Earth, to deploy the nuclear power plant, and to conduct a MCCS systems check. Once the

MCCS is secure, check valves will open on all MCCS storage tanks allowing the filler gas to be released, dropping tank pressure. Next, the ISRU plant begins production of CH_4, O_2, H_2O, and BG.

The tanks on the MCCS will be filled in a specific order requiring increasing amounts of power at different stages of production. The order of tank filling and corresponding tank filling times are given in figure 6.



Top view of tank arrangement. Numbers correspond to the order in which the tanks are filled.

Figure 6: MCCS tank filling times and filling order.

Under normal conditions the propellant production will be finished one year after landing. Normal conditions constitute no cryocooler, condenser, or tank failures during production. Following confirmation that fluid production is complete, the crew will launch from Earth. Figure 7 shows how the mass and power consumption of the MCCS will change with production. The conditions shown are for normal operation.

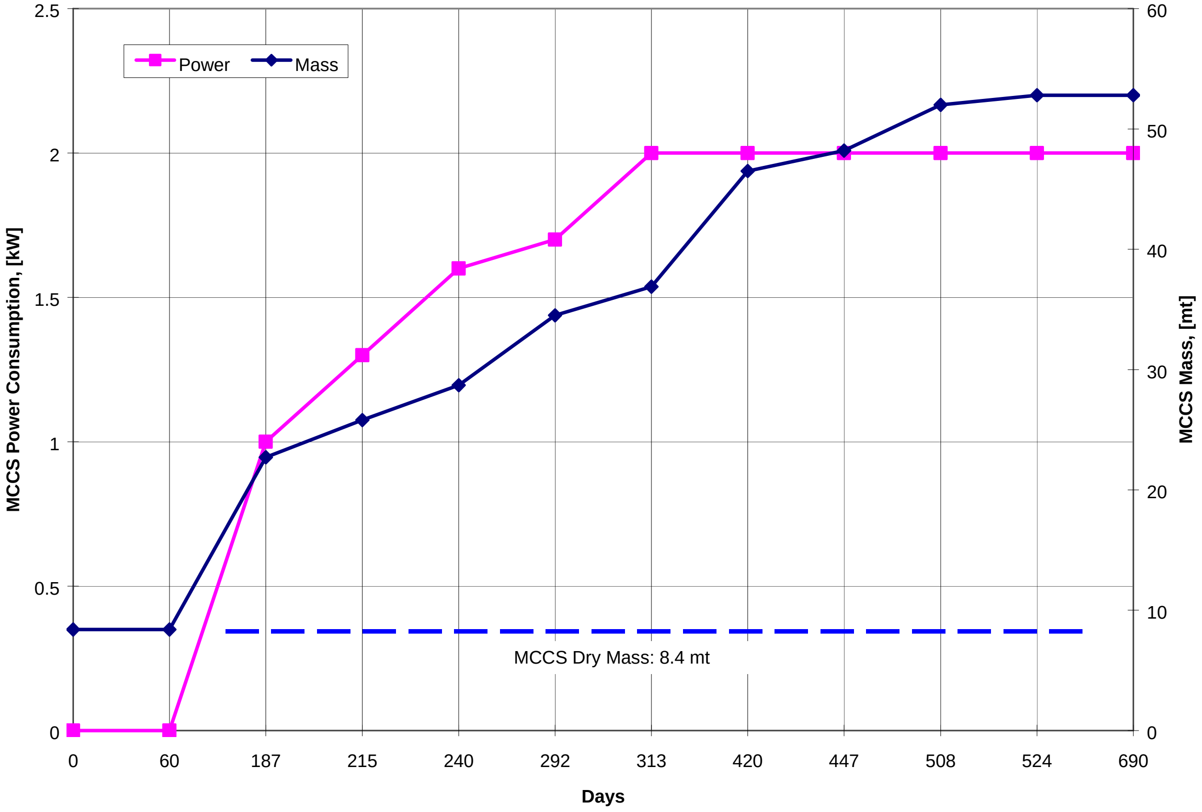


Figure 7: Mass and power consumption of MCCS during ISRU plant production.

During this phase, the possibility exists that a primary propellant storage tank will fail requiring the transfer of the propellants to the MAV propellant tanks. Should this occur, the cryocoolers on the MAV propellant tanks are turned on and transfer is initiated. This process is carried out autonomously.

6.2 Phase 2: Post-Crew Arrival Operations

Upon arrival the crew will be required to assemble the habitat transfer hoses. A primary and secondary hose will be laid for the 500 m distance between the MCCS and the habitat. Once in place, the crew can transfer consumables to the habitat at any time during their stay. The laying of the hose is not expected to exceed 20 days. Figure 8 below shows this arrangement.

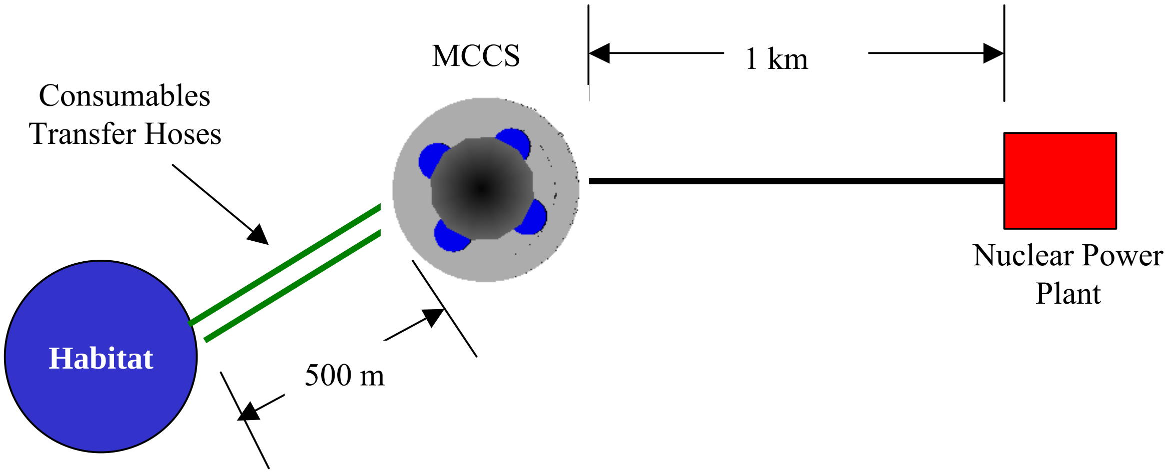


Figure 8: Surface arrangement.

At times, daily activities will necessitate access to the stored consumables. It is a mission requirement that the consumables at the MCCS be accessible to quickly service both manned and unmanned rovers and EVA suits. Therefore, the AMS will be equipped with a valve/hose system that allows for local access to the cryogens or H_2O.

When the surface operations of the crew conclude, the propellant tanks on MAV must be filled. Provided that no propellant has been stored on the MAV due to a primary tank failure, the crew will initiate the hose transfer. Once initiated by the crew, the system will carry out the transfer autonomously.

Prior to MAV launch the propellant transfer hoses, cryocoolers, and condensers will be deployed. The deployment of these components is discussed in Section 15. Then the crew gains access to the MAV with a ladder and launches into orbit where it will rendezvous with the ERV.

Any consumables that are left unused by the crew in this mission will be maintained at the conditions specified in Table 3 (found in Section 4) for use by the crew of the second mission.

7. MCCS Subsystem Design Methodology

The Apollo design philosophy encompassed the following: simplicity of basic component design, redundancy wherever appropriate, and adequate safety margins in cases where redundancy could not be applied. The Apollo design philosophy is adopted for our purposes to ensure the highest degree of design reliability for the MCCS.

7.1 Functions of the MCCS

The MCCS has two main functions. One function is to store propellants for the MAV. The second is to store consumables for emergency use by the crew. The production and storage of consumables on the surface of Mars is an emergency cache for the habitat since the crew will bring sufficient H_2O and BA for the 500-day surface operations [10]. Thus, the primary function of the MCCS is to store propellants. If the MCCS fails to adequately store the propellants the crew will not be able to leave the surface of Mars. Thus, every effort must be made to ensure that the propellants are stored in dependable and efficient systems.

7.2 Method of Design

Understanding the role and importance of the MCCS in a human mission to Mars will drive the design of the MCCS. The methodology undertaken to design the MCCS is shown in figure 9. The design of each MCCS subsystem required several trade studies, which are also identified in figure 9.

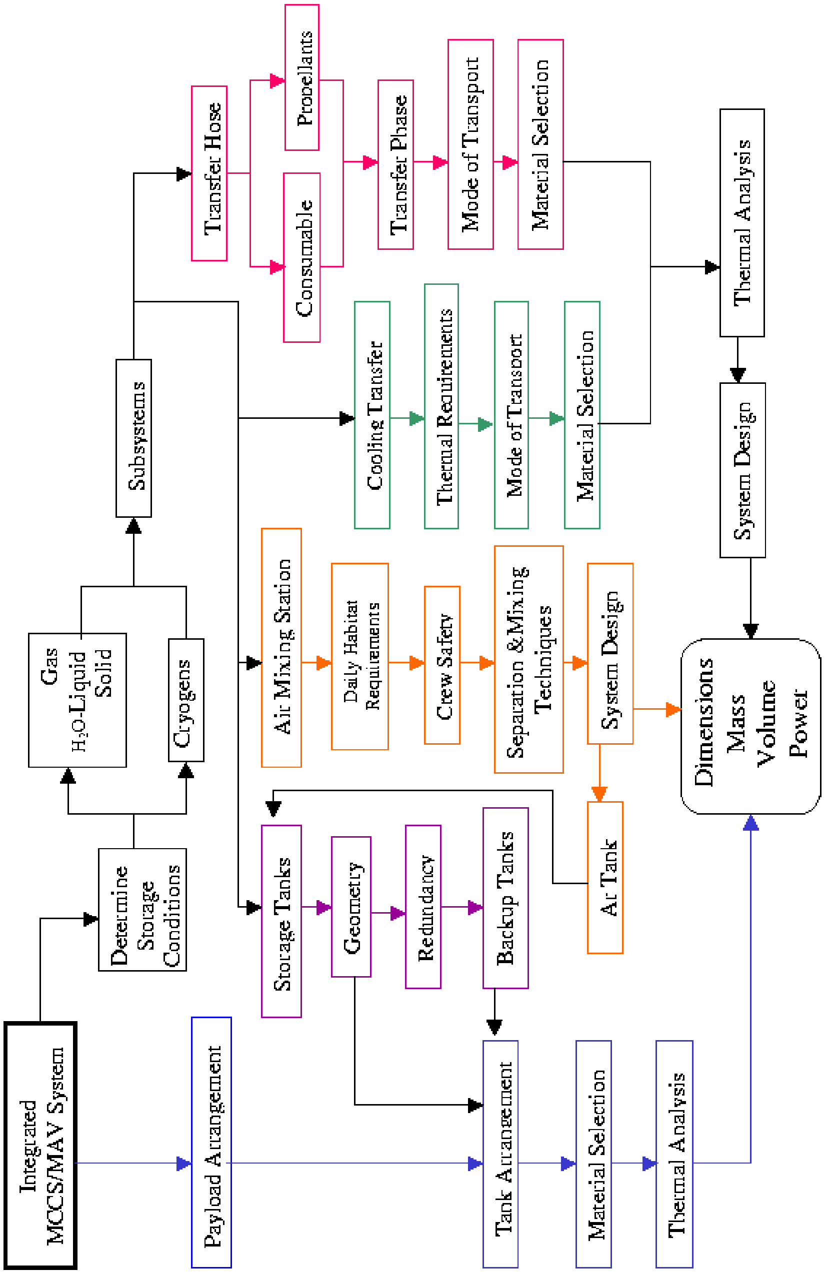


Figure 9: MCCS design methodology.

8. Payload Arrangement Study

The payload of the Cargo-1 Lander consists of several surface components in a single unit. The components considered in the design of the MCCS are the MAV, ISRU plant, and the hydrogen feedstock. The payload and surface arrangement of these components will influence the design of the MCCS. The function and mass of each system were considered in the arrangement.

At the end of production the combined mass of the fluids stored on the MCCS is 44.4 mt. This does not include the mass of the storage tanks and associated cooling mechanisms. Locating this mass as close to the ground as possible will allow for a low CM for the MCCS. This also allows for easy access to H_2O, BA, and O_2 at the MCCS by the crew to service rovers and EVA suits. For these reasons the MCCS will be placed close to the ground.

The MAV will liftoff from the surface of Mars when the 500-day surface operations by the crew end. For a single payload unit, the MAV will be placed above the MCCS to ease the liftoff process. This arrangement will require precautions to protect the MCCS storage tanks if the tanks are intended for future use. Adequate blast protection can be designed to protect the tanks and is not considered a disadvantage for this arrangement decision.

During production of consumables and propellants the ISRU plant is expected to generate heat. Placing the ISRU plant below the MCCS storage tanks may not prove to be thermally efficient. An optimal place for the ISRU plant is above the MCCS storage tanks to allow for convective heat transfer of the ISRU plant heat. Additionally, this configuration allows for gravity-fed drainage of ISRU plant outputs into the storage tanks. Therefore, the ISRU plant will be placed above the MCCS and below the MAV. Blast protection will also be required to protect the ISRU plant during MAV launch.

The hydrogen feedstock necessary to produce all of the consumables and propellants stored on the MCCS is 5.4 mt. The fluid and tank mass will be considerable for a thermally controlled hydrogen storage tank. Thus, the hydrogen feedstock will also be placed close to the ground.

8.1 Payload Arrangement Summary

The payload and surface arrangement decisions made here are summarized in figure 10 below. The MCCS and hydrogen feedstock are placed as close to the ground as possible. The ISRU plant will be placed above these and below the MAV.

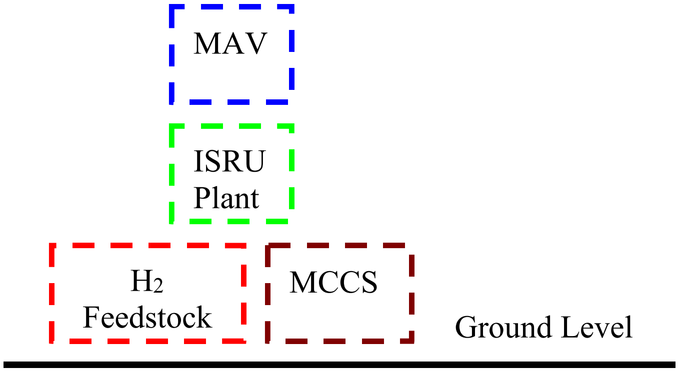


Figure 10: Component payload and surface arrangement.

9. Consumables and Propellant Storage Decisions

In the ±15° latitude region, it is assumed that the martian surface will experience temperatures ranging from 150 K to 300 K. Under unregulated storage conditions the ISRU plant outputs, CH_4, O_2, and N_2/Ar will exist as gases, while the H_2O will exist as a solid. As mentioned in Section 3, the CH_4, O_2, and N_2/Ar must be liquefied. H_2O can be stored as a liquid or a solid. To achieve the liquid or solid storage requirement, storage temperatures and pressures of all ISRU plant outputs were chosen.

9.1 Methane, Oxygen and Buffer Gas Storage Conditions

The ISRU plant output conditions and design storage conditions are shown in Table 6. The storage temperatures of CH_4, O_2, and BG were chosen to be approximately 10 K below the boiling point. The storage pressures of CH_4 and O_2 were then chosen such that they exist as cryogens. At these temperatures an increase in pressure will not induce a phase change in these liquids.

Table 6: ISRU Plant Output Conditions and MCCS Storage Conditions.

	ISRU Plant Output Conditions		MCCS Storage Conditions	
Constituent	Temperature [K]	Pressure [kPa]	Temperature [K]	Pressure [kPa]
CH_4	525	152	100	132
O_2	300	3040	80	132
N_2/Ar	240	30	90	690
H_20	525	152	285	100

The storage pressure of the BG was selected such that both N_2 and Ar exist as liquids at the chosen storage temperature. The major constituents of the martian atmosphere are 95.3 % CO_2, 2.7 % N_2 and 1.6 % Ar. It is assumed that the ISRU plant extracts N_2 and Ar from the atmosphere at the same percentage. Therefore, at the end of BG production, the total BG mass will consist of 63% N_2 and 37% Ar. Under the BG storage conditions given in Table 3, the N_2 and Ar will not separate. Advantages of a known N_2/Ar ratio in the mixture will aid in the mixing of breathable air for habitat use.

9.2 Storage Conditions for H_2O

The decision to store H_2O as a liquid emerged from an extensive trade of the advantages and disadvantages of storing H_2O as a liquid versus storing it as a solid.

The advantage of storing H_2O as ice is the potential reduction in energy required to maintain it as a liquid for the 6 years on Mars. First, since water is an emergency cache, it may not be used during the surface mission. Second, it is expected that an ice storage system requires little or no insulation due the ambient conditions of Mars compared to storing H_2O as a liquid. However there are many disadvantages associated with storing H_2O as a solid. Storing H_2O as a solid requires specially designed tanks that can expand and contract with repeated melting and freezing processes. Other disadvantages include uncontrolled freezing, non-uniform melting, and inefficient use of energy to thaw the ice.

Uncontrolled freezing of the H_2O in the tank can lead to a non-uniform solid in the tank, resulting in an inefficient use of space. The hot steam sprayed onto the cold tank wall will condense and then freeze. The walls must be heated above the H_2O freezing point, allowing the liquid to collect and produce a single solid. Maintaining the temperature of the tank walls above freezing requires heat input (i.e. heating coils in the tank) and/or insulation on the tanks, which increase mass. This results in a complex system of sensors and heating elements.

Uniform melting of the ice is a complex process. Depending on the cylindrical diameter of the water tanks, the heating coils on the surface of the tank may not be able to melt all of the ice, therefore other heating elements are needed on the bottom of the tank and/or through the center of the tank. To retain the heat from the coils in the tank some amount of insulation is required.

Thawing the ice from the Mars mean ambient temperature requires energy. As an example Table 7 below shows how long it would take to thaw different amounts of ice based on one sol's supply (see Appendix F) using 120 kW (the amount of available power at normal MCCS conditions).

Table 7: Time Required to Melt One Sol's Supply of Ice.

# sols	Mass of Ice [kg]	Time to melt
1	40	2.5 min
25	1000	1 hr 3min
125	5000	5 hrs 10 min

Melting one sol's supply of ice in a timely manner is not problematic (making it readily accessible), but it is not efficient considering the MCCS only uses approximately 40 kW during normal operations. The power consumption associated with long-term liquid storage may prove to be more efficient.

Storing the H_2O as a liquid is advantageous. The water is readily accessible and will not depend on available power to melt it. Proper design of an insulated tank will not require extensive heat input during storage. The total heat input required to maintain H_2O as a liquid depends on the effectiveness of the insulation. Using an MLI system on the two water tanks requires approximately 7 watts each to maintain the H_2O was a liquid. The heat can be supplied at the bottom of the tank using a heating element. Heating coils along the length or inside the tank are not necessary. This is a mass savings over the ice storage method.

The advantages and disadvantages of each storage option are summarized in figures 11 and 12. The simplicity and efficient use of power for long-term storage of H_2O as a liquid are clear advantages over storing it as a solid. Therefore it was decided that H_2O will be stored as a liquid at the storage conditions shown in Table 6. Storing H_2O as a liquid will require insulated tanks with heating elements on the bottom. The thermal analysis presented here does not consider the temperature gradients in the ice and the tank during freezing and thawing, so an extensive analysis is recommended for future work.

Advantages: Solid H_2O Storage
1) Readily accessible
2) Minimal insulation mass required
3) Short term power consumption (melting process)

Disadvantages: Solid H_2O Storage
1) Tanks must be able to expand the contract with freezing and melting
2) Difficulties associated with uncontrolled freezing
3) Heating system required for uniform melting
4) Minimal melting time requires maximum power consumption
5) Requires insulation to retain heat in tank during melting

Figure 11: Advantages and disadvantages of storing H_2O as ice.

Advantages: Liquid H_2O Storage
1) Readily accessible
2) Minimal power required to maintain as a liquid
3) Standard tank design can be used

Disadvantages: Liquid H_2O Storage
1) Increased tank mass due to MLI system

Figure 12: Advantages and disadvantages of storing H_2O as a liquid.

10. Storage Tanks

In the previous section the optimal storage conditions for each ISRU plant output were determined. The CH_4, O_2, BG, and H_2O will be stored as liquids on the MCCS. The discussion that follows will detail the design of these storage tanks.

10.1 Design Methodology

The tank design methodology is shown in figure 13 below. The details of each phase of the design are discussed in detail in the following sections. All trade studies are identified and design decisions are summarized.

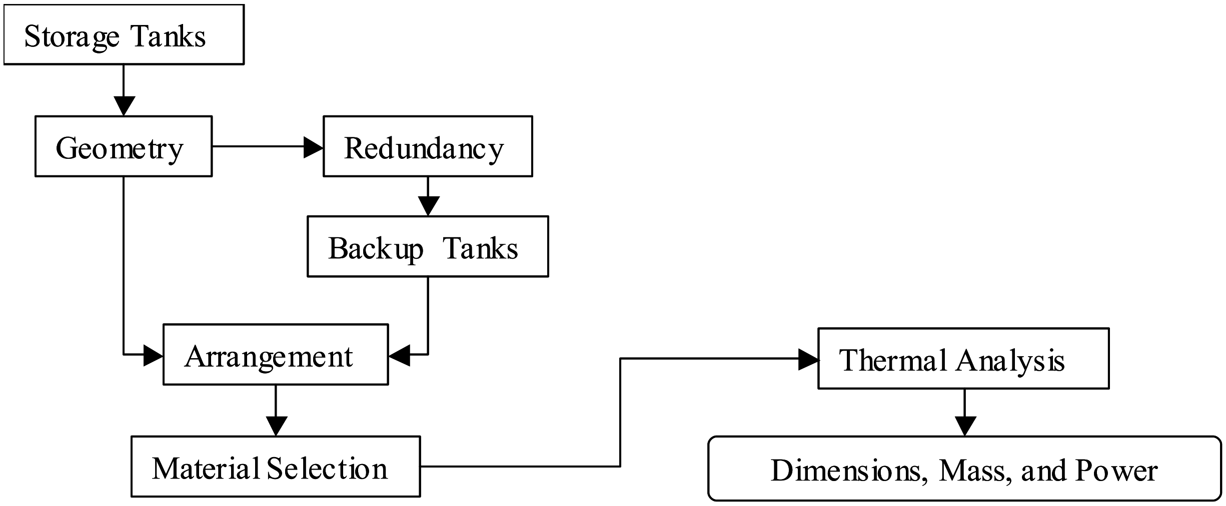


Figure 13: Tank design methodology.

10.1.1 MCCS Tank Geometries

The shape of the storage tanks will have a significant impact on the overall design of the MCCS. The fluid volume versus storage volume for each constituent is shown in Table 8. The storage volume is determined by increasing the fluid volume by 10 %. The 10 % increase allows room for cryogenic equipment and cryogen boil-off. Boil-off will occur when the temperature of the cryogen reaches the boiling point of the fluid.

Table 8: Constituent Fluid and Storage Volumes.

Constituent	Fluid Volume [m^3]	Storage Volume [m^3]
CH_4	13.21	14.53
O_2	21.02	23.12
N_2/Ar	3.63	3.99
H_2O	10.00	11.00

Three different tank geometries were compared for storage of these fluids. The first is conformable tanks. Conformable tanks are currently being developed by Thiokol Industries for spacecraft applications (see Appendix D) [2, 46]. A composite "bag" in an aluminum shell contains the fluid. The outer shell can be formed to any geometry, and the "bag" will conform to this shape, resulting in an efficient use of the available volume. This technology is an improvement over rigid tanks, but is unproven for long-term and large-scale cryogenic storage. Therefore, the MCCS storage tanks will be rigid.

For uniform distribution of tensile stresses, common storage tanks are either spherical or cylindrical in shape. Spherical tanks can be considered optimal because the least surface area is used to occupy a given volume. This translates into minimal surface area for thermal exchange and a minimal mass configuration. The main disadvantage is that there is an inefficient use of available payload volume. The available cylindrical payload volume of 1224.0 m^3 is 27.7 meters high with a diameter of 7.5 meters [14]. To accommodate a single spherical storage tank for each constituent, the tanks will occupy approximately 52.4 m^3 or 10% of the required cylindrical volume of 543 m^3 (12.3 m height and 7.5 m diameter). A tank stack of this height will increase the mass of the support structure, compromise MCCS stability, and is an inefficient use of payload volume. Multiple spherical storage tanks can be considered, but also result in an inefficient use of available payload volume.

Alternatively, cylindrical storage tanks offer packing flexibility and reduced tank stack height when compared to spherical tanks. A disadvantage in the use of cylindrical tanks is the increase in the surface area for a fixed volume compared to spherical tanks, resulting in an increase of the heat loss/gain of the tank. Table 9 shows how the surface area of a cylindrical CH_4 tank changes with increasing cylinder height relative to a spherical tank of the same volume. Despite the increase in surface area, the ability to efficiently occupy a given volume with cylinders of varying heights outweighs the disadvantages of increased surface area. Therefore, the MCCS storage tanks will be cylindrical.

Table 9: Spherical and Cylindrical Tank Surface Areas Compared.

Spherical Tank		Cylindrical Tank			
A_s [m^2]	Radius [m]	A_s [m^2]	Radius [m]	Height [m]	A_s % Difference
28.65	1.51	28.65	1.51	1.51	--
		33.62	1.52	2.0	17
		35.95	0.96	5.0	23

10.1.2 Redundancy

The primary objective of the MCCS is the storage of propellants. The production and storage of consumables on the surface of Mars is a secondary system since the crew will bring sufficient H_2O and BA for the 500-day surface stay. Thus, every effort must be made to ensure that the propellants are stored in reliable systems. Here a tank system failure describes a cooling system malfunction or loss. A tank failure describes a damaged tank that cannot effectively store the fluid.

Two options have been identified that addresses both types of failures. Option 1 is to have redundant propellant storage tanks on the MCCS. If a single cylindrical storage tank for each propellant is used, there will be two propellant storage tanks on the MCCS. Redundant propellant tanks will raise the total to four. The MAV also has a minimum of two tanks. This is six propellant tanks, four of which are capable of long-term cryogenic storage. The addition of two redundant propellant tanks will result in a higher Earth liftoff mass and payload volume.

Option 2 is to use the MAV propellant tanks as backups for the MCCS propellant tanks. This will require that the MAV propellant tanks be capable of long-term cryogenic storage. The TCS (insulation, cryocoolers, etc.) will add mass and increase the number of points of failure for the MAV, but the Earth liftoff mass and payload volume savings by using these tanks as backup propellant tanks for the MCCS outweigh the disadvantages. Therefore, the MAV propellant tanks will serve as backup MCCS propellant storage tanks. Efforts will be undertaken to reduce the MAV launch mass and risk associated with this configuration. This will be discussed in Section 15.

10.1.3 MCCS Tank Arrangement

In Section 9 it was established that the H_2 feedstock and MCCS must be as close to the ground as possible due to their mass. This will be accomplished by placing both on the same level. The effective use of space and the filling and emptying of the storage tanks determined the arrangement of the H_2 and the MCCS storage tanks.

A 7.5 m diameter cylinder, 27.7 m height defines the cylindrical Cargo-1 Lander payload dimensions [10]. The 7.5 m diameter constitutes a 44.18 m^2 area. This area will be termed the circular payload area.

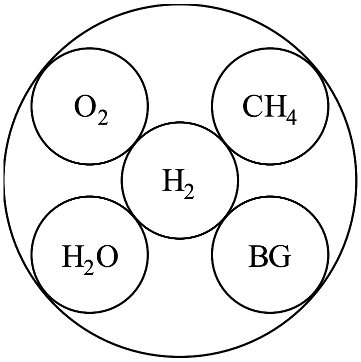
The rate of production and filling of the ISRU plant outputs is known and is shown in Table 1 of Section 3. However, the rate of depletion of H_2 is unknown. Thus, to effectively balance the H_2 and ISRU plant outputs during production the H_2 feedstock will be placed at the center of the of the circle defined by the payload area. The mass and volumes of H_2 is shown in Table 10. Placing the 5.4 mt of H_2 in the center eliminates the need to balance the H_2 with the ISRU plant outputs at all phases of the mission.

Table 10: Hydrogen Feedstock Data.

Fluid	Density [kg/m^3]	Mass [kg]	Fluid Volume [m^3]	Storage Volume* [m^3]
H_2	70	5420	77.43	85.17

*storage_volume = (1.1)fluid_volume

In Section 10.1.1 it was decided that cylindrical tanks be used to store the liquids. Assuming a single tank for each fluid, including H_2, five circles of equal area were sized to maximize coverage of the circular payload area. Doing so determined the height of each tank for that diameter. The results are shown in figure 14. The dimensions of each tank are based on the storage volume and do not consider tank or insulation thickness.



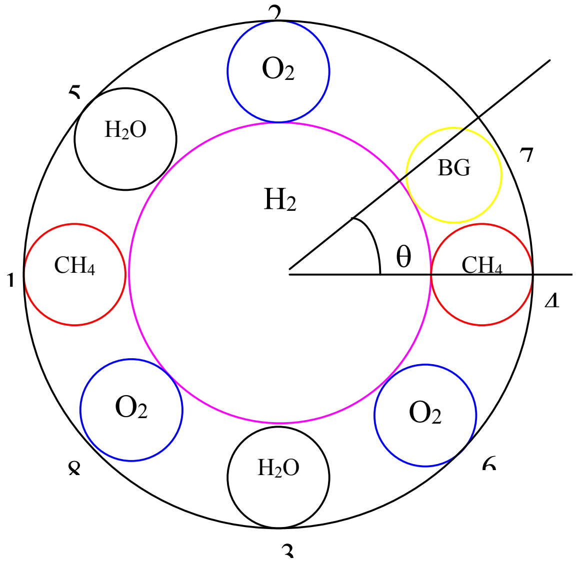
Constituent	Diameter [m]	Height [m]
CH_4	2.5	3.7
O_2	2.5	5.9
N_2/Ar	2.5	1.0
H_2O	2.5	2.8
H_2	2.5	21.7

Figure 14: Potential MCCS tank arrangement.

For these dimensions the height of each tank is no more than 6 m with the exception of the 21.7 m H_2 tank. This arrangement is not practical due to the height of the H_2 tank. A tank with this height will result in a high MCCS CM. Additionally, for this arrangement the mass of each fluid is not easily managed during production and MAV fueling. This is due to the dissimilar production rates of each constituent. Thus, it is not possible to balance the fluid mass during production and MAV fueling using a single tank for each constituent.

Manageability of the constituent masses during production and fueling can be accomplished with multiple tanks about a single H_2 tank. An advantage of this arrangement is that dividing the stored mass of each constituent reduces the amount of fluid loss in the event of a catastrophic tank failure. A disadvantage is the increased system mass. Despite the increase in mass for multiple tanks, the ability to balance the fluid mass during and after production necessitates the use of more than one tank per constituent.

It was determined that one BG tank, three O_2, two CH_4, and two H_2O tanks, were easily balanced during ISRU plant production. For this number of tanks the height of the H_2 tank can be minimized such that all the tanks fit into the circular payload area. The height of the H_2 tank is expected to be less than 10 m for this arrangement. The tank arrangement is shown in figure 15. The tanks shown represent optimal locations and not actual dimensions. The dimensions of each tank cannot be determined until a full analysis is carried out. The placement of the tanks is based on the rates of production.



Constituent	Order	θ [deg]
CH_4	1	180
O_2	2	90
H_2O	3	270
CH_4	4	0
H_2O	5	138
O_2	6	315
N_2/Ar	7	29
O_2	8	222

Figure 15: MCCS tank arrangement.

The numbers next to each tank shown in figure 15 represent the time at which that tank is full. For example, tank 1 (CH_4) is full after approximately 190 days of filling. Tank 2, O_2, is full after 210 days of production. Note that more than one tank is filling at the same time. If these tanks are filled in this manner the MCCS will be balanced throughout production.

During MAV propellant transfer the O_2 and CH_4 MCCS storage tanks must be drained in a uniform manner if optimal stability is desired. Emergency situations that require transfer from a damaged tank will not promote this, but it is expected that the stability of the payload arrangement will not be compromised. Once tank dimensions and masses have been determined a CM study will be conducted.

The sizing of the H_2 tank will be done such that the desired number of tanks for each constituent fit into the proposed arrangement shown in figure 15 and a minimal height for the H_2 tank is achieved. The storage volume of H_2 in Table 10 and an insulation thickness of 20 cm were considered to try and represent a realistically sized tank.

10.1.4 MAV Tank Arrangement

The DRM specifies that the maximum dimensions for the MAV are 9 m high and 6 m in diameter. The maximum crew vehicle dimensions of the MAV are given as 2.5 m high and 4 m in diameter. For reasons discussed in Section 10.1.2 the MAV tanks will be used as backup tanks for the MCCS propellants. Major design considerations for the MAV tank arrangement included symmetric placement, stability, and shape of the tanks. Additionally, the collective dimensions of the tanks must not exceed the allowable MAV payload dimensions given in the DRM. Several symmetric tank configurations were considered using the storage volume of CH_4 and O_2 given in Table 8 of Section 10.

The first arrangement consists of four spherical tanks: two O_2 and two CH_4 tanks, as shown in figure 16. Despite the thermal benefits of minimal surface area tanks, this arrangement is difficult to balance. At the completion of propellant transfer the O_2 tanks each have a fluid mass of 10 mt while each CH_4 tank has 2.9 mt making it impossible to balance. Also, this arrangement did not fit into the allotted payload volume.

The second arrangement consists of two cylindrical tanks each for O_2 and CH_4 and is shown in figure 16. Again the mass of the fluid in each tank made it difficult to maintain balance during propellant transfer and launch. This arrangement, however, fit within the allowable dimensions.

A third arrangement consists of four cylindrical O_2 tanks and one cylindrical CH_4 tank. This arrangement, shown in figure 16, ensures balance during storage and launch and fits into the specified payload volume and is the arrangement chosen for the MAV.

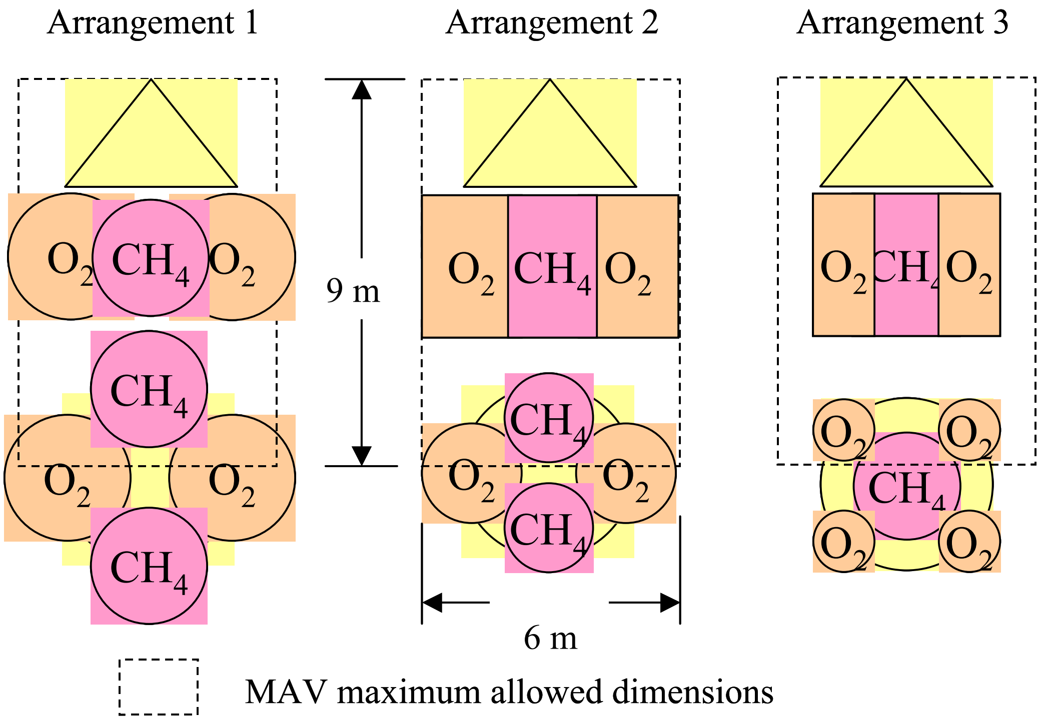


Figure 16: MAV tank arrangements.

10.1.5 Tank Material Selection

The storage masses of the consumables and propellants require lightweight tank materials capable of sustaining high tensile stresses that are proven for long-term cryogenic applications. Three classes tank materials were considered for the MCCS storage tanks: aluminum alloy, stainless steel, and composite graphite\epoxy. Table 11 provides data of each material used as a basis of comparison.

Table 11: Tank Material Comparison.

Material Type	UTS [MPa]	Density [kg/m^3]	Cryogenic Applications	O_2 Reactivity
Aluminum Alloy AA 6210	330	2.6×10^3	Yes	Yes
Stainless Steel (AISI 216)	690	7.0×10^3	Yes	Yes
Composite G\E (AS 3501)	> 1000	1.3×10^3	No	No

Noting the storage pressures shown in Table 3, Section 4, thin wall theory for cylindrical pressurized vessels was used to determine the stress allowances for all materials considered and the minimum tank thickness capable of sustaining the loads due to the weight of the stored fluid [7]. The ultimate tensile strength (UTS) of each material is well above these stresses, thus all of the materials considered are capable of supporting the loads imparted by the fluid during storage. Note that the cylindrical tanks will have spherical end caps. For purposes of mass calculations and dimensionality the end cap thickness was assumed to be equal to the tank thickness. However, further analysis is required to determine an optimum end cap thickness.

A design objective is to minimize the overall mass of the MCCS. Thus, the density of each material was examined. Stainless steel is the densest of the materials and considered a disadvantage. The aluminum alloy and composite G\E have comparable densities so either one will provide a mass savings over the use of stainless steel.

The cryogenic feasibility of aluminum and composite G\E is now examined. A pure composite tank is unproven due to a degradation of the composite at cryogenic conditions. Micro-cracks have been known to develop resulting in micro-leaks [37]. A composite G\E tank can be designed with a metal liner, much like the O_2 tanks on the space shuttle. The O_2 is stored cryogenically, but the tanks are serviced after each mission. Long-term metal lined composite G\E storage containers for cryogens have not been developed to the level at which the advantages in strength and mass can be a realistic advantage. The aluminum alloy provides adequate tensile strength and has proven reliability over G\E. Therefore, aluminum alloy 6210 will be used to construct the MCCS storage tanks. The remaining issue is the aluminum reaction with O_2.

Aluminum alloy 6210 consists of approximately 99% Al. Aluminum in the presence of oxygen produces a layer of aluminum oxide (Al_2O_3). This layer of Al_2O_3 has many desirable characteristics. The layer is nontoxic, corrosion resistant, and protects the sub-layer Al from further exposure to O_2. However, the layer may be non-uniform and thicker than desired, which will increase the mass of the aluminum alloy. This process can be accomplished commercially producing a desired thickness and is called anodizing.

Several anodizing methods exist of which some will work for long-term cryogenic purposes. Two common methods are sulfuric acid anodizing and Chromic acid anodizing. The former is not recommended because sulfuric acid residue can become entrapped in micro-cracks at low temperatures and pressures and can compromise the integrity of the storage vessel. Chromic acid anodizing (commonly referred to as a Type I finish) is the recommended method because this process will not compromise the integrity of the aluminum [50]. Type I is commonly used in many aerospace applications. The layer can be thin (10^{-6}), is flexible, and more reliable for long-term applications. The drawback to this method is the difficulty associated with disposing of the chromic waste after the treatment process is completed. The desired anodizing technique, however, is Chromic acid anodizing.

To summarize, the MCCS and MAV storage tanks will be constructed of aluminum alloy 6210 and Chromic anodizing is the desired finishing technique. The mechanical properties of aluminum alloy 6210 are provided in Appendix D.

10.1.6 Cryocooler Technologies

The long-term storage of cryogens requires insulated tanks and cryocoolers. Cryocoolers remove the heat that leaks into the tanks and maintains the constituents as liquids. Currently, there are no existing coolers for large cooling requirements like those on the MCCS [39]. However, in the past decade there have been several technological advancements in cryogenic coolers.

The Cryogenic Technologies Group at the National Institute of Standards and Technology, NIST, has made significant advancements in cryogenic coolers. Recently, they have developed a Mars Oxygen Liquefier Prototype. It is designed for the 2007 flight goal, which will liquefy enough O_2 to launch a small spacecraft into orbit from the surface of Mars. The O_2 liquefier is of the pulse tube type; when compared to a Sterling engine, it is as efficient (20%), has fewer moving parts and exhibits less vibration. Additional advantages include a lower cost, less mass, more compact, have increased launch survivability, have a longer lifetime, and a larger orifice (which prevents plugging) than conventional liquefiers [35].

Despite these advances, designs for the large cooling systems required by the MCCS are still under development. The disadvantages of pulse tube liquefiers are their recent development (not space tested), the heat dissipation at the cold end, and they exhibit an awkward staging geometry. Currently, conventional cryocoolers are not capable of removing more than 150 W from a fluid [22]. The thermal capabilities of the cryocoolers used in the MCCS and MAV tanks will dictate the type and thickness of insulation. Therefore, conventional cryocoolers will be used on the MCCS storage tanks. Since the MCCS cooling temperatures are greater than 80 K, single stage cryocoolers are sufficient.

10.1.7 Tank Insulation Selection

The martian environment, desired storage conditions, and cryocooler capabilities will dictate the thermal control system requirements of each storage tank. In particular, the insulation system must be determined. For cryogens the insulation requirements include

- A low thermal conduction coefficient (*k*)
- A low density

A thermal model was developed that incorporates convective, conductive, and radiative heat transfer for a storage tank with varying insulation conduction coefficients. As a basis of comparison, a cylindrical cryogenic tank with negligible thickness, with a height of 3 m and a diameter of 1.5 m was used. Ambient temperature was taken to be 300 K and a cryogen temperature of 90 K. It was found that for an insulation thickness of 25 cm, the insulation must have a conduction coefficient (*k*) less than 0.018 W/m to maintain the desired storage conditions (details of this analysis can be found in Appendix D). Thus, four different types of insulation were identified that can satisfy the conduction coefficient requirement. These insulations are shown in Table 12. In this report Min K-1301®, Cerachrome-8®, and Cryogel® are termed "blanket" insulations.

Table 12: Types of Insulations.

Name	Density [kg/m^3]	Thermal Conductivity [W/mK]
Min K-1301®	320.4	0.03029
Cryogel®*	200	0.015
Cerachrome-8®	128.1	0.0388
MLI	120	0.00016

* Cryogel® numbers are derived from Aerogel® parameters [6, 12, 33].

Min K-1301® and Cerachrome-8® (C-8) have been researched at the NASA Johnson Space Center and were used on the Pathfinder mission [33]. Cryogel® is produced by Aspen Systems Inc. and has been tested at the NASA Kennedy Space Center for the past 3 years in the Cryogenics Test Laboratory [9]. Cryogel® was developed with recent advances in Aerogel® technologies and may one day replace MLI systems. However, Cryogel® still remains unproven in large-scale applications and will not be used on the MCCS storage tanks [9].

The remaining "blanket" insulations are Min K-1301® and C-8. If a minimal mass configuration is desired it is advantageous to use the less dense C-8. As an example, a thermal analysis was conducted using a cylindrical tank of negligible tank thickness with a height of 3 m, and a diameter of 1.5 m insulated with C-8. If the tank contains a 90 K cryogen (like the BG), approximately 35 cm of C-8 minimizes the heat gain of the fluid below 150 W (cryocooler limit) at the highest expected ambient temperature. The results are shown in figure 17. This will increase the diameter of the tank by 70 cm, approximately half of the tank diameter. The same is true for Min K-1301®. A "blanket" type insulation is not a realistic option for long-term storage of the cryogens on the MCCS.

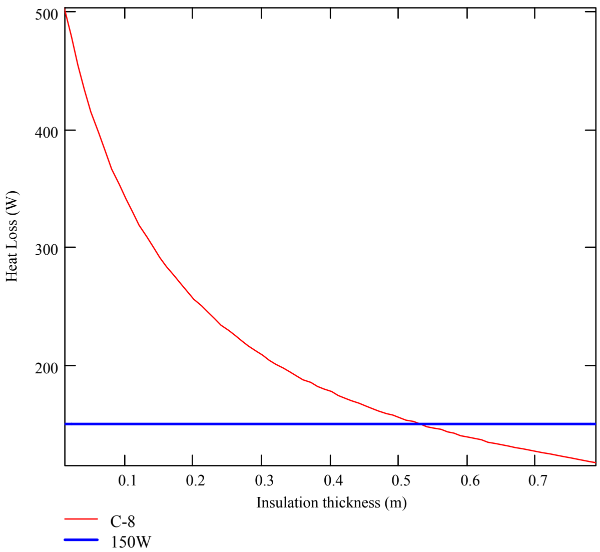


Figure 17: Heat loss versus insulation thickness for C-8.

Most cryogenic storage tanks use Multi-Layer Insulation (MLI) in an evacuated shell for thermal control. MLI consists of several thin layers of aluminized Mylar and Kapton. To increase thermal efficiency the layers are "crumbled" to leave few contact points among the sheets and the tank and outer shell, figure 18 shows this arrangement.

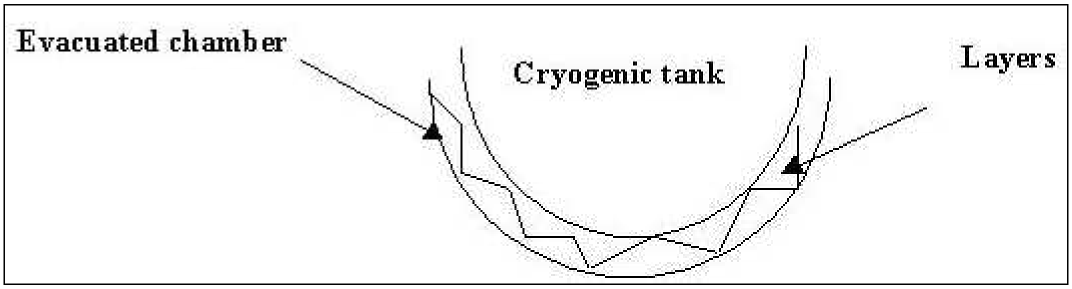


Figure 18: Multi-Layer-Insulation system for cryogenic storage.

In comparison to the "blanket" insulations, the MLI system is complex and may be massive. Blanket type insulation does not require the outer shell and an evacuated region. The use of a MLI system, however, will only increase a tank diameter by 12 cm (for the same case described above) and provide superior thermal control. Thus, to ensure proper thermal management of the cryogens, a MLI system will be used on all storage tanks. The use of a MIL system on the H_2O tanks will be discussed in detail in Section 11.

10.2 MCCS and MAV Tank Summaries

Following the design methodology described in Section 10.1, the MCCS and MAV tank shape, arrangement, material, and TCS were determined. All tanks are constructed of anodized aluminum alloy 6210. The cryogenic TCS consists of an MLI system and cryocoolers. The H_2O

tanks have an MLI system and heating elements as the TCS. The heating elements consume 10 W per tank. Details on the power requirements of the water tanks can be found in Section 11.

The dimensions, mass and volume of the MCCS and MAV storage tanks are given in Tables 13 and 14, respectively. A sample tank mass calculation can be found in Appendix D.

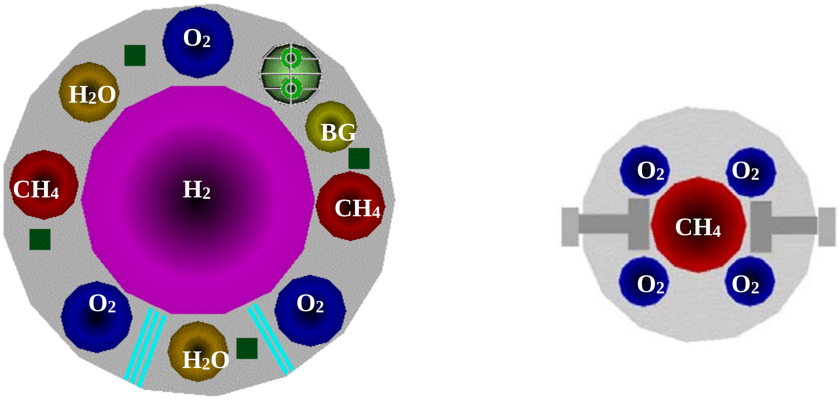
Table 13: MCCS Tank Summary.

Constituent	CH_4	O_2	N_2/Ar	H_2O	Ar	H_2
Quantity	2	3	1	2	1	1
Storage Volume [m^3]	7.3	7.7	4.0	5.5	1.4	85.2
Tank Height [m]	5.5	5.5	5.5	5.5	5.5	6.0
Tank Diameter [m]	1.3	1.4	1.0	1.1	1.2	4.3
Tank Thickness [mm]	4.7	4.7	4.7	4.7	4.7	4.7
MLI Thickness [mm]	8.4	8.4	8.4	8.4	8.4	200.0
Shell Thickness [mm]	3.2	3.2	3.2	3.2	3.2	3.2
Total Tank Diameter [m]	1.3	1.4	1.0	1.2	1.2	6.0
MLI Mass [kg]	25.9	27.4	18.9	22.3	5.0	2840.0
Shell Mass [kg]	213.1	225.4	155.8	183.4	41.0	949.5
Tank Mass [kg]	311.0	330.0	226.0	268.0	41.3	1346.0
Total Cryocooler Mass [kg]	52	78	26	--	26	NA
Heating Elements [kg]	--	--	--	28	--	--
Total Tank Mass [kg]	1153.0	1827.0	427.0	960.0	113.3	5136.0

Table 14: MAV Tank Summary.

Constituent	CH_4	O_2
Quantity	1	4
Storage Volume [m^3]	14.5	5.5
Tank Height [m]	3.3	3.3
Tank Diameter [m]	2.4	1.5
Tank Thickness [mm]	4.7	4.7
MLI Thickness [mm]	8.4	8.4
Shell Thickness [mm]	3.2	3.2
Total Tank Diameter [m]	2.4	1.5
MLI Mass [kg]	34.3	19.0
Shell Mass [kg]	281.6	156.2
Tank Mass [kg]	415.4	228.7
Total Cryocooler Mass [kg]	26	52
Total Condenser Mass [kg]	80	80
Total Tank Mass [kg]	811.4	1695.0

The MCCS and MAV tank arrangement is shown in figure 19 below. For the MCCS tank arrangement shown in figure 19, the MCCS tanks are arranged such that the mass of each fluid is manageable during all phases of ISRU plant production. To balance the constituents during all phases of production the tanks will be filled in such a way that the CM of the MCCS does not vary more than one-meter from the center of the arrangement.



MCCS **MAV**

Figure 19: MCCS and MAV tank arrangement.

In Table 15 the day of ISRU plant production at which an MCCS tank becomes full is identified. On this day the CM of the MCCS is determined and is shown in figure 20. The numbers in Table 15 correspond to the legend in figure 20.

Table 15: Tank Filling on Day of Production.

Constituent	Order at which tank becomes completely full	Day tank becomes full
CH_4	1	187
O_2	2	215
H_2O	3	240
O_2	4	292*
CH_2	5	313
H_2O	6	420
O_2	7	447
N_2/Ar	8	508
O_2	9	524

* On this day a tank switching occurs between two different O_2 tanks. Half of an O_2 tank is filled then the filling of another O_2 tank is begun for balancing purposes.

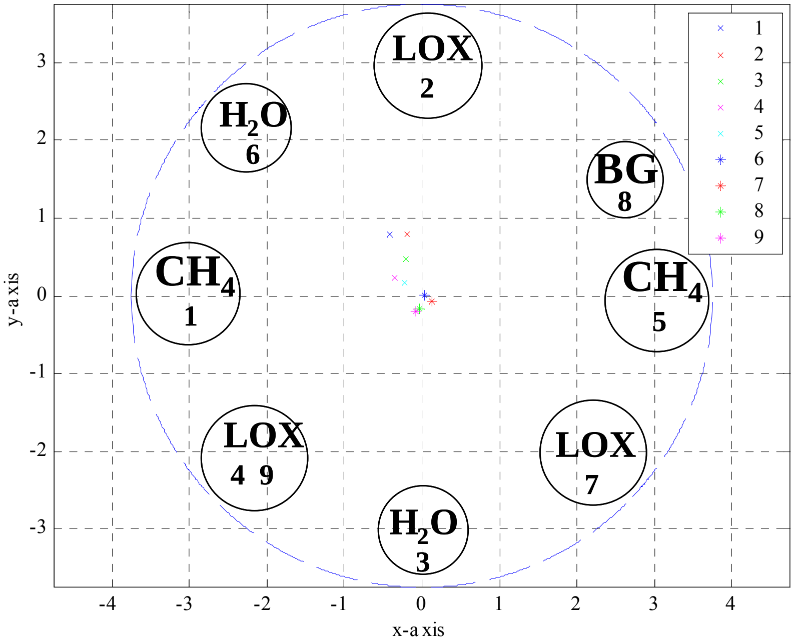


Figure 20: MCCS center of mass at different times during ISRU plant production.

Figure 20 shows that the CM of the MCCS will not vary more than one-meter from the center of the arrangement during production. As production comes to an end the CM of the MCCS will settle to within 0.2 m of the center.

10.3 MCCS Control System

The constituent flow from the ISRU plant to the tanks is controlled by a series of electronic sensors and valves. Completely redundant systems exist for each tank. Sensors include pressure, flowrate, temperature, and liquid level monitors. All sensors are integrated into the MCCS control system. Thermal management of the heat generating tank systems is accomplished using convective cooling, but daily variances of the winds on Mars may require cooling fans. A description of the pressure control and cooling fans is provided here.

10.3.1 Pressure Control

Pressure control of the cryogenic tanks is important to prevent damage from over-pressurization due to rapid boil-off. The selected storage pressures of each constituent are considerably lower than maximum allowable tank pressures, with the exception of the BG tank. Table 16 shows the design pressures for each tank type.

Table 16: Pressure Allowances for Each Tank.

Constituent	ISRU Plant Output Pressure [kPa]	Storage Pressure [kPa]	Emergency Release Pressure (+30%) [kPa]	Max Allowable Tank Pressure [kPa]
O_2	3030	132	185*	900
CH_4	152	132	172	1248
N_2/Ar	30	690	897	1673
H_2O	152	100	130	983

* The relief valve for O_2 is at 40 % storage pressure for propellant transferring purposes

In the event of a cooler failure the cryogen will boil-off increasing the pressure in the tank, which can exceed the ISRU plant output pressure. This will prevent the fluid from entering the tank. A pressure release valve will trigger at 130% of the storage pressure releasing the boil-off into a pipe that directs the constituent to the condenser. The pipe will allow expansion and cooling of the constituent. The fluid is then routed to a condenser, where it is re-liquefied and transported back into the tank. Simultaneously, the control system initiates the backup cooler. Together the cooler and condenser reduce the pressure in the tank. As a final safety measure, a direct-to-atmosphere release valve will be installed on all tanks. This valve is activated if the pressure in the tank reaches 60% of the maximum allowable tank pressure. This pressure was chosen based on the limitations of the cryocoolers in the tanks.

10.3.2 Cooling Fans

The heat expelled from the use of many cryocoolers, condensers, and the ISRU plant created a challenging thermal management problem. One option considered was to use this excess heat to warm the water tanks. Doing so required that the water tanks be placed above all the heat expelling hardware. An arrangement of this type could decrease the stability of the MCCS during production. Thus, an economical, structurally sound method has not been found to harness the excess heat.

The storage tanks on the MCCS are arranged in such a manner that the heat generation of the coolers and condensers can be expelled to the atmosphere by convective heat transfer. To aid in the process, four fans, located 90 degrees from each other, will ensure that this heat is transferred to the atmosphere and not absorbed by the tanks.

10.4 Deployable MAV Components

Using the MAV tanks as backup tanks for the storage of propellants requires that the MAV tanks be designed with a TCS. The TCS includes cryocoolers and an MLI system. The TCS must be integrated into the design of the MAV without compromising flight capabilities. To reduce MAV launch mass it is desirable that the all or part of the TCS be removed prior to launch. The MLI system is integrated into the tank design therefore it cannot be removed. However, the cooling hardware of the TCS can be removed. Thus, to reduce MAV launch mass the cryocoolers are equipped with quick-disconnect attachments allowing rapid and easy removal.

In addition to removing the cryocoolers prior to launch the propellant transfer hoses must be removed. For ease of removal, the transfer hoses and cryocoolers will be contained on two arms positioned 180° from each other on the MAV, as shown in figure 21. The contents of each arm are detailed in Table 16. The condensers are included for tank over-pressurization maintenance, which is discussed in Section 10.3.2. The arrangement of these components is depicted in figure 22 below. Removing these components prior to launch will reduce the MAV liftoff mass by approximately 240 kg.

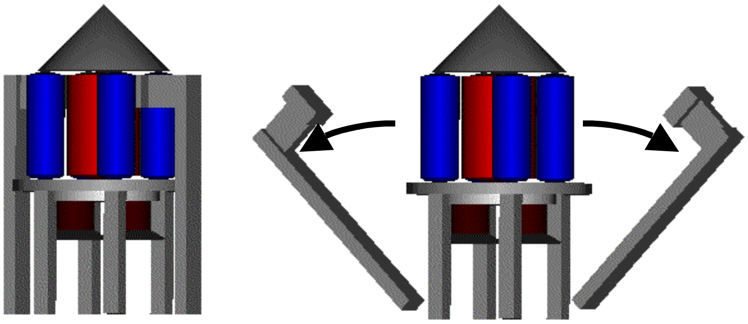


Figure 21: Deployment of MAV components.

Table 17: Contents of MAV Deployable Arm.

Component	O_2	CH_4	Total
Cryocooler	2	1	3
Condenser	1	1	2
Transfer Hose	1	1	2
Total # of Components In Each Arm			7

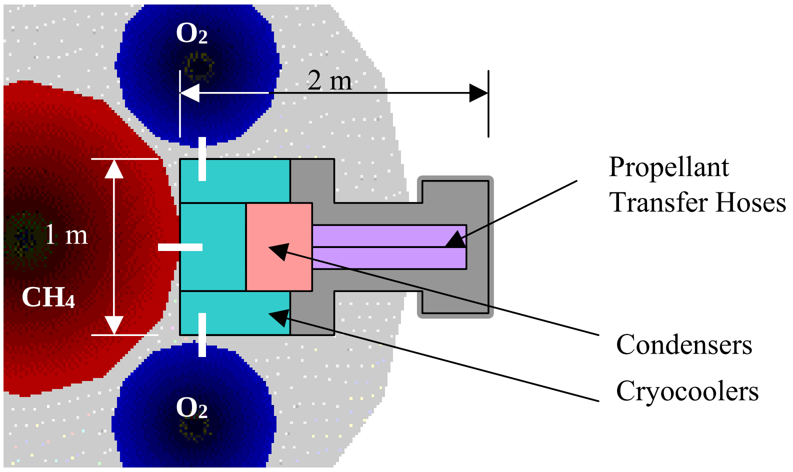

Top View

Figure 22: Arrangement of deployable components.

11. Cooling-Transfer System

A design objective of the MCCS is that CH_4, O_2, and BG must be liquefied and stored. For reasons explained in Section 9.2, the H_2O will also be liquefied and stored. The ISRU plant releases the constituents at high temperatures relative to the desired storage temperature. Therefore, heat must be removed from each substance. The ISRU plant output and MCCS storage conditions are shown in Table 18. It is desirable to design a system between the ISRU plant and the tanks such that it removes the maximum amount of heat allowed by the ambient temperature of Mars. A system design based on knowledge of the ambient conditions on Mars allows for a flexible design and effective use of system components.

Table 18: Constituent ISRU Plant Output Conditions and Storage Conditions.

	ISRU Plant Output		MCCS Storage		
Constituent	Temperature [K]	Pressure [kPa]	Temperature [K]	Pressure [kPa]	Boiling Point [K]
CH_4	525	152	100	132	112
O_2	300	3030	80	132	90
N_2/Ar	240	30	90	690	100
H_2O	525	152	285	100	373

Transport of the constituents from the ISRU plant to the tanks is performed by the Cooling-Transfer System (CTS). The CTS includes all transfer pipes, pumps, condensers, valves, and sensors needed to transport and liquefy the constituents from the ISRU plant to the respective tanks. The design of the Cooling-Transfer System is now presented.

11.1 Cooling-Transfer System Design Methodology

The design methodology used to determine the dimensions, mass and power of the CTS is given in figure 23.

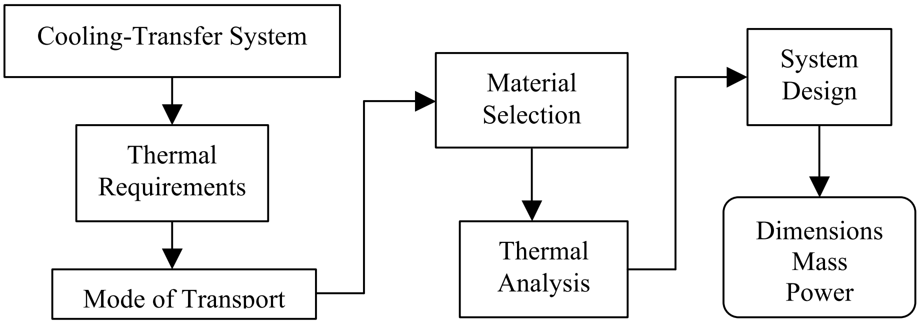


Figure 23: CTS design methodology.

Assumptions made in the design of the CTS include the steady state condition (i.e. constant flowrate), uniform pipe temperature (i.e. start up conditions are ignored), and the length of the pipes from the ISRU plant to each tank are five meters. The length of the pipes is based on the tank arrangement for the MCCS given in Section 10.1.3 and the assumption that the ISRU plant output will be at the center of the arrangement one meter above the storage tanks. Detailed schematics of the CTS for each constituent are provided in Appendix E.

11.1.1 Thermal Requirements

A thermal analysis was conducted to determine how many watts needed to be removed from the ISRU plant output gas to liquefy and store it. The watts to be removed from each constituent are provided in Table 19. The equations and constants used for this analysis can be found in Appendix E.

Table 19: Watts Removed to Reach Storage Temperature.

Constituent	Oxygen	Methane	Buffer Gas	Water
Watts to Remove	338	454	49	959

The thermal requirements of each constituent, given in Table 19, necessitate an efficient transfer medium that is capable of removing the heat needed to achieve storage conditions.

11.1.2 Mode of Transport and Material Selection

Recall the ISRU plant output pressure versus the MCCS storage pressure in Table 18 for each constituent. With the exception of the BG, all of the tank storage pressures are less than the ISRU plant output pressure, which allows for easy transport of the constituent to the storage tank. Maintaining the N_2 and Ar in a liquid mixture requires a tank pressure of 690 kPa. Moving the BG from the ISRU plant to the storage tank requires a pump to overcome the pressure difference between the ISRU plant and the BG storage tank. Two pumping methods were considered.

One method is to use the O_2, which leaves the ISRU plant at 3030 kPa, to drive a pump that pressurizes the BG. However, because of the increased complexity to the system and the unknown location of each ISRU plant output another method of pumping was explored. The second option employs the use of an electric pump near the ISRU plant BG outlet to move the constituent to the high-pressure storage tank. This method is desirable in that it does not depend on the production of another constituent and makes use of the available power. Therefore, an electric pump will be used to transfer the BG into the storage tank. The transfer medium will now be determined.

Both rigid metal or composite pipes and flexible hoses were considered as options for the transfer system. Hoses, despite the flexibility, cannot withstand cold temperatures like metals or composites. The watts that must be removed from each ISRU plant output will require a material capable of transferring the heat to the environment. Common hose materials like neoprene have much lower thermal conductivities than metals, which is not desirable for a system of this type. Also, constituents may become trapped in hoses after long-term use. Rigid pipes are more durable for launch, transit, and landing. Therefore, rigid pipes were chosen for the CTS.

Rigid pipe material options explored were anodized aluminum alloy 6210 (k = 237 W/m*K and ρ = 2700 kg/m^3) and composite graphite\epoxy AS 3501 (k = 168 W/m*K and ρ = 1400 kg/m^3). Compared to aluminum, the graphite\epoxy (G\E) is less dense, but has a slightly lower conduction coefficient. Also, aluminum has been thoroughly tested under space conditions. The mass benefits of G\E cannot be fully realized for a system of this nature without future development. Therefore, it was decided that the transfer pipes be made of anodized aluminum.

11.1.3 Thermal Analysis and System Design

Identification of the pipe material now permits a thermal analysis to determine the optimum dimensions for the transfer pipes of the CTS. The heat loss through a five-meter length pipe must be determined, as a function of the diameter and thickness of the pipe, the thickness of the insulation, and the ambient temperature. The thermal analysis of the transfer pipes for each cryogen is similar so only the details of the CH_4 CTS are explained here. H_2O, however, required a separate analysis, which is also presented. A complete thermal analysis is provided in Appendix E for each constituent.

To optimize the thermal effectiveness of the pipes, Program A written in Matlab (Appendix E), was used. Program A uses the equations outlined in Appendix E to identify trends related to: 1) the lengths of pipe required to remove the heat using the expected range of ambient temperatures, 2) the amount of heat loss through the pipes for the range of ambient temperatures, and 3) the range of pipe diameters explored that maximize heat loss. Figure 24 shows the CH_4 heat loss in a 1 mm thick transfer pipe for varying diameters over the range of expected ambient temperatures.

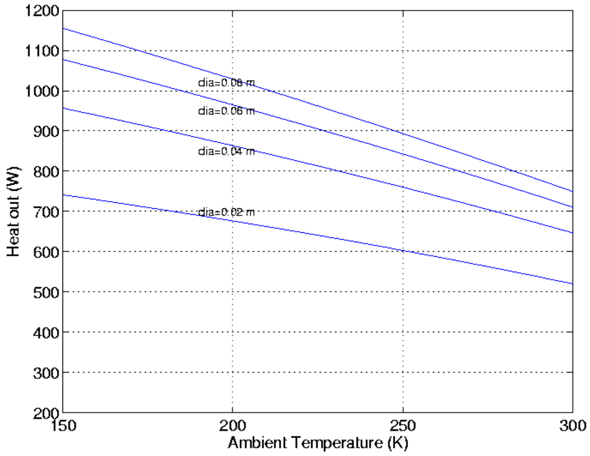


Figure 24: Heat loss without insulation.

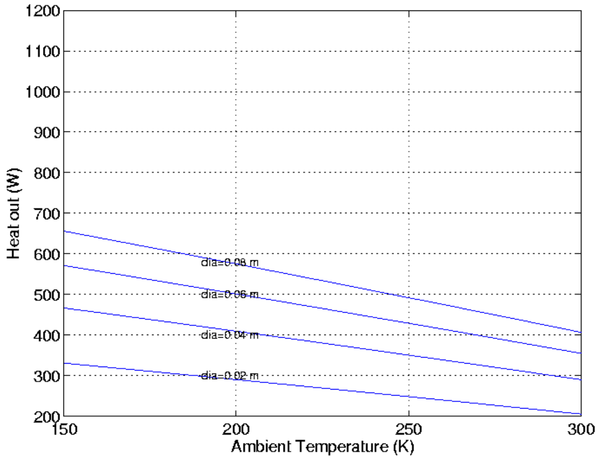


Figure 25: Heat loss with insulation.

In figure 25 the smallest pipe diameter considered was 0.02 m. For this pipe diameter approximately 525 W are transferred to the atmosphere, 75 W more than are desired to obtain the desired storage temperature. This is due to the large heat capacity of gaseous methane. Thus, insulation is needed to reduce the number of Watts lost to the atmosphere. Insulation options considered are Cryogel®, MLI, and Cerachrome-8® (C-8). The characteristics of these insulations are provided in section 10.1.5. The complexity of an MLI system and the current development of Cryogel® resulted in the use of C-8 insulation for the CH_4 pipes.

The insulation thickness for the pipe was determined by adding enough insulation such that only 454 W are transferred to the atmosphere at the coldest expected ambient temperature. For an insulation thickness of 15 mm the heat loss for different diameters are shown in figure 25. An outer pipe diameter of 4 cm with 15 mm of C-8 satisfies the thermal requirement.

A similar analysis was performed for the O_2 and BG transfer pipes, which indicated that these pipes do not need insulation. Table 20 lists the dimensions, mass, and total watts transferred by the transfer pipe for each constituent.

Table 20: Transfer Pipe Specifications.

Constituent	ID [m]	OD [m]	Insulation Thickness [m]	Pipe Length [m]	Mass [kg]/tank	Max Watts Transferred
CH_4	0.019	0.020	0.015	5.000	3.9	255
O_2	0.029	0.030	--	5.000	2.4	-22
N_2/Ar	0.029	0.030	--	5.000	2.4	-73
H_2O	0.019	0.02	0.007	5.000	2.7	631

The H_2O aluminum transfer pipes must have insulation to ensure that the steam does not condense to a solid in the pipes. The insulation thickness on the pipes depends on the type and amount of insulation on the water tanks. Recall that in section 9.2 the decision was made to store H_2O as a liquid. Transferring the ISRU plant steam (H_2O at 525 K) into the water tank will increase the pressure in the tank, so using the steam to heat the water is not an acceptable option. Thus, 959 W (from this point referred to as Q_{atm}) must be removed from the steam to reach the desired storage temperature of 285 K at the coldest expected ambient temperature of 150 K. Note that 118 W of heat (Q_{temp} from this point on) is required to change the temperature of the water from 373 K to the 285 K storage temperature. Therefore, a tank and pipe system that can transfer at least 841 W (Q_{atm} - Q_{temp}) from the steam to the atmosphere must be designed. Two water tank and pipe configurations were considered.

The first configuration is a tank and pipe with C-8 insulation. It was found that no combination of insulation thickness on the tank and pipe ensured that liquid H_2O between the temperatures of 373 and 285 K entered the tank for the range of expected ambient temperatures. Therefore, a C-8 system is not realizable for storage of H_2O.

The second configuration consists of an insulated tank and pipe that uses a condenser. A MLI and C-8 insulated tank was compared using C-8 insulated pipes. It was determined that 0.068 m of C-8 insulation on the tank yielded the same insulation mass as the MLI. Thus, a thermal analysis was performed that compared the performance of these two configurations using a 7 mm C-8 thickness on the pipes. Using 7 mm of C-8 on the pipes permits the temperature change of the steam from the ISRU plant output to the tank storage temperature. The results are shown in figures 26 and 27.

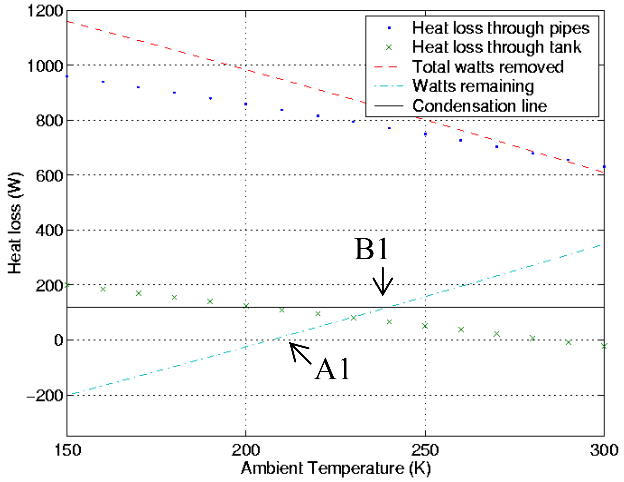


Figure 26: C-8 insulated tanks and pipes.

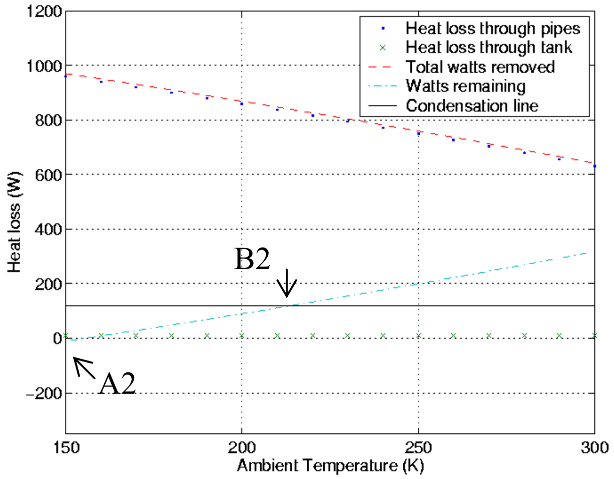


Figure 27: MLI tanks and C-8 insulated pipes.

The dotted line in figures 26 and 27 represent the heat loss through the pipes (Q_{pipes}) where the maximum was determined to be 959 W at the coldest expected temperature. The x's indicate the heat loss through the tank insulation (Q_{ins}). The red dashed line (Q_{system}) is the sum of Q_{pipe} and Q_{ins}. Subtracting Q_{system} from Q_{atm} produces the dot-dashed line. For ambient temperatures less than 270 K for C-8 and 150 K for MLI (points A1 and A2 respectively) the tank must be heated. For ambient temperatures greater than 239 K for C-8 and 213 K for MLI (points B1 and B2 respectively) a condenser is required to liquefy the steam from the ISRU plant. At a given ambient temperature the wattage required to heat the tank or condense the ISRU plant steam is determined by the corresponding value along the dot-dashed line.

For the C-8 configuration, figure 26, a heater and a condenser is required over the range of expected ambient temperatures during production. After production of H_2O is completed, the watts required to prevent the freezing of the water in the tank(s) at a given ambient temperature is indicated by the x's on figures 27 and 28. Approximately 200 W is needed to heat the water at the lowest expected ambient temperature.

For the MLI tank, point A2 is at the lowest expected ambient temperature. Thus, there are no ambient temperatures at which the tank must be heated during or after production. During production, the condenser will be needed at ambient temperatures as low as 213 K (B2), resulting in a higher workload when compared to the C-8 system.

The MLI system proved superior for H_2O storage using C-8 insulated transfer pipes when compared to the C-8 system. An MLI system has less insulation mass versus the C-8 system. An MLI equipped water tank will require no heating during H_2O production. A disadvantage of the MLI system is the increased condenser workload during production, requiring more power. However, the long-term power consumption after the water tank has been filled is much less for the MLI system than for the C-8 system. Thus, the reduced insulation mass and low long-term power consumption of an MLI equipped tank will be used to store the H_2O on the MCCS.

The amount of watts transferred by the CTS pipes determines the size of the condensers needed to liquefy the constituents. The amount of heat transferred on the warmest day through the pipes and by the tank was subtracted from the maximum number of watts that need to be transferred to reach the storage temperature. The difference determines the amount of heat the condenser must remove from the constituent. Given the specified pipe dimensions, the approximate condenser requirements are given in Table 21. The day-night temperature variations, which can be as much as 50 K, require that the condenser(s) for the MLI system be temperature controlled.

Table 21: Condenser Heat Removal Requirements.

Constituent	Total Watts to be Transferred	Max Watts Transferred by Pipes	Max Watts Transferred by Condenser
O_2	338	-22	360
CH_4	454	255	199
N_2/Ar	49	-73	122
H_2O	959	633	328

It is desirable to place the condensers as close to the tank as possible so that the condensed liquid does not vaporize before entering the tank, but not close enough to increase the temperature in the tank. Therefore, the condensers will be placed approximately 0.5 m above the tanks.

11.2 Cooling-Transfer System Mass and Power Summary

Mass and power estimates for the CTS are based on the design decisions outlined in this section and are found in Table 22. The number of condensers is equal to the number of tanks for each constituent. The power consumption is for one condenser working at one time for each constituent. A redundant Cooling-Transfer System exists for each tank. All condenser mass and power consumption estimates are based on those found in the Reference Mission 3.0 [10].

Table 22: Cooling-Transfer System Summary.

			Mass			Power
Constituent	Component	#	Each [kg]	Total [kg]	Redundant System [kg]	During Production [W]
CH_4	Condenser	2	41	82	164	2093
	Pipes/C-8	10 m	6.6	6.6	13.2	--
O_2	Condenser	3	43	129	285	2215
	Pipes/C-8	15 m	7.5	7.5	15	--
N_2/Ar	Condenser	1	41	41	82	2093
	Pump	1	3	3	6	36
	Pipes/C-8	5 m	2.5	2.5	5	--
H_2O	Condenser	2	41	82	164	2093
	Pipes/C-8	10 m	4.6	4.6	9.2	--
	CTS Total Mass [kg] and Power [W]				743.4	8530

12.Crew Consumables

A design objective of the MCCS is that a distribution system be designed that allows immediate access to consumables stored on the MCCS. Failed recycling systems or storage facilities on the habitat are emergencies that require immediate transfer of consumables to the habitat. Therefore, the amount of BA and water required by the crew per sol must be determined before a distribution system can be designed.

It has been determined that a crew of six requires 24.0 kg of BA in per sol [10, 38, 41]. On Earth the concentrations of O_2, N_2, and Ar are: 21, 78 and 1 percent, respectively. These concentrations are the basis for the required mass of each constituent shown in Table 23. Table 23 also shows how many sols of each constituent is available on the MCCS.

Table 23: Crew of Six Daily Breathable Air Requirements Compared to MCCS Stockpile.

Intravechicular Requirements	21% O_2	78% N_2	4% Ar
Mass for one sol [kg]	5.02	18.64	0.24
Stored on MCCS [kg]	4500	2457	1443
$m_{stored}/m_{one\ sol}$ [sol]	897	140	6039

There are 897 and 6039 days supply of N_2 and Ar stored on the MCCS, respectively. The limiting cryogen is N_2, allowing only 140 days worth of BA. Details of this analysis can be found in Appendix F.

In addition to BA, the crew will need water for daily activities. Water supplied to the habitat will be used water for drinking and washing [18]. Surface activities by the crew are expected to last approximately 500 days. Based on 40.2 kg of water per sol for a crew of six, Table 24 shows the amount of water available on the MCCS [10]. Appendix F provides details of this analysis.

Table 24: Water Cache on MCCS Compared to Daily Consumption by a Crew of Six.

Water	
Mass for one sol [kg]	**40.2**
Stored on MCCS [kg]	10000
$m_{stored}/m_{one\ sol}$	249

These daily requirements of BA and water for a crew of six are used as a basis of design for the distribution system of consumables to the habitat.

13. Air Mixing Station

In Section 12, the daily requirements of BA for a crew of six were defined. Thus, a method of producing BA from the O_2 and the N_2/Ar mixture stored on the MCCS must be designed. The mixing of safe BA for the crew is performed by the Air Mixing Station (AMS). The AMS design methodology is now described.

13.1 Air Mixing Station Design Methodology

The methodology undertaken to design the AMS is shown in figure 28. The design of the AMS is now detailed.

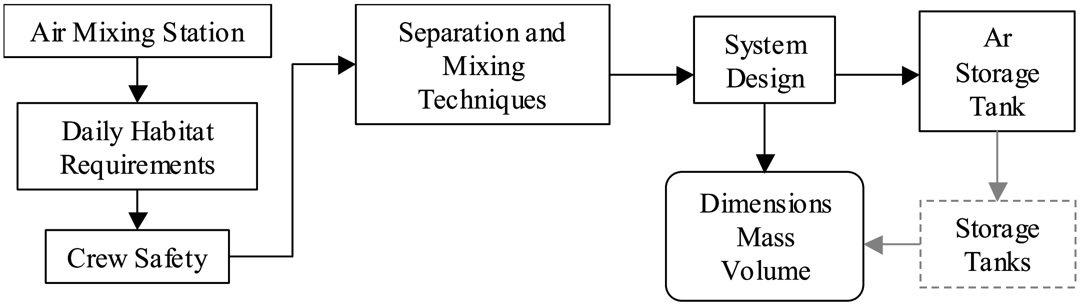


Figure 28: AMS design methodology.

13.1.1 Crew Safety

To transport breathable air to the habitat, accurate proportions of the constituents are essential. Mixing the oxygen and buffer gas directly from the tanks results in the following mixture: 21% O_2, 50% N_2 and 29% Ar. The breathable air on Earth is composed of 21% O_2, 78% N_2 and 1% Ar. Relative to Earth, mixing the BG and O_2 directly from the storage tanks results in high concentrations of N_2 and Ar. Unacceptable levels of Ar and O_2 in air have been known to cause the following effects:

Ar concentrations in air (acting as an asphyxiate) [26]:
- 33% concentration in air, mild symptoms appear
- 50%, the symptoms become marked
- 75%, unconsciousness and death occur quickly

Oxygen concentrations in air [27, 28]:
- <15% O_2, asphyxiation
- 90 to 95% for 6 hours will cause fever and tracheal irritation
- >95% for 16 hours causes lung damage
- >21% in breathable air, fire hazards exist

Since an abundance of one component over another can be fatal, the O_2 must be mixed with the BG in Earth-like concentrations before being transported to the habitat. Attaining and maintaining acceptable levels of O_2, N_2, and Ar in the breathable air necessitates regulation of the mixing process. This is essential to the survival of the crew on Mars. To eliminate the dangers described above, a system must be designed to ensure crew safety.

13.1.2 Separation and Mixing Techniques

To achieve safe concentrations of O_2, N_2, and Ar in BA a system was designed such that the BG is separated into its two constituents, N_2 and Ar. At a range of temperatures and pressures the BG can be separated into gaseous N_2 and liquid Ar. As separate elements, the safe and desirable concentrations of each are regulated for a BA mixture. Two separating and mixing options are now considered.

Option 1 requires active temperature and pressure regulation about the boiling point of Ar in a closed separation chamber. When acceptable concentrations of gaseous N_2 and Ar are achieved the BG mixture is directed to a mixing receptacle where it is mixed with gaseous O_2. Then the breathable air mixture is sent to the habitat. This configuration is shown in figure 29. The disadvantage of this is in the complexity of the control system. The temperature and pressure must be monitored to achieve the desired gaseous concentrations of 78% N_2 and 1% Ar.

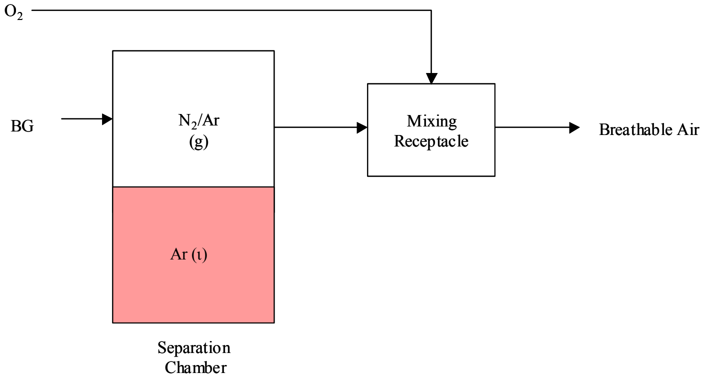


Figure 29: Buffer gas separation and gaseous mixing of BA.

Option 2 is similar to option 1. The BG, however, is completely separated using a larger range of pressure and temperature, and in a continuous fashion. The main difference between the systems is that the percentage of gaseous Ar needed for breathable air is extracted from the liquid, see figure 30. Therefore, the breathable air is produced on demand and is not dependent on optimal conditions in the separation chamber as in option one. The desired and acceptable concentrations of N_2, Ar, and O_2 are managed with mass flow controls into a mixing receptacle before directing it to the habitat. This option is shown in figure 30. The advantages of this system over option one are the simple and effective use of the separation chamber, more control over the regulation process, and precise mixing. Option 2 was chosen as the separation method and is now discussed further.

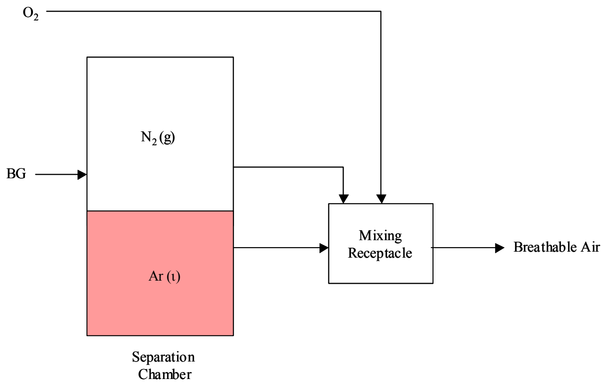


Figure 30: Buffer gas separation and gaseous and liquid mixing of breathable air.

As the buffer gas is extracted from the atmosphere of Mars, it is assumed that the ratio of N_2 to Ar is 2.7:1.6. In Earthlike conditions, this ratio is approximately 2.7:0.15. When the BG is separated excess liquid Ar accumulates in the separation chamber. Three options were considered to manage the excess Ar. Option 1 is to release the Ar to the atmosphere. Releasing the Ar to the atmosphere is environmentally safe, there is no increase in launch mass, no excess work by system mechanics, and few points of failure. However, the Ar is not recycled for future use. Option 2 is to direct the excess Ar back into the BG tank. There are setbacks to option 2. First, pumps are needed to pump the Ar back into the tank, increasing system power and mass. Second, the ratio of N_2 to Ar will decrease. For a continuous system, more BG must be separated before the required amount of N_2 needed for breathable air is obtained. Option 3 is to divert the excess Ar into a separate tank equipped with cryocoolers. This is advantageous in that the Ar is available for future use as a purge gas or in pneumatic tools. Therefore, option 3 was chosen for the final system design. The Ar tank was sized using the same methodology described in Section 10. Details of the Ar tank design are provided in Appendix G.

13.1.3 System Design and Separation Chamber Sizing

Compiling the chosen options, the final design is termed the Air Mixing Station (AMS). The AMS is shown in figure 31. Specifically, the AMS is comprised of a separation chamber, hoses, valves, mass flow regulators, and pressure regulators to ensure quality-breathing air.

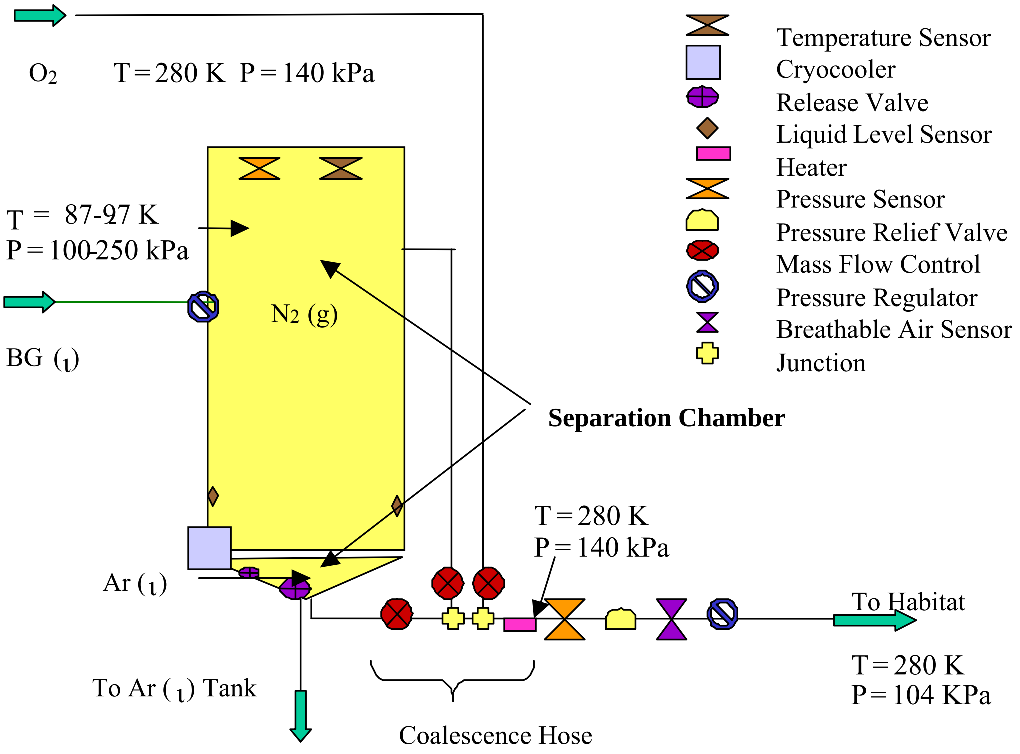


Figure 31: Air Mixing Station schematic.

The BG is pumped as a liquid directly from the ISRU to the separation chamber through insulated hoses at 90 K and 690 kPa. A pressure regulator at the entry to the separation chamber reduces the pressure to a known pressure between 140 kPa and 250 kPa. As shown in figure 32, liquid Ar exists at pressures as low as 100 kPa. However, the pressure must be higher in the separation chamber than in the coalescence hose (140 kPa) to ensure continuous flow. The temperature of the separation chamber is controlled by a cryocooler to ensure that the Ar and N_2 will separate into a liquid and a gas, respectively.

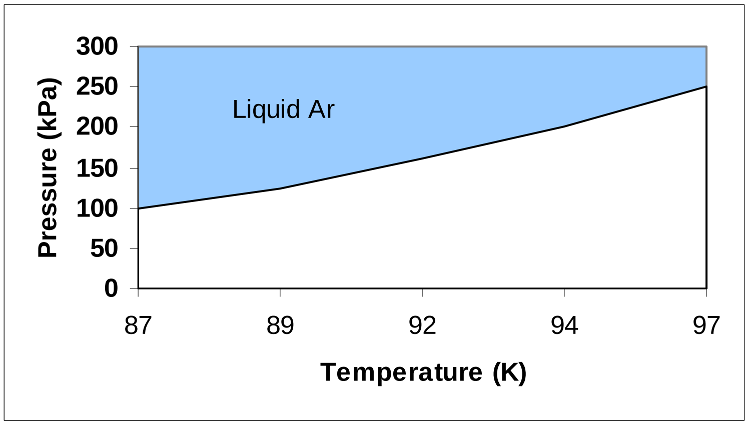


Figure 32: Temperature and Pressure Conditions for Liquid Ar.

Pressure and temperature sensors are affixed to the interior of the separation chamber to ensure proper separation conditions. A change in temperature signals the pressure regulator to adjust the pressure in the separation chamber to comply with the variation in temperature.

The N_2 gas and the liquid Ar are each filtered through separate mass flow controls to regulate the amount of each constituent in the breathable air (see Appendix G). A heater is affixed in the coalescence hose to heat the Ar and N_2 to 280 K. Meanwhile, the O_2, in gaseous form, is sent directly from the O_2 tanks through another mass flow control to converge with the N_2 and Ar. The temperature and pressure in the coalescence hose is at 280 K and 140 kPa respectively. A pressure sensor, pressure regulator, and a breathable air sensor are installed in the coalescence hose to ensure a proper mix of gases. A pressure relief valve is available in the event of pressure increase. After a reduction in pressure to 104 kPa, this breathable air is sent to the habitat.

The geometry of the separation chamber is designed to use the gravity of Mars to ensure a continuous flow of Ar to a single point. The bottom of the separation chamber, designed for liquid Ar flow, is conical. The top half of the chamber is a cylinder to accommodate the gaseous nitrogen. This separation chamber with insulation is 0.4 m in diameter. This allows space for an additional separation chamber for redundancy. The separation chamber is sized to accommodate one-hour supply of buffer gas. This system will operate for 140 sols, until the N_2 in the buffer gas tank has been depleted. In the event of a long-term emergency in which breathable air must be sent to the habitat for longer than 140 sols, the concentrations of breathable air constituents can be changed. If the N_2 is decreased to 54% and the Ar increased to 25%, there is no health hazard presented to the crew, and the breathable air supply will increase to 191 sols. Details of the BA concentrations discussed here are found in Appendix F. The separation chamber was sized to accompany either a long-term (190 sols) or short-term (140 sols) emergency supply of N_2 and Ar. Dimensions are shown in Table 25.

Table 25: Dimensions of Separation Chamber.

	Inner Radius [m]	Height [m]
N_2 Section	0.18	1.7
Ar Section	0.18	0.1
Separation Chamber Dimensions	0.18	1.8

The AMS is a continuous flow system. All but one of the components of this system (valve to the Ar tank) will remain at a specified mechanical setting throughout production. If this valve fails, it will not endanger the crew. There is a pressure release valve on the Ar tank that will release the Ar to the atmosphere if a tank component failure is detected. Three liquid level sensors are located on the inner periphery 0.1 m from the base of the separation chamber to alert a control system of rising Ar levels. This placement of the sensors was chosen because the AMS may not be placed evenly on a surface. This placement allows for the system to tilt slightly and still function as originally intended. When all level sensors indicate a rising level, a release valve will open to divert excess Ar to a separate thermally controlled spherical Ar tank. The excess Ar is stored for future use in research tools and mechanical applications. In the event of a release valve failure, another valve is located in the Ar section that will release the Ar to the atmosphere if necessary.

The separation chamber is constructed of aluminum alloy AA 6201. The mass of the separation chamber of this size is 74.7 kg. The temperature and pressure requirements of the separation chamber necessitate the use of an MLI system and cryocoolers. Dimensions and material information are found in Appendix G. The cryocoolers needed to maintain the temperature in the separation chamber and the Ar tank will each meet the requirements of a maximum 20 watts of heat loss and operate at temperatures between 87 K and 97 K. The coalescence hose is 0.5 m long to allow space for mechanics and has a radius of 0.056 m, the same radius of the connection hose to the habitat. Settings and power distribution of individual components of the AMS are listed in Table 26. Total power used by the AMS is approximately 315 W. This total mass and power of the system mechanics is based on specifications of similar commercially available instruments used today. The power required by the heater to raise the temperature of Ar from 85 K to 280 K is 2.5 W if there were no heat loss through the pipe (see Appendix G). However, ambient temperatures can drop to 150 K, so insulation is needed to maintain the 280 K temperature. If 3 cm of insulation is used for the coalescence hose, 60 W will be needed. This calculation is shown in Appendix E. No insulation is needed for the 1.5 m N_2 pipe connecting the upper separation chamber and the coalescence hose since it is intended to increase temperature.

Table 26: AMS Component Mass Summary.

Component	Quantity	Setting	Power [W]	Mass [kg]
N_2 Mass Flow Control [g/s]	2	0.20	15	4
Ar Mass Flow Control [g/s]	2	0.01	15	6
O_2 Mass Flow Control [g/s]	2	0.06	15	4
PR1 [kPa]	2	207	2	8
PR2 [kPa]	2	103	2	8
Level Sensor Height [m]	6	0.10	4	--
Heater Operating Temperature [K]	2	285	63	--
Pressure Release Valve	2	--	--	4
Cryocooler Operating Temperatures [K]	3	91-97	200	60
Connections	--	--	--	10
Power and Mass Totals			316	104

13.2 Air Mixing Station Mass and Power Summary

The complete mass of the AMS is found in Table 27. Transport of the O_2 from the LOX tanks to the coalescence hose requires a 3 m hose and no insulation or pumps since the boil-off rate is greater than the mass flowrate required by the AMS. The hose carrying the buffer gas from the storage tanks to the separation chamber require 8.5 mm thickness of MLI insulation with a 3.2 mm thick outer shell to maintain minimum heat loss (see Appendix C). The BG will not require pumps since it is stored at approximately 480 kPa greater than what is required in the AMS. The approximate distance between the AMS and BG tank is one meter. Thus, a standard flexible vacuum jacketed hose can be used to transfer the BG to the AMS. All mass specifications of breathable air constituent transport are found in Appendix G.

Table 27: Air Mixing Station Summary

Component	Quantity	Mass [kg]	With Redundant System [kg]
Separation Chamber	2	74.7	149.4
Insulation	2	2.5	4.9
Ar Tank	1	83.7	83.7
Insulation	1	4.1	4.1
N_2 pipe	2	3.6	7.1
Coalescence Hose	2	1.2	2.4
Insulation	2	0.6	1.2
O_2 Hose	2	8.3	16.5
BG Hose	2	13.8	27.5
Insulation	2	6.7	13.4
System Mechanics	2	32.0	104.0
	Total AMS Mass [kg]		414.1

14. Transfer Hose

A design objective for the MCCS is distribution of consumables to the habitat and propellants to the MAV. In the event of an emergency, the reliable and timely transfer of consumables to the habitat is mission critical. In addition to the transfer of consumables, the propellants must be transferred to the MAV prior to launch or in the event of a tank failure. The design of systems for both of these objectives is detailed here.

14.1 Transfer Hose Design Methodology

The design of the propellant and consumables transfer hoses followed similar methodologies. The design methodology is shown in figure 33. The design of the consumable transfer hoses will be discussed first, followed by a description of the propellant transfer hoses.

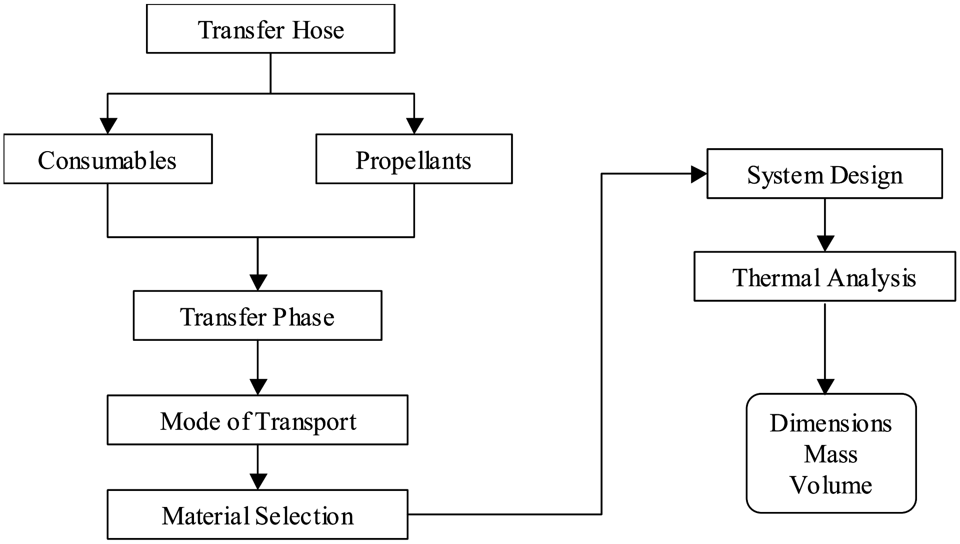


Figure 33: Transfer hose design methodology.

14.1.1 Transfer Phase and Mode of Transport

Once manned operations begin on the martian surface, consumables must be readily available for emergency use by the crew. For reasons given in Section 9, the H_2O is stored and transferred as a liquid. The AMS produces a BA mixture at the MCCS, thus a transportation system is required. Options are presented for both BA and water transfer to the habitat.

One option for consumables transport to the habitat includes the use of autonomous rovers. An autonomous rover system is desired to reduce the workload on the crew during emergency operations. With current technology, autonomous vehicles can be developed for this purpose. However, the size and mass of the rover will depend on the needs of the habitat in an emergency.

Citing the requirements in Tables 23 and 24, the rover must transport a minimum of 24.0 kg of breathable air and 40.2 kg of water per sol. Considering spherical transportation tanks for breathable air and water, inner tank diameters are 4.08 m and 0.2 m, respectively. An individual tank for each consumable is not practical. Inclusion of an autonomous rover with these tank sizes will reduce the available volume in the launch vehicle for important scientific packages. For system redundancy a rover of equal proportions will be needed, further reducing storage volume. Multiple trips between the MCCS and habitat can reduce the size of the breathable air tank, but the risk of failure increases.

The use of autonomous rovers for transport of consumables for non-emergency or emergency use will necessitate highly complex systems, increase launch mass, and degrade the reliability of consumables transfer to the habitat. The varying terrain of Mars and extreme weather conditions can also present transportation problems. As an alternative, the consumables can be pumped to the habitat via hoses.

Pumping the consumables to the habitat in hoses has several advantages. The system allows for immediate transfer of the consumables, effective use of available volume, all weather transport, and increased reliability over autonomous transport. Disadvantages include laying the hose over the one-kilometer distance between the MCCS and habitat, heating control, and high power consumption for pumps and heating. However, these disadvantages are overcome with innovative design choices. For these reasons, the consumables will be pumped to the habitat via hoses.

14.1.2 Material Selection

Material selection for these hoses is based on the expected ambient temperatures (150 to 300 K) on the surface of Mars. Common hose materials like nylon, rubber, and silica were considered but proved to be brittle at these temperatures. Stainless steel flexible hoses can survive these temperatures, but at the 500 m transfer distance they are too massive (density > 2000 m^3/kg). Commercially available Teflon® can withstand these temperature extremes. Advantages of Teflon® over stainless steel are flexibility, strength, inertness, moisture resistance, low coefficient of friction, and it is ageless [47]. For these reasons, Teflon® will be used as the hose material. The material properties are shown in Table 28.

Table 28: Material Properties of Teflon®.

Density [m^3/kg]	Temperature Range [K]	Thermal Conductivity [W/mK]
2150	103 to 533	0.25

Transferring the consumables in hoses over a 500 m distance will require pumps. Pump sizing is based on the needs of the crew (described in Section 12), power consumption, and minimal mass of the entire transport system.

It is a possibility that some of the hoses may develop leaks. These leaks can occur due to manufacturing defects, at valve interfaces, or as a result of a poor seal. If one of these failures occurs, water will freeze when exposed to ambient conditions or air will be released to the atmosphere. There are several options to consider in the event of a failure. One option is to capture the escaping water or breathable air and isolate the damaged hose segment. Another option is to quickly isolate the leak in the hose and allow the constituent to be released to the atmosphere.

In both cases the isolation of the leak is crucial. A single 500 m hose does not allow for leak isolation, it is difficult to pack in the Earth launch vehicle, and it offers a low level of system reliability. Advantages of a segmented design include ease in launch vehicle packing, terrain adaptability, and the ability to replace damaged segments with spare segments. Segmented consumables hoses are chosen to ensure reliable and uninterrupted transport of the consumables and allow for leak isolation. Fitting hose with shutoff valves at both ends will isolate the leak in a damaged segment. Extra segments are included to replace damaged segments.

14.1.3 System Design and Thermal Analysis

The design of the consumables transfer hoses was based on fluid dynamics principles [32]. Details of the design can be found in Appendix H, but a brief summary of the analysis will be given here. Before the fluid analysis was conducted, the transfer temperature and pressure was chosen. Standard room temperature and pressure was selected. These conditions are preferred so that neither the BA nor water will require heating or cooling after transfer. Theses values can be found in Table 29.

Table 29: Transfer Conditions for Consumables.

Fluid	Mass [kg]	Temperature [K]	Pressure [kPa]
BA	24.0	300	101.4
H_2O	40.2	300	101.4

Now that the transfer conditions have been selected, the flowrate for both BA and water was determined based on the daily needs of the crew. The BA flowrate was fixed relative to a martian day or sol, and different flowrates were considered for the transfer of water. Analysis was carried out that considered different diameter hoses, ranging from 5 to 90 mm. For each respective diameter the Reynolds Number (Re) was determined. Then the corresponding friction factor was obtained from a Moody chart or directly calculated (for laminar flow only). The head loss was determined which is related to the amount of power that the fluid must gain as it travels down the 500 m length hose at a constant velocity. This is directly related to the actual work that must be provided by a pump to keep the fluid moving at this constant rate. Considering a pump that is only 85% efficient the shaft work provided to the pump was determined.

Having determined the shaft work, the wattage that is needed to pump the BA or water to the habitat was found. The horsepower and wattage was then divided up along the total length of the hose to determine an optimum number of smaller pumps that can push the fluid at the desired flowrate. Additionally, the maximum allowable elevation change from the MCCS to the habitat was determined. Details of this fluid analysis, which includes plots and equations, can be found in Appendix H.

Using the analysis described above minimum inner hose diameters were found for both BA and water. The minimum inner hose diameter for BA and water that could support the largest elevation change from the MCCS to the habitat was determined to be 56 mm and 24.4 mm, respectively. These diameters were then used to in the thermal analysis. The flowrate did not have a direct impact on the inner water hose diameter, but did have an impact on the power required to pump the fluid at increasing flowrates.

The thermal analysis of the hoses used the same equations that are outlined in Appendix E. The properties of Teflon® and C-8 (described in Section 10) were used in the analysis. The C-8 “blanket” insulation was chosen over MLI due to the desired flexibility and minimal mass of the transfer hose. The thermal analysis was carried out using a 1 mm hose thickness for both the BA and water hose. In addition to the thermal analysis the corresponding mass of the hose with a thickness of insulation was determined.

It was found that for these hose dimensions and varying insulation thickness at the lowest expected ambient temperature of 150 K, the BA and water could be transferred without losing heat to the atmosphere. However, this resulted in massive hoses, on the order of metric tons. Then it was determined that for a reduced hose mass more power could be used. This power would be used to heat the BA and water during transfer or at the habitat.

For a hose with no insulation it was found that transferring the BA only required 10.8 kW to heat it back to the desired temperature of 300 K. Further analysis showed that for the water hose with no insulation a range of flowrates was found that required no heating of the water during transit. However, residual water might exist in the hose after pumping is completed, so to heat the hoses to prevent the water from freezing requires approximately 2.8 kW over the 500 m hose length. Both of the configurations described here are of low mass and high power consumption. Plots and results are shown in Appendix H for the thermal analysis described here.

14.2 Consumable Transfer Hose Mass and Power Summary

The options above resulted in the following design of the consumables transfer hoses. The air and water hoses are constructed of 5 m segments along the 500 m distance between the MCCS and habitat. The 24.0 kg of breathable air is transferred over a 24-hour period at 300 K, requiring 18.8 W to pump and 10.8 kW to heat the BA at the habitat. Transferring the 40.2 kg of water in 6.25 minutes at 300 K requires only 7.4 kW. Tables 30, 31, and 32 summarize the consumables hose design. The thermal analysis described in the previous section determined that both the water and air hose do not require insulation. For redundancy, a secondary hose for the air and water hose are included. If a hose becomes disabled due to a material or mechanical failure the secondary hose is employed.

Table 30: Hose Dimensions.

Constituent	ID [mm]	OD [mm]	Segment Length [m]
Air	56.0	58.0	5
Water	24.4	26.4	5

Table 31: Individual Hose Masses.

Constituent	# Hoses	# Segments	# Extra Segments	Segment Mass [kg]	Total Segment Mass [kg]
Air	2	100	25	0.96	409.1
Water	2	100	25	0.43	182.3
				Total Hose Mass [kg]	591.4

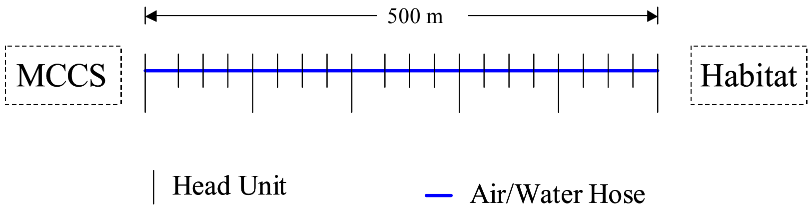
Table 32: Hose Power Requirements.

		Power Consumption		
Constituent	Transfer Time	Pumping [kW]	Static [kW]	Heating [kW]
Air	24.6 hr	0.002	--	10.8
Water	6.25 min	7.4	2.8	--
	60 min	0.78	2.8	--

Transferring water in one hour requires no heating, but heating coils are provided to prevent the freezing of residual water causing clogs in the hose. Approximately 3 kW of static power is required to keep the water from freezing in the hose (see Table 32). The air will require 10.8 kW of power to keep it at 300 K. The air will be heated at the habitat, not along the 500 m hose length to avoid additional points of failure. Also, heating the air at the habitat will isolate any potential problems due to heating.

The water hose system is capable of delivering the 40.2 kg (10.6 gallons) of water to the habitat in 6.25 minutes. The system was designed with variable flowrates to accommodate different delivery times. Thus the pumps were sized relative to the fastest transfer time of 6.25 minutes. This translates into a flowrate of 1.7 gallons/minute, which is the flowrate of common household faucets.

The sizing of the pumps was done in a manner such that small pumps located along the 500 m length keep the fluid moving. Figure 34 shows the placement of each pump along the 500 m length. The pumps are enclosed in a Head Unit (HU). The HU's include a pump, pump motor, flow meters, and other necessary electronics. The fluid pressure is monitored along the way to ensure that the desired flowrate is maintained.



- 21 total HU's for each line: includes pump and monitoring equipment for Air and water
- HU's on MCCS and Habitat are fixed
  - 19 HU's have to be manually positioned between MCCS and Habitat at 25 m increments

Figure 34: Head unit placement along the 500 m distance between the MCCS and habitat.

If a leak is detected the escaping water or air can be captured. The advantage in this is that the consumables are saved. A system that isolates the leak and captures the consumable will be a complex one. Upon detection of a leak in a segment, rapidly closing valves located at each end of the segment will close resulting in the loss of only that amount which is contained in the segment. Considering a segment length of 5 m, inner hose diameters of 24.4 mm and 56.0 mm, and the daily needs of the crew, the percentage of air and water lost in a single segment is shown in Table 33. Immediate leak detection will minimize the amount of consumable lost.

Table 33: Minimum Consumable Loss in an Isolated Segment.

Constituent	Mass in a Segment [kg]	Daily Total [kg]	% Lost from 1 sol Total
Air	0.01	24.0	< 1
Water	2.3	40.2	< 6

The fact that water will not exist on the surface of Mars as a liquid is important. It is expected that if a leak were to develop in a water transport hose the leak will be contained by the freezing water. Capturing the escaping consumable is desirable but is not necessary for the amount that can be saved. Therefore, capturing the escaping consumable from a leak will not be included in the hose design.

14.3 Crew Operations

Upon arrival, the crew will have 90 days for site preparation, construction, and verification of surface systems [14]. Included in these 90 days the crew will have to lay the hose. The hose is stowed on the MCCS in five different bundles. The location of the bundles is shown in figure 35. Each bundle contains 25 water hoses and 25 BA hoses in five-meter lengths. Only four of the bundles are required for the 500 m distance between the MCCS and habitat. The fifth bundle contains 50 extra segments, 25 each for water and BA. Hose construction is not expected to take more than one sol.

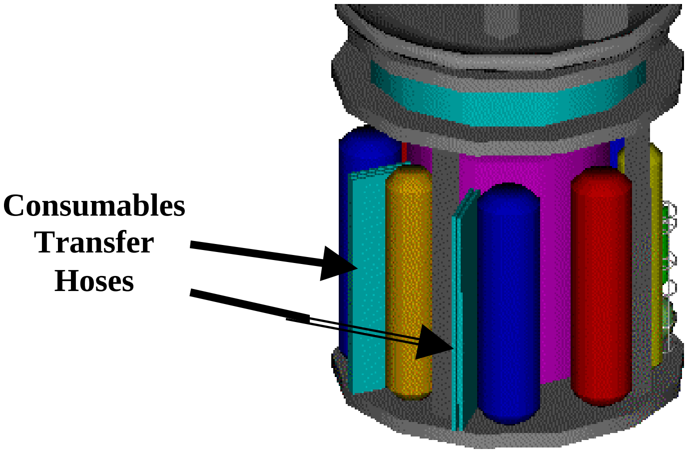


Figure 35: Consumables transfer hose stowage location on MCCS.

14.4 Propellant Transfer

The propellants are stored on the MCCS while the MAV tanks serve as backup tanks. Two different situations will require transferring the cryogens from the MCCS tanks to the MAV tanks. First, prior to crew liftoff from Mars the MAV tanks must be filled. Second, if a system failure occurs in any of the MCCS tanks, the cryogens must be transferred from the MCCS tanks to the MAV tanks.

The transfer of the propellants from the MCCS to the MAV can be accomplished in two different phases, gaseous or liquid. Gaseous transfer requires three steps. The stored liquid is vaporized, transferred and then re-liquefied at the MAV. The advantage of this method is in the natural ability to boil-off the liquid with variable temperature cryocoolers. A disadvantage is that there is added mass to the MAV due to the complexity of the liquefying system.

Transferring cryogenically is the second option. The advantages of cryogenic pumping are that it does not require a phase change and transfer time can be variable. Disadvantages include the use of vacuum jacketed (VJ) pipes and power consumption by the pumps. Insulated hoses do not provide sufficient thermal protection. Using flexible static VJ hoses versus rigid VJ pipes is a mass savings of approximately 50% for the 15.8 m transfer distance. Flexible VJ hoses also resist condensation making the worksite safer. Thus, flexible VJ hoses will be used in the transferring of propellants from the MCCS to the MAV.

The two most common methods of cryogenic transfer are pressure pumping and conventional pumping. Pressure pumping is accomplished by increasing the pressure in the tank with a common “pressure gas”, e.g. helium or N_2. The increase in pressure pushes the cryogen out of the tank. Since buffer gases are readily available on the MCCS, this mixture can be used as the “pressure gases”. Conventional cryogenic pumping involves the use of an axial flow (submersible) pump. This method of pumping is no different from the pumping of water from one tank to another. For our purposes, the principles of both pumping methods will be used to transfer the propellants from the MCCS to the MAV as liquids.

To eliminate potential failures associated with the pumping of a pressure gas, the liquid cryogen will be allowed to boil-off providing the required change in pressure. Methane requires 149.6 kPa of head pressure to move all the liquid into the MAV tank, where oxygen requires 169.33 kPa of head pressure. Potentially, monitoring and controlling the boil-off rate of the cryogen will allow for complete transfer of the propellants. Emergency situations may require the use of pumps during uncontrolled boil-off in the tank to prevent dangerous pressure buildup. Due to the fact that boil-off of the liquid is always possible, the pumps are not sized to transfer all of the cryogen. Thus, a minimum wattage is required for pumping.

The CH_4 and O_2 pumping arrangements include primary and secondary pumps, hoses and valves for each MCCS storage tank. Each MAV tank is equipped with a liquid level sensor and a phase separator that prevents irregular spray or drainage into the MAV tank. The liquid CH_4 from both MCCS tanks is transferred into one MAV tank, whereas, the liquid O_2 is transferred from three tanks to four. The schematics of these pumping arrangements are presented in Appendix H.

The proposed method of propellant transfer described here requires future work. Thus, the total system mass for the CH_4 and O_2 transfer systems has not been determined.

15. Additional Components and Systems

In this section additional components and systems are identified that complement the MCCS.

15.1 Blast Shield

When the MAV leaves Mars the MCCS storage tanks must be protected from the rocket plume. A blast shield below the MAV and above the ISRU plant can provide this protection. To minimize the mass of the shield it can be constructed of composite G\E. However, the G\E alone cannot survive the high temperatures of launch. A layer of thermal protection is needed.

A common thermal protection material is MA-25, manufactured by Lockheed Martin. This material is used on the space shuttle and other high temperature applications when short duration exposure to temperatures exceeding 922 K is encountered. MA-25 is a filled elastomeric silicone, which cures at room temperature and can be applied with conventional spray equipment [30]. The density of MA-25 is approximately 400 kg/m^3, which will not significantly increase the mass of the blast shield. The ease of application, low density, and thermal protection characteristics of this material make it a desirable treatment. The G\E blast shield can be sprayed with a 4 mm layer of MA-25 [30]. A layer of this thickness can provide adequate blast protection for the short-term exposure during MAV launch.

The blast shield will be shaped such that the plume is directed away from the ISRU plant and MCCS tanks. The shape of the blast shield is shown in figure 36. It is expected that the curvature of the “cup” will sufficiently deflect the plume.

The mass of the blast shield is approximately 1923 kg. The mass and dimensions presented here are preliminary estimates and require future work. The proposed use of G\E and MA-25 is feasible and these materials are recommended for the blast shield.

Figure 36: MAV blast shield.

15.2 Support Structure Material

The MAV/MCCS support structure is designed to support the loads for all phases of the mission. These loads include over 12 metric tons of plumbing and hardware and over 4500 N of thrust generated at MAV liftoff [23].

Aluminum alloys such as AA 6201 have a high strength to weight ratio compared to most metals and for these reasons, Apollo mission designers used it extensively [21]. Therefore it is recommended that aluminum alloy AA 6201 be used as the support structure material.

15.3 Leak Detection

Due to the potential for violent reactions between various fluids stored on the MCCS, the mission lifetime and crew safety require a leak detection system. Leak detection systems are common in nearly all space applications that involve propellants like methane, oxygen, and hydrogen. The Cryogenic Transfer System Mechanical Design Handbook [15] provides examples of using inert gases such as nitrogen or helium to purge external parts of space vehicles. Since the BG is a mixture of inert nitrogen and argon, it can be the primary source of purge gas on the MCCS. If circumstances require BA transfer to the habitat, a reserve of argon will be available and can also be used as a purge gas.

The MCCS tanks will be exposed to the Mars atmosphere allowing convective cooling. However, if a leak develops the fluid is expected to gain heat. Thus, a leak detection system is needed to ensure proper maintenance of the tanks and the fluids. A leak detection system will include various gas sensors located on the MCCS and MAV tanks. The leak detection system will closely monitor the internal pressures and temperatures in the tank. If a leak is detected by either the internal and/or external sensors, the control system will attempt to isolate the outflow. Four responses are described if a leak is detected on the MCCS. 1) If a CTS pipe leaks, the leak detection system will initiate valves to transfer the consituent into the backup pipe. 2) If a propellant leak is detected from a tank and the leak cannot be isolated, the leak detection system will initiate propellent transfer to the MAV tanks. 3) If a water leak is detected from the tank; indicated by the pressure drop in the tank; the water in the tank will be allowed to freeze. When the crew has reached the surface they can asses the damage and repair the leak (if possible) before reheating the water. 4) If a leak from the BG tank is detected and cannot be isolated, the emergency release valve will be opened to allow the boil-off to escape to alleviate pressure buildup in the tank. The argon tank can be used to store BG in the event of an emergency. (This presumes that the ISRU plant can always extract BG from the atmosphere).

Currently there are several technologies under development to improve space environment leak detection. For example, a Silicon Carbide based microfabricated gas sensor is being developed at NASA Glenn Research Center and Case Western Reserve University [16].

15.4 Crew Access to the MAV

For the current payload arrangement, the MAV is located 15.8 m above the ground. Prior to launch the crew must remove the deployable MAV components. This necessitates easy access to the MAV during launch preparations. Ladders located around the payload arrangement will allow easy access to the MAV at all times during launch preparations.

15.5 Tank Filler Gas

All of the tanks are filled with a light inert “filler” gas (e.g. helium) prior to launch. The gas maintains the structural integrity of the tanks during launch and landing. The “filler” gas will be released to the atmosphere before ISRU plant production begins. This will produce desirable pressure change and aid in the filling of the tank.

16. Conclusion

The MarsPort Cryogenics and Consumables Station (MCCS) described in this study efficiently and reliably stores and distributes propellants and consumables on the surface of Mars ensuring crew safety.

The design of the MCCS, however, revealed areas that require future evaluation and analysis. These areas include the use of boil-off to initiate fluid transfer, large-scale cryogenic cooling methods, benefits of composite graphite\epoxy as a tank material, and techniques to shield MCCS components during MAV launch.

Using boil-off to initiate fluid transfer is incorporated into the design of the propellant transfer system. This concept, while physically possible, requires further work to accurately explain the temperature and pressure requirements. Once these requirements are established an accurate control of fluid transfer will be possible. This control may eliminate the need for the pumps currently in the system.

Effective cryogenic cooling methods were not fully defined in the MCCS, because the cryocooling requirements are not fully understood. Current cooling technology can withdraw heat at a rate of approximately 150 –200 Watts. This rate is too low and must be increased to effectively cool a system of this nature. An increase in this rate will permit the use of lightweight insulation, effectively reducing the mass of the thermal control system. Additionally, enhancement of the cooling system increases the reliability of the system, allowing improved control over temperature and pressure.

The mass and strength benefits of using a composite graphite\epoxy storage tank was discussed, but research showed this technology to be immature. However, research in this field is growing and cryogenic storage tanks of composite graphite\epoxy will be a reality in the near future.

The final area requiring evaluation is a method of shielding MCCS components from the heat generated during MAV launch. Materials were identified that possesses the thermal properties to adequately protect the MCCS components, but future work is needed to accurately determine an effective shape for the blast shield.

The design process began by establishing a baseline system from which future designs would be derived. A design philosophy was adopted that consisted of a low mass, low power and high reliability approach. Each step of the design process was thoroughly evaluated to ensure this philosophy was employed.

After establishing the design philosophy and discussing general design concepts, the MCCS was divided into four sub-categories. These categories are liquefaction of ISRU plant outputs, storage of ISRU plant outputs, propellant and consumable transfer, and the production of breathable air. The MCCS is designed to ensure mission success and astronaut safety, while incorporating a low mass and thermal efficient design philosophy. Thermo- and fluid dynamic properties are exploited to reduce the system mass and power requirements. System reliability was studied and all single points of failure were identified. When these points of failure could not be eliminated by redundancy, sufficient safety margins were employed.

The innovative ideas and design decisions of this team produced a MarsPort Cryogenics and Consumables Station that effectively maintains and distributes propellants and consumables on the surface of Mars taking full advantage of the ISRU plant capabilities. The goal of a manned mission to Mars in the near future is a realistic one with the development of the systems identified in this study.