LEVITATE: Lunar Exploration Vehicle for Intra-planetary Transport and Terrestrial Expansion

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Executive Summary

LEVITATE is a lunar exploration vehicle capable of providing intra-lunar transportation of two astronauts to any scientifically interesting or resource-rich location by means of orbital and sub-orbital transfers. It has the capability to sustain two astronauts for up to fourteen Earth days at the remote site.

LEVITATE is motivated by a dichotomy in the way our nation has previously planned to explore the Moon, as presented in the Review of U.S. Human Spaceflight Plans Committee's analyses of possible lunar missions. LEVITATE enables global lunar access in addition to lunar base development.

Orbital calculations demonstrate that LEVITATE is capable of performing the required maneuvers with a wet mass of approximately 25,000 kg and a dry mass of 5,000 kg. Liquid oxygen and liquid hydrogen fuel tanks have been designed to supply the Pratt and Whitney Common Extensible Cryogenic Engine. The fuel tanks are designed to avoid frequent maintenance and/or replacement of parts.

Aluminum Weldalite 049-T8 is the main structural material for all supportive members. Silicon-oil shock absorbers dampen the vehicle response during landings.

Wire-locked stainless steel pinned connections with PTFE-lubricated bearings are simple to manufacture or replace. 3M's NEXTEL 601 fabric is secured over all moving joints with Military specification hook and loop fasteners to shield dynamic components from lunar regolith.

The habitat is protected from micrometeorite damage by shielding derived from the ISS. Radiation shielding is provided by externally mounted fuel tanks, various layers of aluminum structure, and borated high density polyethylene. Astronauts egress/ingress through two suitport airlocks to minimize regolith entrance to the habitat.

Life support routing components are primarily manufactured from stainless steel. Commercial-off-the-shelf components are heavily used in the design of the life support systems for their flight heritage, ease of integration, and reduced cost. Life support systems are designed to optimize regenerative cycles and to reduce overall mass.

Projections indicate that the production of LEVITATE will cost approximately $3.1 billion. This cost includes design, development, testing and evaluation. Each unit is predicted to cost approximately $280 million and the entire development will take nine years. This estimate excepts any cost savings across the lunar architecture. LEVITATE's current Technology Readiness Level is 4.

Technical drawings of LEVITATE's major assemblies and their respective parts have been completed. Major systems have been completely defined according to appropriate codes and industry standards and, more importantly, feasibility of the concept has been proven.

Figure 1: The Lunar Exploration Vehicle for Intra-planetary Transport And Terrestrial Expansion, LEVITATE.

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1. Introduction

The Lunar Exploration Vehicle for Intra-planetary Transport And Terrestrial Expansion (LEVITATE) is a crewed exploration vehicle that provides access to the entire lunar surface through suborbital and orbital maneuvers. This vehicle supports a crew of two for up to fourteen days at any resource or science-rich lunar location. LEVITATE also provides transportation between lunar bases and access to low lunar orbit. LEVITATE is fully resuppliable with resources gathered on the Moon. The following report provides a high-level systems overview of LEVITATE's main components.

Based on the Solidworks model, the total vehicle mass is 24,871 kg. A brief overview of the mass by system is shown in table 1 and further detail can be found in Appendix A.

Subsystem	Approximate Mass (kg)
Structural Hardware	2741
Propulsion Hardware	1240
Fuel	20000
Life Support	270
Habitat	620
Total	24871

Table 1: Mass list of major subsystems of LEVITATE.

1.1 Motivation

LEVITATE is a solution to a lunar exploration dichotomy seen in the final report of the Review of U.S. Human Spaceflight Plans Committee and previous lunar exploration architectures [1-6]. When humans return to the Moon they will have a choice between exploring the entire lunar surface with independent, Apollo-like missions or building an outpost and being restricted to walking and roving distances. The first option is attractive because it allows exploration of the most scientifically-interesting locations on the Moon but 'throws away' all landed mass at the end of the seven day mission [7-11]. An outpost-based exploration architecture maximizes the future utility of all landed mass but ties all lunar exploration to a single geographic region for a decade or more.

1.2 Design Rationale

LEVITATE enables both global lunar access and lunar base development. Designed to be resuppliable with resources extracted from the lunar surface, mission frequency is limited only by the fuel production rate. LEVITATE fills a previously unforeseen need for a multipurpose science and transportation vehicle. Initial uses include global geology, targeted orbital observations, and sensor emplacement. In the longer term, LEVITATE may be used for transportation between multiple lunar outposts and rendezvous in low lunar orbit.

Though LEVITATE is a new concept in lunar exploration, it is based on: lunar lander, rover, and habitat designs from the Apollo Program, 2000 Decadal Planning Team, 2004 Vision for Space Exploration, 2005 Exploration Systems Architecture Study, Constellation Program, Review of U.S. Human Spaceflight Plans Committee, academic studies, and multiple field tests [1-7, 10, 12-25]. Previous studies have considered 'lunar flyers,' simple, generally terrain-following vehicles with the express purpose of quickly transporting astronauts (commonly two) across the lunar surface, without appreciable cargo or exploration equipment [26].

Nearly all envisioned lunar architectures have included a wheeled surface vehicle whose primary purpose was astronaut transportation. LEVITATE will not replace the utility of manned rovers, as they will be required for transportation around the lunar outpost, resource gathering, and science objectives near the outpost but will greatly expand the range of scientific exploits.

1.3 Assumptions

The development of LEVITATE required assumptions to be made about the future status of lunar infrastructure development, In-Situ Resource Utilization (ISRU), Heavy Lift Vehicle (HLV) development, and multiple communications satellites around the Moon. These assumptions are in accordance with development of the Constellation Program and the 'Moon First' scenario from the final report of the Review of U.S. Human Spaceflight Plans Committee [6].

The first assumption is the existence of a manned lunar base at the south pole of the Moon, likely in the Aitken Basin. The lunar base will serve at least four astronauts who are engaged in, among other tasks, fuel extraction from the lunar soil (hereafter regolith).

The second assumption is that the outpost is capable of harnessing resources available on the Moon to resupply LEVITATE. Hydrogen, oxygen, and nitrogen need to be extracted from the regolith as they are consumed during the fourteen day mission.

The third assumption is the existence of an HLV capable of transporting a fully assembled vehicle to lunar orbit. Note that any significant lunar exploration architecture requires an Ares V-class vehicle.

The final assumption is that continuous communications are provided by lunar satellites. Without a satellite network there would be no direct line-of-sight for communications with the side of the Moon not facing Earth, effectively cutting off the astronauts from mission control.

2. LEVITATE Design

2.1 Propulsion

NASA technical reports from Apollo establish an optimal trajectory for LEVITATE's orbit. Apollo's orbital altitude of 15.24 km is a compromise between safety and fuel efficiency. The compromise is that it is more fuel efficient to orbit closer to the lunar surface but also more dangerous due to terrain variations which can reach up to 6.1 km [27].

Launching LEVITATE along these orbital trajectories is an engine derived from the flight-proven RL-10, with attitude control provided by reaction control assemblies.

2.1.1 Common Extensible Cryogenic Engine (CECE)

The engine chosen for LEVITATE is the Common Extensible Cryogenic Engine (CECE) manufactured by Pratt and Whitney. The CECE was originally developed for the 2004 Vision for Space Exploration Program, which was the basis for the Constellation program and the Altair lunar lander. The CECE is based on the flight-proven RL-10 and has undergone significant testing in recent years to ensure the same reliability and margin of safety as the RL-10, while adding the capacity to throttle.

The performance of the CECE, as reported from the hot-fire testing, fulfills the requirements for LEVITATE's main propulsion. This engine provides 66.7 kN of thrust with a specific impulse of 445 sec and a mass of 160 kg. The largest advantage of the CECE is the deep throttling range, starting at 9% of the nominal vacuum thrust and extending to 102% [28]. Throttling is necessary for starting descent and for maneuvering during landing. The throttling range of the CECE is sufficient to perform all of the ascent and descent maneuvers discussed previously and seen in Appendix B. Ascent maneuvers require 102% of nominal thrust while descent maneuvers require 13.8%.

2.1.2 Reaction Control System (RCS) Thrusters

Twelve reaction control thrusters control LEVITATE's pitch, yaw and roll. Bipropellant liquid oxygen (LOX) / liquid hydrogen (LH2) thrusters from Northrop Grumman produce 4.4 kN of thrust, each with a specific impulse of 404 sec [29]. These thrusters are advantageous because they use the same fuel as the CECE. The RCS provide enough thrust to land the vehicle in the case of catastrophic failure of the CECE, providing an additional level of redundancy.

2.1.3 Propellant tanks

2.1.3.1 Sizing

Simulation of the maximum fuel expenditure, a pole-to-pole mission, shows that LEVITATE requires 20,000 kg of fuel. The CECE and RCS use a mixture ratio of 5.5:1, driving the fuel and oxidizer tank sizes while providing room for possible boil-off or ullage. These calculations are shown in Appendix C.

2.1.3.2 Materials

The oxygen and hydrogen tanks experience significant loads and thermal gradients, requiring materials with high strength to density ratios and largely temperature-invariant properties. The shells and inner components of the liquid hydrogen tanks use Titanium 6AL-4V. Since titanium and liquid oxygen spontaneously combust, Inconel 718 is used for the oxygen tanks. Tank shell thicknesses satisfy the MIL-1522 requirement of a 1.5 factor of safety on the propellant tank walls to avoid buckling of the tank under operational loads.

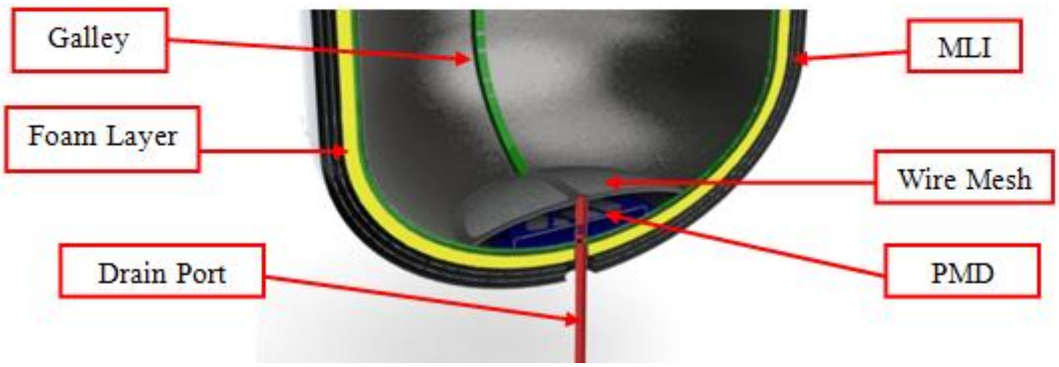


Figure 2: Important components of the LH2 fuel tanks.

2.1.3.3 Thermal Control

Energy input from thermal and radiation sources must be limited to prevent excessive boil-off and maintain cryogenic temperatures. The mission duration of 14 days negates the need for an active cryocooler [30]. Instead, the LH2 tanks seen in figure 2 use a combination of BX-265 rigid polyurethane foam and a multi-layer insulation (MLI) blanket made with alternating layers of double aluminized Mylar (DAM), polyester Dacron netting, and bumper layers. The LOX tanks feature the same BX-265 insulation as the LH2 tanks, surmounted by a 0.75 mm thick Hexcel AS4C carbon fiber shell to retain the foam.

Together these mitigate heat transfer between the tanks and external environment while offering a simple and robust system that is not dependent on electronics or computer control. In the case that there is a significant amount of ullage pressure from boil-off, a de-tanking port is at the top of each fuel tank. This port has a cryogenic pressure sensor and solenoid valve that will only open if the tank pressure exceeds operational levels, generally 100 psia.

2.1.3.4 Propellant Management Device (PMD)

The LOX and LH2 tanks must ensure that there is propellant next to the fill/drain port at all times. Seen in figure 2, vertical and elliptical galleys direct fuel towards the drain end of the tanks, using capillary effects, where the propellant is captured in the wire screen for future use. Wire screen layers on the bottom of the tanks are composed of 50 x 250 plain Dutch Weave wire mesh with a 60 µm porosity, which allows the fluid flow through and along the mesh [31, 32]. Unlike diaphragm and bladder systems which must be replaced after as few as 10 uses, this system is robust enough to withstand years of use with little to no maintenance [31, 33].

2.2 Structure

LEVITATE's structure must perform in harsh conditions and conserve mass wherever possible. Careful selection of materials, systems, geometries, and connecting methods ensures these requirements are met. Compliance with standard AIAA-S-110 2005 ensures that all structural components have a factor of safety no less than 1.4. Structural components under the largest stresses were evaluated with finite element methods to determine the factor of safety. The members evaluated were those bearing engine loads or subjected the weight of the fuel tanks. Stress calculations can be seen in Appendix D.

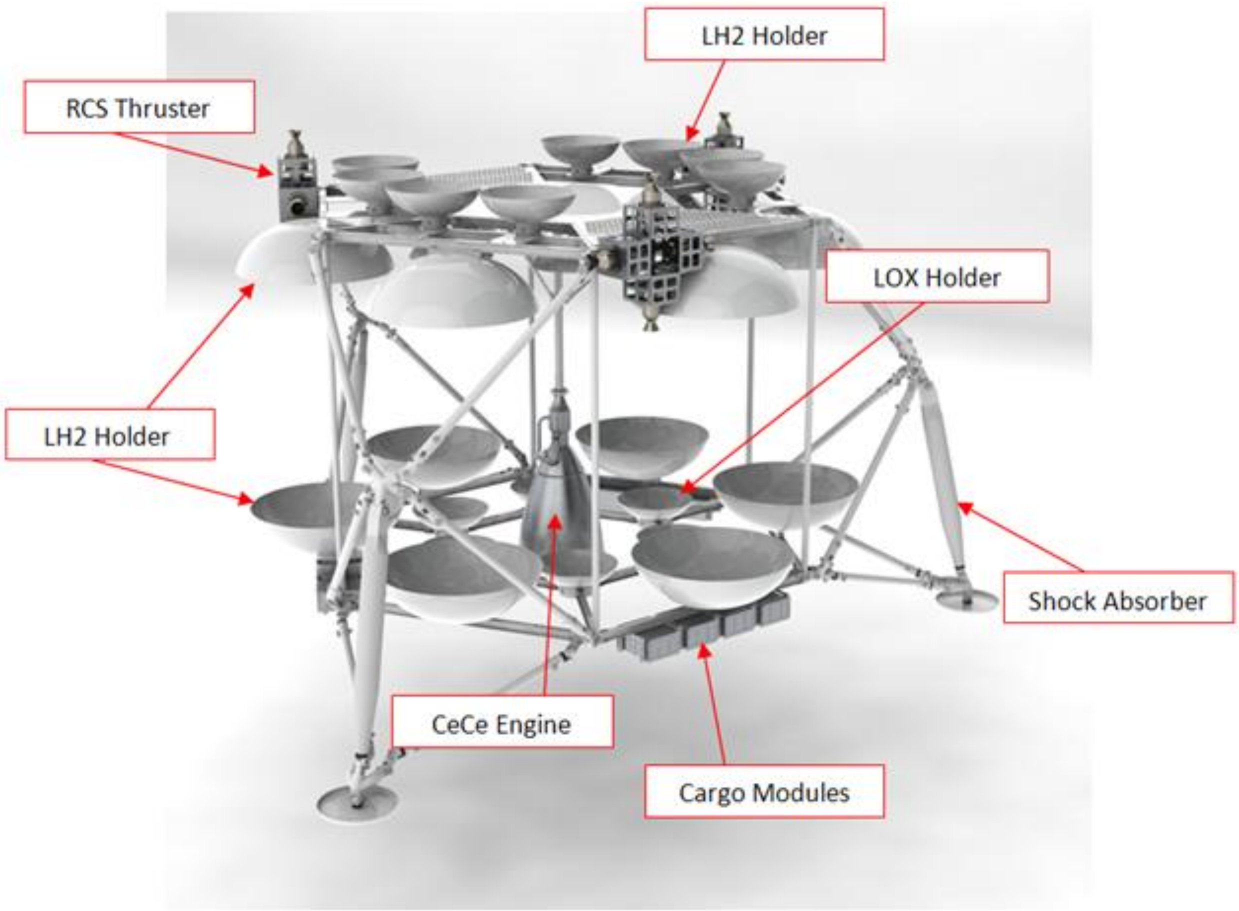


Figure 3: Principle structural components of LEVITATE.

2.2.1 Material

The vast majority of LEVITATE's structural components are designed from aluminum alloy 2195 which is more commonly known by its trade name, Weldalite. The T8 temper of this alloy boasts superior yield strength (~85 ksi) and first mode fracture toughness (~35 ksi $\sqrt{\text{in}}$), even at cryogenic temperatures [34]. Weldalite also offers a nearly 25% increase in yield strength and an approximately 3% decrease in mass compared to typical high strength aluminum alloys. Additionally, Weldalite is easily forged, extruded, and machined [35]. Supplier Alcan Rolled Products has confirmed via telephone that all required Weldalite stock sizes and extrusion profiles are producible [36]. Weldalite is a proprietary product of Lockheed Martin and can consequently be expensive. Despite Weldalite's relative obscurity and associated high costs, it was selected as the primary structural material for LEVITATE because of its superior mechanical properties at cryogenic temperatures.

2.2.2 Geometry

LEVITATE's structure is largely hexagonal, as seen in figure 3. The hexagonal structure provides room for fuel tanks. This also allows three RCS assemblies to be placed evenly around the circumference for attitude control. Finally, a three leg arrangement is inherently stable and requires less mass than many-legged vehicles, such as Altair.

The design of LEVITATE also carefully considered the geometries of the structural members. Much of the structure is made of I-beams or tubular beams. Tubular beams are utilized in compression whereas standard Army-Navy I-beams are used when loading results principally in bending stresses. Structural members were tested using analytical and finite element methods to determine optimum geometries, with factor of safety per appropriate standards and with minimum mass. The results of these analyses can be seen in Appendix D.

2.2.3 Fastening

Connections between the structural members are the most susceptible to failure. The legs of the landing structure use pin joints which are retained in place with lockwire. Pins were selected for connections in the legs because they are easy to manufacture, have well understood failure mechanisms, and are easy to replace in harsh environments. The pins will be loaded entirely in shear, so that the lockwire will provide a simple, effective way of securing the pins in joints. In connections that were not pinned, bolts and locknuts were chosen as the fasteners. Welded joints were not used because they have poorly understood failure modes and cannot be inspected or replaced easily, especially in a lunar environment.

2.2.4 Landing Loads

When landing on the lunar surface, damping mechanisms must absorb the impact to maintain structural integrity. A shock absorber was specified to integrate with the leg assembly and provide sufficient damping over a range of impact velocities. The shock absorber specified is similar to the R-Series EFDYN 4 inch Bore Spring Return Model Custom Orifice Shock which has a weight equivalent range of 9-57.6 kips (40-256 kN) giving LEVITATE a safe landing in the range of 0-10 ft/s (0-3.12 m/s). The shock absorber has a 2 ft stroke, giving the undercarriage of the vehicle adequate spacing between the surface at maximum displacement. The working fluid chosen for the shock absorber is silicone-oil, which was used on the Apollo mission lunar rovers and was chosen for LEVITATE because it has been tested and validated as a working fluid in a damper on the lunar surface [37].

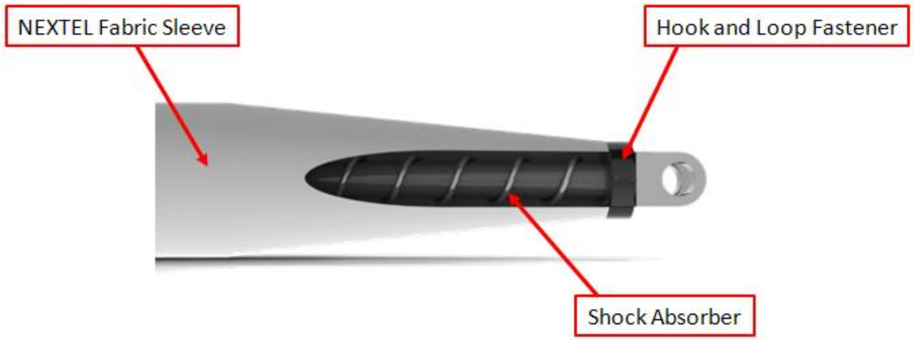


Figure 4: Partial section view showing protective sleeve and underlying shock absorber.

2.2.5 Regolith Contamination

Moving joints of the leg structure are at risk of seizing up and becoming inoperable without protection from regolith [38]. 3M NEXTEL 601 ballistic fabric was chosen to protect these joints based on its similarity to the outer fabric used on current space suits and micrometeoroid shields [21]. This ballistic fabric is lightweight and prevents the penetration of regolith particulates. Polyester Class 3 hook and loop fasteners per Military specification A-A-55126A connect the covers to the structural members spanning the joints.

2.2.6 Bearings

When LEVITATE lands, relative motion between structural members will occur. Sleeve bearings, press-fit onto the pins, prevent galling of the aluminum surfaces. These tri-layer self-lubricating bearings can operate from -330 °F to 530 °F, which is ideal for lunar conditions. The outermost bearing layer is a mild carbon steel to provide structural rigidity, the mid-layer is sintered porous bronze for heat dissipation, and the inner-most layer is polytetrafluoroethylene (PTFE), which minimizes friction [39].

2.2.7 Cargo Modules

The cargo modules will provide a location for lunar samples, extravehicular activity (EVA) equipment, and scientific instruments to be stored while the vehicle is in transit. These modules are standard ISS Fastrack modules, allowing easy integration with current instruments [40]. They are ground accessible for convenient access by the crew.

2.3 Crew Systems

Living in LEVITATE is no more detrimental to an astronaut's health than living at the lunar base. LEVITATE provides full protection from the lunar micrometeoroid environment, thermal and energetic radiation, and extreme temperatures.

The habitat module is a hexagonal cylinder that provides 12.7 m^3 (450 ft^3) of livable space, or approximately double that which the Apollo Lunar Excursion Module offered. The habitat design is driven by vehicle features and the underlying support structure. The airlock requires a planar face for all locking operations and the choice of three landing legs determines the location of major structural elements. Habitat loads must be transferred to these structural elements, creating a strong argument for similarity between the chassis and habitat structures. These considerations led to the hexagonal structure shown in figures 1 and 3.

2.3.1 Suitport Implementation

Frequent vehicle egress/ingress can introduce significant quantities of lunar dust into the habitat, as was seen in Apollo. To minimize this, the suitport airlock concept replaces the traditional, variable pressure chamber with a specialized door mechanism and spacesuit interface. Derived from the literature, this system forms an airtight seal between the spacesuit and habitat module through astronaut-operated clamp mechanisms [17, 18, 21, 41-51]. This concept requires the habitat and spacesuit to operate at the same pressure.

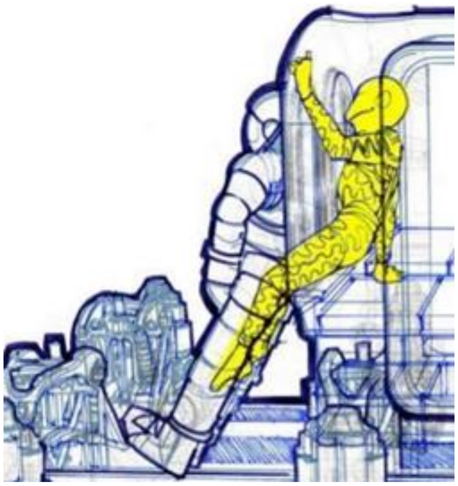


Figure 5: Left – the suitport provides an airtight path between the interiors of the vehicle and spacesuit. Right – suitport on LEVITATE, showing external clamps.

The system presented in figure 5 consists of two independent airtight seals between the spacesuit and the vehicle. The 1.6 mm thick PTFE outer seal can withstand exposure to the lunar environment while the inner 1 mm thick silicone seal needs only to operate in standard room temperature. Compressing the outer seal is the bottom rail and five toggle clamps, which each deliver a 24 kN clamp force. The interior seal is compressed to 75% of its nominal thickness through three screw clamps. An illustrative suitport docking operation is given in Appendix E.

Since LEVITATE lacks a standard airlock interface, all crew consumables and any interior systems must be transferred through the suitport. Suitport cargo transfer modules interface in the same manner as the spacesuits but instead transport cargo [52]. The suitport concept is still under research but it is a very promising way to minimize regolith entrance, atmosphere loss (due to airlock cycling), and ingress/egress time [21].

Figure 6: Suitport cargo transfer module.

2.3.2 Pressure Vessel

The habitat walls are loaded by an internal atmospheric pressure of 14.7 psi and at all times have a factor of safety against failure of 1.4, as required by AIAA S-100-2005. Finite element analyses showed that a panel with a thickness of 2.8 mm and a maximum unsupported span of approximately 300 mm will not yield throughout lunar vehicle operation. Supporting the roof panels is a multi-sectioned arrangement of standard Army-Navy I-beams. The wall panels are supported by these same I-beams in the vertical direction and Z-beams in the horizontal. Each beam is chosen to minimize bending during loading to ensure consistent pressure vessel sealing throughout vehicle operation.

The pressure vessel panels and beams are joined by aluminum rivets formed according to Military specification 20470. The rivet pitch of twice the shaft diameter is expected to prevent leakage from the habitat. Information on riveted space vehicle construction techniques could not be found, but these techniques have been successfully used in the Gemini, Apollo, and Space Shuttle vehicles.

2.3.3 Meteoroid and Orbital Debris (M/OD) Protection

As the Earth-Moon system orbits the Sun, micrometeorites can impact the lunar surface at up to 70 km/s, though the average impact velocity is approximately 17 km/s [53, 54]. Protecting against the full M/OD spectrum requires massive shields that are impractical for most vehicles.

LEVITATE's M/OD shielding is the same as the International Space Station shielding assemblies with the exception of the outermost shielding layer [55, 56]. On LEVITATE, this layer consists of 6 mm thick, 40 pores-per-inch aluminum 6101 foam with two sheets of 2.5 mm thick aluminum 6061 brazed to the inner and outer surfaces. Initial tests show that the shield induces shocks in incoming debris, leads to quicker particle breakup, eliminates directional dependence, and requires less mass than previous shielding arrangements [56, 57].

2.3.4 Thermal

LEVITATE's thermal shielding must mitigate the effect of external solar irradiance on the interior temperature. This is accomplished through a fifteen layer insulation blanket, consisting of vapor-deposited aluminum on both sides of polyimide film from Sheldahl, Inc. This film is embossed in a regular pattern, negating the need for a separate spacing layer. A conservative estimate predicts a total thermal energy transfer of ±50 W, as detailed in Appendix F. This is well within the thermal management capabilities of the life support system, which are discussed later.

2.3.5 Radiation

LEVITATE is designed so that time spent onboard imparts no greater risk to the astronauts than if they were at the lunar base. As such, LEVITATE ensures a maximum crew exposure of 50 rem per year, as defined in NASA STD-3005.

To shield against Solar Photon Events (SPEs), the habitat walls are lined with high density polyethylene infused with elemental Boron (Borated HDPE), which is currently used in medical radiation shields [4, 18, 58]. The exact shielding requirements cannot be specified without a radiation transport analysis, however their design is well understood and is able to provide sufficient shielding. The additional shielding materials are bolted to the interior Z-beams. Like previous manned spacecraft, this shielding arrangement does not provide protection against Galactic Cosmic Radiation [59].

2.4 Life Support Systems

The Environmental Control System (ECS) on LEVITATE has been designed to provide a livable environment for two astronauts in a remote location of the lunar surface for up to fourteen Earth days. Readily available, space rated components are heavily utilized in the ECS design. With prior use in space applications or extensive testing histories, these commercial off the shelf components can allow for substantial financial savings by minimizing design time and custom machining operations.

While operating, the life support systems will consume approximately 2080 W and have a total mass of approximately 270 kg. Appendix G provides full design detail of the ECS, including: system flow diagrams, required contaminate removal rates, required carbon dioxide removal rates, required liquid oxygen and nitrogen stores, and estimated power consumption.

2.4.1 Airflow Routing

To ensure no air leaks into or out of the system, all routing tubing and routing connections in the ECS have been made with ultra high vacuum rated ($1x10^{-8}$ torr) International Organization for Standardization (ISO) Kwik Flanges (KF) and Conflat (CF) type flanges from MDC-Vacuum. These fittings can seal against the vacuum of space and can also provide a seal while the routing lines are pressurized. Both the KF and CF type fittings can be seen in figure 7.

Figure 7: Conflat and Kwik type flange fittings.

2.4.2 Mounting/Routing

CF Flanges also provide a useful way to mount the components, as brackets can be mounted via the circular bolt pattern found along the circumference of the CF flange. Many subsystems of the ECS were mounted in this fashion using brackets formed from structural aluminum 7075-T6 alloy.

The design of LEVITATE's ECS process lines draws heavily upon the use of corrosion resistant stainless steel. While mass reductions may be possible in the future by implementing more aluminum style valves, flanges and routing lines, as of now, the chemical response of the contaminated air cannot be characterized well enough to allow process lines and major components to be made from aluminum.

2.4.3 Airflow Inlet/Circulation

Air is drawn into the ECS via three ducts in parallel which are routed from various areas of the cabin. Each inlet duct contains a Swagelok particulate filter capable of removing 99.9999999% of all particulates 0.003 µm diameter or larger in the air, including any regolith which may happen to enter the cabin environment [60]. Air is circulated through the ducts using a brushless DC motor blower from AMETEK (model #150403E). This motor is quieter and requires less power and mass than traditional centrifugal blowers while still providing adequate flow rate and pressure head throughout the system. Similar blowers are used in the Trace Contaminate Removal System (TCRS) and Carbon Dioxide Removal System (CDRS).

After air passes through the inlet filtration assembly, it flows into a major duct where it can be pulled into the TCRS or the CDRS. Schematics of both the TCRS and CDRS can be found in Appendix G. Both of these systems utilize absolute and differential pressure sensors to monitor pressure drops throughout their respective systems. With these pressure sensors in place and the CF/KF type flanges used for quick access, problems can be quickly identified, accessed, and resolved before cabin contaminate levels become a problem.

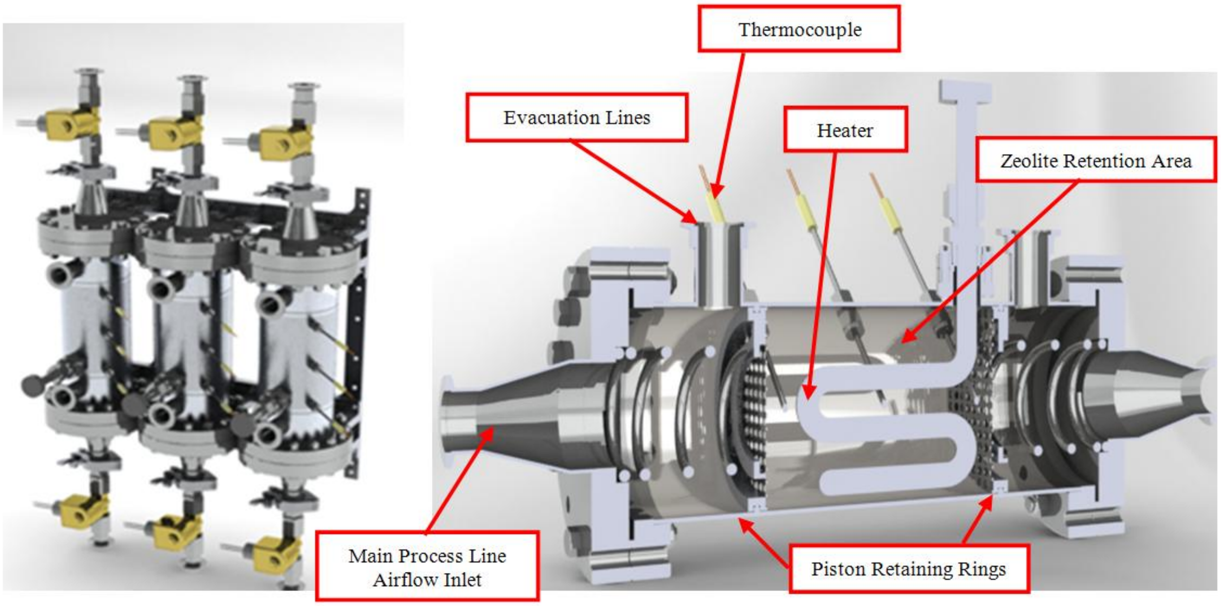


Figure 8: Left - Zeolite bed mounted assembly. Right - Zeolite bed cross section.

2.4.4 Carbon Dioxide Removal System (CDRS)

The CDRS utilizes Zeolite 5A media to remove CO_2 from the process air. It achieves this by adsorbing CO_2 in the pores of each Zeolite bead. The benefit to this media is that it has the ability to desorb and release the carbon dioxide at elevated temperatures. LEVITATE takes advantage of this to create a fully regenerative system. The CDRS uses three Zeolite 5A charcoal beds as shown in figure 8. Each charcoal bed contains a large bolt heater, three thermocouples, and vacuum evacuation flanges for the desorbing process.

The three beds cycle through three stages, with various solenoid valves controlling the process flow. During stage one, air from the cabin flows through the bed and the Zeolite adsorbs CO_2 from the process lines. During stage two, the process flow lines are closed and the Zeolite is heated with the embedded bolt heater to strip it of the previously adsorbed CO_2. Finally, during stage three, the vacuum valves are opened and the CO_2 is released to the vacuum of space. This provides a constantly regenerating system. Previous missions have relied upon bulk quantities of non-regenerable CO_2 adsorbing media [61]. The fully regenerative system in LEVITATE reduces the required Zeolite mass. The media is held in place by a piston retaining ring with an o-ring face seal around the inner diameter of the Zeolite bed along with a perforated disc and retention spring as shown in figure 9.

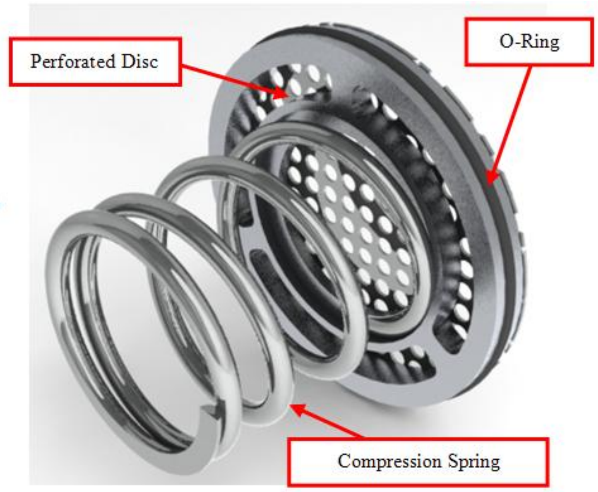


Figure 9: Piston Retaining Ring Assembly.

2.4.5 Trace Contaminate Removal System (TCRS)

Airstream contaminants that arise from human metabolic processes and electronic off-gassing are removed in the Trace Contaminate Removal System (TCRS). Another brushless DC motor blower from AMETEK (model #150193) pulls air in from the process lines into the TCRS. LEVITATE then uses an activated charcoal bed to remove high molecular weight compounds like dichloromethane and toluene, as well as a High Temperature Catalytic Oxidizer (HTCO) to remove low molecular weight components like methane and carbon monoxide. The activated charcoal bed contains two stages of media to remove the volatile organic compounds (VOCs). The first stage is comprised of Purafil's AM media and targets ammonia. The second stage is comprised of Purafil's SP Blend media and targets the remaining high molecular weight components. The charcoal bed is made from stainless steel to prevent the phosphoric acid infused media from eroding the media bed housing.

Immediately downstream of the charcoal bed, the airstream splits into two flows via a butterfly control valve. To achieve proper flow rates in the HTCO, 20% of the airflow goes into the HTCO while the remainder bypasses it. Again, stainless steel construction is used throughout, especially since high temperature combustion reactions occur in the HTCO. Since carbonic acid results from these catalytic oxidations, a lithium hydroxide media bed is placed downstream of the HTCO to neutralize the acidic airstream.

2.4.6 Nitrogen and Oxygen Control (NOC)

Nitrogen and oxygen are used for the cabin internal volume control and human respiration. The nitrogen and oxygen are both stored cryogenically inside of the cabin and released as needed. Liquid oxygen tanks were chosen over traditional on-board oxygen generation methods because of the short mission duration.

3. Cost and Schedule

The NASA-Air Force COst Model (NAFCOM) creates design, development, testing, evaluation, and unit production cost estimates based on previous NASA vehicles. As applied to LEVITAE, this tool provides a preliminary, order-of-magnitude estimate for the costs traditionally encountered in the development and production of vehicles and/or systems similar to those used on LEVITATE. LEVITATE-specific data is used wherever possible and systems that are currently undefined are based on Shuttle, Apollo Lunar Module, Apollo Command Service Module, and/or Gemini costs, depending on the specific system's similarity with prior systems. Also, the authors have no specific training in cost estimation, so one of the first items of a continued study is a thorough cost estimate. That said, LEVITATE is estimated to require $3.1 billion for design, development, testing, and evaluation while each unit will cost $280 million.

The design schedule presented in Appendix H is also derived from the NAFCOM cost estimate. Cost efficient vehicle operations require significant ISRU-derived resupply capabilities. These have not been demonstrated in any lunar context but must be proven before significant vehicle development begins. Assuming significant development of ISRU capabilities at the outset of lunar exploration, LEVTIATE design could begin within the first year of a return to the Moon. Based on this start date and the NAFCOM estimate, vehicle delivery would occur nine years later. As with the cost analysis, the schedule is not sensitive to the degree to which systems are shared with the rest of the lunar architecture, which may significantly speed development and lower upfront costs.

4. Systems for Future Development

Significant design of major systems has proven initial vehicle feasibility, however, additional work remains on the guidance, navigation, and control (GNC), communications, power, fuel distribution, and vehicle interior subsystems.

The GNC is a subsystem whose selection depends on the lunar architecture. GNC provides autonomous control, serving a dual role - to land initially when LEVITATE arrives at the Moon and as an autopilot for emergency crew return.

LEVITATE's communications architecture must provide multiply redundant communications with mission management on Earth and enable cis-lunar communication. Beyond allowing continuously-available communications, the architecture must support high data rate transmissions for video downlink and enable astronauts to share finds mid-EVA with Earth managers and scientists to guide the remainder of the mission.

The power supply and distribution system has not been specified. This power architecture will be similar to that of the Space Shuttle, but instead consisting of only one 12 kW oxygen-hydrogen fuel cell to the Shuttle's three.

The fuel routing system needs to be developed with multiple layers of redundancy to tolerate failure of the main lines. Fuel routing technology exists, as do methods for making RCS and main engine lines redundant, but these must be integrated once the design of LEVITATE is finalized.

Fuel distribution must be at least doubly redundant, but has not been specified in this initial design. Similarly, the fuel resupply system cannot be designed until the fuel distribution is complete and ISRU fuel processing has been demonstrated.

The vehicle interior requires additional development. Currently, the interior surfaces are lined with HDPE but no crew accommodations were included in the vehicle design. The vehicle needs sleeping arrangements, secure seating during orbital maneuvers, crew hygiene equipment, and food preparation and storage.

4.1 Technology Readiness Levels (TRLs)

LEVITATE's TRL of 4 is determined by the lowest TRL of any subsystem. Subsystem TRLs were evaluated based on literature and prior art and are given in table 2. TRL's for specific subsystems can be found in Appendix I.

Subsystem	TRL
Propulsion	6
Structure	6
Habitat	4
Life Support	6

Table 2: Major subsystem TRLs.

5. Similarities in Possible Lunar Architecture

Having considered LEVITATE in the context of previous lunar architectures, several similarities with other elements are apparent. LEVIATE's core functionality is similar to that of proposed lunar landers, in particular the Constellation Program's Altair. As envisioned, LEVITATE and Altair share the same CECE engine and will likely have similar propulsion components and GNC systems. A lunar outpost will require a number of equipment launches which will each have a lunar lander. Commonality between LEVITATE and these landers may provide a source of replacement parts. Alternatively, and with suitable foresight, the lunar lander and LEVITATE may share a propulsion module with only the cargo or habitat changing between missions.

6. Other Potential Uses

While LEVITATE's main purpose is to explore the lunar surface in fourteen day sorties, there is potential for other mission types. Unlike the Altair lunar lander, LEVITATE has the advantage of being a single stage, refuelable, multi-use vehicle. As the lunar infrastructure grows, LEVITATE may potentially be used for transportation between multiple lunar bases, as a cargo module to transport cargo from low lunar orbit (LLO) to the lunar surface, or as an orbiting lunar outpost without any changes to its design. Additionally, if LEVITATE were redesigned with multiple fuel stores or stages, it could be used as a vehicle to transport astronauts from the lunar surface to low Earth orbit (LEO) or from LEO to the surface of the Moon. The versatility of this vehicle is a valuable asset and will enable both these and unforeseen uses, especially as the human lunar presence increases.

7. Conclusion

The most significant challenge that LEVITATE faces is the current lack of a commitment to lunar exploration. This is represented most notably in the proposed FY2011 budget proposal which has called for the cancellation of the Constellation Program and diversion from lunar exploration, an underlying assumption of this design.

Nonetheless, LEVITATE is a versatile vehicle for the construction of lunar bases, in-situ lunar science, and transportation of supplies and astronauts between the surface and LLO. The ability to access any location on the lunar surface will increase the type and quantity of lunar science possible. While some systems have yet to be fully specified, the major systems have been completely defined according to appropriate codes and industry standards and, more importantly, feasibility of the concept has been proven.

References

[1] "DPT Architecture & Scenario Groundrules and Assumptions," 2000.

[2] "L1 Lunar Lander Element Conceptual Design Report," pp. 52, 2001.

[3] "Design Reference Missions Summary," 2002.

[4] D. Stanley, S. Cook and J. Connolly, "Exploration Systems Architecture Study Final Report," 2006.

[5] B. L. Jolliff and C. R. Neal, "Lunar Science Workshop," 2007.

[6] N. Augustine, W. M. Austin, C. Chyba, C. F. Kennel, B. I. Bejmuk, E. F. Crawley, L. L. Lyles, L. Chiao, J. Greason and S. K. Ride, *Review of U.S. Human Spaceflight Plans Committee: Seeking a Human Spaceflight Program Worthy of a Great Nation.* Washington, DC: National Aeronautics and Space Administration, 2009.

[7] C. Culbert, "Constellation Program Overview," 2008.

[8] B. K. Joosten, "Exploration in the Earth's Neighborhood - Architecture Analysis," pp. 39, 2000.

[9] G. Yoder, "Lunar Capability Concept Review (LCCR)," 2008.

[10] G. Yoder, "Lunar Capability Concept Review (LCCR) Overview," pp. 22, 2008.

[11] R. Destefanis, F. Schaefer, M. Lambert and M. Faraud, "Selecting enhanced space debris shields for manned spacecraft," *Int. J. Impact Eng.*, vol. 33, pp. 219-230, 2006.

[12] B. Romig, J. Kosmo, M. Gernhardt and A. Abercromby, "Desert Research and Technology Studies 2008 Report," 2010.

[13] W. P. Schonberg, F. Schäfer and R. Putzar, "Some Comments on the Protection of Lunar Habitats against Damage from Meteoroid Impacts," *J. Aerospace Eng.*, vol. 23, pp. 90, 2010.

[14] "NASAfacts: Lunar Electric Rover Concept," pp. 4, 2009.

[15] B. Bailey, "The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities," 2009.

[16] C. R. Neal, "The US Lunar Exploration Analysis Group & The Lunar Exploration Roadmap," 2009.

[17] B. Romig, J. Kosmo, M. Gernhardt and A. Abercromby, "Desert research and technology studies 2008 report," in *Proceedings of the International Conference on Environmental Systems,* 2009, .

[18] M. L. Gernhardt and A. F. Abercromby, "Health and Safety Benefits of Small Pressurized Suitport Rovers as EVA Surface Support Vehicles," *Aviat. Space Environ. Med.*, vol. 79, pp. 246, 2008.

[19] H. Thronson, "NASA's Decadal Planning Team (DPT) and the NASA Exploration Team (NEXT)," pp. 6, 2007.

[20] "Lunar Exploration Objectives," NASA, < http://www.nasa.gov/exploration/home/why_moon_objectives.html>, 2006.

[21] S. J. Hoffman, "Advanced EVA Capabilities: A Study for NASA's Revolutionary Aerospace Systems Concept Program," pp. 174, 2004.

[22] M. M. Cohen, "Mobile lunar base concepts," in *Proceedings of Space Technology and Applications International Forum - STAIF 2004*, 2004, pp. 845-853.

[23] *Stepping-Stones to the Future of Space Exploration: A Workshop Report.* Washington, DC: National Research Council; National Research Council, 2004.

[24] "Solar System Exploration," NASA, 2003.

[25] "Human Subsystem Working Group: Human Planning Guidelines and Constraints," pp. 114, 2001.

[26] G. A. Landis and D. Linne, "Mars exploration with a self-refueling hopper," in *Concepts and Approaches for Mars Exploration*, 2000, pp. 2.

[27] F. V. Bennett, "Apollo lunar descent and ascent trajectories," in *AIAA 8th Aerospace Sciences Meeting*, New York, New York, 1970, .

[28] V. J. Giuliano, T. G. Leonard, W. M. Adamski and T. S. Kim, "CECE: A deep throttling demonstrator cryogenic engine for NASA's lunar lander," in *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 8, 2007 - July 11*, 2007, pp. 4611-4618.

[29] "LOX/LH2 Bipropellant Thruster," Northrop Grumman, Inc., 2010.

[30] E. C. Fox, E. R. Kiefel, G. L. McIntosh, J. B. Sharpe, D. R. Sheahan and M. E. Wakefield, "Multipurpose hydrogen test bed - system definition and insulated tank development," Martin Marietta Astronautics, Denver, Colorado, 1993.

[31] N. Fries, K. Odic and M. Dreyer, "Wicking of perfectly wetting liquids into a metallic mesh," in *2nd International Conference on Porous Media and its Applications in Science and Engineering*, Kauai, Hawaii, USA, 2007.

[32] M. M. Weislogel and S. H. Collicott, "Capillary rewetting of vaned containers: spacecraft tank rewetting following thrust resettling," *AIAA J.*, vol. 42, pp. 2551-61, 12, 2004.

[33] J. E. Bell, W. R. Killian, J. E. Penner, D. H. Pope and H. E. Sutton, "Development of positive expulsion systems for cryogenic fluids," BEECH AIRCRAFT CORP BOULDER CO BOULDERDIV, BOULDER, COLORADO, 1962.

[34] A. R. C. Westwood, "New materials for aerospace industry," 1990.

[35] J. P. Immarigeon, "Lightweight Materials for Aircraft Applications," 1994.

[36] T. L. Feyereisen and S. McQueen, "Alcan Rolled Products on Capability of Forming Weldalite," Telephone Conversation, 2010.

[37] C. Benson and W. Faherty, *Moonport: A History of Apollo Launch Facilities and Operations.* NASA History Series, 1978.

[38] J. R. Gaier, "The Effects of Lunar Dust on EVA Systems during the Apollo Missions," *NASA/TM—2005-213610,* 2005.

[39] PI Bearing Technologies, <http://www.pibearingtechnologies.com/>, 2010.

[40] D. Jett, J. Miller, B. Carmine and M. Danford, "EXpedite the PRocessing of experiments to space station (EXPRESS) rack payloads interface definition document," National Aeronautics and Space Administration, Johnson Space Center. Houston, Texas, Tech. Rep. SSP 52000-EDD-ERP, 2002.

[41] B. A. Romig, C. S. Allton and H. L. Litaker, "1-g Suit Port Concept Evaluator 2008 Test Results," *System,* 2010.

[42] T. J. Cognata, B. Conger and H. L. Paul, "Results of the particulate contamination control trade study for space suit life support development," in *Proceedings of the International Conference on Environmental Systems*, 2009, pp. 19.

[43] J. Chartres, B. Koss, C. Brivkalns, B. Webbon, B. Romig and C. Allton, "Preliminary development of a suit port for planetary surface EVA part A: Design studies," in *Proceedings of the International Conference on Environmental Systems*, 2009, pp. 9.

[44] C. Culbert, "Constellation Program Overview," pp. 22, 2008.

[45] K. Ford, D. Fraser, R. Hauck and J. Logsdon, "Exploration Committee," 2008.

[46] H. Jones, "Planetary airlock and suitlock requirements and alternate approaches," in *Proceedings of the 37th International Conference on Environmental Systems (ICES),* 2007.

[47] B. Webbon, B. Luna, J. Brown, A. Gonzales, H. Jones, B. Koss and D. Smith, "Innovative concepts for planetary EVA access," in *Proceedings of the 37th International Conference on Environmental Systems (ICES),* 2007, pp. 43.

[48] P. J. Rae and D. M. Dattelbaum, "The properties of poly(tetrafluoroethylene) (PTFE) in compression," *Polymer,* vol. 45, pp. 7615-7625, October, 2004.

[49] I. Abramov, N. Moiseev and A. Stoklitsky, "Concept of space suit enclosure for planetary exploration," 2001.

[50] M. M. Cohen, "US Patent 484222,", 1989.

[51] T. S. Cory, C. C. English, R. M. Hardman, J. C. Martinez, K. C. Moss, J. M. Wileman and M. M. Wolaver, "Personnel Transfer Airlock," vol. 58, pp. 167, 1987.

[52] NASA Desert RATs, "SPTM," <http://www.flickr.com/photos/nasadesertrats/3894258633/>, 2009.

[53] *Protecting the Space Station from Meteoroids and Orbital Debris.* Washington, DC: National Academy Press, 1997.

[54] V. Vanzani, F. Marzari and E. Dotto, "Meteroid impacts on the lunar surface," in *Lunar and Plantary Science 1997,* 1997, pp. 3-4.

[55] Anonymous *Protecting the Space Station from Meteoroids and Orbital Debris.* Washington, DC: National Academy Press, 1997.

[56] E. L. Christiansen, "Meteroid / Debris Shielding," pp. 114, 2003.

[57] S. Ryan, E. Ordonez, E. L. Christiansen and D. M. Lear, "Hypervelocity impact performance of open cell foam core sandwich panel structures," in *Proceedings of the 11th Hypervelocity Impact Symposium,* 2010, .

[58] J. Miller, L. A. Taylor, M. DiGiuseppe, L. H. Heilbronn, G. Sanders and C. J. Zeitlin, "Radiation Shielding Properties of Lunar Regolith and Regolith Simulant." *LPI Contributions,* vol. 1415, pp. 2028, 2008.

[59] F. A. Cucinotta, M. Y. Kim and L. Ren, "Evaluating shielding effectiveness for reducing space radiation cancer risks," *Radiat. Measur.,* vol. 41, pp. 1173-1185, October, 2006.

[60] "Swagelok Catalog MS-02-156," Swagelok, Inc., <http://swagelok.com/downloads/webcatalogs/EN/MS-02-156.pdf>, 2010.

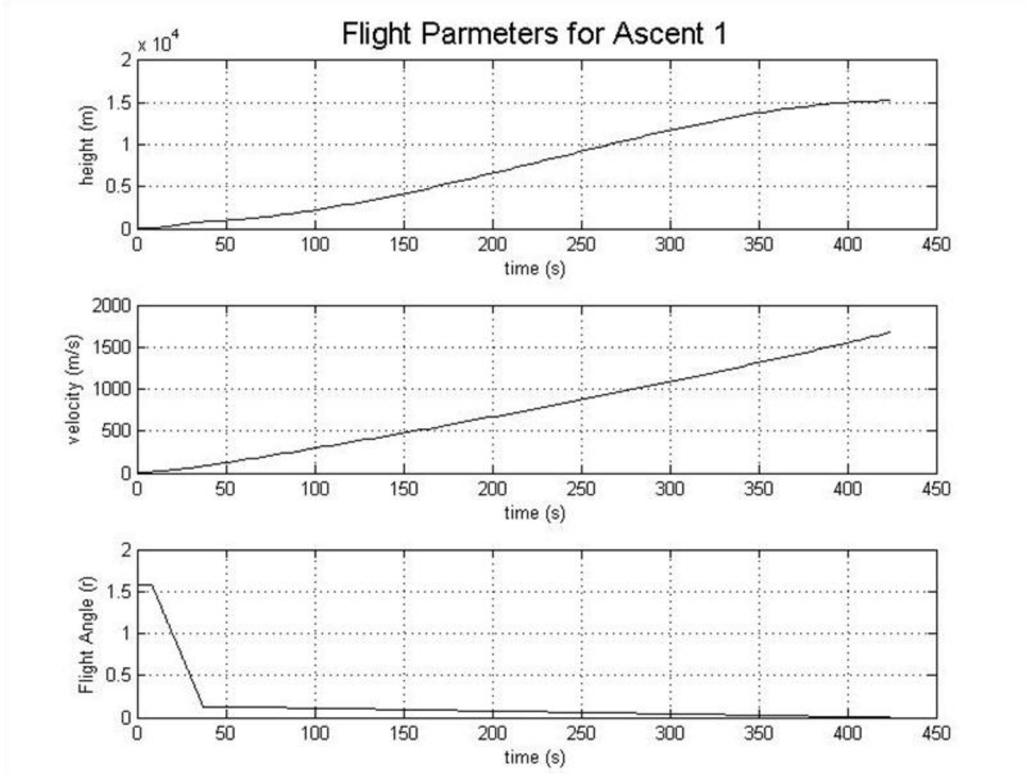
[61] "International space station environmental control and life support system," Tech. Rep. FS-2002-05-85-MSFC, 2002.

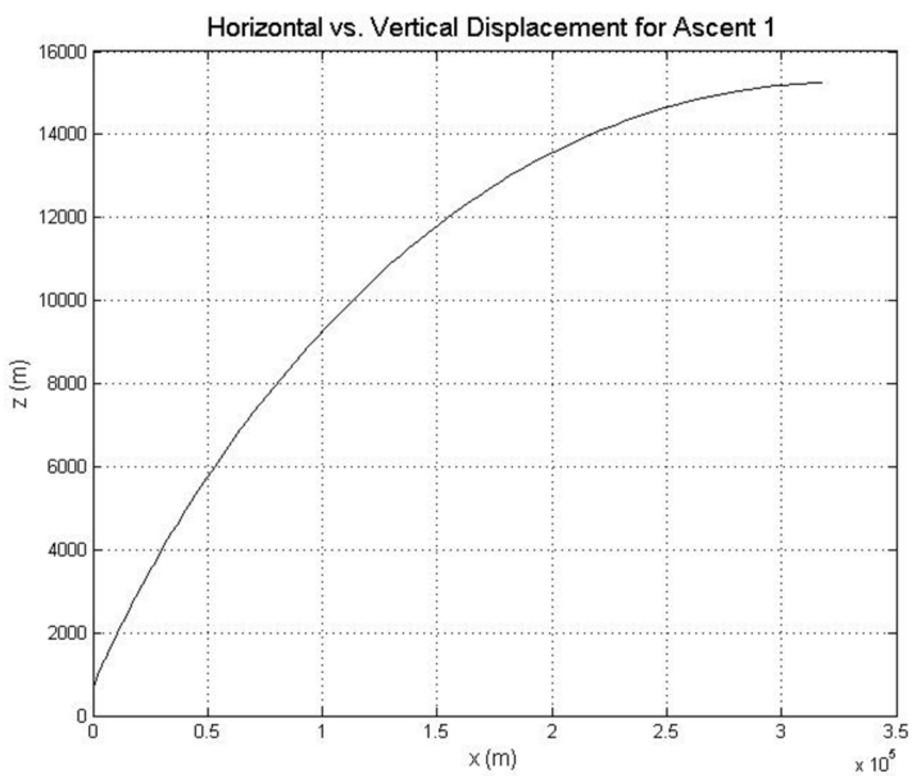
Contents of Appendices

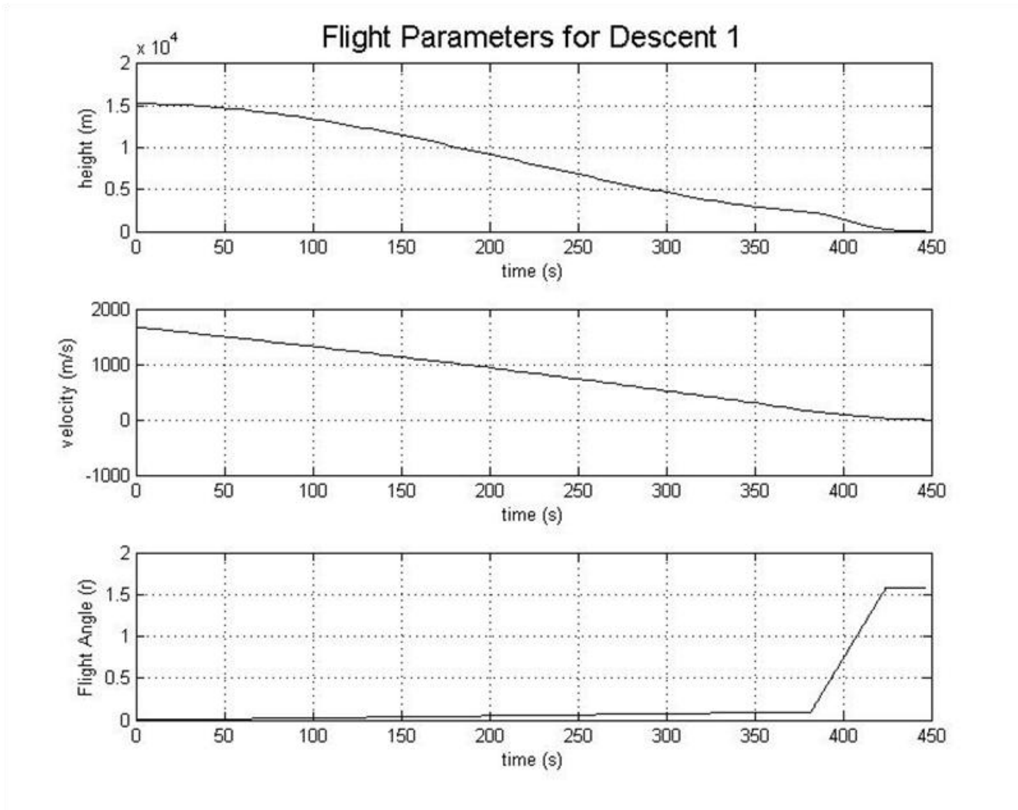
Appendix A – Mass Tally

Subsystem	Component	Mass (kg)	
Structure	Leg Assemblies	1875	2741
	Top Deck	290	
	Engine Box	76	
	RCS Assemblies	230	
	Tank Caps	210	
	Misc Fasteners	60	
Propulsion Hardware	CECE Engine	150	1240
	Fuel Tanks	1090	
Fuel	LOX	16923	20000
	LH2	3077	
Life Support	Life Support System	270	270
Habitat	Wall Panels	236	620
	Roof Panels	130	
	Suitports	234	
	MLI	20	
	Total	**24871**	

Appendix B – Orbital Maneuvers



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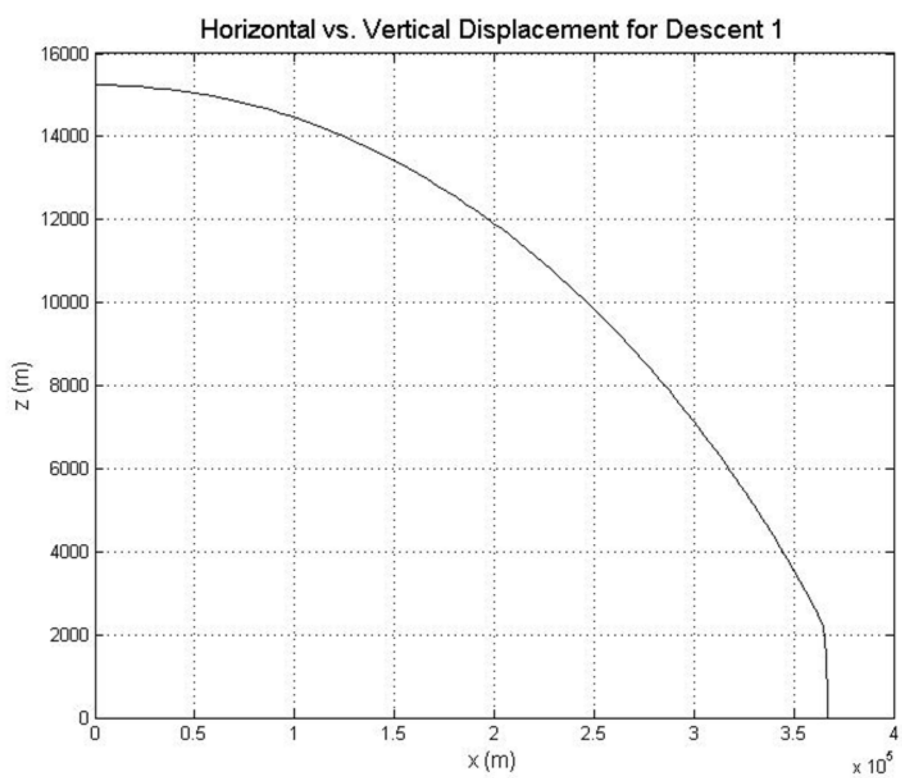
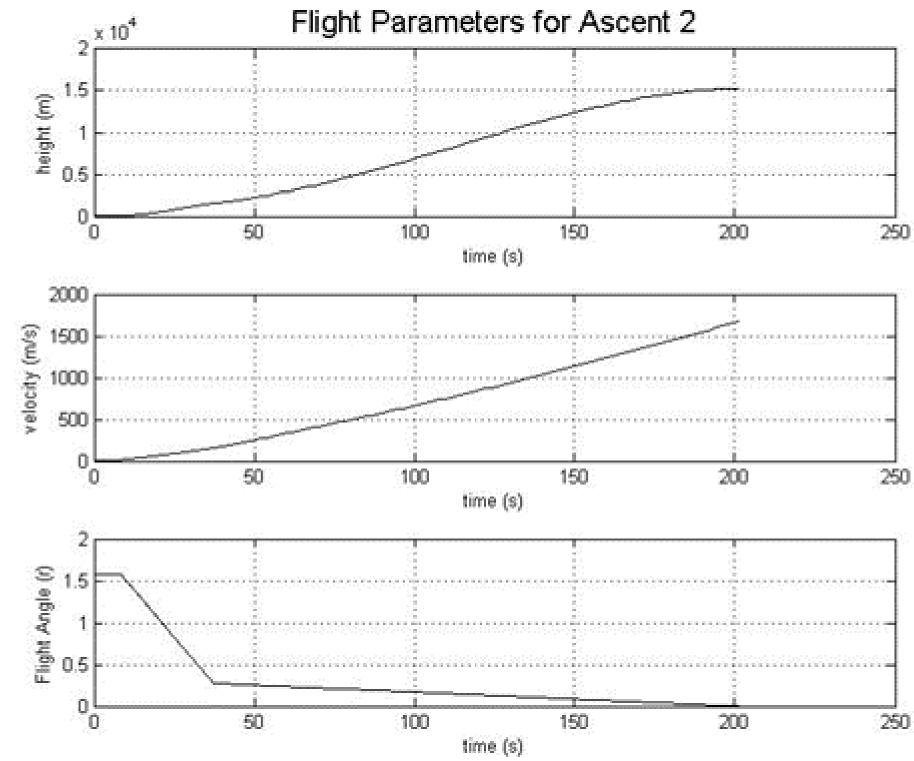
height (m)
time (s)
velocity (m/s)
time (s)
Flight Angle (r)
time (s)


Horizontal vs. Vertical Displacement for Descent 1
z (m)
x (m)
x 10^5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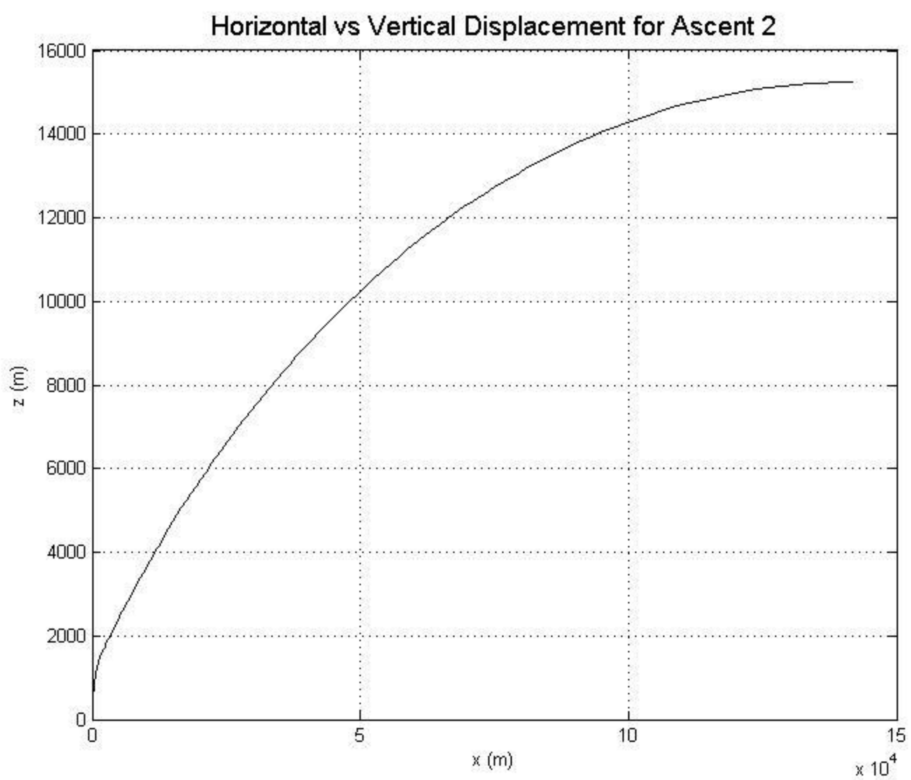
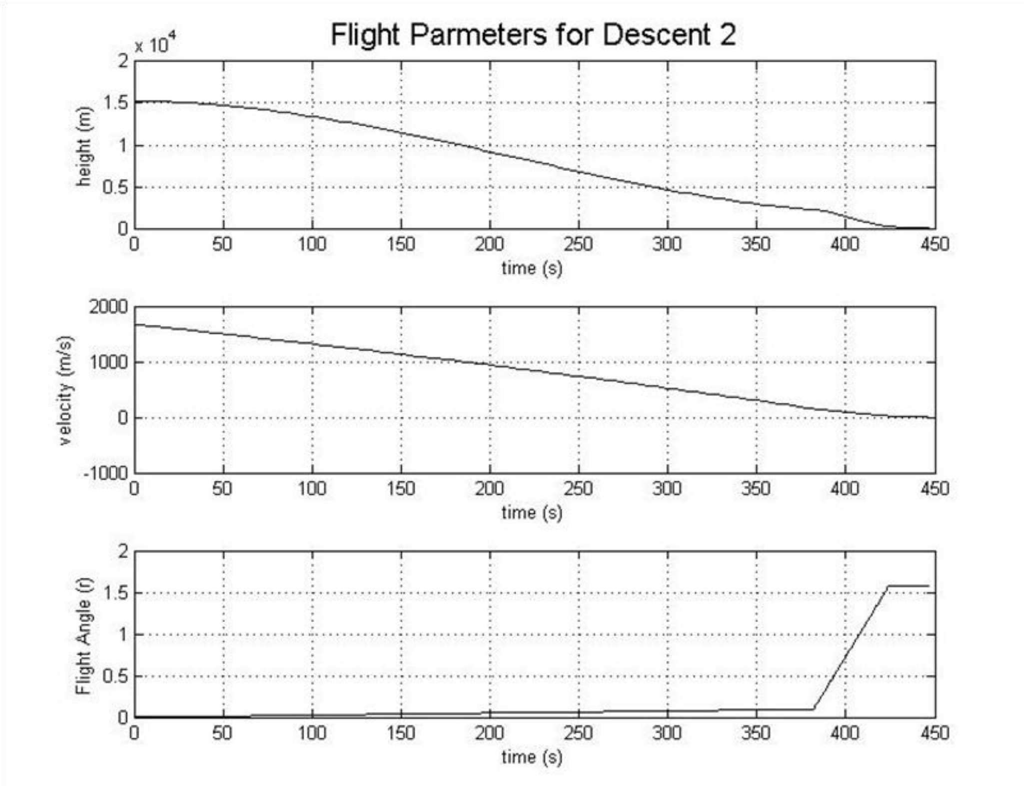
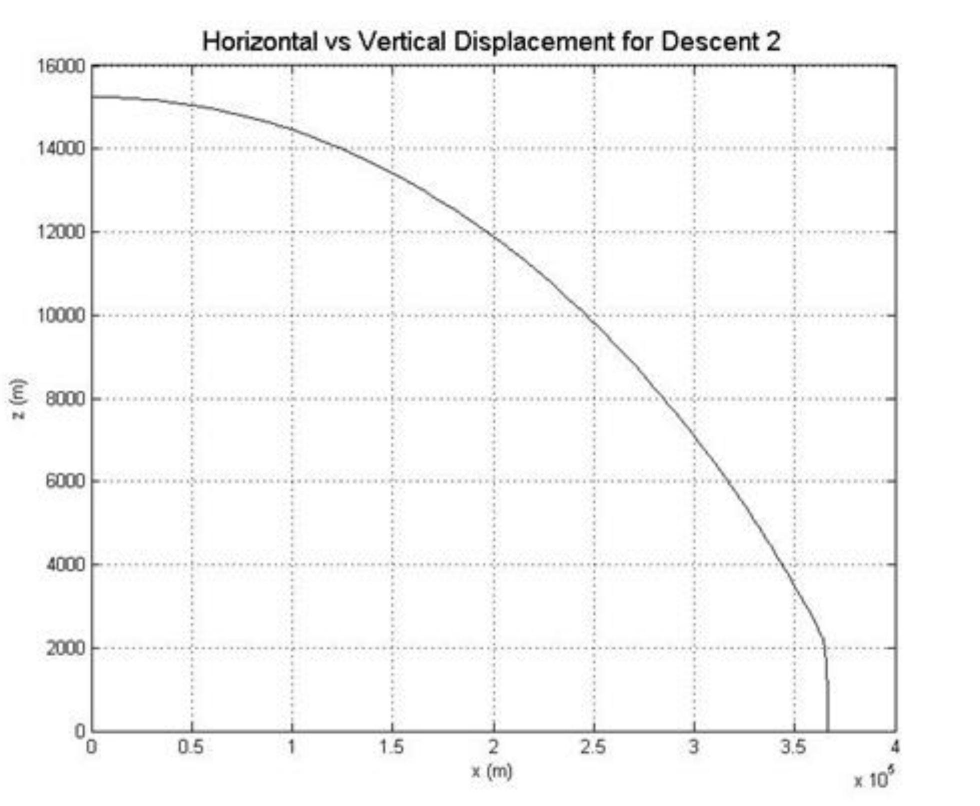
height (m)
time (s)
velocity (m/s)
time (s)
Flight Angle (r)
time (s)


Horizontal vs Vertical Displacement for Ascent 2
z (m)
x (m)
x 10^4


Flight Parmeters for Descent 2
x 10^4
height (m)
time (s)
velocity (m/s)
time (s)
Flight Angle (r)
time (s)


Horizontal vs Vertical Displacement for Descent 2
z (m)
x (m)
x 10^5

Appendix C – Tank Design

Overall NEEDED Fuel Volume

$v_{lh2} = 48.6039$ [m^3] LH2 Volume

$v_{loxx} = 15.4981$ [m^3] LOX Volume

Top LH2 Tanks

$h_{lh2t} = 3$ [m] Tank Height

$a_{lh2t} = 0.4554$ [m] Tank Ellipse Semi Major Axis

$b_{lh2t} = \frac{a_{lh2t}}{\sqrt{2}}$ Tank Ellipse Semi Minor Axis

$v_{lh2t} = \frac{4 \cdot \pi \cdot a_{lh2t}^{2} \cdot b_{lh2t}}{3} + \pi \cdot a_{lh2t}^{2} \cdot c_{lh2t}$ Volume of Top Tanks

$h_{lh2t} = c_{lh2t} + 2 \cdot b_{lh2t} + 2 \cdot t_{insulation,lh2}$ Cylinder height

Bottom LH2 Tanks

$h_{lh2b} = 4$ [m] Tank Height

$v_{lh2b} = \frac{v_{lh2} - v_{lh2t}}{6}$ Tank Ellipse Semi Major Axis

$b_{lh2b} = \frac{a_{lh2b}}{\sqrt{2}}$ Tank Ellipse Semi Minor Axis

$v_{lh2b} = \frac{4 \cdot \pi \cdot a_{lh2b}^{2} \cdot b_{lh2b}}{3} + \pi \cdot a_{lh2b}^{2} \cdot c_{lh2b}$ Volume of Top Tanks

$h_{lh2b} = c_{lh2b} + 2 \cdot b_{lh2b} + 2 \cdot t_{insulation,lh2}$ Cylinder height

Bottom LOX Tanks

$h_{lox} = 4$ [m] Tank Height

$b_{lox} = \frac{a_{lox}}{\sqrt{2}}$ Tank Ellipse Semi Major Axis

$v_{lox} = \frac{v_{loxx}}{6}$ Tank Ellipse Semi Minor Axis

$v_{lox} = \frac{4 \cdot \pi \cdot a_{lox}^{2} \cdot b_{lox}}{3} + \pi \cdot a_{lox}^{2} \cdot c_{lox}$ Volume of Top Tanks

$h_{lox} = c_{lox} + 2 \cdot b_{lox} + 2 \cdot t_{insulation,lox}$ Cylinder height

Thickness of MLI and foam insulation layers

$t_{insulation,lh2} = 0.07112$ [m]

$t_{insulation,lox} = 0.02616$ [m]

Design Factors

$K = 0.7875$ Design Parameter

$K_{a,b} = 1.414$ Ellipse Design Parameter

$E_{des} = 4.59$ Design Multiplier

$p = 344738$ [pa] Operating Pressure

$Sw_{lh2} = 6.386 \times 10^{8}$ [pa] Maximum stress for lh2 using mil-1522

$Sw_{lox} = 1.11971 \times 10^{9}$ [pa] Maximum stress for lox using mil-1522

$E_{titanium} = 1.103 \times 10^{11}$ [pa] Elastic Modulus for titanium 6al-4v

$E_{inconel} = 2.1581 \times 10^{11}$ [pa] Elastic Modulus for inconel 718

Top LH2 Tank Thickness

$$t_{k,lh2t} = \frac{K \cdot p \cdot a_{lh2t}}{Sw_{lh2}}$$ Knuckle Thickness

$$t_{cr,lh2t} = \frac{p \cdot b_{lh2t}}{2 \cdot Sw_{lh2}}$$ Crown Thickness

$t_{e,lh2t} = 0.0005$ [m]

Bottom LH2 Tank Thickness

$$t_{k,lh2b} = \frac{K \cdot p \cdot a_{lh2b}}{Sw_{lh2}}$$ Knuckle Thickness

$$t_{cr,lh2b} = \frac{p \cdot b_{lh2b}}{2 \cdot Sw_{lh2}}$$ Crown Thickness

$t_{e,lh2b} = 0.0005$ [m]

Bottom LOX Tank Thickness

$$t_{k,lox2} = \frac{K \cdot p \cdot a_{lox}}{Sw_{lox}}$$ Knuckle Thickness

$$t_{cr,lox} = \frac{p \cdot b_{lox}}{2 \cdot Sw_{lox}}$$ Crown Thickness

$t_{e,lox} = 0.0003$ [m]

Tank Outside Radius Measurement

$$r_{lh2,top} = a_{lh2t} + t_{e,lh2t} + t_{insulation,lh2}$$

$$r_{lh2,bottom} = a_{lh2b} + t_{e,lh2b} + t_{insulation,lh2}$$

$$r_{lox} = a_{lox} + t_{e,lox} + t_{insulation,lox}$$

Tank Material Density

$\rho_{titanium} = 4428.78$ [kg/m^3]

$\rho_{inconel} = 8179.83$ [kg/m^3]

Metal Shell Mass

$$W_{lh2t} = \left[\frac{\pi \cdot E_{des}}{k_{a,b}} \cdot a_{lh2t}^{\ 2} \cdot t_{e,lh2t} \cdot \rho_{titanium} + \pi \cdot \left(\left(a_{lh2t} + t_{e,lh2t} \right)^2 - a_{lh2t}^{\ 2} \right) \cdot c_{lh2t} \cdot \rho_{titanium} \right] \cdot 8$$

$$W_{lh2b} = \left[\frac{\pi \cdot E_{des}}{k_{a,b}} \cdot a_{lh2b}^{\ 2} \cdot t_{e,lh2b} \cdot \rho_{titanium} + \pi \cdot \left(\left(a_{lh2b} + t_{e,lh2b} \right)^2 - a_{lh2b}^{\ 2} \right) \cdot c_{lh2b} \cdot \rho_{titanium} \right] \cdot 6$$

$$W_{lox} = \left[\frac{\pi \cdot E_{des}}{k_{a,b}} \cdot a_{lox}^{\ 2} \cdot t_{e,lox} \cdot \rho_{inconel} + \pi \cdot \left(\left(a_{lox} + t_{e,lox} \right)^2 - a_{lox}^{\ 2} \right) \cdot c_{lox} \cdot \rho_{inconel} \right] \cdot 6$$

Insulation thickness components

$t_{foam} = 0.0254$ [m]

$t_{dam} = 0.4572$ [m]

$t_{epoxy} = 0.000762$ [m]

Critical Axial Stress

$$Sc_{lh2t} = \left[9 \cdot \left(\frac{t_{e,lh2t}}{a_{lh2t}} \right)^{1.6} + 0.16 \cdot \left(\frac{t_{e,lh2t}}{c_{lh2t}} \right)^{1.3} \right] \cdot E_{titanium}$$

$$Sc_{lh2b} = \left[9 \cdot \left(\frac{t_{e,lh2b}}{a_{lh2b}} \right)^{1.6} + 0.16 \cdot \left(\frac{t_{e,lh2b}}{c_{lh2b}} \right)^{1.3} \right] \cdot E_{titanium}$$

$$Sc_{lox} = \left[9 \cdot \left(\frac{t_{e,lox}}{a_{lox}} \right)^{1.6} + 0.16 \cdot \left(\frac{t_{e,lox}}{c_{lox}} \right)^{1.3} \right] \cdot E_{inconel}$$

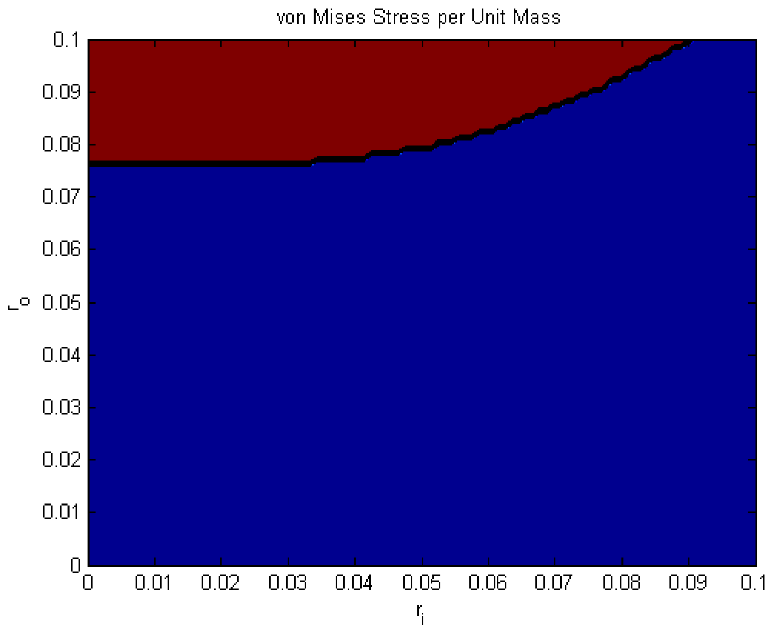
Unit Settings: [kJ]/[K]/[Pa]/[kg]/[degrees]

$a_{lh2b} = 0.8481$ [m]	$a_{lh2t} = 0.4554$ [m]	$a_{lox} = 0.4697$ [m]	$b_{lh2b} = 0.5997$ [m]
$b_{lh2t} = 0.322$ [m]	$b_{lox} = 0.3322$ [m]	$c_{lh2b} = 2.658$ [m]	$c_{lh2t} = 2.214$ [m]
$c_{lox} = 3.283$ [m]	$E_{des} = 4.59$ [dim]	$E_{inconel} = 2.158E+11$ [pa]	$E_{titanium} = 1.103E+11$ [pa]
$h_{lh2b} = 4$ [m]	$h_{lh2t} = 3$ [m]	$h_{lox} = 4$ [m]	$K = 0.7875$ [dim]
$k_{a,b} = 1.414$ [dim]	$p = 344738$ [pa]	$\rho_{inconel} = 8180$ [kg/m^3]	$\rho_{titanium} = 4429$ [kg/m^3]
$r_{lh2,bottom} = 0.9197$ [m]	$r_{lh2,top} = 0.527$ [m]	$r_{lox} = 0.4962$ [m]	$Sc_{lh2b} = 7.009E+06$ [pa]
$Sc_{lh2t} = 1.859E+07$ [pa]	$Sc_{lox} = 1.521E+07$ [pa]	$Sw_{lh2} = 6.386E+08$ [pa]	$Sw_{lox} = 1.120E+09$ [pa]
$t_{cr,lh2b} = 0.0001619$ [m]	$t_{cr,lh2t} = 0.00008692$ [m]	$t_{cr,lox} = 0.00005113$ [m]	$t_{dam} = 0.4572$ [m]
$t_{epoxy} = 0.000762$ [m]	$t_{e,lh2b} = 0.0005$ [m]	$t_{e,lh2t} = 0.0005$ [m]	$t_{e,lox} = 0.0003$ [m]
$t_{foam} = 0.0254$ [m]	$t_{insulation,lh2} = 0.07112$ [m]	$t_{insulation,lox} = 0.02616$ [m]	$t_{k,lh2b} = 0.0003605$ [m]
$t_{k,lh2t} = 0.0001936$ [m]	$t_{k,lox2} = 0.0001139$ [m]	$v_{lh2} = 48.6$ [m^3]	$v_{lh2b} = 7.814$ [m^3]
$v_{lh2t} = 1.722$ [m^3]	$v_{lox} = 2.583$ [m^3]	$v_{loxx} = 15.5$ [m^3]	$W_{lh2b} = 285.7$ [kg]
$W_{lh2t} = 149.7$ [kg]	$W_{lox} = 175.9$ [kg]		

Appendix D – Stress Calculations

Optimal Tube Sizing

```
% Code to determine proper inner and outer radii of structural tubing,
minimizing mass producible on request but omitted for brevity.
```



Red is the region where the tubing has a factor of safety greater than 1.4

Shock Absorber Weight Equivalent

```
% Code to determine weight equivalent range of shock absorber producible on
request but omitted for brevity.

We =

  2.8876e+004
```

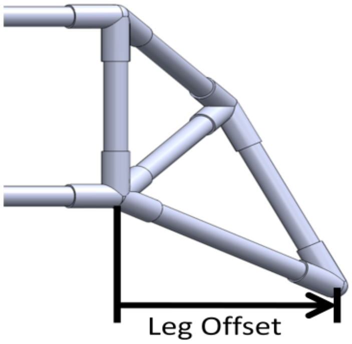
Engine Box Critical Buckling

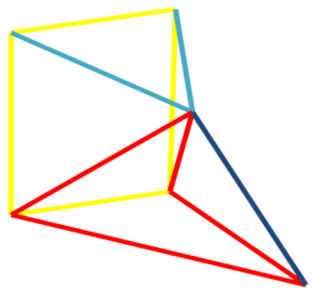
```
% Code to determine critical buckling force in engine box producible on
request but omitted for brevity.

F =

  1.2581e+011
```

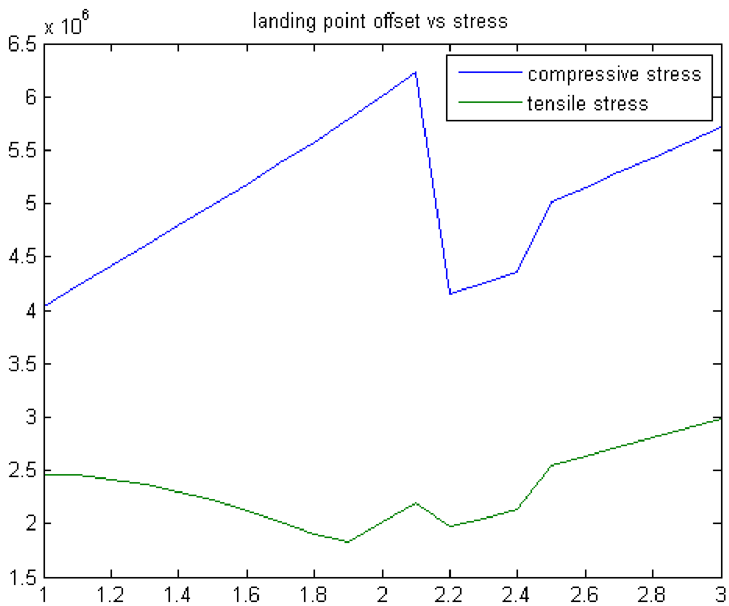
Optimal Leg Offset



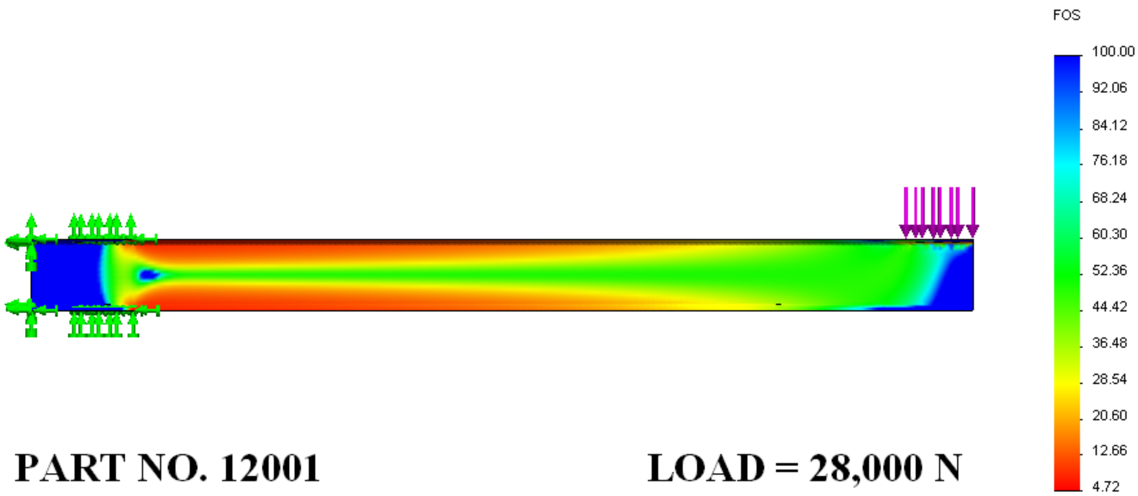


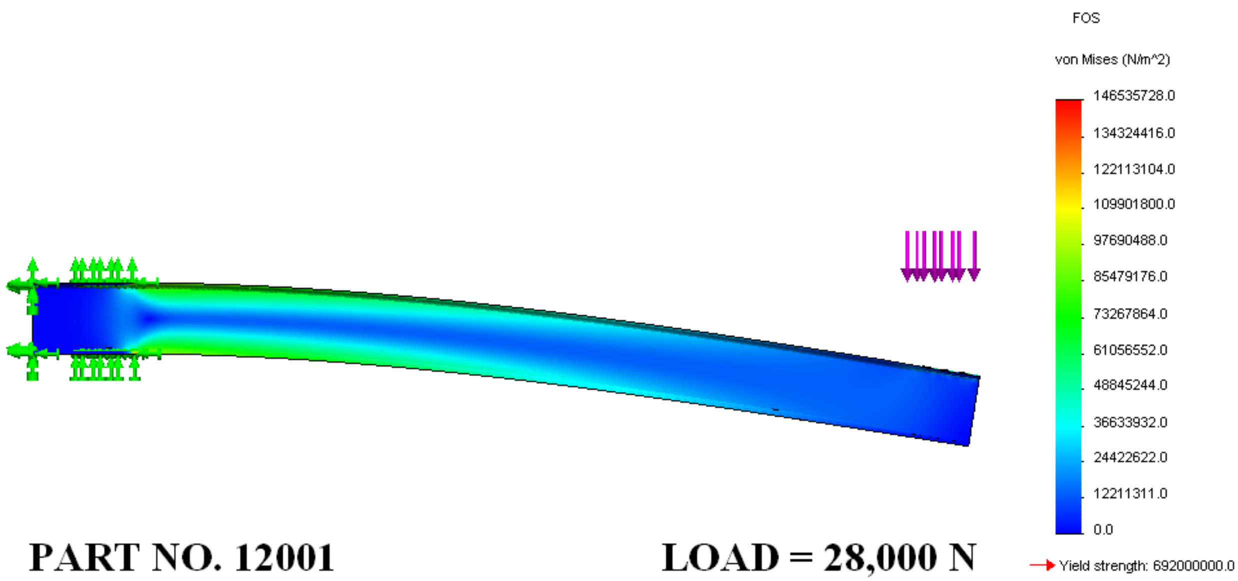
The legs were subjected 1/3 weight of LEVITATE to determine optimal leg offset distance under static load.

% Data from ANSTS plotted in MATLAB

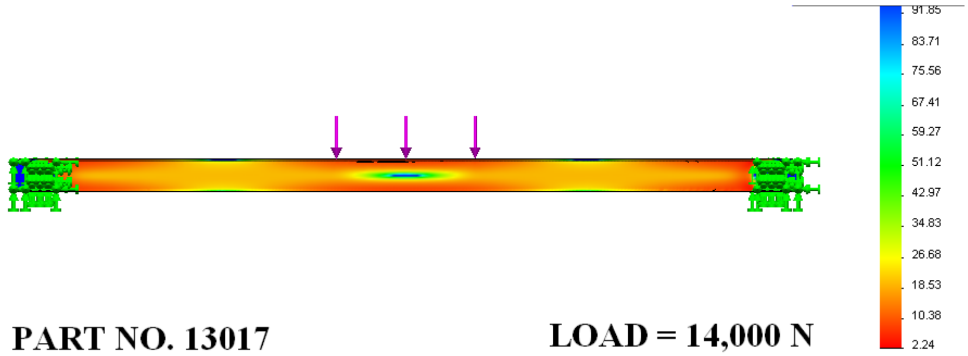


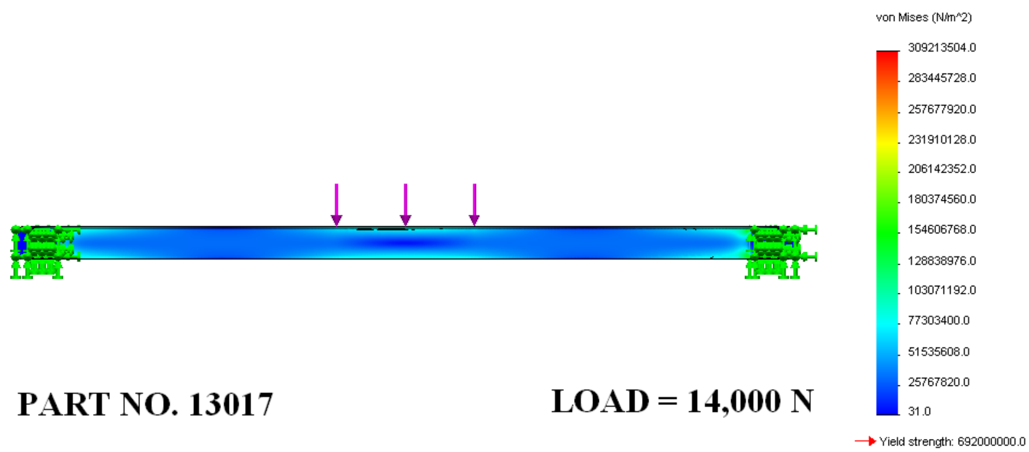
Finite Element Analyses



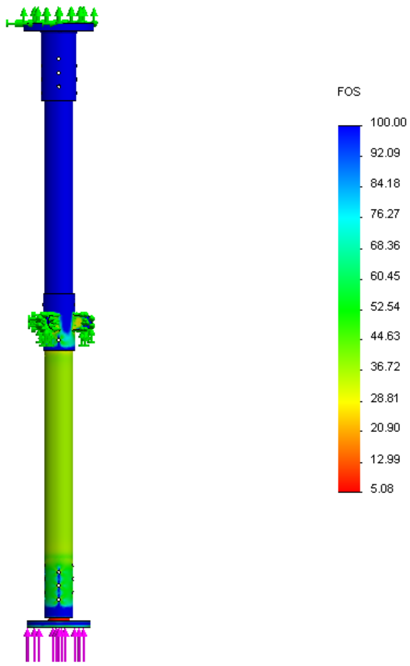


This beam supports the LH2 tanks over a span, the load is Earth launch.

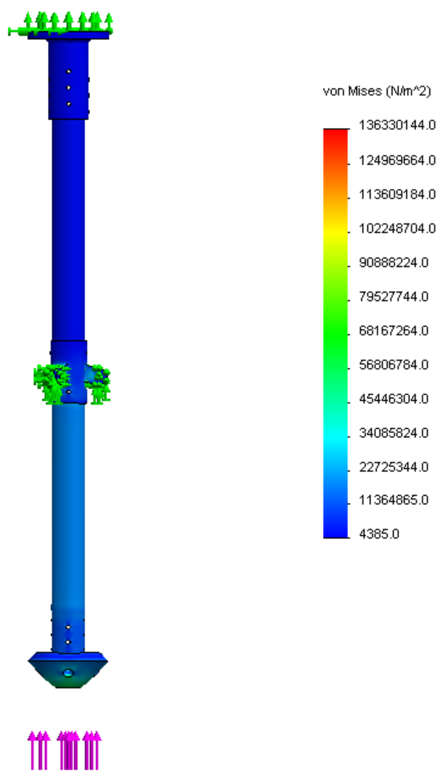




This beam supports additional fuel tanks on the bottom structure, the load is Earth launch.

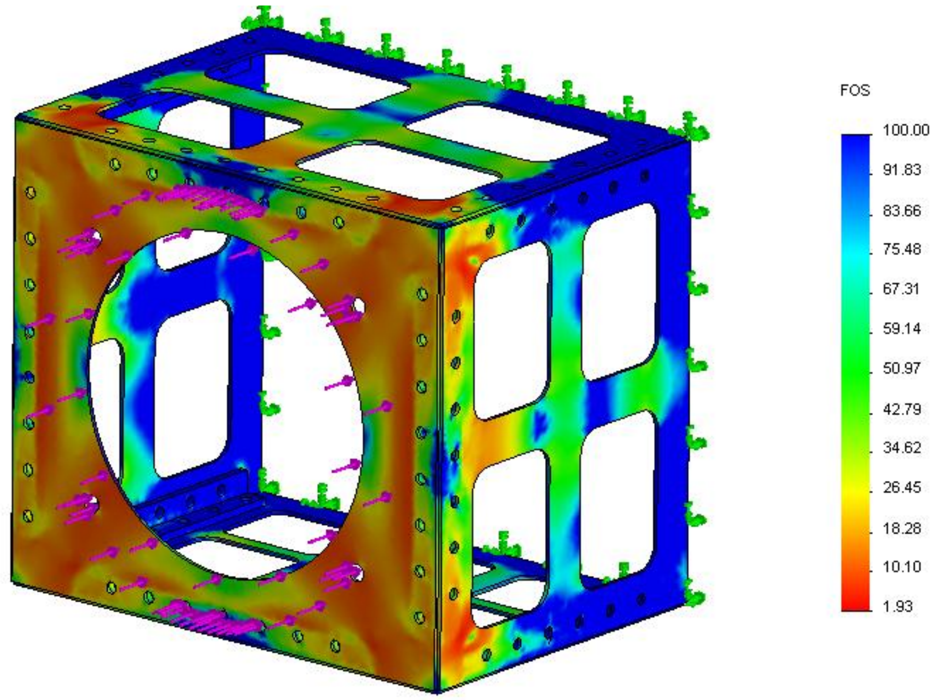


PART NO. 14000 LOAD = 67,000 N

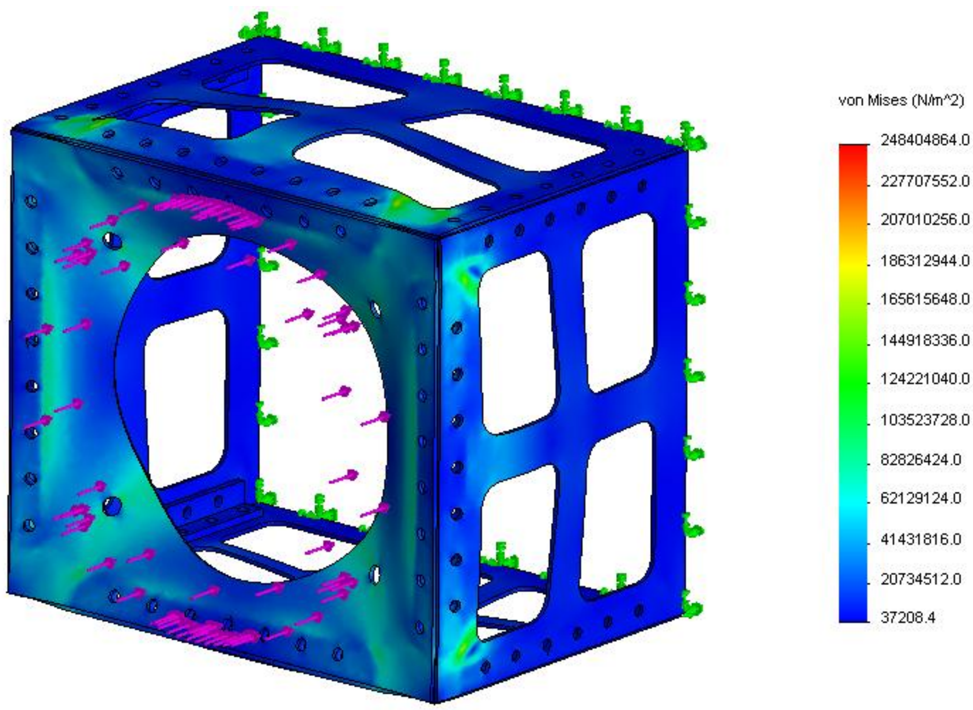


PART NO. 14000 LOAD = 67,000 N

This is the engine box under the full thrust of the CECE engine.

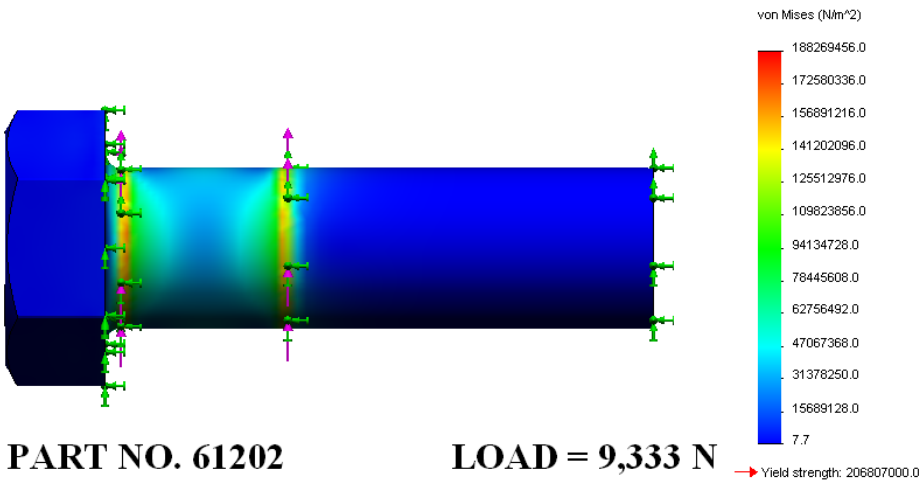


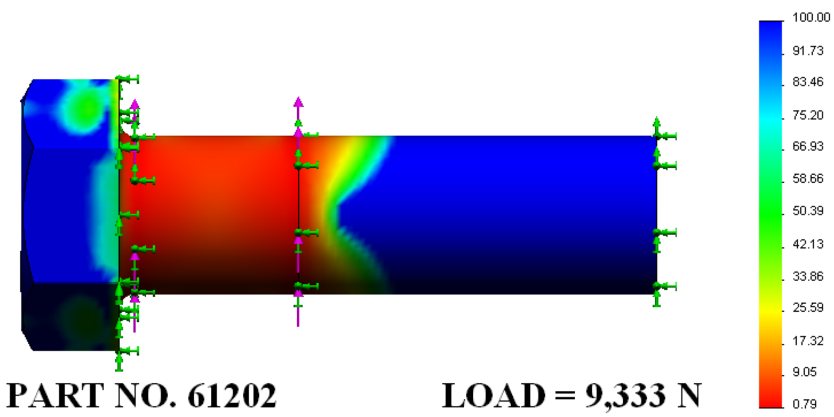
PART NO. 23100 LOAD = 4450 N



PART NO. 23100 LOAD = 4450 N

This is the RCS housing box under the fuel thrust of the RCS engine.





This bolt is in shear underneath the heaviest full tank on Earth launch. The bolt yielded so the number of bolts supporting the fuel tank was increased by a factor of two, satisfying factor of safety requirements.

Appendix E – Crew Systems

Suitport Operation

Frequent vehicle egress/ingress can introduce significant quantities of lunar dust into the habitat, as was seen in Apollo. To minimize this, the suitport airlock concept replaces the traditional, variable pressure chamber with a specialized door mechanism and spacesuit interface. Derived from the literature, this system forms an airtight seal between the spacesuit and habitat module through astronaut-operated clamp mechanisms[1-14]. This concept requires the habitat and spacesuit to operate at the same pressure.

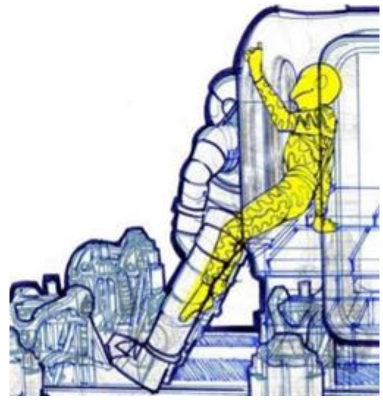


Figure CS1: Conceptual representation of the suitport, courtesy Ford et al. [6]

As shown in figure CS2, the system consists of a number of clamps and a new spacesuit. To enter the vehicle, the spacesuited astronaut first inspects the seals and ensures that the exterior clamps operate. Next, they remove as much regolith from the spacesuit as possible to minimize suit wear, potentially with the device described by [15]. Having prepared suit and airlock for docking, figure CS3 left, and facing away from the habitat, the astronaut seats the bottom edge of the spacesuit in the lower rail. The astronaut pushes rearward to mate the suit with the 1.6 mm thick polytetrafluoroethylene (PTFE) seal. Actuating first the lower clamps and ending with the overhead clamp, the astronaut secures the spacesuit to the habitat pressure vessel. The final configuration is shown in figure CS3 right. The outer clamps are similar to Carr-Lane 600HVTC heavy duty toggle clamps and each is capable of supplying 24 kN clamping force to the PTFE seal.

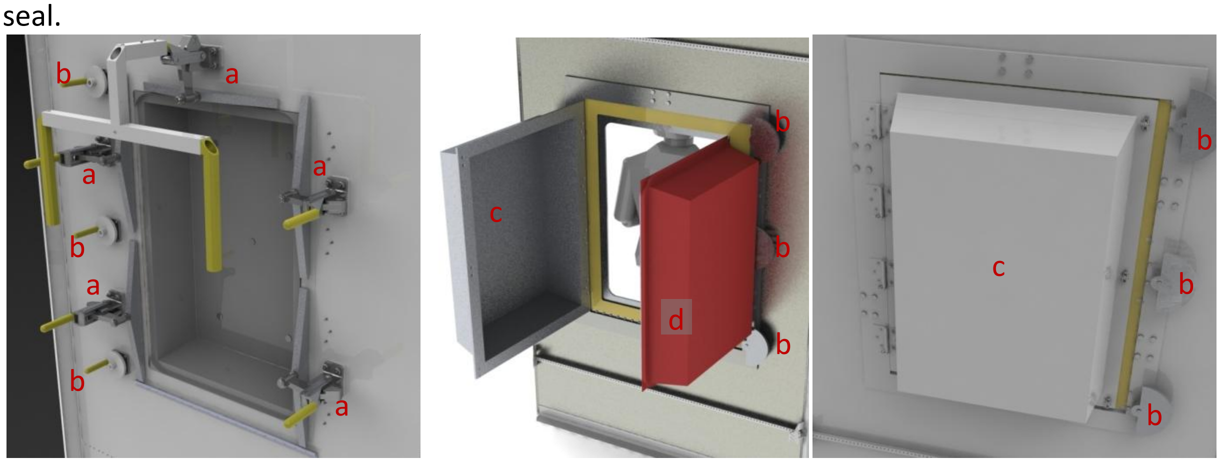


Figure CS2: Left – suitport exterior showing (a) exterior clamps and (b) interior clamps. Center – interior view showing the interior pressure door (c) and regolith shield (d). Right – habitat interior showing closed suitport. Interior pressure panel (c) clamped in place by rotating screw clamps (b).

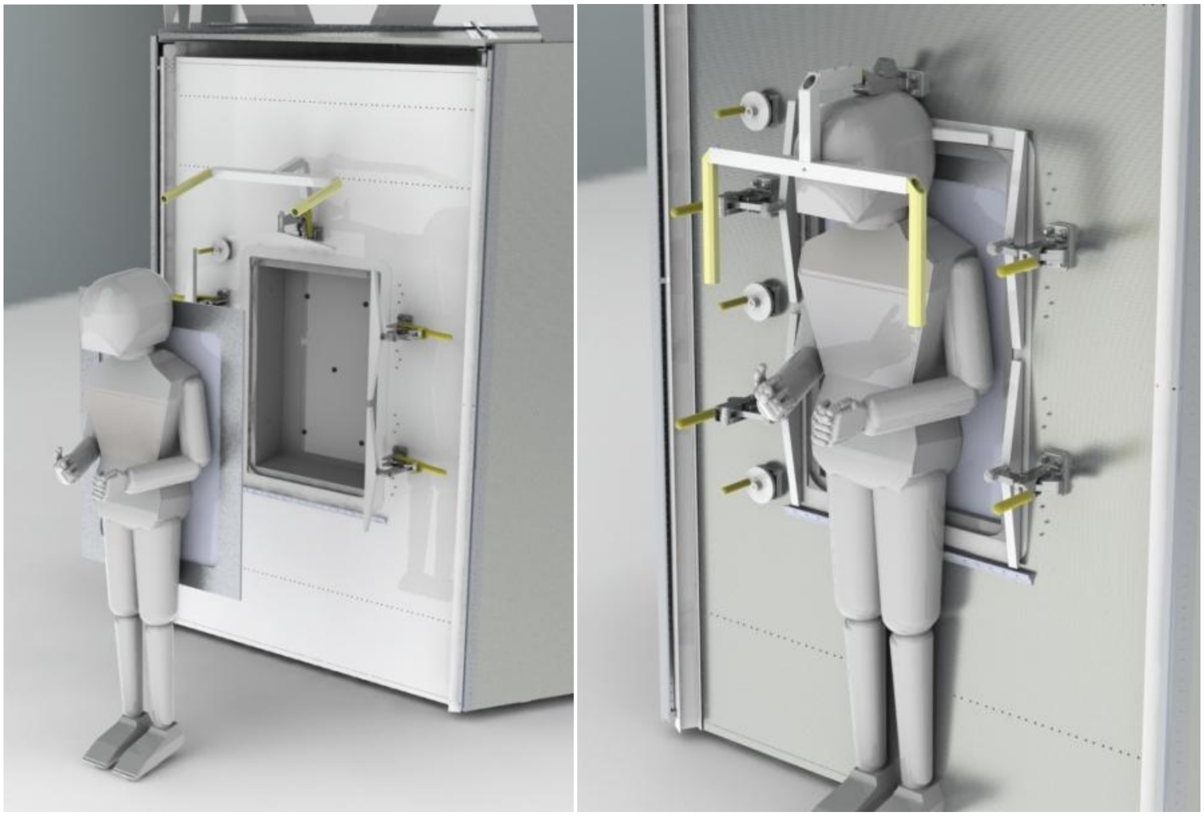


Figure CS3: Top left – Clamps open, astronaut on approach. Top right – spacesuit secured to pressure vessel.

With the spacesuit secured to the pressure vessel, the astronaut performs a leak check between the interior pressure and the exterior pressure seals. Having verified the outer seal, the astronaut releases the interior pressure clamps and opens the rear of the spacesuit into the habitat. During this process, a lightweight cover attaches onto the back panel of the spacesuit forming a large debris seal around the Portable Life Support System (PLSS) to prevent significant amounts of regolith from entering the cabin atmosphere while the interior pressure door and spacesuit door are open.

If spacesuit recharging requires connections to the interior of the spacesuit, the safest time to resupply the suit is immediately after entrance to the habitat. Once this is complete the astronaut will close the spacesuit and interior pressure doors and reengage the interior pressure door clamps. These rotating clamps have an inclined surface which contacts a ball bearing mounted to the interior pressure door. As the clamp rotates the inclined surfaces compresses the 1 mm silicone gasket.

Habitat Pressure Vessel

Finite element analysis in ANSYS 12.0 guided wall panel sizing and the placement of reinforcing members. Computational limits prevented analysis of the complete pressure vessel, so critical elements of the habitat structure were tested instead. Figure CS4 shows a typical analysis set, letting the support beam geometry and panel thickness vary.

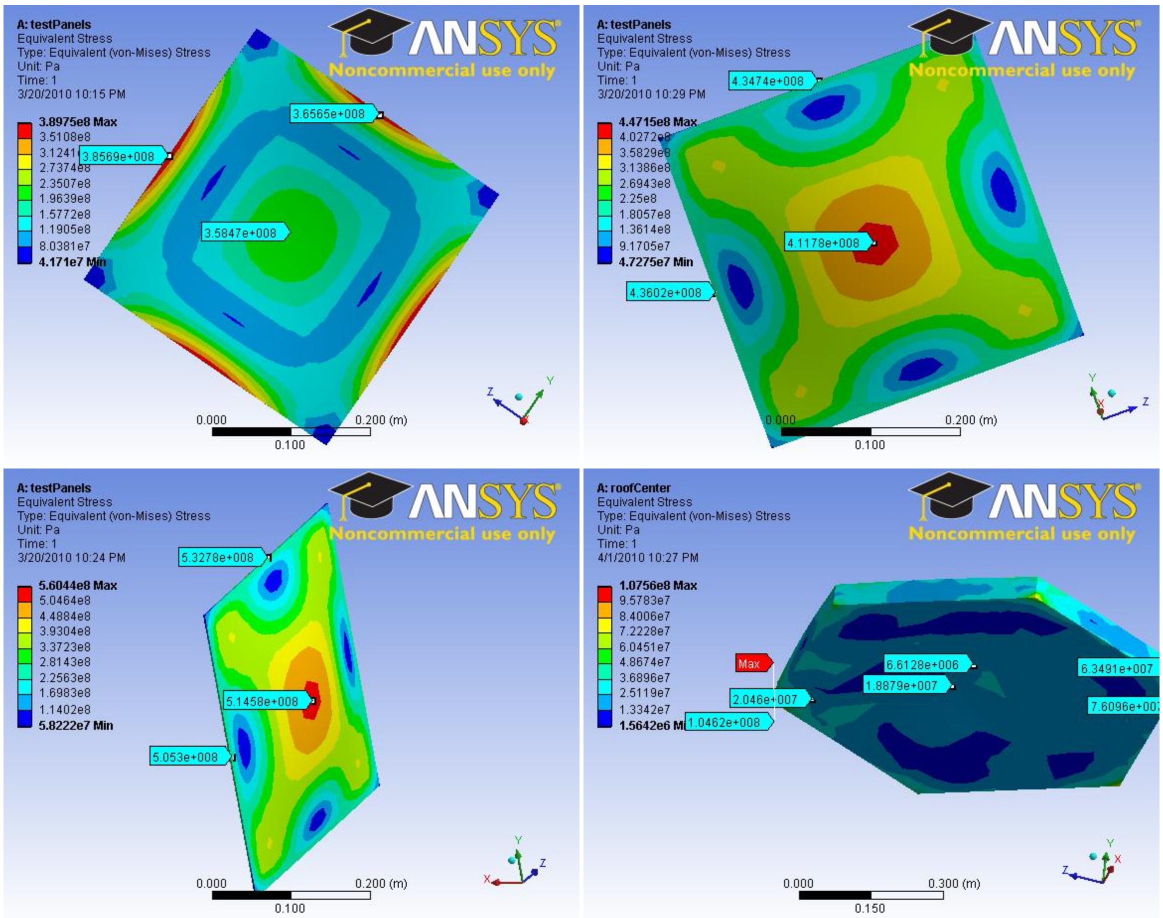


Figure CS4: Testing panel configurations in Ansys 12. Top – successful geometries. Lower left – geometry fails 1.4 factor of safety at panel center. These motivated the choice for a 300 mm maximum unsupported span and a 2.8 mm thick panel. Lower right – center panel of roof in the same analysis.

LEVITATE will experience maximum Earth and lunar operation accelerations of 39.24 m/s^2 (4g) and 9.8 m/s^2, respectively, which the habitat must also endure [16]. During Earth launch both the relative atmospheric pressure and habitat atmosphere pressure will be 14.7 psi, requiring the habitat to withstand only the 39.24 m/s^2 acceleration. The roof will experience the greatest stresses during these launches, leading to factors of safety of 57,600 and 204 for the Earth and lunar launches, respectively. These are obviously quite large and more than sufficient to avert failure during Earth and lunar launches.

References

[1] B. A. Romig, C. S. Allton and H. L. Litaker, "1-g Suit Port Concept Evaluator 2008 Test Results," *System,* 2010.

[2] T. J. Cognata, B. Conger and H. L. Paul, "Results of the particulate contamination control trade study for space suit life support development," in *Proceedings of the International Conference on Environmental Systems,* 2009, pp. 19.

[3] B. Romig, J. Kosmo, M. Gernhardt and A. Abercromby, "Desert research and technology studies 2008 report," in *Proceedings of the International Conference on Environmental Systems,* 2009, .

[4] J. Chartres, B. Koss, C. Brivkalns, B. Webbon, B. Romig and C. Allton, "Preliminary development of a suit port for planetary surface EVA part A: Design studies," in *Proceedings of the International Conference on Environmental Systems,* 2009, pp. 9.

[5] C. Culbert, "Constellation Program Overview," pp. 22, 2008.

[6] K. Ford, D. Fraser, R. Hauck and J. Logsdon, "Exploration Committee," 2008.

[7] M. L. Gernhardt and A. F. Abercromby, "Health and Safety Benefits of Small Pressurized Suitport Rovers as EVA Surface Support Vehicles," *Aviat. Space Environ. Med.,* vol. 79, pp. 246, 2008.

[8] H. Jones, "Planetary airlock and suitlock requirements and alternate approaches," in *Proceedings of the 37th International Conference on Environmental Systems (ICES),* 2007, .

[9] B. Webbon, B. Luna, J. Brown, A. Gonzales, H. Jones, B. Koss and D. Smith, "Innovative concepts for planetary EVA access," in *Proceedings of the 37th International Conference on Environmental Systems (ICES),* 2007, pp. 43.

[10] S. J. Hoffman, "Advanced EVA Capabilities: A Study for NASA's Revolutionary Aerospace Systems Concept Program," pp. 174, 2004.

[11] P. J. Rae and D. M. Dattelbaum, "The properties of poly(tetrafluoroethylene) (PTFE) in compression," *Polymer,* vol. 45, pp. 7615-7625, October, 2004.

[12] I. Abramov, N. Moiseev and A. Stoklitsky, "Concept of space suit enclosure for planetary exploration," 2001.

[13] M. M. Cohen, "US Patent 484222,", 1989.

[14] T. S. Cory, C. C. English, R. M. Hardman, J. C. Martinez, K. C. Moss, J. M. Wileman and M. M. Wolaver, "Personnel Transfer Airlock," vol. 58, pp. 167, 1987.

[15] S. A. Curtis, P. E. Clark, F. A. Minetto, C. I. Calle, J. Keller and M. Moore, "SPARCLE: Creating an electrostatically based tool for lunar dust control," in *Proceedings of the 40th Lunar and Planetary Science Conference,* 2009, pp. 2.

[16] P. Sumrall, B. Morris, "Ares V: Game Changer for National Security Launch," 2009.

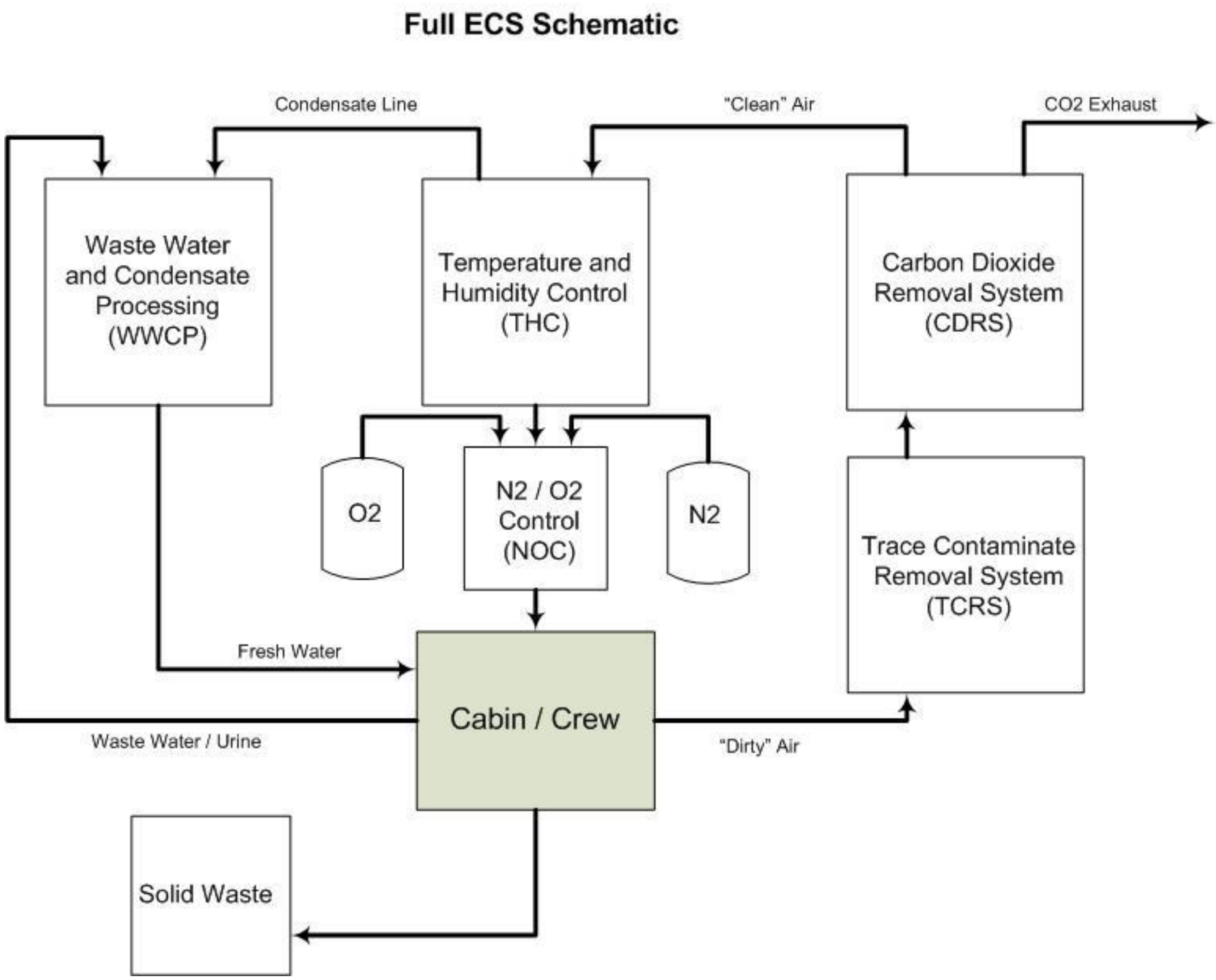
Appendix F – Thermal

MLI sizing was determined by consideration of radiative heat transfer through the micrometeoroid protection, fifteen layer double-aluminized mylar MLI blankets, and habitat pressure vessel. The heat transfer range accounts for whether the vehicle is in complete Sun or darkness.

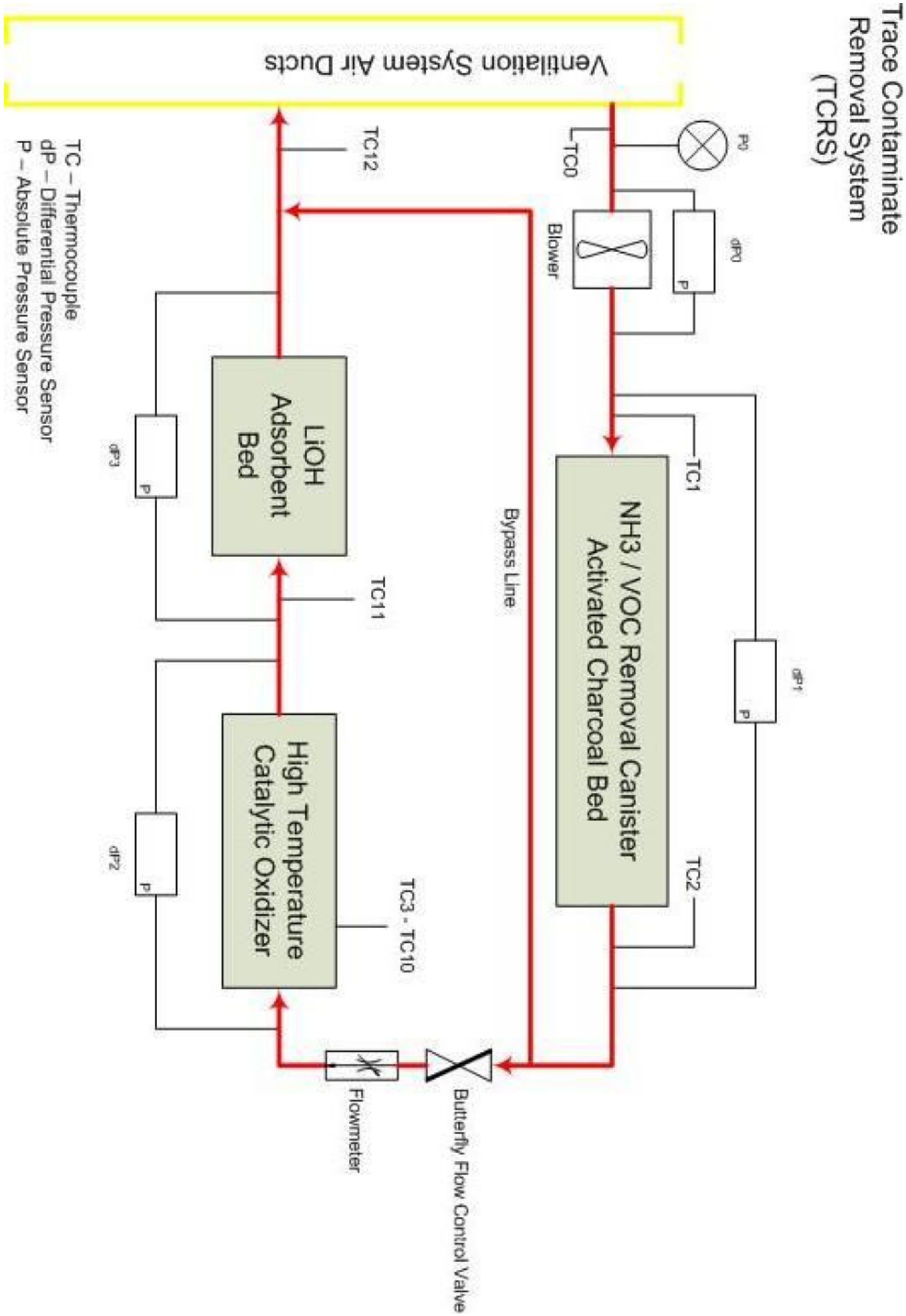
Interior temperature = 22.2222 C
Exterior temperature = 116.5 or -203.5 C
Solar irradiance = 1413 or 1321 W/m2 at 1 AU
Heat transfer per unit area = -1.4425 or 1.3088 W/m2
Total heat transfer area = 41.8766 m^2
Heat transfer = -60.4077 or 54.8077 W
Total habitat panel mass = 1887.0287 kg

Appendix G – Life Support systems

Full ECS Flow Diagram



Trace Contaminate Removal System (TCRS) Flow Diagram



TCRS Spacecraft Maximum Allowable Concentrations (SMAC)

Compound	Equipment Rate (mg/kg-day)	Metabolic Rate (mg/man-day)	Total (mg/day)	30-Day SMAC (mg/m^3)	SMAC PPM
Ethanol	7.85E-03	4	47.3	2000	1062
methanol	1.27E-03	1.5	9.4	90	70
2-propanol	3.99E-03	0	20.0	150	60
n-butanol	4.71E-03	1.33	26.2	80	Varies
toluene	1.98E-03	0	9.9	60	16
xylene	3.67E-03	0	18.4	217	50
chlorobenzene	1.54E-03	0	7.7	0.326	0.1
dichloromethane	2.15E-03	0	10.8	24	7
trifluoroethane	1.89E-02	0	94.5	20	4
tricholorofluoromethane	1.41E-03	0	7.1	790	140
methane	6.39E-04	160	323.2	3800	5300
acetone	3.62E-03	0.2	18.5	52	22
2-butanone (Methyl Ethyl Keytone)	6.01E-03	0	30.1	30	10
4-methyl-2-pentanone	1.41E-03	0	7.1	143	35
cyclohexanone	6.62E-04	0	3.3	4.89	25 (TLV)
carbon monoxide	2.03E-03	23	56.2	11	10
ammonia	8.46E-05	321	642.4	7	10
Carbon Dioxide	0.00E+00	1000000	2000000	12600	7000
Based on two persons and 5000kg of equipment off gassing				TLV = Threshold Limit Value	

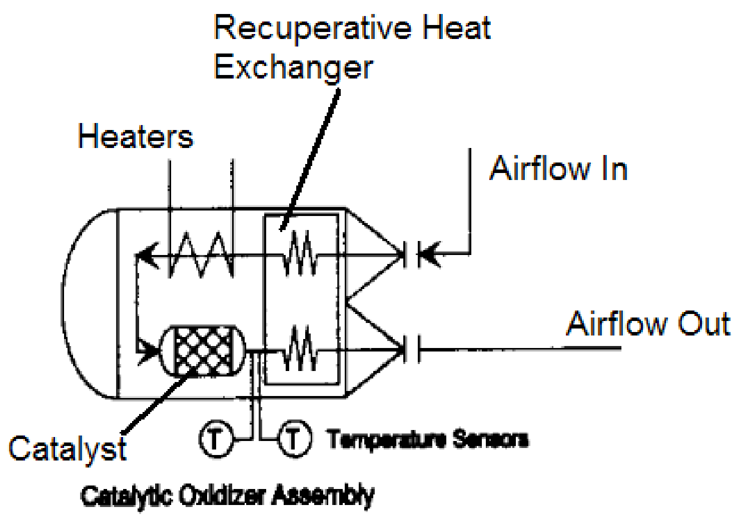
TCRS Activated Charcoal Media Quantities

Media	Removes	Est. Yearly Load (kg)	With Factor Of Safety, 1.5 (kg)	Media Capacity (kg VOC / kg media)	Required Media Mass (kg)	Media Bulk Density (kg/m^3))	Required Media Volume (m^3)
Puracarb AM	Ammonia	0.23448	0.35173	0.058	6.064	720	**0.0084**
Purafil SP Blend	VOCs	0.10971	0.16456	0.1	1.646	640	**0.0026**

TCRS Residence Times in Activated Charcoal

Activated Charcoal Bed Cross Section Sizing and Residence time (5.0 CFM Flow Rate)							
Media	**Bed Radius (ft)**	**Cross Section (ft^2)**	**Required Volume of Media (ft^3)**	**Required Length (ft)**	**Air Velocity (ft/min)**	**Residence Time (min)**	**Residence Time (s)**
Puracarb AM	0.250	0.196	0.297	1.513	25.47	0.06	**3.56**
Purafil SP	0.250	0.196	0.091	0.462	25.47	0.02	**1.09**

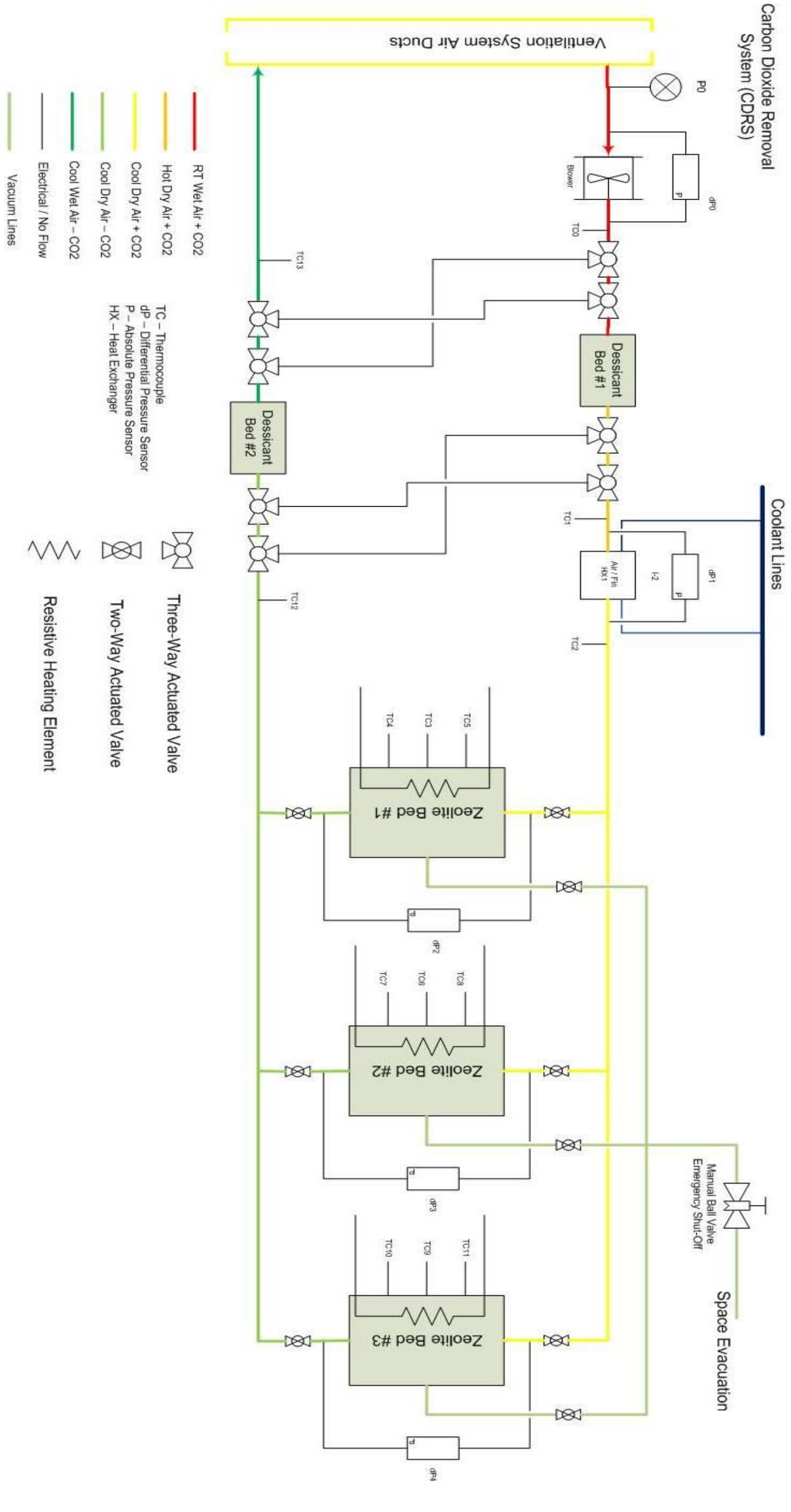
TCRS HTCO Schematic and Typical Reaction



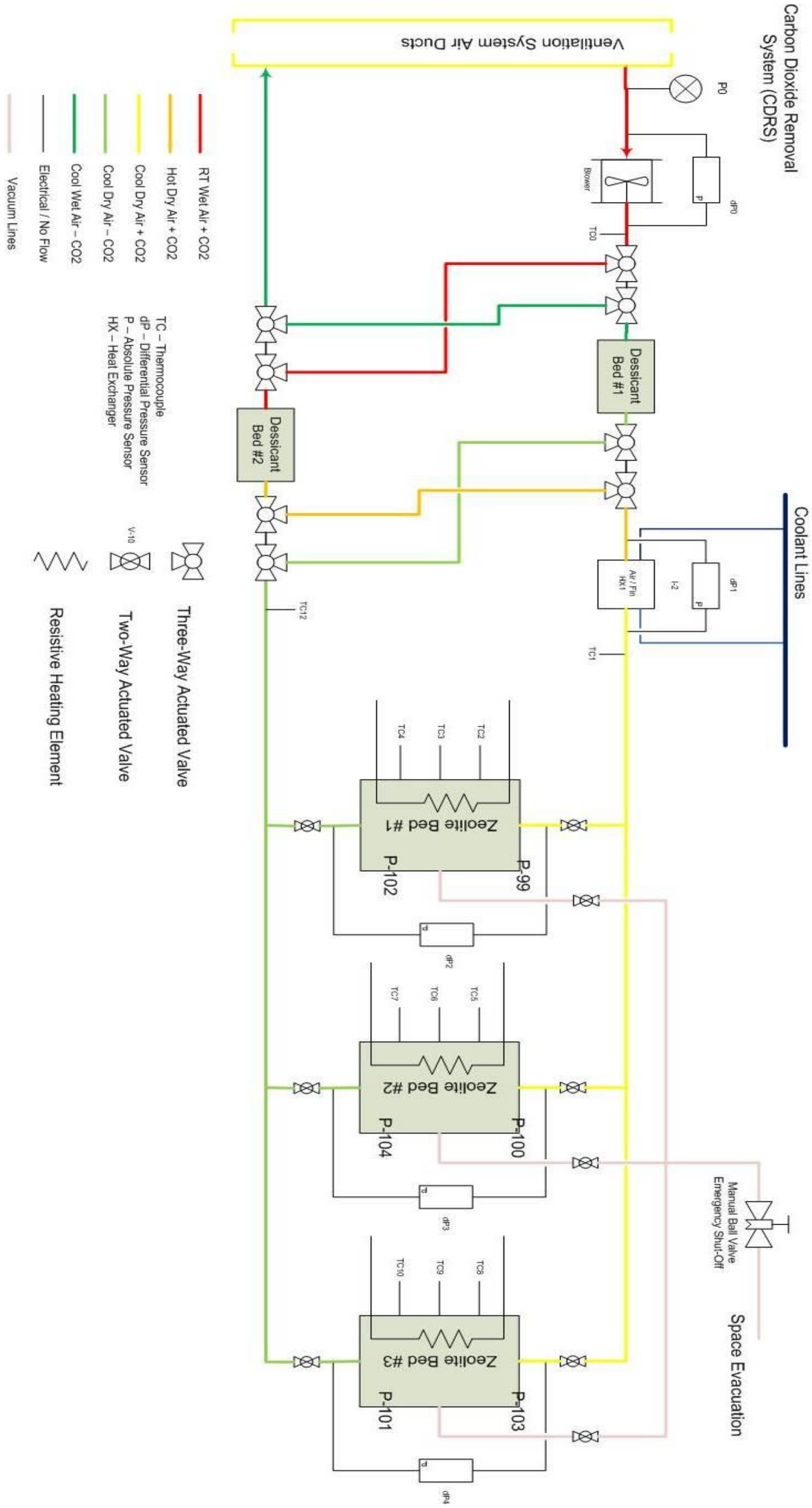
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 891\ KJ/mol$$

(Methane Combustion)

Carbon Dioxide Removal System (CDRS) Flow Diagram, Airflow Path A



Carbon Dioxide Removal System (CDRS) Flow Diagram, Airflow Path B

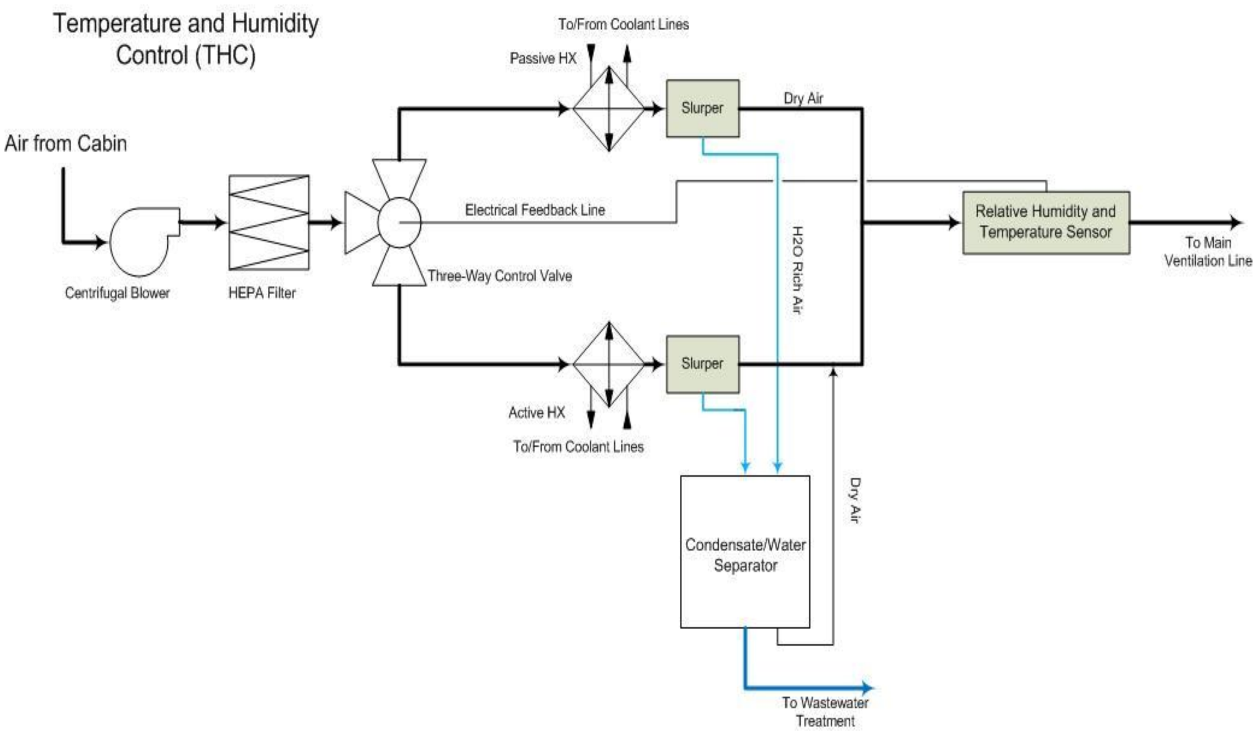


CDRS Desiccant and Zeolite Bed Cycles

Desiccant and Zeolite 5A Bed Cycles. Each Stage Represents One Hour.

Assembly	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Key
Desiccant Bed #1							Drying Incoming Air
Desiccant Bed #2							Wetting Outgoing Air
Zeolite 5A Bed #1							Removing CO2
Zeolite 5A Bed #2							Stripping CO2 (Heat)
Zeolite 5A Bed #3							Evacuating CO2 (Vacuum)

Temperature and Humidity Control (THC) Flow Diagram

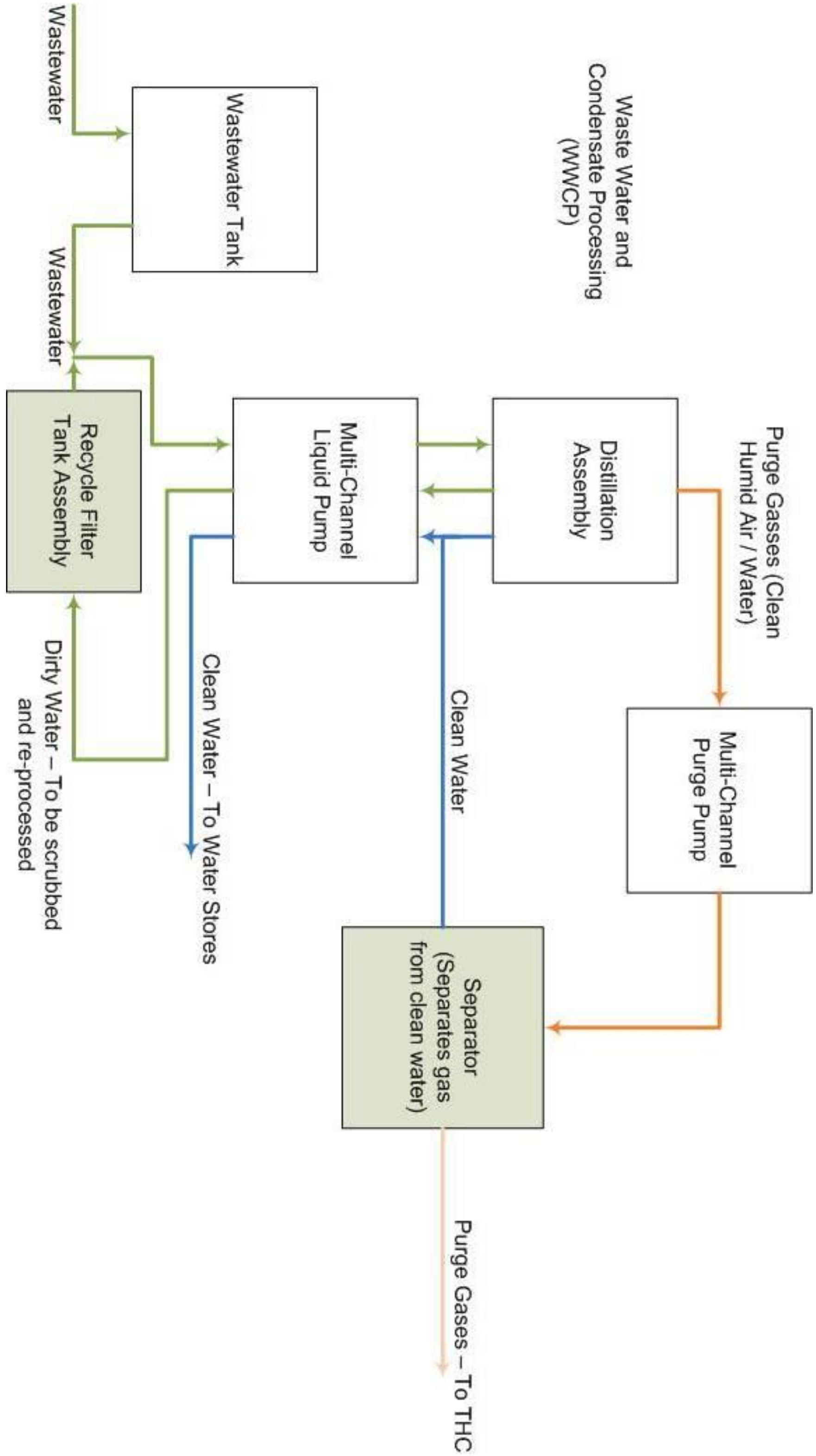


Nitrogen and Oxygen Control (NOC) Cabin Partial Pressures

Component	Required Partial Pressures (%)	Partial Pressure (psia)	Initial Atmospheric Requirements (L)	Metabolic Regeneration Required (L)	Total Gaseous Volume Required (L)	Total Required (mol)	Total mass Required (kg)	Liquid Density (kg/L)	Liquid Volume Required (L)
Oxygen (O2)	0.203	3.0	11165	16380	27545	1229.7	39.4	1.141	**34.5**
Nitrogen (N2)	0.785	11.5	43175	0	43175	1927.5	54.0	0.807	**66.9**
			Gaseous					Liquid	

Wastewater and Condensate Processing (WWCP) Flow Diagram

Power



Estimates

3xxxx - Life Support Power Requirements		
System	Operational Power (W)	Stand-by Power (W)
CDRA	368	162
TCRS	461	154
THC	551	451
NOC [1]	50	50
WWCP [1]	654	380
TOTAL	**2084**	**1197**

Carbon Dioxide Removal Assembly (CDRA)							
Component	**Manufacturer**	**Supply Voltage**	**Operational Power (W)**	**Stand-by Power (W)**	**Amount**	**Total Op Power (W)**	**Total SB Power (W)**
3-Way Solenoid Valve - 73317BN4UN00NKHZ04C2	Parker Hannifin	24V DC	2	0	8	16	0
Blower - 150193	AMETEK	24V DC	150	150	1	150	150
2-Way Solenoid Valve -7121KBN2SV00N0C111P3	Parker Hannifin	120V AC 60Hz	3.3	0	9	29.7	0
Differential Pressure Transmitter - PX291-010WDI	OMEGA	24V DC	0.24	0.24	7	1.68	1.68
Bolt Heater	Tempco	120V AC 60Hz	53.3	0	3	159.9	0
Data Acquisition System - OMB-DAQ-56	OMEGA	12V DC	10	10	1	10	10
Thermocouple Probe - KMTXL-125-G-06	OMEGA	-	0	0	9	0	0
Pressure Transducer - PX302 - 030AV	OMEGA	12V DC	0.25	0.25	1	0.25	0.25
				Totals (Estimates)		**367.53**	**161.93**

Trace Contaminate Removal System (TCRS)							
Component	**Manufacturer**	**Supply Voltage**	**Operational Power (W)**	**Stand-by Power (W)**	**Amount**	**Total Op Power (W)**	**Total SB Power (W)**
Pressure Transducer - PX302 - 030AV	OMEGA	12V DC	0.25	0.25	1	0.25	0.25
Blower - 150193	AMETEK	24V DC	110	110	1	110	110
Differential Pressure Transmitter - PX291-010WDI	OMEGA	24V DC	0.24	0.24	4	0.96	0.96
Thermocouple Probe - KMTXL-125-G-06	OMEGA	-	0	0	13	0	0
DAQ - OMB-DAQ-56	OMEGA	12V DC	10	10	1	10	10
High Temperature Catalytic Oxidizer [1]	???	120V AC (?)	300	23.2	1	300	23.2
Flowmeter - MFA5427ST-AIR	OMEGA	12V DC	9.6	9.6	1	9.6	9.6
Butterfly Control Valve - 253B-20-40-1	MKS	12V DC	30	0	1	30	0
				Totals (Estimates)		**460.81**	**154.01**

Temperature and Humidity Control (THC)							
Component	**Manufacturer**	**Supply Voltage**	**Operational Power (W)**	**Stand-by Power (W)**	**Amount**	**Total Op Power (W)**	**Total SB Power (W)**
Blower - 150403E	AMETEK	24V DC	450	450	1	450	450
RHT&P Sensor - HXP86	OMEGA	24V DC	1.2	1.2	1	1.2	1.2
Butterfly Control Valve - 253B-20-40-1	MKS	12V DC	30	0	2	60	0
Condensate Water Seperator Assembly (CWSA) [1]	??	??	40	0	1	40	0
				Total		**551.2**	**451.2**

(1) - Estimates based on NASA Documentation, JL Perry et al

Appendix H –Cost and Schedule

LEVITATE design, development, testing, evaluation, production cost estimates were produced by the NASA-Air Force COst Model, 2007 version.

Elements	Type	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Stage	DDT&E	3,011.90	326.3	958	724.8	459.3	279.7	158.7	72.8	29.3	3.2
	FU	284.8	1	6.6	17.8	46.9	73.8	66.5	33.5	24.2	14.5
SSTO	DDT&E	1,880.00	268.2	759.6	488.5	234.8	96.3	31.1	1.5	0	0
Subsystems	FU	208.5	0.9	5.4	14	39.8	64.4	55.1	20.9	5.9	2.2
SSTO System	DDT&E	961.4	39.6	144.2	195.2	198.6	167.5	118.5	67.2	27.6	3
Integration	FU	76.3	0.1	1.2	3.8	7.1	9.5	11.4	12.6	18.3	12.3
Fee	DDTE	0	0	0	0	0	0	0	0	0	0
	FU	0	0	0	0	0	0	0	0	0	0
Program	DDTE	0	0	0	0	0	0	0	0	0	0
Support	FU	0	0	0	0	0	0	0	0	0	0
Contingency	DDTE	0	0	0	0	0	0	0	0	0	0
	FU	0	0	0	0	0	0	0	0	0	0
Vehicle Level	DDTE	170.5	18.5	54.2	41	26	15.8	9	4.1	1.7	0.2
Integration	FU	0	0	0	0	0	0	0	0	0	0
									costs in $ millions		

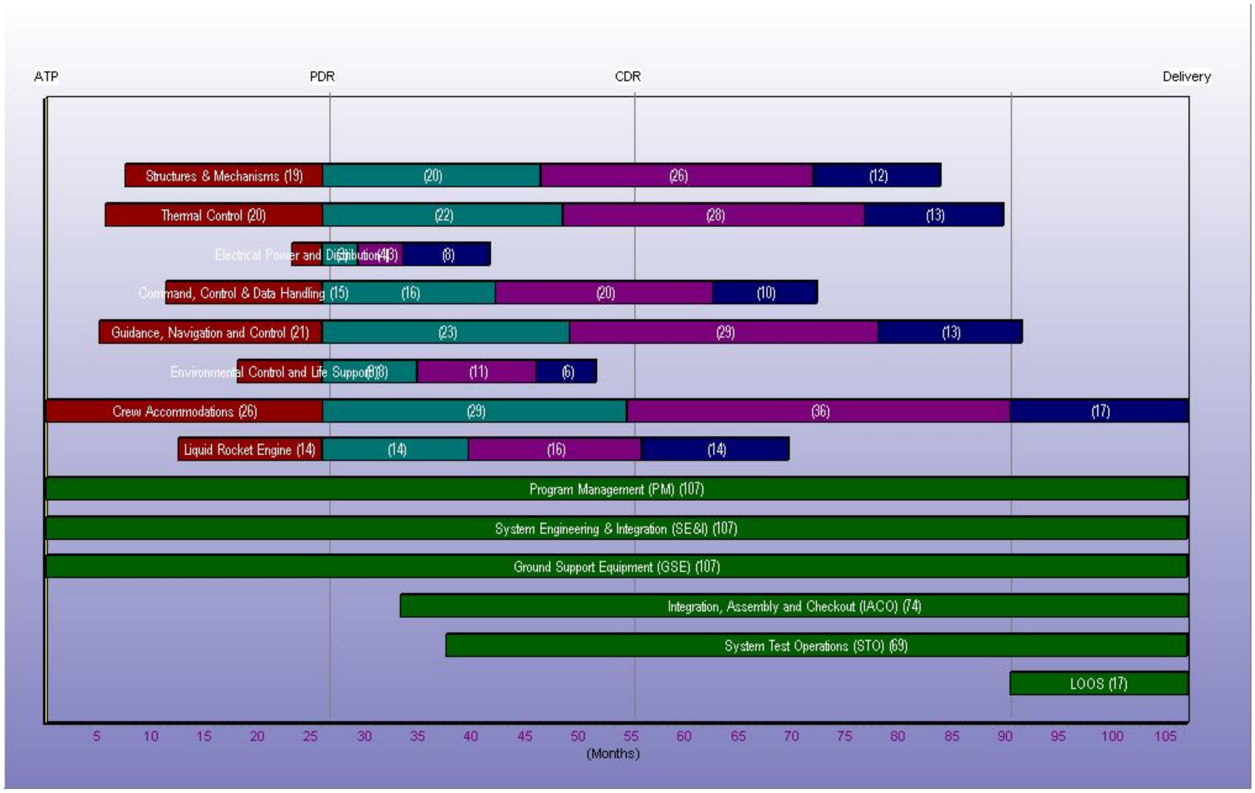
Costs per year, in $ millions.

Elements	DDT&E	Flight Unit	Produc	Total
Stage	2,919.50	256.9	256.9	3,176.50
SSTO Subsystems	1,849.50	190.4	190.4	2,039.90
SSTO System Integration	904.7	66.5	66.5	971.3
Fee	0	0	0	0
Program Support	0	0	0	0
Contingency	0	0	0	0
Vehicle Level Integration	165.3	0	0	165.3

Costs by development stage, in $ millions.

	DDT&E:	Flight Unit:	Production:	Total:
Labor Hours (millions)	14.9	1.4	1.4	16.3
Engineering	11.3	0.4	0.4	11.7
Manufacturing	2.8	0.9	0.9	3.7
Other	0.8	0.1	0.1	0.9
Total Dollars	2,754.20	256.9	256.9	3,011.10
Labor	632.1	53.4	53.4	685
Engineering	498.6	18	18	516.6
Manufacturing	100.3	32.5	32.5	132.8
Other	33.2	2.8	2.8	36
Material	164.9	26.3	26.3	191.2
Subcontracts	751.1	70.1	70.1	821.2
Overhead	853.3	72.1	72.1	925.3
Other Direct Charges	102.4	11.7	11.7	114.1
G&A	250.4	23.4	23.4	273.7
FBS Factor	1	1	1	

Functional breakout of costs by major elements and development stage, in millions of man-hours and $ millions.


ATP
PDR
CDR
Delivery
Structures & Mechanisms (19)
(20)
(26)
(12)
Thermal Control (20)
(22)
(28)
(13)
(8)
Command, Control & Data Handling (15)
(16)
(20)
(10)
Guidance, Navigation and Control (21)
(23)
(29)
(13)
(11)
(6)
Crew Accommodations (26)
(29)
(36)
(17)
Liquid Rocket Engine (14)
(14)
(16)
(14)
Program Management (PM) (107)
System Engineering & Integration (SE&I) (107)
Ground Support Equipment (GSE) (107)
Integration, Assembly and Checkout (IACO) (74)
System Test Operations (STO) (69)
LOOS (17)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105
(Months)

Appendix I – Technology Readiness Levels (TRLs)

Structural Components			
Component	**Part No**	**Previously Flown?**	**TRL**
Shock Absorber	11101	N	6
Aluminum 2195 - Weldalite	N/A	Y	9
ISS FASTRACK Cargo Modules	11200	Y	9
Bolted Connections	6xxxx	Y	9
Pinned Connections	11055, 11056	Y	7
Lockwire	11053	Y	9
NEXTEL Sleeve Coverings	11400, 11500	N	8

Propulsion Components			
Component	**Part No**	**Previously Flown?**	**TRL**
Common Extensible Cryogenic Engine	14009	N	7
Northrop Grumman Bipropellant Thrusters	23101	N	8
Fuel Tanks	22100, 22200, 22300	N	7
Surface Tension Galley	N/A	N	7
Tank Foam Insulation	22139, 22239, 22339	Y	9
MLI Blanket Insulation	22141, 22142, 22143	N	7
Tank Electronics (InterTechnology and Magnatrol)	22131, 22133	Y	9

Environmental Control System (ECS)			
Component	**Part No**	**Previously Flown?**	**TRL**
CDRA Desiccant Beds	31003	N	7
CDRA Heat Exchanger	31200	N	8
Blowers	31403 , 36321	N	7
CDRA Zeolite Media Beds	31698	N	7
TCRS Activated Charcoal Media Bed	32199	N	8
TCRS Bypass Assembly	32299	N	6
TCRS High Temperature Catalytic Oxidizer	32303	Y	9
TCRS Lithium Hydroxide Media Bed	32401	N	8
Subsystem Fittings (MDC-Vacuum)	360xx	Y	9
Particulate Mitigation Filter (Swagelok)	36215	N	6
Compression Fittings (Swagelok)	362xx	Y	9
Electronics - TC, dP/Absolute Pres Sensors - (OMEGA)	364xx	N	8
Solenoid Valves (Parker-Hannifin)	364xx	Y	9

Habitat			
Component	**Part No**	**Previously Flown?**	**TRL**
Suitport	513xx	N	4
Habitat Pressure Vessel	523xx, 512xx	N	6
Multi-Layer Insulation (MLI)	5160x, 5165x	Y	5
Micrometeoriod and Orbital Debris Protection (M/OD)	15xxx	N	6
Radiation Protection	N/A	N	5

Appendix J – Product Design Specifications (PDS)

	Specification Element
The performance demanded or likely to be demanded should be fully defined; how fast, how slow, how often — continuously or discontinuously, loadings likely (maximum and average) — electrical, hydraulic or pneumatic, tolerance of speed, rate of working, Duty Cycle, etc. Remember that the more complex the product, the more likelihood there is of ambiguities and conflict between the performance figures specified — for example, the specification of an electrical cable to carry 20 kVA to an underwater vehicle when the sum of the vehicle power requirements amounted to 50 kVA? Is the performance demanded attainable in an economic manner? A common failing in specifying performance is to ask for the ultimate, rather than that which is obtainable. Research evidence shows that successful design teams pay great attention to establishing objectives that can be attained. It is extremely easy to tighten up a performance specification to such an extent that if one designed to meet that performance, the customer would not be willing or able to afford it, even if the company could possibly afford to make it in the first place. Sales departments and clients never cease to be amazed that the product emerging from their specification costs so much. It takes little effort or thought to specify ± zero as a tolerance for any parameter, which in reality means infinite cost. While the practice of over-specifying (belt and suspenders) sometimes occurs in mass production industries, it is more likely to occur with specialist equipment, particularly in the large, one-of field where the client does not really know the adequate level of performance needed to suit his requirements. Beware therefore of 'over-specification' of performance, and also remember that performance is but one component of the PDS. It is not uncommon, say, with hydraulic pumps, for manufacturers to specify performance parameters that are not attainable *coincidentally,* but independently with reductions in the other parameters — for example, pressure and flow for variable delivery pumps. In other words, maxima do not always occur together.	**Performance** Long Range Travel: Max: Half circumference per jump (5,640km) Min: 50 km Duration: 8 Hour Min, 336 Hours Max Turn around time: 12 Hours Payload: >226 kg + 2 equipped astronauts Landing Accuracy: 5.0 meters in any direction Landing Area: 10˚ from horizontal Ground height Variation: 0.5m
All aspects of the product's likely environment should be considered and investigated: Temperature range pressure range (altitude) humidity shock loading (gravity forces) dirty or dusty — how dirty? — how clean? Corrosion from fluids — type of fluid or chemical noise levels insects vibration training and background of those who will use and maintain the equipment •— likely degree of abuse? Any unforeseen hazards to customer, user or the environment —for	**External Environment** Temperature Range: 70 - 390K Pressure Range: 0 atm to 1 atm Humidity: 0 – 100% RH Gravity: 0.1645g Regolith: 20 micron diameter particulates Radiation: 1364.5-1367.5 (W/m^2) dependent of solar cycle

example, inclusion of CFCs? All manufactured items experience a number of these environmental changes in any or all of the areas before being called on to function for the user. These may occur at the following stages: During manufacture — exposure to cutting fluids, solvents, fluxes (flow soldering), acids (plating and cleaning), etc. During storage — in the plant. During assembly — assembly forces, contamination from sweating hands? During packaging. During transportation. During storage — at a wholesaler's warehouse. During display. During use. These environmental subsets must be considered at the outset, otherwise the essential performance required during usage may never be achieved, or at best may be somewhat less than the user expectation.	Hazards: Potential meteorite strikes of Density: 0.5 g/cc Speed: 11.1-72.2 km/sec Internal Environment Meeting Vol I Sec 5 of MSIS chart 5.8.3.1-1
Should service life be short or long and against which criteria should this be applied? Against which part of the PDS is (or should) the product life be assessed? One year on full performance, 24 hours a day, seven days a week, or what? Consider the Duty Cycle.	**Life in Service (performance)** 5 Earth Years
Is regular maintenance available or desirable? Will designing for maintenance-free operation prejudice the design to such an extent that the product will become too expensive to buy in the first place? Does the company, or indeed the market into which the product will ultimately go, have a definitive maintenance policy? Is the market used to maintaining equipment once it is purchased? The following points are relevant: •Specify ease of access to the parts that are likely to require maintenance. It is no good calling for regular maintenance if it takes 10 days to reach the part. • What is the maintenance and spares philosophy of the company and market? • What is the likely need and desirability of special tools for maintenance?	**Maintenance** Every Trip: Basic diagnostics – automated systems Every 5 Trips: Visual inspection of all major structural components and subsystems. Every 20 Trips: Ultrasonic structural testing. Major subsystem disassembly and inspection inside of the lunar base.
Target production costs should be established from the outset and checked against existing or like products. Invariably, all target costs are on the low side, and in many cases they are unattainable within the constraints of the PDS. Care should be taken at this stage to ascertain whether the target cost is compatible with competitors' products and, most importantly, with the manufacturing facility available to make the product. Cost patterns should be established and studied in detail before setting the target cost. If a life cycle cost model is the norm in the company or market area into which you are entering, then this should be properly analyzed, with particular reference to maintenance trade-off and down time. Make sure you specify retail price, production cost, or something else as you consider this item. There are large differences dollar differences in these numbers	**Target Product Cost**
A thorough analysis of competition must be carried out, including a comprehensive literature search, patent search and product literature search relating not only to the proposed product area, but also to analogous product areas. The nature and extent of existing and likely competition is probably the most important aspect of a PDS, at least from a comparative viewpoint. If, for example, the evolving specification shows serious mismatches or deficiencies when compared with what already exists, then the reasons for such departures must be fully understood. Therefore, it is essential that a proper analysis be carried out (perhaps a parametric analysis). Typical magnitudes of such searches are: Useful papers: 300—600 Relevant patents: 10-100	**Competition** LER

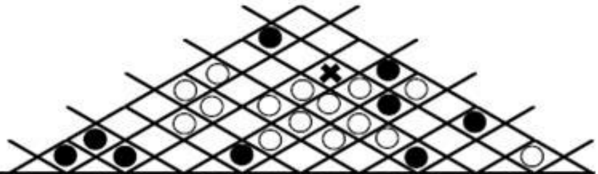
Competing products: 2—80 Useful parametric graphs: 5—30 (from a selection of perhaps 100). In order to stay in business, more and more companies are carrying out these sort of searches very thoroughly indeed, and are looking for world-class parameters.	
It is necessary to determine how the product is to be delivered: By land, sea or air — home or overseas; what type and size of truck, pallet container (look to ISO standards) or type of aircraft used for the type of product under consideration. It is not unknown for equipment not to be able to pass through cargo hatches of aircraft or ships, or to be expensive in terms of shipping volume. This can affect the subassembly breakdown of the product. A product may be competitive here, but by the time it is shipped overseas it may have become too expensive. For example, a pump designed for land irrigation and sold mainly overseas became non-competitive because it was made portable (a good idea) by putting it on a trolley. The consequent doubling of shipping volume rendered it non-competitive even though the increase in basic prime cost of the pump itself was very small. Lifting capability, provision of lifting points.	**Shipping** Mass and overall size must fit within specifications of next generation HLV (potentially Ares V)
Depending on the type of product being designed, some form of packaging may be necessary for transport, storage, etc. The cost of packing will add to the product cost and volume. Should the packaging protect against the environmental effects of shipping such as salt water, corrosion, shock-loading, etc?	**Packaging** Mass and overall size must fit within specifications of next generation HLV (potentially Ares V)
Likely numbers to be produced by run and by year over the product life will affect all aspects of a product's design. A one-off may require very little tooling, although there are exceptions, such as the Channel Tunnel. Moderate numbers may require cheap temporary tooling, while large numbers may require permanent, expensive tooling. Further, purchasing quantities, purchasing discounts and inventory costs for raw materials and finished goods have a considerable effect on the supportive investment required.	**Quantity** 1
Are we designing to fill an existing plant or is the plant and machinery involved a constraint to our design? What are the plans for new plant and machinery? It is no good designing for a one-plant set-up to find a new one in existence by the time the production phase arrives. Make or buy policy: is the product constrained to techniques with which the company is familiar? Is our proposed flexible manufacturing system the ultimate in inflexibility? More and more companies are resorting to subcontract manufacture which will make them less capital intensive and reduce their fixed costs. It also allows them the ultimate in flexibility in terms of manufacturing processes and technologies.	**Manufacturing Facility** Multiple commercial and government design firms
Are there any restrictions on the size of the product? Size constraints should be specified initially. So many designs 'grow' like Topsy, with the result that the equipment will not fit into the space provided, and even though it may do so ultimately, access for maintenance could be difficult. Does the product size and shape make it difficult to handle?	**Size** 8.77m x 9.31m
What is the desirable weight? (Remember that, for a given technology, weight is frequently related to cost.) Allied to size, weight is important when it comes to handling the product on the shop floor during manufacture, in transit, during installation or in the user situation with the customer. Should the design be modular to assist in the size/weight area? Should lifting points be provided	**Weight** <71100 kg
The appearance of a product is a difficult thing to specify and therefore, in many instances, it is left to the designer: the complaints come afterwards. Color, shape, form and texture of finish should always be considered from the outset. Advice and opinion should always be sought either from within the company or without. Sales, marketing, production and others will always criticize a design once it exists. Therefore, efforts should be made to obtain these opinions before the design commences, and certainly as it progresses. Every person is a	**Aesthetics, Appearance and Finish** No requirements

design critic, accomplished or otherwise. So often the final appearance of a product 'just happens' and then strenuous efforts are made to make it look better, which usually prejudices the design in all aspects.	
The choice of materials for a particular product design is invariably left to the design team. Usually, this is not a bad thing. However, if special materials are necessary, they should be specified, preferably by quoting the appropriate standard. The converse is also true. If it is known that certain materials, such as lead-based paint for consumer products, must not be used, they should not be specified. Aluminum or its alloys on exposed surfaces for underground coal-mining equipment is forbidden in the UK but not in the USA. For material selection assistance, see ASM Vol 20, pg 288 & vicinity.	**Materials** Materials must withstand external lunar environment.
Some indication of the life of a product as a marketable entity should be sought. Is it likely to remain in production for two years or 20 years? The answer is crucial as it can affect the design approach and interacts with the market and competition, tooling policy, manufacturing facility and the like. Product life spans are reducing rapidly for example. Consider printers and calculators.	**Product life Span** Possible use for 50 years
The product must designed to current US, international, and perhaps other standards. If so, then these should be specified and copies obtained. Cross-correlation of such standards should be carried out prior to commencement of the design. It is difficult, costly, time consuming, and inefficient to attempt retrospective matching of finalized designs to such standards. Also, bear in mind that while standards are extremely useful and essential, they generally represent an industry or technology consensus at a point in time. They must not be allowed to freeze innovation However, reasons for not following particular standards must be carefully evaluated and documented for the inevitable day of the product liability law suit. Further, some standards are mandated by Law—EPA, OSHA, state and local building codes, etc. These MUST be followed in the design.	**Standards and Specifications** ISO NAS NASA (MSIS etc) AIAA SAE ASME
All products have, to some degree, a person—machine interface, certainly during manufacture, and if not directly during usage, again at the time when maintenance is required. It is therefore necessary to elucidate the likely nature of the interaction of the product with humans. What height, reach, forces and operating torque are acceptable to the user. Postures and lighting should be considered; the devices must be a delight to use—potential users must be consulted	**Ergonomics/Human Factors** Fully operable by one astronaut Automatic return button
It is essential to obtain first-hand information on customer likes, dislikes, preferences and prejudices. Eyeball-to-eyeball discussion, question and answer, and examination of competitors' trends and specifications are all useful inputs to the specification. To a great extent, such input will depend on whether there are product line precedents already on the market or whether it is a product breaking new ground. Customer input is, nevertheless, essential to success. The degree of difficulty with which this input is obtained varies enormously from the large one-of turnkey type of project where the designer will interface directly with the customer, to the mass-produced product where s/he will not.	**Customer** NASA
The laying down of levels of quality and reliability necessary to ensure product success and acceptability in a particular market is a cause for increasing concern. They are the most difficult aspects to quantify in absolute terms, although statistical data from company product precedents are helpful here. In electronics, mean time before failure (MTBF) and mean time to repair (MTTR) are familiar expressions, although it must be remembered that by comparison with mechanical, hydraulic, pneumatic and even electrical components, electronic components experience a relatively controlled, sheltered life. Nonetheless, some quantitative expression must be made in respect of quality and reliability at the specification stage. A company must ensure adequate feedback of any failure analysis to the design team and the safety team.	**Quality and Reliability** Mean time for basic repairs: 24 man-hours Mean time to replace subsystems / parts: Dependent on launch schedule. Approx 6 months (Augustine)

A factor often overlooked in specifications is that of 'shelf life' (applied to units) or storage on site (as applied to a complete plant). With respect to units, shelf life must be specified at the outset and the means to combat decay considered, otherwise rusty gearboxes, hardened rubber components, seized bearings, defective linings, corrosion and general decay will occur. The designers of a complex plant should also be aware of these problems, since equipment designed on the assumption of immediate installation and commissioning may lie around on site for months on end without adequate protection and storage.	**Shelf Life (Storage)** Earth storage, pre-launch: <10 years in controlled conditions (STP) Lunar storage: <1 year
In-house process specifications, as opposed to manufacturing techniques, are vitally important. If special processes are to be used during manufacture, they should be defined — for example, plating specifications wiring specifications. Alternatively, the relevant standards —US, international, foreign, in-house, etc. — should be called upon.	**Processes** To be specified during design Highly specified processes anticipated
What is the time-scale for the project as a whole, in parts or phases? Is there a need to fit in with the time-scales of others concerned with the project? Lead times allowed for design activity are frequently inadequate, but they determine the time-scale for the whole project up to manufacture and product launch. Design time must be adequate to ensure that the product is designed effectively and efficiently — in other words, professionally. Lack of adequate time spent at the beginning of a design project will be made up for later and to other people's time-scales due to defective products, market mismatches, overwhelming competition and the like. There is no alternative to adequate design time. Use Microsoft Project to monitor your own design progress.	**Time-scales** Design time: 1 semester Construction and testing time: 6 years Deployment time: 1 month
Most products require some form of testing after manufacture, either in the factory, on site or both. Products for the consumer or engineering markets usually require a factory test to verify the quality of the product and its compliance with the PDS. Curiously, this usually relates to the performance aspects which, although essential, represent a narrow view of the whole question of product evolution. Do we sample test one in ten, one in a hundred, or what? Do we need a new test facility? How can we be sure that the product is designed to have rapid engagement with and detachment from the test rig? Data collection and product history are needed to answer these questions. An initial test specification should be written at this stage. It is too late after the design has been completed! Process plants and projects of this nature usually have acceptance and witness tests, in addition to factory tests. As with all testing, these require careful planning and execution, not only to ensure compliance with the PDS, but also to limit the cost. Do not forget to include testing relating to product safety and the potential of product liability legislation.	**Testing** System tests: Rockets Life support Landing gear Vibration Operability Power systems ... Before lunar flight will test every system (twice)
The safety aspects of the proposed design and its place in the market must be considered. Indeed, there is a substantial body of law and standards covering this aspect of design. Companies pay large sums on a daily basis because they failed to adequately consider this element of design. First, one must identify each and every hazard. Then, one must in decreasing order of desirability: Design out the hazard Guard the Hazard Warn of the Hazard Labeling should give adequate warning. Likely degree of abuse, whether obvious or not, should also be considered; also likely misrepresentation of function of equipment. Definitive operating and maintenance instructions must be prepared.	**Safety** Redundancy: 3x redundant for critical life systems Factor of Safety for structural components: 1.5 Landing Abort Capabilities: Yes First Contact:
Feedback from the market place should be considered. It is poor design to incorporate certain firm's engines in equipment for some Middle East countries, as they will not accept them. The first rough terrain telescopic handler was designed to utilize a range of Ford engines. At that point in time, and for the foreseeable future, Ford products were unacceptable in the Middle East. Therefore, the design was changed to accommodate	**Market Constraints** Preference for Commercial Off-The-Shelf & Flight-qualified parts/systems

Perkins engines, as well as Ford engines. Knowledge of local conditions, particularly overseas, combined with a full knowledge of the market must be incorporated in the PDS at the beginning of the project and as the design evolves. Otherwise, if during the course of the project the market disappears, the whole activity may have proved to be a waste of time.	
The likely effect of the product on the political and social structure of the market or country for which it is to be designed and manufactured should be considered. Typical factors include the effect of consumer movements, the stability of the market, and the avoidance of product features that can create social unrest and upset.	**Political and social implications** Substantial: inspire youth, beat China/India/Russia/Japan/Brazil/Malaysia/ EU
Many products must interface with other products or be assembled into larger products (or buildings). Installation therefore must be considered in the PDS. This will include fixing holes and lugs, access, the volume available for the product, system compatibility, power compatibility and the like.	**Installation** Should integrate with larger lunar architecture
Product documentation is always important in terms of instructions to the user, the maintainer or others. Even with consumer products, it is an important and vital task that must not be shirked (see ‘Safety’ and ‘Legal’. With large turnkey projects, the associated documentation can become a substantial part of the overall design task, say for a power station. In the light of previous comments re legal requirements, it is imperative that full documentation is prepared for all projects — this should be done formally, not informally. It is not unusual to refer to detailed documentation many years after a product is in service.	**Documentation** Significant, should be readable on-site
Disposal has been included as a primary element as the effects of products and product design impinge more and more on our environment. With many products, it is not possible to ‘forget’ about the item after ownership has passed to the customer. If the product contains hazardous or toxic parts, or indeed parts worth reclaiming, these should be considered at the PDS stage. Should we, for instance, design for disassembly? This is becoming an increasing problem with many products, and is not necessarily confined to time-expired nuclear reactors, chemical process plants and the like. Non-biodegradable plastic packaging and items made from plastic present a problem of increasing magnitude — in fact the whole problem of waste disposal and recycling looms large indeed. While the preceding points discussed represent the primary elements or ‘triggers’, thus enabling the preparation of a PDS, never forget that a specification will be, and should be, subject to amendment and alteration with the passage of time, it is *evolutionary.* When a design has been completed, the evolved specification may be suitably embellished with detail. Almost by definition, it provides the basic material for handbooks, sales and technical literature. The PDS becomes the specification of the product itself, rather than the specification for its design. Therefore, it provides the basis for the user or producer to make his decisions in a comprehensive manner. There are no alternatives to a meticulous and thorough approach o PDS preparation in a competitive world. It is perhaps worthwhile reiterating that the PDS is defined as that which sets. out in detail the requirements to be met to achieve a successful product or process. When the product has been designed, it is itself specified by the drawings, documentation, etc., which go to describe the product in great depth. This is known as the specification of the product — the product specification. Try to avoid the use of loose semantics where the one may be confused with the other. There is a great deal of evidence to the effect that a poor PDS is a very common cause of unsuccessful designs.	**Disposal** Historical Monument

Appendix K – Quality Function Deployment (QFD)



● Strong Positive
○ Positive
× Negative
✖ Strongly Negative

Customer Requirements \ Design Requirements (HOWs)	Importance (1-5)	Mass	Fuel Capacity	Size	Standards	Existing Technology	Fuel Composition	Redundant Systems	Power System	Structural Integrity	Life Support
Improvement Direction		↓	↑	↓	↑	↑	↑	↑	↑	↑	↑
Duration	2	3	9	1					7		7
Range	4	9	9	1					3		
Safety	5				9	7		9		9	9
Turn Around Time	1		1			1	7				1
Capital Cost	2	9		3	5	7		3	3		
Maintenance Cost	3				5	7	9			7	9
Payload	3	9	9	5						5	
Sustainable	5				5	5	9		9	7	
Landing Accuracy	3		5	5						1	
Operability	2			7	5	5					
Lifetime	2				5	7	1		3	9	7
Communications	5				5	7		9	9	7	
HOW Importance		87	97	56	140	155	81	96	128	172	101
Rank		8	6	10	3	2	9	7	4	1	5
Difficulty (1=Easy 5=Hard)		5	3	2	1	1	1	4	2	4	4
Customer Satisfaction Targets	Quantified in PDS										

1 - Weak
9 - Strong