SYSTEM STUDY OF A SURFACE HABITAT AND A TRANSIT VEHICLE FOR A MANNED MISSION TO AND FROM MARS

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Executive Summary: The continued technology advancement over the last several decades has provided the impetus for ambitious individuals to look towards exploration and possible settlement of the frontiers that exist beyond the boundaries of Earth.

NASA has expressed a need for the development of a system to provide life sustaining functions for the duration of a three phase mission to and from Mars, including a 500 day expedition on the surface. A preliminary design for a Mars habitation and transportation system was developed to fulfill the need expressed by NASA after down-selecting from several conceptual designs. The design team assigned to this task was divided into subteams responsible for key function groups. These function groups are avionics, power and mobility, environmental controls and life support (ECLSS), and structures. This systems report gives an overview of the total system with attention given to each of these key functional groups. For further information and detail on a specific functional group, refer to the individual reports for that function group.

The problem definition section of the report includes the need statement and need analysis, from which the specific need is expressed and the key system constraints imposed. The major functions resulting from the need analysis were that the habitation and transportation system must provide transportation, meet the constraints imposed by the shuttle, provide habitation needs, and allow for a Martian surface expedition. Following the function structure are the functional and performance requirements, which allocate specific numbers and constraints to particular concepts of the need. Calculations as well as assumptions are involved in the process of determining system performance requirements.

The system description contains basic drawings of the system and a description of major interfaces. A failure modes and effects analysis and a summary of component costs of the system are also included.

Note from the editor: This report is an excerpt of a Systems Integration Report submitted by the authors for their senior Mechanical Engineering design course at Texas A&M University. This report was the result of the first semester of study in a two semester design series. Contributing to this report were 12 students broken into four areas of study; systems integration/avionics, structures, power/mobility and life support/thermal systems. A complete copy of each of these four reports can be obtained by contacting Aaron Cohen in the Mechanical Engineering Department at Texas A&M University.

Need Statement: Provide accommodations for a six person crew research mission to Mars. Sustain the crew for a 500 day surface stay and return them to Earth safely.

Need Analysis: The transportation and habitation system design will be launched in currently available launch facilities to low earth orbit (LEO) fully outfitted. The three-stage mission includes a 200 day journey to Mars, a 500 day expedition on Mars, and a 200 day return trip. The system will be implemented in multiple launches with each launch configuration designed to fit within the payload bay of the Space Shuttle. Its payload capacity implies volume and weight constraints. This includes an available volume of 4.7 m diameter by 15.7 m usable. In addition, the weight of the module cannot exceed 24,400 kg. The system must be lightweight and strong enough to carry itself and all required outfitting to orbit. The module must maintain functional and structural integrity during launch, The living space should be maximized to provide a healthy atmosphere for six occupants. Basic human needs should be provided for including exercise, nutrition, hygiene, medical treatment, entertainment, and sleep. This includes a climate control system and an advanced regenerative life support system (ECLSS) that provides 100% self-sufficient air/water without re-supply. Life sustaining requirements of air and water include circulation, thermal control, sanitation, and pressurization. Liquid and solid wastes must be recycled or disposed of. Food must be supplied to meet the nutritional requirements of six crew members for the duration of the mission. Power requirements for all internal components are considered in the design. For the flight to and from Mars, power must also be provided for the module. Since the module is required to be self sufficient, methods and tools for needed repairs are to be readily available.

Transportation needs include communications, controls, shielding, and effectively meeting time constraints imposed by the mission profile. Communication systems must be available for both long range and short range communications between the crew and communication between the module and Earth. Guidance navigation control and instrumentation systems for avionics must be imposed. The module must include a meteoroid and orbital debris (M/OD), thermal, and radiation protection system. The module must interface to a hard structure for boost from LEO to high earth orbit (HEO), trans Mars injection, and Mars deceleration.

The module must also be able to adapt to the Martian surface and provide safe habitation for the crew during the 500 day surface expedition. This involves accounting for the change in gravity, pressure, and atmosphere. A power system for use on the Martian surface must be supplied. In addition, all previously discussed life sustaining requirements must be met.

FUNCTIONAL REQUIREMENTS / PERFORMANCE REQUIREMENTS

Functional Requirements	Performance Requirements	Source
TIME RESTRICTIONS		
Travel Time to Mars	200 Days	Mars Ref. Mission Webpage, 1-8
Travel Time from Mars	200 Days	Mars Ref. Mission Webpage, 1-8
Time on Mars	500+ Days	Mars Ref. Mission Webpage, 1-7
COMMUNICATION		
Equipment	Mass = 1361 kg	Mars Ref. Mission Webpage, 3-82
Downlink	Ka-band (33.60 to 33.80 GHz)	Mars Global Surveyor Project Plan
Communication time window	4.5 hour DSN Window	Mars Global Surveyor Project Plan
CONTROL		
Avionics	Power 5 kWe (including communications and propulsion system)	Mars Ref. Mission Webpage, 3-93
Guidance	Must determine corrective state vector and attitude	Assumption from Dr. Cohen
Navigation	Must measure attitude and state vector	Assumption from Dr. Cohen
Control	Must control attitude and system interfaces	Assumption from Dr. Cohen
Airlock Interface	Must have a complete seal, pressurize from 0-103.421 kPa	Assumption/Shuttle Ref. Manual - Airlock Support
Power Supply Interface	Must be rated for similar voltage, power, and current	Assumption
Propulsion Interface	Must have thermal protection	Assumption
Braking System Interface	Must reduce momentum to avoid critical impact	Assumption
AIRLOCK		
People Capacity	Must hold 2 astronauts simultaneously	Shuttle Ref. Manual - Airlock Support
SHIELDING		
M/OD Protection Requirements	Stop average 1 cm diameter meteorite travelling 7 km/s	JSC Speaker
Radiation Shielding Requirements	No more than 3% increase risk to cancer due to cosmic radiation	Mars Ref. Mission Webpage, 3-13
Thermal Shielding Requirements	Maximum Temperature on entry must be less than 32.2 deg C	Shuttle Ref. Manual
SHUTTLE CONSTRAINTS		
Structural Integrity of Module Interface to Shuttle	Must withstand vibration and gravitational forces	Calculation
Release Mechanism of Module Interface	Must release avoiding damage	Design Assumption
Attachment Method	Must attach and maintain integrity	Design Assumption
Payload Weight Capacity	24,400 kg	Space Shuttle General Description, pg. 278
Payload Diameter (usable)	4.7 m	Space Shuttle General Description, pg. 278
Payload Length (usable)	15.7 m	Space Shuttle General Description, pg. 278
Payload Weight Distribution	Must balance around the center of gravity	Calculation
ECLSS - Environmental Control and Life Support System		
Air Quantity	0.80 kg O2 per person per day / 3.49 kg N2 and 4.08 kg O2 lost per day	Shuttle Ref. Manual Webpage (Cabin Pressurization)
Air Distribution	80% Nitrogen, 20% Oxygen	Shuttle Ref. Manual Webpage (Cabin Pressurization)
Tank Capacity	0.42 m^3	Calculation (ECLSS System)
Air Pressure	O2 at 19512.2-23097.4 Pa	JSC 38571
Air Volume	4.48 m^3	Mars Transhab
Air Weight	800kg	Mars Transhab
Air Contaminant Tolerance	Max CO2 levels at 1.8 kg/m^3 and particles filtered at 50 kg/m^3	A Case for Mars, Zubrin
Air Circulation	3 air changes per hour, 15-40 feet per minute	JSC 38571
Water Quantity	159.6 kg H2O/day recycled potable and wash water	A Case for Mars, Zubrin
Water Volume	1.61 m^3	A Case for Mars, Zubrin

FUNCTIONAL REQUIREMENTS / PERFORMANCE REQUIREMENTS

Functional Requirements	Performance Requirements	Source
Water Weight	962kg	Mars Transhab
Water Circulation	Prevent bacteria growth, circulate 5-20% of volume/hour	Assumption
Water Temperature	Chilled 7 - 13 deg C, Ambient 18 - 24 deg C, Hot 38 - 104 deg C.	Shuttle Ref. Manual Webpage (Crew Equipment)
Waste Water Quantity	29.08 kg/person-day	JSC 38571
Waste Water Volume	1 tank - 74.8 kg, 90.2 cm length, 39.4 cm dia., 17.9 kg dry	Shuttle Ref. Manual Webpage (Supply and Waste Water)
Potable Water Volume	1 tank - 74.8 kg, 90.2 cm length, 39.4 cm dia., 17.9 kg dry	Shuttle Ref. Manual Webpage (Supply and Waste Water)
Potable Water Regeneration	3 fuel cell power plants equals 11.4 kg max per hour	Shuttle Ref. Manual Webpage (Supply and Waste Water)
Solid Waste Quantity	3.08 kg/person-day	JSC 38571
Solid Waste Volume	2.38 m^3	Mars Transhab
Habitation Humidity	25-75%	JSC 38571
Habitation Thermal Power	2.2 kWe	Mars Ref. Mission Webpage 3-93
Habitation Temperature	Air Temp. 18.3 - 26.7 deg C	Shuttle Ref. Manual (Cabin Air Revitalization)
Module Pressurization for Cabin	68.9 kPa - 103.4 kPa	Shuttle Ref. Manual Webpage (ECLSS 1 of 5)
Module Pressurization for Airlock	0 to 101.4 kPa Variable Pressure Capacity	Shuttle Ref. Manual Webpage (Airlock Support)
INTERNAL POWER		
Lab Equipment	0.7 kWe	Mars Ref. Mission Webpage, 3-93
Health Maintenance Equipment	1.7 kWe	Mars Ref. Mission Webpage, 3-93
ECLSS Power	14.2 kWe	Mars Ref. Mission Webpage, 3-93
Attitude, Avionics, Propulsion, Braking Control	5.0 kWe	Mars Ref. Mission Webpage, 3-93
Airlock Control	0.6 kWe	Mars Ref. Mission Webpage, 3-93
Communications Power	0.5 kWe	Mars Ref. Mission Webpage, 3-93
Personal Quarters	0.4 kWe	Mars Ref. Mission Webpage, 3-93
Audio/Video	0.4 kWe	Mars Ref. Mission Webpage, 3-93
Hygiene	0.7 kWe	Mars Ref. Mission Webpage, 3-93
Galley	1.0 kWe	Mars Ref. Mission Webpage, 3-93
Logistic Module	1.8 kWe	Mars Ref. Mission Webpage, 3-93
Command Center	0.5 kWe	Mars Ref. Mission Webpage, 3-93
Data Management System	1.9 kWe	Mars Ref. Mission Webpage, 3-93
HEALTH		
Laundry Generated	27.7 kg laundry/day	Calculation
Personal Items	cleanliness, health, and emotional needs (0.3 m^3/man allocated)	Assumption
Food Volume	1200 kg food/man/200 days	A Case for Mars, Zubrin
Food Quantity	Supply 11.3 kJ per crew member per day	Shuttle Ref. Manual Webpage
Kind of Exercise Equipment	Must provide complete body workout (ex.Treadmill and/or "flexrod")	Shuttle Ref. Manual Webpage/Infomercial
Pharmaceuticals	General and emergency care	Assumption
Medical Equipment	General and emergency care	Assumption
Sleeping Space	1 m^3	Calculation
COMMUNITY SPACE		
Entertainment Area	10% of total volume	Assumption
Cockpit Work Area	20-40% of total volume	Assumption
Lab Work Area	20-40% of total volume	Assumption
REPAIR NEEDS		
Spare Parts	Mass = 3000 kg	Mars Ref. Mission Webpage, 3-82
Geological and Lab Tools	Mass = 2370 kg	Mars Ref. Mission Webpage, 3-52
Internal Tools	Mass = 500 kg	Assumption based on mass of other repair needs

FUNCTIONAL REQUIREMENTS / PERFORMANCE REQUIREMENTS

Functional Requirements	Performance Requirements	Source
SURFACE EXPEDITION		
Mobile Rover Exploration Range	500km radius of exploration, 10 day trip	Mars Ref. Mission Webpage, 1-23
Mobile Rover Mass	3992 kg	Mars Ref. Mission Webpage, 1-23
Mobile Rover Capacity	2-4 people	Mars Ref. Mission Webpage, 1-23
Space Suit	Air tight thermal shield / radiation shield	Assumption
Transportable Power Supply	6+ year lifetime (Nuclear Power Generation 10 kWe)	Mars Ref. Mission Webpage, 1-22
Surface Power Supply	15+ year lifetime (Nuclear Power Generation 160 kWe)	Mars Ref. Mission Webpage, 1-13, 1-22
Mars Gravity	3/8 gravity	Mars Ref. Mission Webpage, 1-22
Mars Atmosphere	gases, dust storms	Mars Ref. Mission Webpage, 1-22
Mars Temperature	Max. 25 deg C. but much colder usually	Mars Ref. Mission Webpage, 2-10
Mars Radiation	No more than 3% increase risk to cancer due to cosmic radiation	Mars Ref. Mission Webpage, 3-13
Descent Vehicle Constraints	59000 kg of Cargo (for current vehicle)	Mars Ref. Mission Webpage, 1-21
Mars Surface Pressure	Approximately 1.013 kPa	Mars Ref. Mission Webpage, 2-10
Mass of Surface Habitat	15694 kg (Must be landable)	Mars Ref. Mission Webpage, 3-77
Volume of Surface Habitat	Comparable to transportation habitat volume	Design Calculation

System Description: *Mission Profile.* The Mars habitation and transportation system is designed to be implemented using four space shuttle launches. Figure 1 illustrates the mission profile. The systems contained in the first three launches will be pre-deployed to the Martian surface and their systems will be verified prior to launching the crew in the fourth launch. The first launch will contain the nuclear power system, rover, water, and the plant growth system. All of these systems are for use on the Martian surface during the 500 day research mission. The second launch will contain a near duplicate of the habitation module to be used in transit from Earth to Mars. This module will also be utilized during the surface stay.

The third launch will place the unmanned transportation and habitation module in Low Earth Orbit (LEO). The structure will pressurize and expand in LEO. While in LEO, the power, avionics, and life support systems will be activated and a diagnostic check will be performed on all systems. Solar panels will be expanded and engaged to replace auxiliary battery power. Power must be supplied to communications, guidance navigation control (GNC), and instrumentation in order to guide the module to High Earth Orbit (HEO). The air and water supply system will be activated and tested to insure an acceptable living environment prior to the crew rendezvous in HEO.

After the crew rendezvous in HEO, the module will begin transit to Mars. During transit, the structure will provide a safe habitable environment for the crew. The module is designed to be entirely self sufficient and functional without re-supply or external intervention. The external structure will provide protection against meteorite and orbital debris (M/OD) and will provide hard points for attachment of solar panels and interface with the crew capsule. The internal structure will provide volume for habitation with space allocation taking into account physical and psychological well being of the crew as well as efficient placement of functional components for optimal system operations. The solar power system will maintain power supply at 30 kW for the duration of transit to and from Mars. The environmental control and life support system (ECLSS) will maintain pressurization of the module and supply daily air, water, food, and waste disposal for the crew. The avionics system will provide GNC and communication with Earth throughout transit.

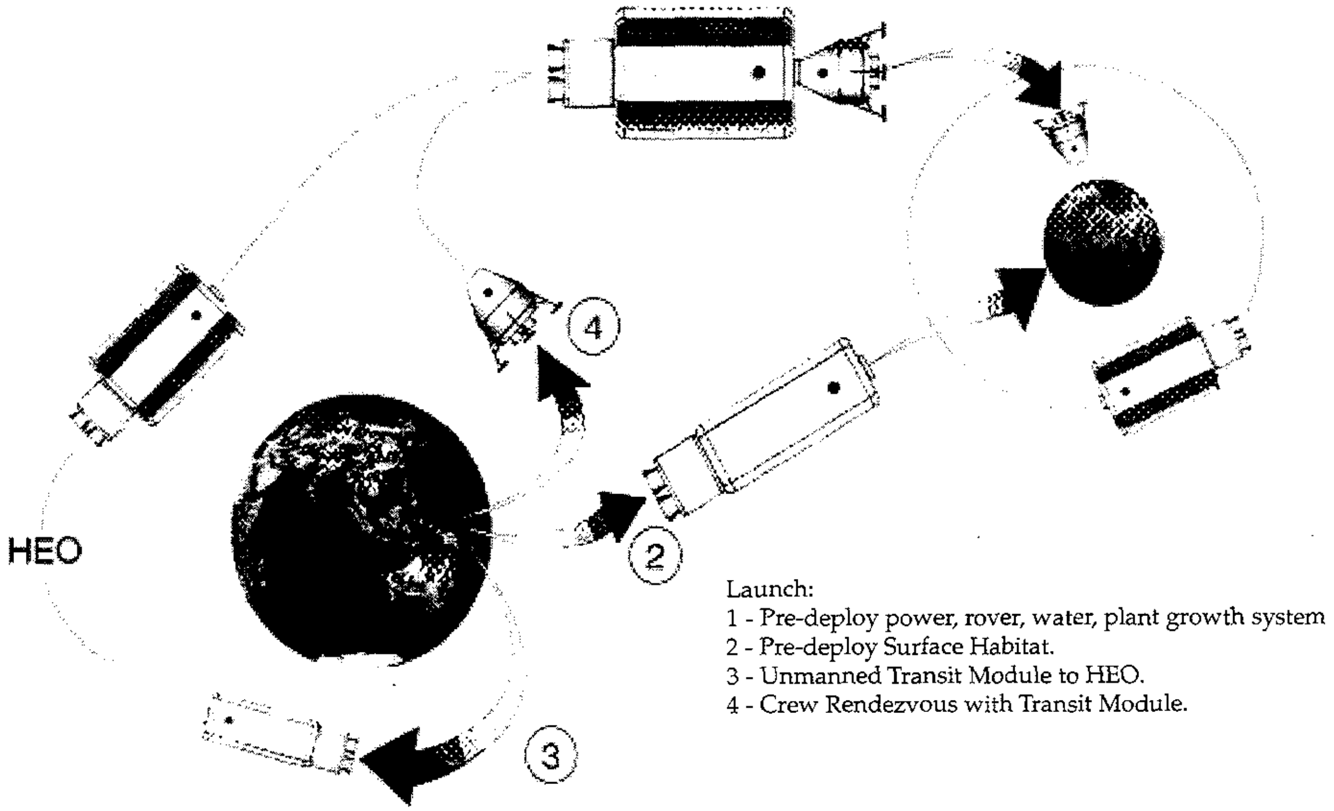

Fig. 1. Sequence of Events.

After Mars orbit capture, a landing capsule will be used to transport the crew from the Mars orbit to the Martian surface. This capsule will enable the crew to rendezvous with the pre-deployed expanded surface habitation module. The transport module will remain in Mars orbit in order to be utilized for the return trip. The surface module will provide a secure living environment for the crew while on the Martian surface. Power on the Martian surface will be supplied by a pre-deployed nuclear power system. This system is designed to provide a minimum of 125 kW to support all systems used for this phase of the mission. The avionics system will provide control and functionality checks of all systems. Communications will be available between all Mars based systems and with Earth. The life support system will be used to pressurize and maintain a livable environment in the surface module and to provide daily food, air, and water for the crew.

At the conclusion of the 500 day research mission, the crew lander will be utilized to return the crew to the orbiting transportation and habitation module. The systems used in the module for the return trip will be identical to those used in transit from Earth to Mars. The return trip will take approximately 200 days.

Structure: Figure 2 shows how the unexpanded transportation and habitation will be packaged within the shuttle payload bay. The unexpanded module is approximately 4.6 m (15 ft) in diameter and approximately 11.3 m (37 ft) in length. Once the propulsion system is attached to the module the total length is 15 m (50 ft). Note that this is well within the limits of the size constraints of the shuttle payload bay. Also, it is important to note that the propulsion system was not within the class scope of the design. Figure 2 also shows the packaging of the secondary solar panels at the front of the module. The secondary solar panels are necessary for supplying the necessary 6 kW from LEO to HEO in order to power up the avionics systems within the module. The thrusters that are located at the bottom of the module demonstrate two of the eight sets of four that are located 90° from each other on the top and the bottom of the module. The windows located at the top of the module are for the astronauts' convenience. Windows tend to be an important issue with the astronauts, especially for such a long duration of time as the Mars mission will require.

Once the module is jettisoned from the shuttle into LEO, it expands to a diameter of 7.9 m (26 ft). The expanded module is depicted in Figure 3. Its expansion is guided along expansion rails located at the top and bottom of the module. The expansion mechanism is constructed of rack and pinion gears with guide rails. The expansion is caused by the pressure differential from the inside of the module and the vacuum of space. The pressure inside the module is kept at a minimum 68.9kPa (10 psi). This is an optimal pressure considering the number of EVAs that are required by the astronauts once on the Martian surface. This pressure minimizes the time required to debreathe the astronauts from 68.9kPa (10 psi) to the space suit's pressure of 34.45kPa (5 psi). The module expands due to the pressurization of the soft shell.

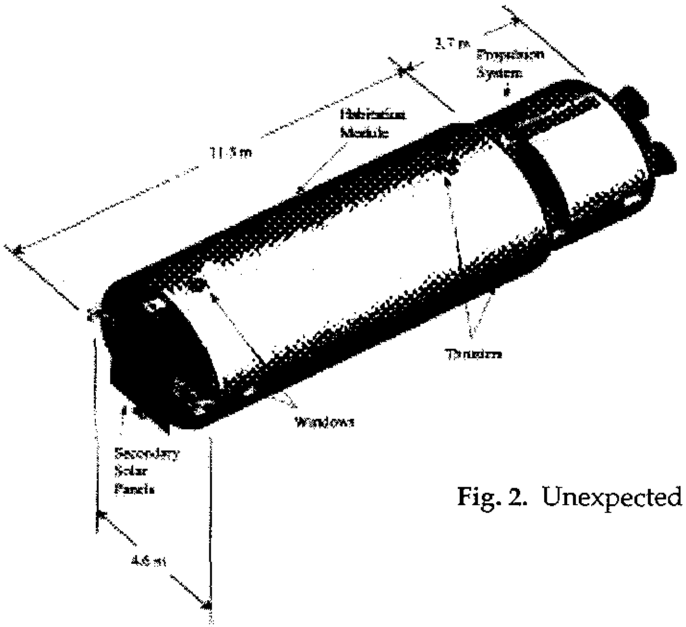

Fig. 2. Unexpected Habitation Module.

The soft shell is made up of a flexible Kevlar and Mylar material. Redundancy is built into the soft shell by multiple bladders layers providing M/OD protection. The hard shell is composed of a Carbon-Carbon matrix with Kevlar and Aluminum layers. There will also be four vertically fastened Aluminum I-beams providing for the necessary structural support on the Martian surface. Figure 3 also shows the airlock positioned at the top of the module. The airlock is made up of a Carbon-Carbon composite attached to an Aluminum layer. This material selection provides for an excellent resistance to the stresses that will be caused by the constant pressurization and depressurization that will occur within the airlock. The airlock serves the purpose of docking and separating of the crew lander with the module, as well as the entry and exit into the module by the astronauts. The basic dimensions of the airlock are 2.1 m (7 ft) in diameter and 2.4 m (8 ft) in length. This the necessary size in order to fit two fully equipped astronauts that fully outfitted in space suits. Figure 5 simply shows the expansion of the secondary solar panels on the expanded transportation and habitation module.

Figure 3 shows the interface of the crew lander with the module in HEO. The lander has the primary solar panels attached on the front such that they will interface with module, providing the necessary 30 kW required for the transit to and from Mars. Note that the lander was not within the scope of the design project; however, the present X-38 crew lander was used for the design. Once the lander has docked with the module, the crew will be able to transfer into the module through the airlock as mentioned previously. Figure 3 simply shows the module's configuration with the attached lander as it will appear in transit to Mars. It is also important to note that the module boosters, provided by the propulsion system, will be used for forward propulsion, while the lander boosters will be used for retro.

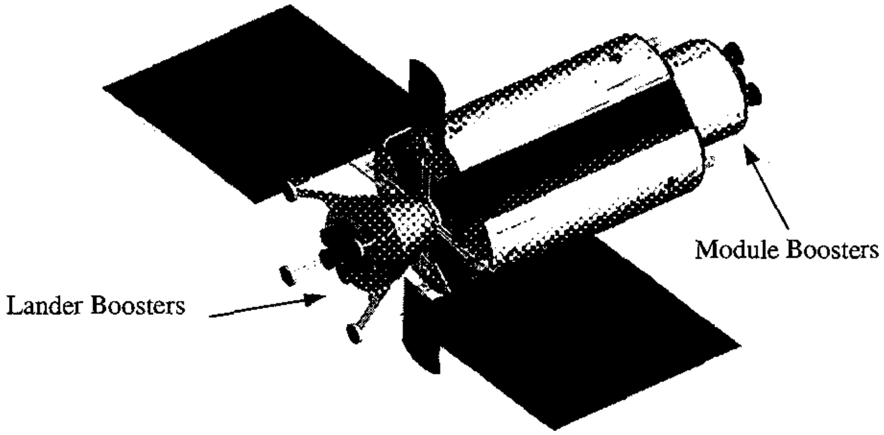

Fig. 3. Expanded Habitation Module Interfaced with Propulsion and Lander Systems.

Once the lander has jettisoned from the transportation and habitation module, which stays in HMO, the lander aerobrakes into the Martian atmosphere. Using parachutes and retro boosters, it will interface with the pre-deployed habitation module that is already operational on the Martian surface. Figure 4 shows the configuration of the habitation module and the lander that will be used for the 500 day stay on the Martian surface. Note that the landing mechanism will be further researched in the fall semester in order to provide the necessary support for the module on the Martian surface.

The basic dimensions for the structure of the internal core are depicted in Figure 5. Each floor is approximately 2.5 m (8 ft) high. The internal core provides for the main structural support on the Martian surface. It is composed of a graphite epoxy attached to an Aluminum matrix. The floors are the same diameter of the unexpanded module while packaged within the shuttle. The floors are constructed of the graphite epoxy material. An integrated fiber cloth will expand outward with the outer shell providing for the added floor space of the expanded module. Note the access pathways located on the different floors such that the astronauts can move from floor to floor.

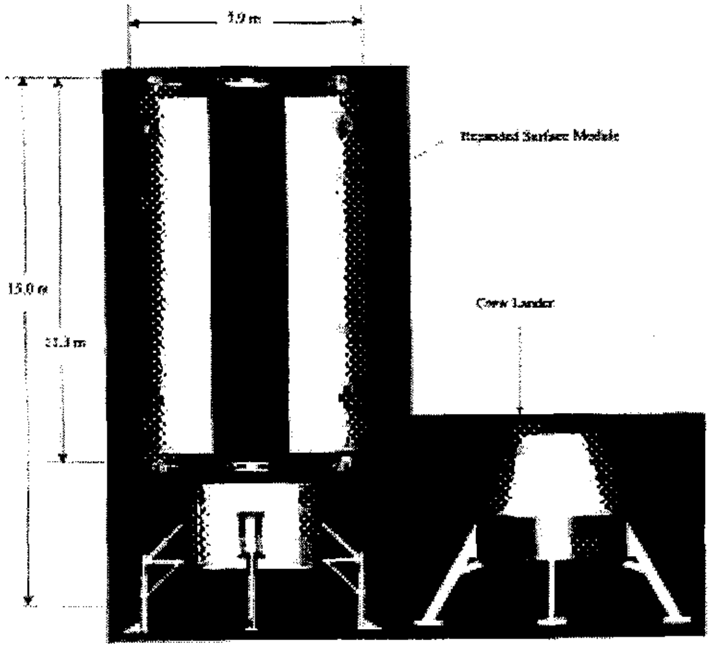

Fig. 4. Crew Interface at Martian Surface.

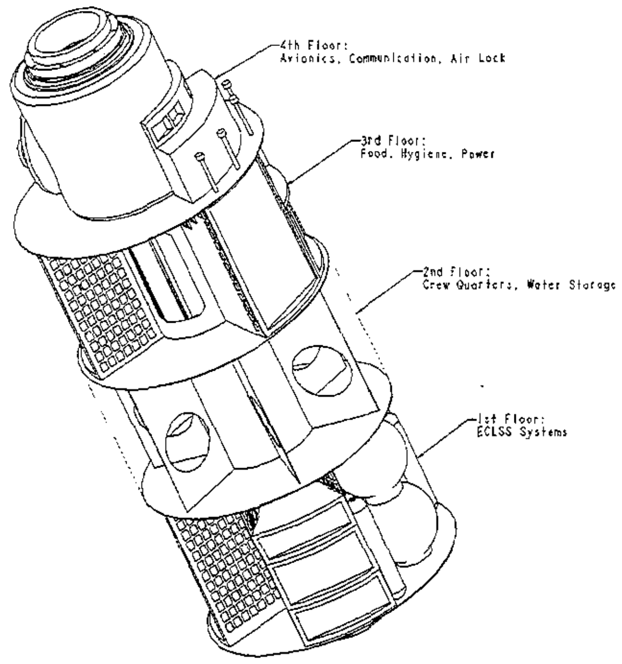

Fig. 5. Location of Systems with Respect to Floors.

Figure 5 shows the internal core and the interfaces between all of the subsystems with respect to the separate floors. The 1st floor provides for the interfaces of the life support systems. This includes the O_2 and N_2 storage tanks, water, O_2 and CO_2 processing units, and atmospheric control systems. The 2nd floor is partitioned into six compartments consisting of the crew quarters surrounded by the water storage system. The crew quarters include such components as beds and showers for the astronauts. The 3rd floor interfaces the food storage and preparation, hygiene facilities, and the power systems. Note that the mass of dry food is approximately 1850 kg (4070 lbs). This is the amount of food for 500 days. The astronauts will consume approximately half of this supply on the trip to Mars. This is noted due to the fact that space that is opened due to food consumption will be used for the 2000 Martian samples that will be returned to Earth. This is assuming a 1g to 500 g (.0022 – 1.1 lb) sample size; thus, filling the weight that was lost due to food consumption for the return trip to Earth. The power system includes storage, converters for AC and DC power, and the distribution into the other subsystems. The 4th floor consists of the avionics systems and the airlock. The avionics systems includes the instrumentation for the module as well as the control systems for the subsystems located throughout the module.

Figure 5 shows an assembly drawing of the integration of the internal core with all of the subsystems – structures, power, avionics, and ECLSS. The purpose of this drawing is to help explain the location of the water storage and life support systems on the first and second floors of the module; thus, creating a lower center of gravity which aides in the stability of the module.

Power: The power that is required for the Mars mission was determined to be 124.9 kW on the surface and 30 kW in transit to and from Mars. Due to the length of the Mars mission and power required, it is necessary to generate power, since it would not be possible to use batteries for the duration of the mission. Solar panels could be used on Mars' surface, but the large distance from Mars to the Sun and the length of the Martian day would require very large solar panels. This is not realistic, because of the large volume and weight this would require. A nuclear power system on the Martian surface is the only practicable solution to the problem, however solar panels can be used in transit.

The surface power system utilizes a SP-100 thermonuclear reactor as the primary source of power and solar panels for backup. For safety purposes, the habitation module must be kept 1 kilometer from the reactor. The nuclear reactor has a seven-year lifetime; hence, subsequent missions to Mars would be able to use the same power system. This would drastically lower the costs of future missions. The SP-100 generates thermal energy, which in turn drives a Stirling engine. The Stirling engine can provide 150 kW per engine. For this mission, two engines would be used. This is done to provide redundancy in the system and allow for future growth. The energy is stored in batteries and sent to a DC power supply. The DC energy is run by a controller, which allocates the energy to the different areas in need of power. These include the module, rover, lander, food production system, and fuel production system. During non-peak operating times, excess energy is sent to batteries and/or dissipated to the atmosphere as thermal energy. The solar panels collect solar energy and send it through a working medium, which generates the DC electrical energy. This energy is then sent through the same system as that generated by the SP-100.

The transit system is based solely on solar power. This is possible, because the transit power requirement is much lower than the surface power requirement, 30 kW as opposed to 124.9 kW. The solar panels are assumed to have 30% efficiency. The size of the panels was calculated based on the surface area required at Mars. Also, the area was increased to provide redundancy in the system. The panels, which consist of Aluminum Gallium Arsenide/Gallium Arsenide solar cells, harness solar energy. This is sent through a working medium and converted to DC electrical energy. The energy is sent to a controller, which distributes it accordingly. For the module, the DC is sent to a converter and transformer before being distributed throughout the module. The DC is also sent to batteries for storage, and excess is dissipated into space as thermal energy.

Avionics: Critical to the operation of the transportation and habitation module is the processing of information related to the performance of all subsystems. This task is handled by the avionics system. The avionics system includes all instrumentation, guidance navigation control, and communication systems. This system composes the main information handling and processing unit of the transportation and habitation module.

The avionics system is decomposed into three subsystems, the instrumentation, guidance navigation control, and communication systems. These three systems are integrated to facilitate manipulation and transferring of data. The integration of these systems allows the main processors to communicate and transfer data as needed. The instrumentation system main processor oversees all other subsystems, including the guidance navigation control and communications systems.

The instrumentation system is built around three main processors working in parallel, one main and two backup processors. These processors operate at 800 to 1000 MHz. These processors coordinate all other activities within the avionics system. These processors monitor the guidance navigation control and communication processors, the ECLSS sensors, crew sensors, structure sensors, power sensors, data manipulation, data storage, and data backup systems. The main processors also send outputs to the ECLSS sensors, generate reports on crew health, and determine power distribution.

The ECLSS, power, crew, and structure sensors read inputs from the various systems and transmit data to the main processor. This data is analyzed by the main processor, which then determines the appropriate response. Data manipulation, data storage, and data backup are also controlled by the main processor. Data manipulation occurs through a human to computer interface. Data storage and data backup utilize a 8868 gigabyte CD ROM tower to store data.

The Guidance Navigation Control (GNC) system is built around two processors, one main and one backup, that operate at 800 to 1000 MHz. This processor receives data from sensors, analyzes these inputs, and transmits data to the actuators. It also transmits data to and receives data from the main processor.

Guidance navigation control sensors include feedback from earth, rendezvous and docking sensors, sun sensors, star sensors, gyroscopic inertial reference units, and feedback from boosters and thrusters. The GNC processor uses the data from these sensors to determine a velocity and position vector, which can then be compared to a predetermined course. Corrections to the course can be made using the thrusters or boosters. Aerobraking equipment is provided for Mars orbit capture.

Cockpit controls are provided in case human inputs into the GNC system are required. All information related to actual and desired position and velocity will be made available to the crew through monitors in the instrumentation system.

The communications system is built around two processors, one main and one backup, that operate at 800 to 1000 MHz. The communications processor receives communication data from video recorders, cameras, microphones, and audio recorders. It may then transmit this data to audio speakers or video screens. This processor may also transmit data to and receive data from the main processor.

Information from outside the transportation and habitation module can be received via either a high gain or low gain antenna. This data is then transmitted by a receiver to the communications processor for routing. Data may also be sent from the module through these same antennas operating through a transmitter.

The entire avionics system uses approximately 7.8 kWe. The entire system will use digital technology to minimize losses due to analog to digital and digital to analog conversion.

Environmental Control and Life Support System: Any manned spacecraft must meet the many needs of the human occupants. This is a difficult task given the inhospitable conditions that lie outside the atmosphere of Earth. The Environmental Control and Life Support System (ECLSS) provides all requirements necessary to maintain crew life and health.

The ECLSS is decomposed by the various tasks it must perform. The Thermal Control System (TCS) controls the heat transfer into and out of the module to maintain a comfortable living environment. The Water Supply and Water Recovery System (WRS) provide clean water for use by the crew. The Atmospheric Revitalization System (ARS) provides the crew with breathable air. A Solid Waste Management System disposes all solid wastes from the module. Food, medical support, and sleep provisions are also provided by the ECLSS.

Thermal Control System: The thermal control system (TCS) consists of a water coolant loop system and an active thermal control system. These systems interact to provide a habitable environment for the crewmembers in the crew living space, laboratory, health maintenance facility and command center in addition to cooling or heating various systems or components.

Water Supply and Water Recovery System: The water supply and water recovery system (WRS) produces potable water for the crew of the habitation module. Water is stored in the storage tank that also serves as a radiation shield during solar activities. The water tank is pressurized to provide directional flow to the water pump that pumps the water to the various outlets in the habitation module. Wastewater that is produced is then treated by the water recovery system. This system utilizes both physical-chemical and biological subsystems to recycle and process wastewater generated by the crew and humidity condensate. The WRS is divided into six major subsystems.

The main water recovery system and the backup water recovery system are 100 percent efficient at recycling wastewater. Water is not lost outside of these systems during each cycle. This efficiency is necessary to reduce the water requirements for long duration missions where resupply is extremely difficult or impossible. For this system, 960 kg of potable water will be stored in the water storage tank initially and the total water amount in the system must be carefully monitored to ensure that there is no significant loss during the duration of the mission.

Air Revitalization System: The atmospheric revitalization system in the module must intake the air from the module and output clean, breathable air for the crewmembers. The atmospheric composition is also monitored to keep the ratio of nitrogen to oxygen at about 80/20. The ARS consists of four main subsystems. The Trace Contaminant Control Subsystem (TCCS) removes contaminants from the air. The Four Bed Molecular Sieve Subsystem (4BMS) concentrates the CO_2 for further processing downstream. The Carbon Dioxide Reduction Subsystem (CRS) uses the Sabatier reaction to convert Hydrogen and CO_2 to methane and water. The Oxygen Generation Subsystem (OGS) uses water to produce Hydrogen and Oxygen.

Solid Waste Management System: An incineration system is used to process solid wastes. The subsystem consists of three major components: a feed system, the fluidized combustion chamber, and the flue gas cleanup system. The feed system consists of a blender and a peristaltic pump. The blender breaks up the waste material. The peristaltic pump then injects the slurry into the combustion chamber. Once in the combustion chamber, the slurry is oxidized using air from the air life support system. A zirconia-based catalyst is used in the combustion system.

Food: In transit to Mars, all food will be supplied. The food will be ready to eat or require minimum preparation. On the surface of Mars, food will be grown. However, all the food requirements for surface will also be supplied to provide redundancy in the plant growth system. It is important to grow food on the surface for several reasons. Mars is being explored and examined to determine its potential for sustaining life. The production of food on the surface will go a long way to prove this objective. Secondly, the food production system is a vital link in the life support system. Not only does it provide nutrient-rich food for the astronauts, it also provides water and acts as a waste filter.

Medical: Even though the astronauts will be extensively screened and monitored for medical problems, the crewmembers will likely need medical care during the mission. The crew should be medically prepared to handle the many conditions.

The following will be provided: physician's instruments, surgery, medical monitoring and medical life support, pharmacy, central supply, medical laboratory, imaging and lighting devices, hyperbaric treatment facility, decontamination equipment, dental equipment, emergency transport equipment, safe haven (and Mars rover) supplies, waste management, and a medical information center (MIC).

The infirmary, including medical equipment, medications, and supplies, is estimated to be 6 m^3 in volume and 2500 kg. During routine operations, the infirmary is expected to draw 0.5 kilowatts of power. During critical care emergencies, the infirmary may require up to 2 kilowatts.

Sleep: Because of the long mission duration, it is important to make sure that the crewmembers are not stressed. Perhaps the best way to combat stress is to insure good sleeping habits. Sleep quality can be maintained by minimizing noise and light, providing a stable temperature and airflow, and allowing exercise during the day.

The habitation module should use lighting to simulate a 24 hour day/night cycle. As the crew gets closer to Mars, the day/night cycle should be slowly adjusted until it matches that of Mars. As the mission progresses, higher light intensities may be needed during the day. The higher intensities help to combat fatigue and increase alertness.

Failure Modes and Effects Analysis: A large system requires the proper function of many components to operate. The Failure Modes and Effects Analysis (FMEA) identifies possible modes of failure for each component and the effect that the failure will have on the operation of th entire system and the particular component. A criticality for each failure may be assigned by determining the effect that the failure will have on the complete system and on the individual component. This analysis helps to identify systems critical to the successful operation of the system. By determining the failure mode, effect, and criticality of a particular component, the proper preventative measure may be determined.

The criticality of each failure mode is defined as follows: (1) Single failure could result in the loss or damage of life. (2) Redundant hardware which, if all failed could result in the loss or damage of life. (3) Single failure which could result in the discontinuance of operation of the module. (4) Redundant hardware which, if all failed could result in the discontinuance of operation of the module. (5) Single failure which could result in the partial discontinuance of the operation of the particular system. (6) Redundant hardware which, if all failed could result in the partial discontinuance of the operation of the particular system. (7) Single or redundant failure which has no effect on the operation of the particular system.

Editor's Note: Only selected systems and components that possessed a criticality of level one were included in this report. See comment from editor after the Executive Summary for information on obtaining the complete FMEA performed.

FAILURE MODE	FAILURE EFFECT	CRITICALITY	PREVENTION
Avionics System			
Guidance Navigation Control			
Feedback From Boosters/Thrusters	Erroneous data	1	Calibration and systems check
Aerobraking	Fails to provide a safe entry	1	Training of correct aerobrake procedure
Instrumentation			
ECLSS Sensors	Fails to return accurate system data	1	Calibration and supply spares for repair
Power Sensors	Fails to return accurate system data	1	Calibration and supply spares for repair
ECLSS Actuators	Erratic operation	1	Periodic inspection
Power Distribution	Partial output	1	Periodic monitoring of system consumption
Power System			
Solar Power System - Solar Collector Unit			
Structural Detachment of Solar Array	Possible Air Leak in Habitation Module	1	Check assembly of solar array before launch
Energy Storage Unit			
Seal Failure	Possible Fire/Explosion	1	Periodically check seals
Tank Ruptures	Possible Fire/Explosion	1	Check tanks for fractures Check tank seals Monitor tank pressure
Overheating	Possible Fire/Explosion	1	Check wire connections
Nuclear Power System – Nuclear Reactor (SP-100)			
Nuclear Reactor Leak	Possible Radiation Exposure to Module	1	Check reactor before launch Diagnostics check before power up Periodic maintenance
Environmental Control and Life Support			
Solid Waste Management System			
Particulate filter fails	Life support systems receive contaminated products	1	Human checks of the filter, Place sensors after the filter to assess air quality
Condenser fails to process the water	Lose water	1	Use as little water as possible in system, Integrate system with other life support systems that use condensers
Carbon filter fails	Trace contaminants enter the air life support system, or the carbon dioxide is not converted to oxygen (lose oxygen)	1	Use two filters in series, clean the filters and check for leaks occasionally
Plant Growth System			
Plants do not grow	Reduction in food supply of astronauts	1	Pre-deploy redundant food supply
Structure			
Module			
Develops leak	Loss of Pressure	1	Provide backup air supply Repair kits
Thermal shields fail	Module burns up	1	Proper design of shields
Module lands too hard	Collapse of structure	1	Avionics problem, they solve
Hard Shell			
MO/D impact	Shell is punctured, Depressurization	1	Provide repair kits
Shell cracks	Loss of pressure and structural integrity	1	Make shell thick enough to withstand stresses
Shell buckles on Martian Surface	Structure collapses	1	Use aluminum supports along length of segments
Soft Shell			
MO/D impact	Shell is punctured, Depressurization	1	Use buffer zones
Hard Shell/ Soft Shell Interface			
Pressure seal fails	Loss of pressure	1	Use double seals
Airlock			
Airlock shell fails	Airlock open to space	1	Strengthen shell with Aluminum
Exterior Hatch fails	airlock open to space; crew cannot leave module	1	Maintain good seals
Interior hatch fails	airlock not usable; crew cannot leave module	1	Maintain good seals
Inner core			
Core collapses	Loss of structural support	1	Strengthen core
Hard Points			
Shuttle Bay points fail	Structure collapse in shuttle bay on surface, mission fails	1	Design hard points properly
Propulsion module attachments	Module does not operate properly	1	Design proper hard points
Solar Panel attachments	No power; Possible structural damage	1	Design proper hard points
Maneuvering thrusters	Aberrant flight	1	Design proper hard points
Docking port fails	Crew cannot dock	1	Design proper docking port

Cost Estimation Analysis: The cost estimation of the individual systems for the overall mission was performed to realize the high expenses of this long-term space mission. The program used to calculate the costs is PRICE (Parametric Review of Information for Costing and Evaluation). This model is a computer aided program for deriving cost estimates of electronic and mechanical hardware assemblies and systems and was developed in the early 1970's for use by the US Air Force, Navy, and for NASA. It was designed especially for estimating avionics and space system costs [7].

This program takes into account the many aspects of engineering and manufacturing in both development and production phases of a final product. PRICE H provides a probable cost estimation based on project scope, program composition, and demonstrated organizational performance while incorporating operational and testing requirements. It also attempts to predict technology costs and use escalation factors to accurately portray inflation [7].

The PRICE model uses a work breakdown structure derived from the system schematics and applies empirical formulas to inputted parameters for each component. The component parameters have input boxes which apply factors inputted by the user to estimate the cost of each component. These factors can be looked up in tables within the program and are based primarily on the complexity of the chosen platform. [7] The platform chosen for this cost estimation was the manned space mission profile.

Each system required a similar work breakdown structure to estimate the individual components of the mission. Detailed cost estimates were performed for the habitation power, instrumentation, rover, life support system, and structure. The work breakdown structure correlates directly to the schematics and can be compared for verification.

Major factors determining costs in the PRICE program include weight considerations and complexity factors for design. These factors were adjusted as best as possible and give a fairly accurate estimates of each system. It should be noted that these are best estimate costs and not concrete estimates.

The following estimates are a breakdown of the individual component costs of each subsystem for instrumentation, power, rover, ECLSS and structures. Figure 6 summarizes the total instrumentation system including component costs for GNC, communication, and integration. This is the individual component cost breakdown separated into development and production phase costs. It should be noted that all costs are in 1994 dollars.

The main processor is the main command and control center for all the instrumentation and processing of pertinent data and interfaces. The guidance navigation and control system (GNC) component has a main function to process the GNC equipment. The sensors assembly includes the redundant systems for the IMU, star tracker, sun sensors, and docking sensors. The effectors system component is a subassembly of the GNC system and includes the thrusters, boosters, and aerobraking. The communication system serves the communications equipment including transmission and data storage. The instrumentation I&T ties all the subassemblies of the instrumentation system together and includes the testing required for operation.

The power cost estimate was done the habitation module in transit, habitation module on the Mars surface, and transportable power on the Mars surface. In transit, the main source of power will be solar and on Mars, it will be nuclear. A purchased cost component of the SP-100 nuclear reactor was inputted for this cost.

The rover was estimated on the PRICE H program using the same manned space platform and assuming it will be open to the Mars environment. It will carry two astronauts in fully equipped space suits. It has an operating time of 78 hours with an approximate range of 1000 kilometers.

The ECLSS cost estimate takes into account the total life support of the crew including water and air regeneration as well as habitation atmospheric requirements. The system must dissipate excess heat, provide acceptable pressure, and clean and circulate the air and water. The food must be produced and stored as well.

The total ECLSS costs were broken down into separate systems for thermal control, water supply and recovery, air revitalization, solid waste management, and plant growth.

The structure of the habitation module is estimated assuming two identical habitation modules. The estimate is broken down by the outer shell, internal core, expansion rails, propulsion unit, and system integration. The outer shell has hard shell and expandable shell components for the overall makeup.

The overall cost estimate can be summarized in the following chart. This figure gives the relative system cost estimates compared to one another. Figure 6 shows relative amounts of each subsystem for the overall mission costs. This does not include the launch cost of each shuttle launch. However, it is estimated to cost $500MM for each shuttle launch. With four launches, an extra two billion dollars could be added to the mission expenses.

From these figures, it can be seen that the bulk of the costs are attributed to the power system. This is because of the cost of the SP-100 alone cost $118MM. The structures component seems to be a little low, but more detailed estimates will be done in the final design.

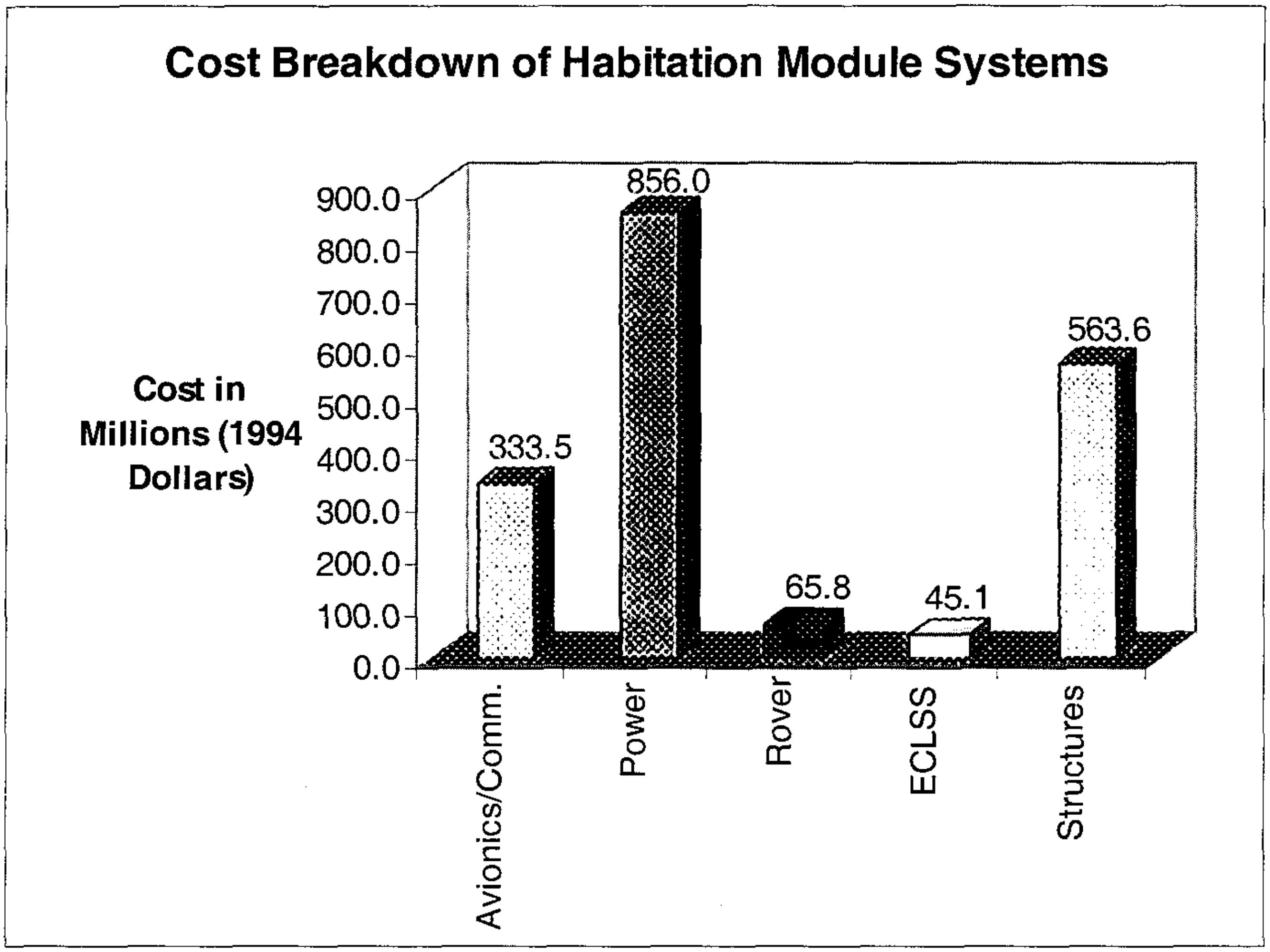

Fig. 6. Relative Cost Amount Comparison of Individual Systems

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