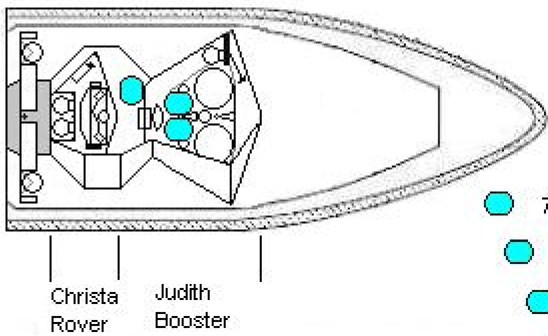
MARS CHALLENGER II

Analysis: Terry Wilson
Illustration: Jordan Pelovitz



- *Typical Launch Vehicle (Atlas V-541)*
- *Two Landers within existing capability*
- *Oxybenzene 97%+ ISRU*
- *Safe samples returned: ASQ for it*

marsdrive

aftercolumbia project

***Mars Challenger II* is a sample return mission concept using In-Situ Resource Utilization (ISRU); After Columbia Project's entry into the MarsDrive Contest. ISRU was originally conceived by Dr. Robert Zubrin in 1989 for a piloted mission plan entitled *Mars Direct* by putting together three industrial chemical reactions in a relationship capable of producing oxymethane propellants using seed hydrogen brought from Earth with locally acquired carbon dioxide. Zubrin went on to found Pioneer Astronautics, Inc. to further explore propellant ISRU chemistry. *Mars Challenger II* uses two elements, the *Judith Booster* and *Christa Rover*, which are launched together on a common launch vehicle and cruise stage, but are landed separately on Mars near each other in the Marte Vallis region, where there are recent Amazonian era water channels and the small possibility of discovering current life.**

The dominant element is the *Judith Booster* and its accompanying fuel plant capable of compressing locally acquired carbon dioxide for use in an oxybenzene propellant reactor. The use of the more complex and high performance oxybenzene ISRU is the only design decision altered from the original *Mars Challenger*. The original design explored the Sabatier/Electrolysis process for oxymethane propellants, and revealed major, but managable problems using the booster's ascent tanks for outbound hydrogen storage. In exchange, *Mars Challenger II* experiences problems with the physical properties of benzene in the cold Martian environment.

The *Christa Rover* is unchanged. It is landed up to several kilometres away from *Judith* and uses its suite of scientific instruments on route to the booster to examine sites and select samples. As with the original, *Mars Challenger II* uses the strategy of determining that samples selected for return to Earth do not contain life harmful to our biosphere.

For reasons of cost and politics, both craft are electrically powered by solar arrays, with a small amount of nuclear radioisotope material in heating units, *Christa*'s scientific spectrometers, and the control sample sterilizers for its laboratory style experiments.

Proven technologies and off the shelf or derived hardware will be used throughout to keep development and qualification costs to a minimum, however several technologies must be converted from terrestrial and experimental equivalents into flight hardware, and protecting the mission's biological integrity is expensive in any case. For example, the development of hydrogen compatible ascent tanks must be done from scratch. The author is convinced that this mission can be accomplished for $1200 million on a six year schedule.

1. Introduction

Traditionally planetary mission concepts have been classified as flyby/impact, landers, orbiters, sample return, piloted exploration and colonization. For Mars, flyby missions and orbiters can be said to be in the same family, as all of their requirements except propulsion are similar. This will hold true with other bodies as we explore them. Landers, and even more so, sample return and piloted exploration designs are dominated by the target planet's characteristics and resources. Mars just happens to be the most difficult solid body to land on. Fortunately, Mars is not an enormously difficult planet to ascend from with its mild gravity, oxygen and carbon chemically available in its thin atmosphere, which is a dominant factor in piloted exploration missions, and sample return mission like this one. An LOX/hydrocarbon propellant combination can be generated quite easily from Earth-supplied hydrogen. Future robotic missions, especially the *Phoenix Mars Scout* currently en route, will answer the question of whether local water (and therefore local hydrogen) is available to a piloted and sample return missions, and how to access it. *Mars Challenger II* is still relying on stored hydrogen, since the acquisition of water on Mars is unqualified until actually carried out.

Sample return offers enormous advantages when compared to landers and rovers with local instruments. Earth laboratories provide a much better environment for examination and experimentation upon Martian material than the tiny confines of a spacecraft and its automated equipment. The science quality can only be surpassed by sending humans, and even then, samples that return with the crew are of enormous value. Earth labs do not have stringent mass and volume limitations, nor do their instruments need expensive flight qualification; they don't have to survive launch. Rather than ruining a billion dollar mission, it's a trip to the shop if they quit working. With even small Mars missions carrying very limited instruments having costs comparable to skyscraper construction budgets, the advantages of a sample return mission are obvious. This is not to impune the difficulty of preserving the scientific and biological integrity of such a facility. *Mars Challenger* had not included the receiving facility as part of program costs, which has been added to *Mars Challenger II*. This report does not contain a detailed analysis of such a facility, which, hopefully, can be developed, designed and constructed at a cost of $400 million or less.

There is a requirement for planetary protection in both directions (protection of Mars from Earth life, and protection of Earth from undetected Mars life.) For outbound contamination, an extensive sterilization and cleanliness program is required from design, assembly/test/launch operations (ATLO) and throughout inflight operations. For inbound contamination, *Christa* requires enough microbiological science to be able to rule out samples containing potentially dangerous life. This concept is called Astrobiological Sample Qualification (ASQ) and gives its name to the resulting scientific investigation payload. Under these circumstances, the risk of contaminating Earth with Martian life in the event of a sample return descent module failure is effectively zero. The design case of *Mars Challenger II* is that such life will not be detected, however, steps to mitigate the Earth's exposure to potentially undetected live are still being employed.

Sterilization of samples selected for return is not recommended. It is likely that the same lifeforms as would be in the samples would find its way onto the sample return descent module and subsequently survive the trip to Earth. Even without such life on the sample module exterior, it would be present on the sample containers' exterior surfaces. Without a program to sterilize the entire sample module and any stages that may enter Earth's atmosphere with it after launch from Mars, sterilization of returned samples does not enhance return contamination safety. Furthermore, harmful life capable of surviving the trip through space outside of *Judith*'s containers will eventually arrive on Earth through panspermia (an asteroid hits Mars and sends them across interplanetary space to us, similar to the Alan Hills and Nahkli meteorites.) Of course, if life is detected and concern for it contaminating Earth's biosphere can't be ruled out, the prudent choice would be to cancel *Judith*'s launch. The mission is obviously not a failure in this context. An effort could then be organized to send an orbital sterilization and return vehicle to meet the sample module on Mars orbit. This would be a worthwhile effort because *Judith*'s sample module is very large in comparison to most sample return design studies, and it would be able to launch more sample mass to Mars orbit, than directly to Earth as planned.

The layout of this report follows that of spacecraft proposal, at least as After Columbia Project currently understands them. Several Appendices follow the main body. The first of these, Appendix A, is a Compliance Matrix. 27 design requirements have been extracted from the Contest Rules and are laid out with *Mars Challenger*'s specific solutions. The designer felt it was important to include because several of the specific science requirements are excluded to control *Christa*'s size, and therefore the cost of the mission. Appendix B relates the design history of the mission, and how the author developed the *Mars Challenger II* concept throughout its history. Appendix C contains synopses of various design analyses used in the final version.

1.1 Table of Contents

1.2 Nomenclature

Before the main body of the report, please understand that this is an areocentric "Mars" paper, so most previous missions with "Mars" in the title have it removed for the purposes of brevity. Occasionally, missions to other destinations will have their planet similarly added. For the following, new or modified terms have been emphasized for those who are already familiar with robotic planetary exploration. The use of acronyms which refer to other missions (i.e.: MER, MPF, MSL, MRO, MGS, etc.) are generally avoided throughout this report.

0710: Example date-based version number, *yymm* format, October 2007 for this example
AFAL: Air Force Specific Impulse tool; downloaded from www.dunnspace.com
ATK: Alliant Techsystems
ATLO: Assembly, Test, and Launch Operations
APQ: Astrobiological Planetary Qualification, an alternative to ASQ
APXS: Alpha Particle X-ray Spectrometer (an instrument by University of Munich)
ASQ: Astrobiological Sample Qualification
Azote: Refers to the chemically inactive part of the atmosphere, first discovered on Earth by Daniel Rutherford in 1772 and given this name Antoine-Laurent Lavoisier two years later. It was later renamed nitrogen, but the original azote also contains the noble gasses, thus forming a convenient moniker for all of the atmosphere's "buffer gas" whatever it may be. Henry Cavendish discovered that not all azote was nitrogen in 1785, even though the noble gasses weren't identified as a family until 1894.[0a] The azote component of breathing atmospheres is important, especially in diving and space travel, where it is needed to prevent and mitigate fires and can have serious effects on human health. Azote gasses include nitrogen, noble gases, and flourocarbons. Martian azote consists of more argon than nitrogen, and this may have an impact on the ISRU design, since it comprises about 5% of Martian air.
Booster: A complete launch vehicle, including all stages, payload and fairing (if applicable.)
CCAFS: Cape Canaveral Air Force Station, a commercial and military space center immediately south of Kennedy Space Center, where all NASA Mars missions to date have been launched
CCD: Charge Coupled Device, the electronic film in modern digital cameras, especially those that fly in space
CIMBRLI: Challenger's Instrument for Microbiology Laboratory Investigations
DIMES: Descent Imaging Motion Estimation Software (from *Exploration Rovers*)
DITA: Descent Imaging Terrain Avoidance
DNA: Deoxyribonucleic Acid, the famous molecule which stores genetic information

DSS: Dual Spacecraft Structure: a multiple payload adapter for the *Atlas V* 4m fairing
DSN: Deep Space Network
EDL: Entry, Descent, and Landing
JPL: Jet Propulsion Laboratory
KOH: Chemical formula potassium hydroxide, the salt used in the electrolysis reactor
LEO: Low Energy Orbit (i.e: Earth LEO, Mars LEO)
LED: Light Emitting Diode, the current state of the art for "light bulb" technology. It is easy to design one to emit light in a narrow spectral band (color) to identify minerals.
LPS: Landing Propulsion System; this is generally used to refer to the hydrazine fueled portion of it, which gets reused during ISRU
MAHLI: Mars Hand Lens Imager (a Malin Science Systems instrument)
MAHOSS: Mars Atmoshere Hydrocarbon and Olefin Synthesis System; this system replaces the S/E ISRU system to produce oxybenzene propellants, and is a bit of a misnomer since benzene is an aromatic hydrocarbon, not an olefin.[16a]
MARDI: Mars Descent Imager (a Malin Science Systems instrument)
MECA: The Phoenix microscope lab.
mRNA: Messenger Ribonucleic Acid, a less famous molecule for storing genetic information in viruses
NASA: National Aeronautics and Space Administration
oxyfuel: For readability After Columbia generally reverts to the use of torch language to describe propellant combinations which use LOX. “LOX/C6H6” in rocket language becomes “oxybenzene” in torch language.
PCR: Polymerase Chain Reaction, a technique for replicating non-living DNA (such as in viruses and homicide investigations.) It is core technology of "DNA fingerprinting" of trace evidence.
PSI: Pressure Systems Incorporated (now a part of ATK)
psia: pounds per square inch absolute
RAT: Rock Abrasion Tool
RPM: Revolutions Per Minute (compressor speed)
RRI: Rocket Research Incorporated (now a part of Aerojet)
RWGS: Reverse Water Gas Shift, a slightly endothermic chemical reaction producing water and carbon monoxide from hydrogen and carbon dioxide
S/E: Sabatier/Electrolysis cycle; *Mars Challenger*’s original chosen method for producing propellants on Mars
SMI: Single Motor Inoperative
TASS2: Trajectory Analysis Spreadsheet, series 2; After Columbia's homegrown tool for analyzing booster ascents. *Mars Challenger II* had planned to use TASS3, but was cancelled due to schedule constraints.
TCM: Trajectory Correction Maneuver
Toriconical: Tank head or heatshield in the shape of a sphere-nosed cone. This term is common in pressure-vessel documentation, but not so in Mars lander papers. It is used to describe lander heatshields.
ULTSI: Ultrasonic Tank and Structure Inspection, carried by the *Judith* lander to support *Judith*’s ascent.

1.3 About the Authors

Our analyst, Terry Wilson was born in Barrhead, AB, and moved to Calgary, AB in 1997. He has been a space engineering enthusiast at least since when he started to retain memories as a child. Unlike most space enthusiasts, he does not recall a “moment” that sparked his interest in space. The detailed space engineering studies that lead to After Columbia Project began in April 2001 and found the title objective on 2 February 2003, approximately 28 hours after *Columbia* was lost on her final mission. So far, After Columbia’s own spacecraft concepts have included *Delta Sprint* (a semi-ballistic piloted crew ferry for Earth LEO applications and returning crews from planetary missions), *Bluestar* (a two stage to orbit runway operated booster which ultimately failed feasibility analysis), *Greenstar* (a medium lift pressure-fed which failed feasibility analysis unusually late in the process) and *Mars Challenger*. After Columbia has had supporting roles in Orbiter Mars Direct Project and the Orbiter Spaceflight Simulator. After Columbia is also known for being highly critical of the *Space Shuttle* and derived vehicles because of the expense of the technology and political structures underlying it.

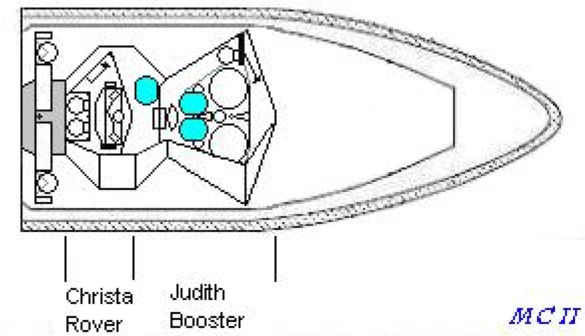
Our illustrator, Jordan Pelovitz was born in St. Croix, in the United States Virgin Islands, and is currently studying New Media Design at Rochester Institute of Technology in Rochester, New York. However, despite his choice of major, he has been an aviation and space enthusiast since the moment he could open his eyes - his first airplane ride is vividly etched into his memory, and one of his crowning achievements was his attainment of his private pilot's license. Now he does whatever he can to further humanity's own achievements amongst the stars. In the past he has worked extensively with 1000 Planets, Inc., developing their 3D visualization work. His current projects, aside from *Mars Challenger II*, are the development of the trans-atmospheric *NuVastra* engine, powering the *Jotun* tourist space craft, along with several other projects involving digital art and video game creation, and the advancement of his pilot certifications.

1.4 Acknowledgments

Walter Tam and Gary Kawahara of Pressure Systems Incorporated (now a subsiduary of ATK) have been instrumental in guiding *Mars Challenger*'s tankage decisions and the author's understanding of the expense and schedules associated with the development of reliable spacecraft. Because of the extensive support they and their colleagues have provided through their correspondence and website documentation, *Mars Challenger* uses PSI tanks and ATK solid motors exclusively. Mark Holtzapple and his colleagues at StarRotor Corporation have played a similar role for the air compressor. Special thanks also goes to Malin Space Science Systems, Cryomech, Pioneer Astronautics, the Artemis Project and Jet Propulsion Laboratory for the extensive information provided on their websites as well as the Chemical Rubber Company for their enormous reference books. There are many authors in addition to those who are in the bibliography who have contributed to the general body of knowledge this report is based on. Thanks to those as well, for being bold enough to publish their wisdom, and sometimes the foolishness that led to it. Finally, our Lord and Saviour Jesus Christ for wisdom, hope, and passion, whose Name (in *"Christa"*) and praise (in *"Judith"*) also flies with *Mars Challenger*.

2 *Mars Challenger* Launch and Cruise Configurations

Figure 2-1: Launch Configuration



2.1 Introduction

Mars Challenger II has selected a dual launch arrangement unique among all known Mars mission proposals (with the exception of *Voyager*, a *Saturn* launched Mars mission proposal predating both *Viking* and the well known *Voyager* multiple flyby spacecraft.) Both major elements, the *Christa Rover* and *Judith Booster*, are launched together with a common cruise stage and landed separately. Much of the cruise stage is designed primarily to provide the shade needed for the cryocooling requirements of the *Judith Booster.* In this manner, the *Judith* tanks can be built like propellant tanks instead of like heavy dewars. This grows a strange stack where the structures, especially the main adapter, are taking extra lateral loads during ascent.

Because of the variety of 5m class medium launch vehicles and payload capabilities, the launch vehicle configuration choice has not been made (*Atlas V* 541 is the current front runner, but other configurations, such as *Delta IV* H, and *Ariane* 5 EC-A are available.) The baseline launch configuration design static envelope is a 4.5m diameter, 5.0m long cylinder topped by a 3m long conic section with 1.5m diameter at the top. This will fit within the *Atlas V* 5m Short fairing, as well as equivalents on other boosters, with some room for deflection (i.e. dynamic payload envelope.)

Both landers are integrated in the inverted position (upside down in relation to their entry attitudes), the customary position for missions where the lander is dominant, including every JPL lander mission that has flown to Mars. The *Judith* lander sits on top of the stack using a 1.2m diameter interface, and the smaller *Christa* lander is in a container underneath. Off the shelf multiple payload adapters were ruled out, so this "Can" will be designed specifically for *Mars Challenger*. The backshell of the *Judith* lander protrudes into the *Christa* container to reduce the stack's height. The container's primary purpose is to transmit the ascent loads from *Judith* around the *Christa* lander to the 1.2m diameter main structure of the cruise stage. Part of the Can's design responsibility will be to provide backing for *Judith* cooling provisions. A hydrogen tank is carried outside of the *Judith* lander structure to provide make-up hydrogen for the four tanks in the lander during the outbound cruise.

One of the unaddressed challenges of this arrangement is integrating the static and dynamic balance requirements each lander needs for entry with the requirements the booster has for ascent. The stack center of gravity is currently estimated at 3.5m above the separation system interface plane.   A new adapter and separation system, as well as new stress analyses of the booster's upper stage structures is an expensive possibility. The alternative was a rightside up integration of the landers, which leads to penetrations of the heatshield for mechanical connections, and wraparound harnessing for the extensive electrical and data connections (with potentially more expensive problems and reliability concerns that won't go away because of their lack of ground testability.) The configuration of *Herschel/Planck* is taller, heavier, and more asymmetric, suggesting that this is not a problem.[1]

The author's position is that this arrangement is the most conservative that can be done at this scale of mission, counting the landing difficulties elaborated in the next chapter on the landers. The following sections progress in order from the bottom of the stack up.

Table 2-1: *Mars Challenger* Launch Mass Estimation
Mars Challenger 0710 Launch Mass Estimation Tool

	Mass	Number	Total	Non-Mass Parameter		
Christa Rover	821.20	1.00	821.20			22.06%
Judith Booster	1788.94	1.00	1788.94			48.06%
Gross Lander Mass					**2610.14**	70.13%
Cruise Propellant Tanks	7.35	2.00	14.70	PSI 80385		
Reaction Control System	10.00	1.00	10.00			
Cruise Propellant	72.00	2.00	144.00	Delta v (2200m/s Isp)		91.73
Equipment Deck	300.00	1.00	300.00			m/s
Solar Power	12.00	1.00	12.00			
Hydrogen make-up tank	11.50	1.00	11.50	same as Judith 2nd		
Hydrogen load	13.60	1.00	13.60	stage seed hydrogen		
The Can (cryo radiators built in)	300.00	1.00	300.00			
Christa Separation	30.00	1.00	30.00			
Judith Separation	50.00	1.00	50.00			
Can Separation	30.00	1.00	30.00			
Total Separated Mass					**3525.94**	94.73%
Main Adapter	196.00	1.00	196.00	*Atlas V* B1195		
Total Launch Mass					**3721.94**	100.00%

2.2 Main Adapter

The dunnage connecting any spacecraft to its booster is usually called the adapter and separation system. Often there are separate "launch vehicle" and "payload" adapters as defined in booster manuals. Preliminary comparisons of the rough (and conservative) estimate of the 3.5m center of gravity have been made to *Atlas V* documentation.

The payload is light enough to avoid truss adapters intended for heavy low energy payloads. This is important because using a truss adapter would complicate the arrangement of solar cells on the cruise stage, and generally make things much more expensive. The basic mass properties are well within the standard, 1575mm interface of *Atlas V*. *Delta IV* adopted this interface as part of the EELV program, while *Ariane 5*'s is slightly wider. This means that it is likely that a new main adapter and separation system could be developed without the onerous analysis of upper stage structures.

Two types of separation system are available. By far the more popular is the Marmon V-clamp band. The interface rings between the booster and payload are precisely machined and matched, and metal strap with several clamps is pulled tight around the pair, holding the two together. The "V-clamp" term comes from the cross section of the clampband/ring interface. The strap is held together by two explosive bolts, only one of which needs to work to release it. A matched set of compressed springs and breakwire separation switches complete the system by pushing the spacecraft and spent upper stage apart and confirming the separation of the spacecraft from the booster. Clampbands are used for the landers, but the mass and center of gravity envelope of *Mars Challenger* is at the very edge of the type B clampband for *Atlas V* (an 1194mm diameter clampband.)

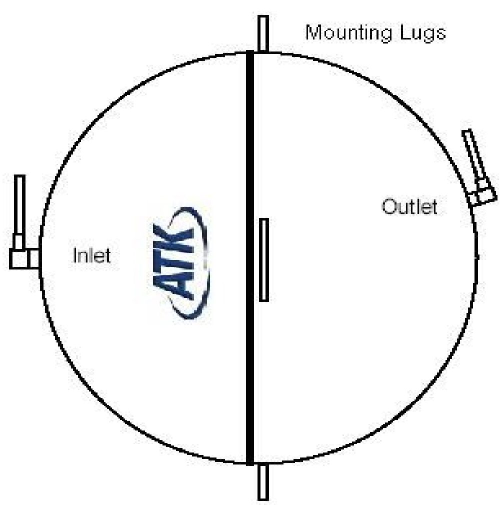
The other type of separation system connects the spacecraft and booster together directly with separation bolts, and is typically associated with truss type adapters. It is stronger for its mass, but less reliable, introduces a more severe shock environment and touchier ground handling. The use of the latter system is more likely for the main adapter, because the whole stack is very large and heavy compared to clampband payloads. *Atlas V*'s standard Type F separation bolt system's mass/center of gravity envelope has not yet been published.

2.3 Cruise Stage

The cruise stage for *Mars Challenger* copies the concept of every cruise stage used on every JPL lander except *Viking*: a central structural tube surrounded by an equipment deck, under which is the solar arrays, and on top of which is all the cruise stages functional components. The landers sit on this 1.6m tube. (The author expects *Science Laboratory* to depart from this pattern as it does not require separate solar power during the cruise stage with its radioisotope source battery.)

Gallium Arsenide SCARLETT solar arrays (pioneered on *Deep Space* 1) have been tentatively selected because of the solar inertial attitude maintained during the cruise phase. These types of cells generate more power per area, but are more sensitive to solar angle. There may be deployable shades to provide passive cooling of the Judith lander's structure and the Can's radiators. The normal attitude of the cruise configuration is to point the cruise stage at the Sun to allow maximum collection of solar power without needing continous two axis steering of the solar arrays, and to provide shade for the *Judith* lander and its hydrogen seed stock using the above hardware. The cruise stage is capable of intermittent three axis control but is normally spin-stabilized.

Figure 2-2: PSI 80385 Hydrazine Tank



The cruise stage requires 60m/s of delta-v for attitude acquisition and course correction. Propulsion is monopropellant hydrazine utilizing two MR-104 thrusters, several smaller thrusters, and hydrazine stored in two PSI 80385 diaphragm tanks (a 570 mm diameter girth mounted sphere) fastened to the cruise stage's equipment deck. This tank is similar to the RCS propellant tank used on the *Centaur* upper stage. The thrusters will be mounted in groups protruding between the radiator "fence" in the cruise stage perimeter. They have reflectors to reduce plume and nozzle radiation in the direction of the *Judith* lander and thermal radiators. The two large axial thrusters are predictably located in the middle of the launch vehicle adapter structure

The thermal radiators form the "fence" around the tanks and radiate their heat in lateral directions. They are in the shade of the solar arrays. If it is sufficiently beneficial to *Judith*, a lip may be put on the radiators to block their radiation in that direction. No other cooling system details have been worked out yet. For heating, rather than use radioisotope heating units (RHU's), cruise stage systems will be selected whenever possible for cold temperature operation, and when not possible (most significantly the propulsion system) will use either a waste heat coolant loop and input heat sink or electrical heaters, whichever is more mass efficient for the application, including considerations of solar array mass.

The upper interface for the cruise stage has two concentric load paths, one for the 1.0m diameter of the *Christa* lander, which is directly mounted to the cruise stage, and one for the container at 1.6m diameter.

Atlas V particular separation systems, if used, would be Type A (937mm diameter) for *Christa* and Type B

(1194mm diameter) for *Judith*. Equivalents for other launch vehicles are available. Orbital Sciences adapters interface with spacecraft through a bolted interface rather than directly to the separation system, simplifying spacecraft assembly, testing, and allowing slightly looser tolerances in that portion of the cruise stage. Because *Christa* uses the *Exploration Rover* aeroshell with no modification at this interface, the same interface will be used.

2.3.1 Single Shift Ascent Correction

A study of JPL Mars missions has shown a trend to have the first trajectory correction maneuver happen further and further away from the initial ascent (the fastest is 2 days by *Mariner* 9, while the slowest is after 36 days by *Pathfinder*; which had problems with its sun sensors. The typical value is 15 days.) A major maneuver for *Mars Challenger* presents a number of really irritating problems for the seed hydrogen system. If *Mars Challenger* is flown like missions today, the mission profile from booster separation through the end of the first Trajectory Correction Maneuver (TCM1) will look like this, with emphasis added on steps unique to *Mars Challenger*):

a) Separation from booster upper stage
b) Confirmation of low attitude rates or propulsive recovery/despin
c) Deployment of solar arrays
d) Acquisition of solar oriented attitude
e) Activation of seed hydrogen cryocoolers
f) Establish roll rate
g) The spacecraft is acquired (typically by DSN Canberra 26m or 34m antenna for CCAFS launches) somewhere between step (d) and after step (f); it needs to be tracked for at least two hours to determine its trajectory accurately enough for correction
h) Several days later, the TCM1 maneuver parameters and execution command are sent to the spacecraft
i) The spacecraft rolls to the proper attitude for the TCM
j) Switch to battery power
k) Pitch to the maneuver attitude (*exposes Judith tanks to solar heat*)
l) Fire thrusters for TCM translation
m) Reacquire solar oriented attitude
n) Reacquire roll attitude and reestablish high gain communications

The name “Single Shift” comes from the notion that this maneuver will be completed before the shift of controllers who observed the launch retire for the day. The advantage for *Mars Challenger* is that it can avoid spending a lot of extra time with the sun shining on the *Judith* lander causing hydrogen boiloff, a rather undesirable condition. As we shall see in Chapter 5, the *Judith Booster* needs a very accurate guidance system for its ascent from Mars. The single shift ascent correction plan can take advantage of this to test its operation and reduce the heat input into *Judith* 's tanks:

a) Separation from booster upper stage
b) Confirmation of low attitude rates or propulsive recovery/despin
c) Immediate acquisition of TCM1 attitude based on *Judith* inertial reference
d) Execution of TCM1 maneuver based on pre-launch parameters and detected booster dispersions occurs within two hours of separation
e) Acquisition of solar oriented attitude
f) Establish roll rate communications standby attitude
g) DSN tracking precisely establishes post-TCM1 trajectory
h) Ascent operations shift determines further need for correction
i) If TCM2 needs are sufficient, a 3 axis maneuver plan is established which will be executed at 24-26 hours after launch (same operations shift on duty) and executed much as conventional steps (h) to (n)
j) If TCM2 needs are minor, a pulse maneuver plan is established after several days and executed while the spacecraft is spin stabilized, perhaps over the course of several hours; the advantage that *Judith* does not need to be brought out of the shade.

One of the enabling factors of this process is that the ascent trajectory is set up to make darn sure (i.e.: 10e-6 probability) that the biologically infested booster upper stage does not hit Mars. This planetary protection bias is planned before launch and we therefore know how to correct it in advance. If *Judith*'s guidance is less to slightly more accurate than the booster that launched it, an automatic TCM1 to correct just the protection bias will eliminate most of the trajectory error, leaving perhaps 12 m/s worth of booster and maneuver dispersions for TCM2. If *Judith*'s inertial guidance beats the launching booster's guidance, it can automatically correct dispersions from the ascent as well (newer *Breeze M* and *Fregat* upper stages do this for heritage low cost Russian boosters *Proton* and *Soyuz* respectively.) Less than 8 hours after launch, this correction would still be done in Earth's gravitational influence, reducing the delta-v requirements as compared to a correction several days later. If it so happens that the first few hours of coast is in Earth's shadow, *Mars Challenger* may be able to execute the TCM1 maneuver and then maneuver to the solar oriented attitude based on inertial guidance and have *Judith* in the shade while it does this maneuver.

An ascent to the trajectory shown in Figure 2-3 has been simulated in the Schweiger *Orbiter* simulator. During this simulation, an eclipse did not occur. The simulated vehicle actually spent the entire period from lift-off in sunlight. A single shift ascent correction has not been ruled out because the Can radiators are warm after lift-off. They would be cool prior to a TCM in deep space, and absorb a lot of heat during the maneuver.

2.3.2 Cruise Make-up Tank

The original *Mars Challenger* had used an additional pulse tube cold head for keeping the hydrogen in the four large original tanks from boiling off. *Mars Challenger II* adopted the oxybenzene ISRU, which requires less hydrogen and less cryocooling than the original oxymethane ISRU. The hydrogen tank is now mounted on the second stage instead of the first stage, and is much smaller. Instead of a pulse tube cold head and gas reclamation device, *Mars Challenger II* uses settled venting and a make up tank. The savings from the smaller tanks, simpler cruise management system, and other system benefits (such as reduced cruise power requirements) are expected to pay for the increased costs of the more complex oxybenzene ISRU plant.

The settled venting procedure begins either when scheduled by mission operations, or by contingency activated when a hydrogen tank’s pressure reaches 350psia (emergency pressure relief devices are set to 400psia, the tanks’ maximum expected operating pressure.) The cruise stage starts by firing its canted –X thrusters to “pull” on the stack, settling the gas to the top of each tank. Once venting begins, the venting hydrogen provides enough thrust to settle the tanks, and the cruise stage thrusters can be deactivated. When all five tanks (four on *Judith* plus the make-up tank) are down to a modest pressure of 100psia, the venting is complete. Needless to say, the translation from both the cruise settling maneuver and the venting need to be incorporated into the spacecraft’s trajectory plan.

The approach settled transfer begins similarly, except that the make-up tank is not vented. The make-up tank actually requires a higher pressure, and *Mars Challenger* may turn to expose the make-up tank to the sun to provide this pressure. The four tanks on *Judith* continue venting while liquid hydrogen is transferred from the make-up tank to them to top them up prior to landing. The feasibility of settled liquid hydrogen transfer has been demonstrated by propellant control onboard *Centaur* and actual experimentation with settled hydrogen transfer has been planned.[0b]

2.3.3 Cruise Solar Power

13 square metres of area is available on the cruise stage, overkill for the current scheme. This could provide about 2600W of power near Earth. At Mars, 1560W of power are available with high efficiency triple junction Gallium Arsenide (GaAs) solar cells. Since about 600W (200W per element, including the cruise stage) is required by *Mars Challenger II*, the cruise stage’s main function is now as a sunshade for *Judith*.

2.4 The *Christa* Can

The "Can" is the bypass structure that transfers the ascent loads from *Judith* around *Christa* to the cruise stage and ultimately to the booster. It also provides the backing for the harnessing and plumbing between the cruise stage and the *Judith* booster, as well as the make-up tank. The Can is not currently intended as a contamination barrier between the two landers.

Atlas V and *Ariane 5* multiple payload structures were briefly considered as a basis for the Can, but it turned out that they were not well suited for the task. All but the *Atlas V* Dual Spacecraft Structure (DSS) being considered for commercial application with the *Atlas V* 4m fairing were too tall and had their separation interfaces in places that didn't allow for a cruise stage. The DSS itself did not have a wide enough diameter for the *Exploration Rover* aeroshell used by *Christa*.

While existing multiple payload systems are not compatible with the mission, some of their components may be usable.

A third type of separation system is the "bellows" style used almost exclusively for fairings. This runs a detonation cord (or two) inside a small bag in a tang and clevis joint. When activated, the cord explodes, filling the bag inside the clevis with gas and thus pushing the tang out of it. In this way, the upper half is separated. The bag contains the gasses so they do not contaminate the spacecraft. This type of system is already ubiquitous in booster fairings and multiple adapter cans.

2.5 Entry Staging Sequence

In the final hours before approach to Mars, the stack is despun, the cruise stage coolant loops are vented. After this, the make-up tank transfers its remaining liquid hydrogen to *Judith* using the settled transfer procedure described earlier. This is followed by a slew to the separation attitude for the *Judith* lander and release of the *Judith* lander for entry. The cruise stage then slews to the separation attitude for the Can. The separation system and attitude are selected so that the Can does not interfere with the entry operations of either lander. The Can and cruise stage will still enter the Martian atmosphere. The cruise stage performs a maneuver to increase the entry angle of the *Christa* lander and compensate for rotation and weather effects. This maneuver is planned before landing and has the goal of landing *Christa* within 5km of *Judith*. Without this maneuver, *Christa* would land well downrange of *Judith* because of her higher drag loading. The cruise stage then adopts the separation attitude for the *Christa* lander and then releases her as well. Finally, the cruise stage adopts the disposal attitude and vents its propulsion system pressurant supply. This disposal attitude will be selected to warm the propellant tanks (the most likely parts to survive to landing) and attempt to ensure that any residual microbes on the cruise stage are unlikely to survive entry.

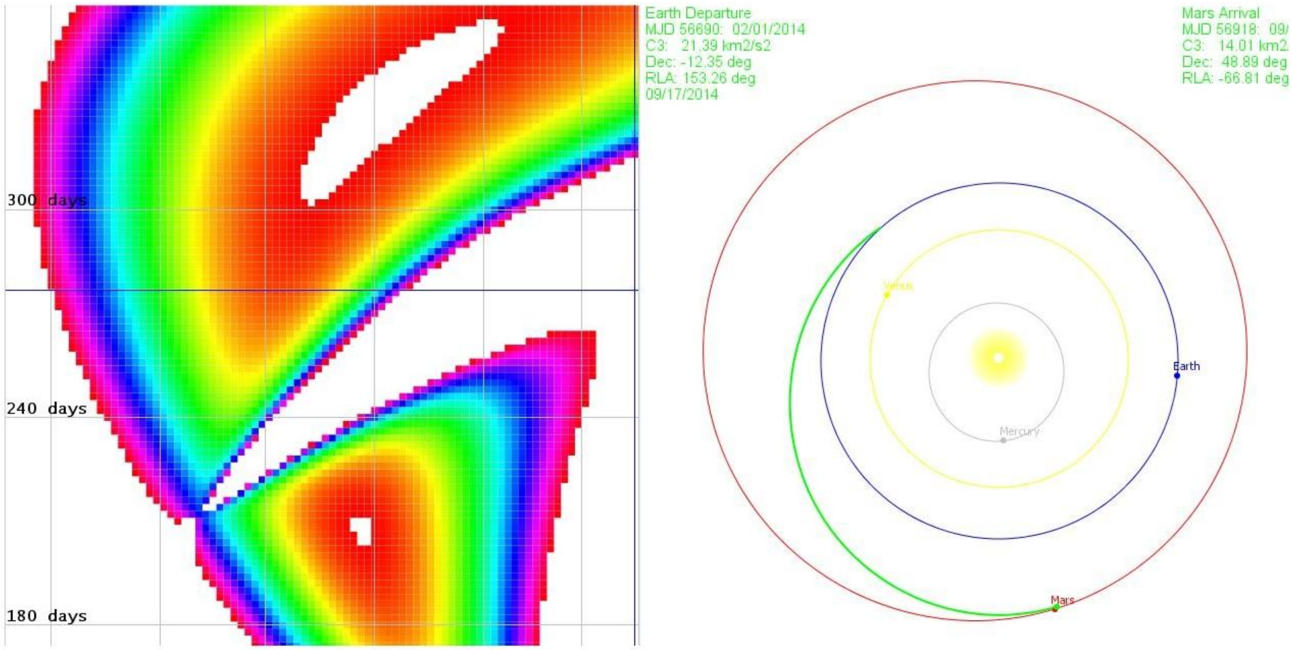
2.6 Trajectory and Launch Schedule

For launch from Earth, *Mars Challenger* has selected the Type I window occurring in January and February 2014 (The center of the window falls on the eleventh anniversary of *Columbia*'s final, unsuccessful entry concluding STS-107.) The rationale is that this is the closest window to the present day which allows a six year development program. Arrival at Mars would be in September 2014. Type I windows offer faster trip times, desirable in light of *Judith*'s hydrogen handling challenges. *Mars Challenger* would need to be approved within 3 months of the completion of this report to have the full six years available for development. The Type I window in February 2016 is more favorable for performance and offers an excellent opportunity for a repeat flight.

For the return to Earth, a generous eight week launch window has been selected in 2015's Type I opportunity. It runs from late October to the end of the year. This offers a minimum of 440 days of surface operations. The sample module arrives at Earth in July 2016, a 31 month mission.

If the 2015 window is missed, the next opportunity is available in February to April of 2018, which brings the samples back to Earth for October 2018. A mission accommodating this opportunity would last 58 months (nearly 5 years.)

Figure 2-3: Departure for Mars



AstroJava.com Mars Challenger Departs For Mars in 2014

The horizontal axis of Figure 2-3 represent launch dates, with 1 February 2014 being the second vertical grey line from the right. This plot represents departure energy from Earth, and this trajectory has been selected for arrival energy at Mars (to make landing easier.) Unfortunately, a good plot of arrival energy could not be acquired. The Type I (less than halfway around the sun) window is the lower half, Type II (more than halfway around the sun) is the upper half. The gap between good trajectories for Type I and Type II represents longer cruise times and less surface stay time on Mars. Because maximum surface stay time is essential for both ISRU and the collection of samples, the Type I window is obvious. A Type II trajectory would also boil off more of the seed hydrogen. The Gregorian arrival date cropped out of Figure 2-3 is 18 September 2014.

Further study of this trajectory was done in the *Orbiter* 060929 simulator by Martin Schweiger. This software is downloadable free of charge from www.orbitersim.com.

2.7 Expected Direction

The cruise configuration's basic two lander layout has been a part of *Mars Challenger* since June of 2006 when After Columbia's efforts began. The biggest change has resulted from the selection of oxybenzene ISRU, which allows the make-up tank to be carried as part of the cruise configuration instead of the cryocooler radiators envisioned to allow the propellant liquification system to keep the hydrogen cold. No substantial changes are expected if the mission were to be approve for flight development.

As time progresses, *Mars Challenger* will assure that it is slotted in a realistic launch window, which means that this mission may be bumped to the 2016 departure. Considerable analysis has been done in support of preliminary studies for the *Astrobiological Field Laboratory* mission concept by the Mars Exploration Program Analysis Group (part of JPL.) This analysis would become the primary reference for trajectory information for the outbound leg, while the return leg would be re-analyzed by After Columbia Project.

3 *Mars Challenger* Landers

3.1 Introduction

The *Christa Rover* is launched with *Judith* on the same launch vehicle from Earth, with a common cruise stage, but a separate lander. So that landing errors are similar, *Christa*'s trajectory will be analyzed and corrected so that its landing point matches that of the *Judith* lander. In this manner, it can be assured that *Christa* will land within driving distance of *Judith*. For launch from Earth, the sample containers will be carried with *Christa*, which will also have all of the dedicated scientific instrumentation.

The processes associated with lander development are ones the author has dedicated quite a bit of time to, as lander performance is a severe limitation on large missions such as these. Also, *Judith* requires a lander of unprecedented complexity to support its launch. Even with a 4.5m diameter, the enormous ascent tanks drive extreme volume limitations in the lander. These limitations interact with thermal management, aeroshell stability, launch plume clearance, and a host of other problems likely to include some the author has yet to discover.

The *Judith* lander has three main tasks to support the *Mars Challenger* mission.

- With the help of the cruise stage, protect the *Judith Booster* from solar and other heat from the interplanetary environment during the cruise to Mars to minimize hydrogen losses.
- Provide an interface between the "Can" and booster for mechanical loading, power, cooling, and data transfer.
- Successfully and gently land itself and the *Judith Booster* at the targeted landing site in Marte Vallis on Mars.
- Support the launch preparations for *Judith*'s ascent.

Both landers use a two phase technique for their powered descent. When the parachute's usefulness has ended, the first step is to halt the 100-150m/s descent using Star 8 solid motors. The second step is to correct the loft from the solid motors and hover to the nearest terrain the in which lander can set down, and finally to do so. The hover propulsion systems of both landers use *Polar Lander*'s Pressure Systems Incorporated 80397 propellant tanks. 445N Rocket Research MR-104 thrusters stand in for the unidentified *Polar Lander* and *Viking* thrusters. The technique's efficiency exceeds that of both conventional powered descent and airbag contact systems, which was a pleasant surprise.

The *Christa Rover* and its lander form a concept lying between *Science Laboratory* and *Exploration Rovers* in both size and technology. The 420kg rover lands using a kitbash of *Exploration Rover* and *Polar Lander* hardware, and *Science Laboratory* 's hover crane technique.

Judith's lander is a custom ballistic design slightly lighter, but considerably larger than the managed energy lander planned for *Science Laboratory*. The single parachute is followed up by larger numbers of the same Star 8 motors, interim MR-104 thrusters and 80397 propellant tanks. *Judith*'s lander is very unusual in that it retains the backshell all the way to the surface because it uses the internal structure as the mounting points for the solar panels.

3.2 Landing On Mars: The Challenge to Meet

While the analysis of the landers for this study is far more rigorous than is generally the case for piloted ISRU mission papers, there is much left undone. This chapter isolates the issue of landing on Mars specifically in order to rule it out that its cost would balloon out of the expected $800 million budget.

The difficulty of landing on Mars has been repeatedly proven by landing failures and close calls, including every Russian/Soviet spacecraft that has attempted to land, the *Polar Lander* and *Beagle 2*. During the development of the *Exploration Rovers*, *Pathfinder* was found to have gotten lucky, with the airbags, parachutes and bridle operating very close to their failure points. At the root of all these difficulties is the thin Martian atmosphere.

For a moment, let us assume a ballistic lander can be designed to survive any condition of descent over any body except impacting the surface at higher than a certain speed. Such a lander would have no trouble at all landing on Venus or Titan because of their thick atmospheres (Venus landers do not even need parachutes.) Landing on bodies with no atmosphere, especially Mercury, the heaviest such body, is much more difficult because the lander would need to use rocket propulsion for all phases of descent. Mars forms an unhappy middle ground, where a lander must have properties of an atmospheric lander followed by a more vacuum type rocket propelled lander. For five of the successful landers on Mars and the vast majority of concepts, this has formed two stages, typically one to handle entry and parachute, and one to handle terminal stop and contact with the ground. *Exploration Rovers* and *Pathfinder* were exceptions because the staging point was after the rocket propelled terminal stop, with contact being handled by a much simpler shell and airbag system. This contact concept was pioneered by the Soviet *Luna 4*, and failed several times until first being successful on *Luna 9*.

Because of the thin atmosphere, a high performance lander must cram several landing system deployments into the span of a few seconds to a minute at the end of descent to Mars, resulting in difficulties achieving reliability and accuracy, as well as horrendously low payload fractions. There is a pressure to keep drag loading (also known as ballistic coefficient or sectional density) low during entry phase, and both low decelleration rates and low drag loading during parachute phase(s). This leads to an irritating scaling problem, which tends to volume limit Mars landers and force them into windows which consider arrival energy more than departure energy, having an effect on landed payloads beyond that of the lander payload fraction. For piloted Mars missions with payloads of over 20,000kg expected, the entire game of landing on Mars will need to be overhauled.

Mars Challenger seeks to launch into a 14-16km2/sec2 C3 arrival energy window to minimize arrival speed at the cost of a less efficient launch from Earth. The landers will hit the atmosphere at 6237-6395m/s, speeds greater than those of *Exploration Rover*.

Conditions which are consequences of other mission factors:
- The *Judith* is not a rover (improves payload performance)
- Multiple lander approach (required to enable a single launch mission and payloads small enough to enter without a big new lander development program)
- Increased arrival C3 energy (reduces; a 5m class booster is launching what is normally a 4m class mission)

Decisions made which should improve payload fraction:
- Hover crane approach: delivering *Christa* on its wheels (improves; employed on *Science Laboratory*)
- Having the payload computer control the cruise and landing stages, saving the mass of separate computers and batteries (employed on *Exploration Rovers*, taken to a greater measure on *Polar Lander*, which shared its propellant supply with the cruise stage; the author is expecting *Science Laboratory* to evolve shared power.) On *Mars Challenger*, the *Judith* ground operations computer set, the most powerful of the three systems, will control the cruise and can simulate landing scenarios in flight. *Christa*'s only computer set will control its landing, while the *Judith* ascent guidance computer set will control the landing of that stage, with the ground operations computers recording environments (including MARDI video).

3.3 *Christa* Lander

Christa is a class of rover in a niche between *Science Laboratory* and *Exploration Rover*. The lander uses the *Exploration Rover* heat shield, backshell (some modifications) and Rocket Assisted Descent (terminal stop) system. The airbag contact lander and Transverse Impulse Rocket System have been eliminated in favour of powered hover crane system similar to that envisioned for *Science Laboratory*. The job of the lander is divided into three phases:
- High energy aerodynamic
- Parachute
- Propulsive

By convention, these are respectively called Entry, Descent, and Landing, or EDL. The 0609 version of *Christa*'s lander, which used a scratch aeroshell and heatshield, has a mass of 923kg, a diameter of 2.8m, and a payload mass of 410kg. The 0610 version presented here shares the *Exploration Rover* entry mass of 821kg and 2.65m diameter. The unexpected increase of the payload mass to 420kg was the result of the scratch aeroshell's more conservative mass estimate. The following is the mass breakdown.

Table 3-1

Christa 0610 Component Mass Estimation Tool						
	Mass	Number	Total			
Christa Rover	420.00	1.00	420.00	Allocated	51.14%	
Net Landing Mass				**420.00**	51.14%	
Airbag Lander	0.00	0.00	0.00			
Gross Contact Mass				**420.00**		
Hover Propellant Tanks	4.54	2.00	9.08	PSI 80397		
Hover Motors	1.89	8.00	15.12	RRI MR-104		
Hover Propellant	26.00	2.00	52.00	Delta v (2200m/s Isp)	186.46	46.62
Hover Crane	30.00	1.00	30.00	See note below	Delta-v	Hover time
Hover Phase				**639.90**	77.92%	
Terminal Stop Motors	5.20	3.00	15.60	ATK/Elkton Star 8		
Terminal Stop Propellants	12.30	3.00	36.90	Delta v (2608 m/s Isp)	139.84	122.74
					Delta-v	Max Vt
Total At Terminal Stop				**706.80**	86.07%	
Parachute	17.40	1.00	17.40	See note below		
Parachute Sep	7.00	1.00	7.00			
Total At Parachute				**731.20**	89.04%	
Heatshield	90.00	1.00	90.00	*Exploration Rover*		
Backshell	128.10	1.00	128.10	Analysed from *Exploration Rover*		
Total at Entry				**821.20**	100.00%	

The mass of the parachute and empty backshell was estimated based on the analyzed performance of the terminal stop system and published terminal speed of an *Exploration Rover*. As the parachute does not need to be propelled by the terminal stop or hover system, conservatism asks that the parachute mass be allocated to the backshell if it is not known. The initial assumption of 0kg for the parachute did not work because the terminal stop rockets would not have been able to stop it. From *Spirit* and *Opportunity*'s successful landings, it is obvious that they can. 17.4kg is therefore the minimum mass of the parachute. The author expects that the actual *Exploration Rover* parachute is heavier, and the backshell is lighter.

The bridle systems used by *Pathfinder* and *Exploration Rovers* is a rudimentary form of hover crane, but does not offer enough stability for direct contact rovers like *Christa* and *Science Laboratory* (the airbag lander can dangle wildly on its single riser and get away with it.) The "30.00kg" does not reflect the actual mass of the hover crane because the *Exploration Rover* original's mass is not yet known. It reflects the addition of 30kg to the system for *Christa*.

3.3.1 *Christa* Entry

The *Christa* lander will pass 100km altitude at a speed of between 6237 and 6395m/s. If *Christa* enters the atmosphere about a minute after *Judith*, the planet will have rotated about 14km underneath the otherwise common entry track. The lander entry angle and timing are set so that the landing errors will be similar to that of *Judith*, and try to keep the landings within 5km, which the *Christa Rover* should be able to cross in 50 days at *Exploration Rover* speed. The landers will not be able to locate or communicate with each other at any phase during landing.

The ballistic energy entry will produce a profile like this:

- Initial entry is expected to last about three minutes and produce higher decellerations than *Judith* because of the steeper entry angle.
- The parachute is opened at a speed of about 450m/s at a considerably lower altitude than for *Judith*.

The brunt of entry heat is absorbed and then carried away by an ablative SLA-561 heatshield in the lander's base. Entry poses no new challenges for the *Christa Rover*.

3.3.2 *Christa* Descent

Figure 3-1: Star 8 motor used by both landers, has gone to Mars in the *Exploration Rovers* (credit: ATK/Thiokol)

It is expected that parachute opening for *Christa* will be about 2km lower than for *Exploration Rovers*. *Christa*'s hover stage will require the chute to be ejected just after the terminal stop rockets fire, lest it tangle the backshell or rover during the hover. The post-terminal loft of the solid rockets can be accommodated by timing the release of the parachute so that gravity accelerates the backshell to exactly the speed the terminal stop rockets need to bring the rover to a dead stop without a loft. Also, the 46 seconds of hover propellant available can accommodate a loft. The high drag of the backshell compared to the heavy rover will keep the hover crane risers from slackening during this brief period. If this is still a problem, the hover thrusters can be activated at low thrust.

- The parachute is opened at a speed of about 450m/s.
- The heatshield is jettisoned after the parachute reduces the speed to the point where dynamic pressure is no longer a threat to the directly exposed *Christa Rover* .
- The launch locks for the wheels are released, allowing the wheels to be deployed; the wheels will not actually deploy until terminal stop. The suspension and support for *Christa* as well as for *Science Laboratory* are more than they are for *Exploration Rovers* because ground contact will be transmitted directly through the wheels, like on an aircraft's landing gear. This offers better payload fraction than a separate lander shell.
- *Christa* is released from the landing stage on a long set of risers that stabilize the rover for landing.

To deal with potential timeline compression from the weather, all of the steps prior to *Christa* 's release are controlled by accelerometers with software control updatable during cruise. This capability was first used on *Exploration Rover Spirit*, when swelling of the upper atmosphere was detected prior to entry. Failed lander *Beagle 2* (same arrival window) did not have this capability, and while the cause of its failure is unknown, it may have been a victim of this Martian global weather phenomenon. *Christa*'s release will be controlled by radar altimeter.

3.3.3 *Christa* Landing (Propulsive Phase)
The propulsive phase begins with the activation of three ATK Star 8 high performance rocket motors. They are software controlled by parameters from the radar altimeter and visual Descent Imaging Terrain Avoidance (DITA, a step up from the Descent Imaging Motion Estimation Software, or DIMES,

first employed on *Exploration Rovers*, for *Christa*.)

The accelleration of the terminal stop system will provide gravity-like accelleration to deploy *Christa*'s wheels and lock them in the down position. Burnout of the terminal stop propulsion system should leave the rover about 15m above the surface with a slight positive vertical speed, or loft. The hover propulsion system (hydrazine monopropellant supplied by two PSI 80397 tanks, the same tanks as used on *Polar Lander*) is activated just prior to the terminal stop maneuver and is used to stabilize the landing stage during terminal stop propulsion operation. Software logic based on the *Exploration Rover* DIMES and MARDI acquired imagery will bring the rover to a horizontal stop above a point with no large changes in contrast immediately around or under the rover, especially within ones that a ring shaped (which could be large boulders or craters) and then lower the rover to the surface.

As *Christa* is controlling the landing stage, once the rover is released, the landing stage is no longer guided. A relay activates a clearance and crash maneuver when the rover is released. The landing stage is rotated so that it is aligned with a software calculated wind vector based on the horizontal motion given by the DIMES. This ensures that it will wind up downwind. This maneuver is also why this much smaller lander carries nearly the same amount of fuel as the *Judith* lander.

3.4 *Judith* Lander

Judith's lander uses a much more "conventional" approach than that of *Christa* by landing with the landing stage below the payload and intact after contact. This approach is employed because the lander backshell provides the structure for the enormous solar arrays needed for fuel plant operation, and for stability as the lander's mass increases by some 1675kg while resting on the surface. One of *Judith*'s articulated cranes (or robotic arms) is used to lift, place, and integrate the sample descent module heatshield after the samples have been loaded. The crane has other tasks, but lifting the heatshield is the one that will drive the ground settling and stability requirements. The landing sequence has three basic phases:

- High energy aerodynamic descent
- Parachute descent
- Propulsive landing

Entry, Descent, and Landing is often shortened to EDL. *Judith*'s lander has a mass of 1961kg, a diameter of 4.5m, and a rather conventional shape and appearance similar to that of a Hershey Kiss chocolate candy with the very top of it removed. The following is a detailed mass breakdown:

Judith 0710 Component Mass Estimation Tool						
24 October 2007						
	Mass	Number	Total	Non-Mass Parameter		
Judith Booster	586.24	1.00	586.24	Has its own study	32.77%	
Solar Power (inc. hinge/motor)	4.00	32.00	128.00	Power sp (W/kg)	25	
Ground Computer Set	5.00	2.00	10.00	Find a part		
Ground Battery Set	20.00	2.00	40.00	Energy sp (kJ/kg)	100	
Deck Structure	60.00	1.00	60.00	??		
Wiring	5.00	2.00	10.00	??		
Telecom System	5.00	2.00	10.00	??		
Helium Compressors	4.00	2.00	8.00	Air Compressor		
Helium Filters	5.00	2.00	10.00			
Helium Tanks	18.00	0.00	0.00	Now on Judith Booster		
Helium System Plumbing	4.00	2.00	8.00			

Hydrogen Cryocooler	10.00	0.00	0.00	No longer required		
G-M Cryocooler	4.00	2.00	8.00	Air Compressor		
Liquifier Heat Sinks	2.00	2.00	4.00			
Shared/LH2 plumbing	2.50	2.00	5.00			
LOX Plumbing	1.00	2.00	2.00			
Benzene Plumbing	1.00	2.00	2.00			
Radiators	10.00	4.00	40.00			
Air Compressors	4.00	2.00	8.00	See Chapter 6		
Air Filters	2.00	2.00	4.00			
Electrolyser	6.00	2.00	12.00	Based on Cryocooler		
RWGS/Fuel Reactor Package	5.00	2.00	10.00			
Compressed Air Plumbing	1.00	2.00	2.00			
Cranes	20.00	2.00	40.00			
Crane MAHLI cam	0.63	2.00	1.26	LPS XXXVI 1170		
Crane Drill	2.00	2.00	4.00			
Crane SC Handler	2.00	2.00	4.00			
Crane GP Grapple	1.00	2.00	2.00			
SC Crimp/RSW sealer	5.00	2.00	10.00			
Net Payload Mass				**1028.50**	57.49%	
Gross Payload Mass				**1202.66**	67.23%	
Min. Gross Landing Mass				**1307.54**	73.09%	
Hover Propellant Tanks	4.54	4.00	18.16	PSI 80397		
Hover Motors	1.89	12.00	22.68	RRI MR-104		
Hover Propellant	26.00	4.00	104.00	Delta v (2200m/s Isp)	168.37	42.09
MARDI Cam	0.60	1.00	0.60	LPS XXXVI 1214	Delta-v	Hover time
Hover Phase				**1411.54**	78.90%	
Terminal Stop Motors	5.20	8.00	41.60	ATK/Elkton Star 8		
Terminal Stop Propellants	12.30	8.00	98.40	Delta v (2608 m/s Isp)	175.75	158.65
					Delta-v	Max Vt
Total At Terminal Stop				**1509.94**	84.40%	
Parachute	76.00	1.00	76.00	*Science Laboratory*		
Parachute Sep	8.00	1.00	8.00			
Total At Parachute				**1593.94**	89.10%	
Heatshield	195.00	1.00	195.00	10% gross entry		
Backshell Structure	39.00	4.00	156.00	8% gross entry total		
Backshell Insulation	10.00	4.00	40.00	2% gross entry total		
Total at Entry				**1788.94**	100.00%	

The Gross Payload Mass includes several elements of the *Judith* system that are reused after the landing has been safely completed. One of these is the hover propulsion system tanks, shown below in Figure 3-2. This tank is purged and used for storing water produced by the fuel plant as an intermediate product.

3.4.1 *Judith* Entry

The *Judith* lander will pass 100km altitude at a speed of between 6237 and 6395m/s. The *Judith* lander has a lower drag loading than *Christa*'s lander, and also a different, taller shape. The entries happen within seconds of each other, and are carefully analysed to match arrival points and likely weather errors. The goal is to land the vehicles within 5km of each other. Even with the estimated landing zones about 100km long, it should be possible to achieve, because both lander will be entering through the same weather.

With an entry mass of 1961kg, *Judith* approaches the very edge of the capabilities qualified by the *Viking* program, which have been relied upon for all JPL Mars landers and continue to be relied upon in *Phoenix* and *Science Laboratory*. *Judith*'s lander has an unusually tall backshell with a shallower cone angle. The forward portion is exactly the same shape, but 1m larger than *Viking*. Even with this taller shell, there may not be enough room inside it for all the systems currently specified (see Chapter 8 for details.) The heavy landing propulsion and fuel plant systems are concentrated in the base of the lander for stability. *Judith*'s aeroshell is actually larger than *Science Laboratory*'s, as shown in Figure 3-1. *Science Laboratory* is heavier, and unlike *Judith*, controls its entry using aerodynamic lift.

The high energy phase will end at a higher altitude than for *Christa* with parachute deployment at a much higher speed. The landers will not be communicating with each other during entry.

3.4.2 *Judith* Descent

Figure 3-2: PSI 80397 *Polar Lander* tank used by both landers has gone to Mars on board the *Polar Lander* and *Phoenix* (Credit ATK/PSI)

The *Judith* lander will probably use the exact same parachute model as *Science Laboratory*, both of which intend to reach the propulsive phase at higher speeds than have previously flown. In order to stay within the specified budget, the parachute used must be of a design qualifiable by similarity to those altitude tested during the *Viking* program. To qualify a scratch parachute would be very expensive (however the application of modern CFD during the analysis phase should allow a single iteration of the hardware design to pass in such a case.) Fortunately, this parachute has been tested during the *Viking* program, although a smaller one was ultimately selected for the *Viking* landers. Even though *Viking* was relatively unconstrained with regards to cost, we are obviously getting our money's worth!

One very unusual feature of the *Judith* lander is that most of the backshell is retained. In this sequence, *Judith* begins to diverge from *Christa*'s methods more and more as the descent progresses:

- The parachute is opened at a speed of about 700m/s, the limit of the ringsail (or "disk-gap-band") type parachutes qualified under *Viking*. The higher C3 arrival speed will place the lander at a lower altitude at deployable conditions, and also because *Judith*'s parachute is small for the lander's size in order to take advantage of the two-phase propulsive landing, as well as for balance issues.
- The heatshield is jettisoned after the parachute reduces the speed to the point where dynamic pressure

is no longer a threat to the directly exposed *Judith* landing stage. The backshell structure is retained for use as structural support for solar arrays and enhanced stability for crane operations once they are deployed on the surface.
- The launch locks for the landing gear are released, allowing the gear to deploy. The gear will not actually deploy until terminal stop. *Judith* will employ the same sort of aluminum crush struts used on everything from *Lunar Surveyor*'s legs to the seat struts in the *Soyuz* and *Apollo* piloted spacecraft.
- At a software controlled radar altitude reading, the terminal stop maneuver begins.

The parameters used to activate these events are programmable during cruise, so that they can be adjusted on the basis of forecast Martian weather. *Beagle 2* did not have this capability, and while the cause of its failure is unknown, it may have been a victim of Martian weather, which the *Exploration Rovers* (same arrival window) were better equipped to deal with.

3.4.3 *Judith* Landing (Propulsive Phase)

The landing begins with the command to light the terminal stop rocket motors. The terminal propulsion system is currently eight ATK Star 8 solid motors. They are software controlled by parameters from the radar altimeter and visual DITA (Descent Imaging Terrain Avoidance), a step up from the DIMES (Descent Imaging Motion Estimation Software), first employed on *Exploration Rovers*.

During the solid motor firing, the hydrazine fuelled system has been operating at maximum duty cycle (*Polar Lander/Phoenix* thrusters are not throttleable, but are pulsed. If the MR-104 interim thrusters employed for this paper version of *Judith* actually are employed, the system can be throttled in 14.1% increments by turning thrusters on and off in pairs. *Christa* has only three pair and would be severely challenged under similar circumstances.) The accelleration force of terminal stop allows the landing gear to deploy and lock without any deliberate intervention from the lander avionics.

Shortly before the terminal stop maneuver ends, the parachute is jettisoned. An ATK Star 3 Motor (*Exploration Rover* part) may be used to ensure that it carries itself and the parachute clear of the *Judith* lander.

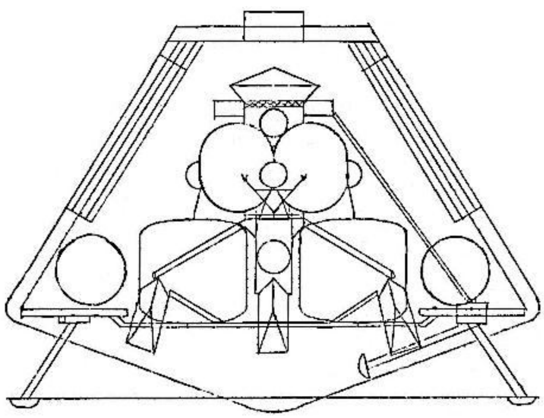
Using software and MARDI imagery, the lander avoids areas of high contrast, and the centers of circular areas of high contrast (boulders and craters) before setting down. *Judith*'s contact phase begins with a hover about 20m above the surface, or at the minimum resolution of the radar altimeter. The thrusters are cut off when compression of the landing gear is detected (indicating contact.) Once down, the backshell petals are immediately released, folded down and locked into the deployed position. This capability can right the lander should it topple at contact with the surface, and under normal circumstances will stabilize the lander against toppling later. Deploying the solar wings and fuel plant radiators will be automatic. The option is available to program the computer to decide when to open the petals based on instrumentation statuses and timings for dust mitigation.

3.5 Expected Direction

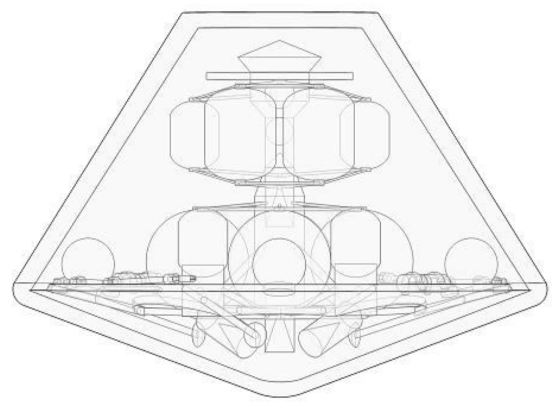
This, unfortunately, is not rocket science but much worse: it's landing on Mars, likely the most difficult planetary object in the solar system to survive impact with.

The *Judith* lander is seriously volume limited, with the booster itself like an elephant in the closet forcing everything else to fit in limited and inconveniently shaped envelopes. *Christa*, however is limited in mass, primarily because its subsystems are denser and because the lander itself is at the limit of the drag loading qualification set by *Exploration Rovers* for ballistic aeroshells. *Christa*, when refined, may turn out to be volume limited instead and may then become lighter.

Judith may lose fuel plant redundancy as the design is detailed. It has already lost a capability known as “Single Motor Inoperative Ascent”. This mode required higher thrusts in the ascent motors, and the ability to operate one ISRU plant at 50% available electrical power. It also required built in repair abilities and much more highly capable cranes. When studied in detail, the option put *Judith* over all of its budgets. Even if mass was no object, money is. Developing a lander capable of the repair activities the Single Motor Inoperative Ascent would require (removing the dead motor, hardware items on the damaged side that interfere with take-off, and perhaps righting the lander itself because of terrain interference) would cost hundreds of millions of dollars.



Mars Challenger Judith 0701



MARS CHALLENGER II Judith 0710

From these pictures, it is easy to see that the overall form of the lander and booster has not changed much, but have undergone a considerable degree of refinement. This trend is expected to continue should development efforts into *Mars Challenger* go on. The case of “refinement” is likely to remain in the landing systems especially, since they are heritage based and the most difficult system to save money on. Due to time constraints, very little of the landing propulsion system has been put into the 3D model.

Akin’s 3rd Law of Spacecraft Design: “Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.”

4 *Christa Rover*

4.1 Introduction

The author believes that obviously a sample return mission is useless without a return vehicle, but at the same time is pointless without surface mobility. The samples available for selection from a fixed lander are limited to the area accessible to its cranes. There is a circulating remark about *Viking* that if a dog had done its metabolic business just a few inches out of reach of the sample arm, there is nothing that *Viking* could have done to prove it was evidence of life. (*Viking*'s slow scanning facsimile cameras probably wouldn't have identified such an animal if that had happened!)

There is a large range of options for incorporating a rover on a sample return mission, from *Tooth*[2] style microrovers that went out and fetched samples (hockey pucks) without doing any science or selection on them, to large *Science Laboratory* flavour of rovers that would incorporate most or all of the mission's scientific instrumentation. For landing the rover, she can be launched with the booster and deployed after the fashion of the *Sojourner Rover* on the *Pathfinder* mission, or she can be launched on a different flight, perhaps even as a different mission. *Mars Challenger* has chosen a compromise.

As the *Judith Booster* concept developed, it was clearly a highly volume limited vehicle, and constraints regarding hydrogen storage favored turning the entire lander into a deep freeze for the cruise to Mars, except in small volumes where it couldn't be helped (landing propellant tanks, batteries, computers.) The support requirements for *Judith*'s launch gobbled up a lot of the room that was left, leaving no room for a rover or scientific instrument. The decision not to scale back to accommodate this effect is a result of the desire to spread the relatively inflexible cost of developing the seed hydrogen system and fuel plant over a larger sample payload, as well as the effect of scaling on thermal management. Why launch a *Discovery* class sample payload when you're already spending flagship level money on the technology development needed for it? As for thermal management, the amount of thermal energy entering the booster per kilogram of seed hydrogen will be even more for a smaller booster because heat transfer is area, not volume, dependent. Overall, it makes more sense to spend the same amount of money as a single launch non-ISRU sample return mission would require, but return more sample mass with it.

Judith also had a number of significant challenges with the science payload. First, it would be stuck at the *Judith* landing site, with big solar panels laid on the ground around the lander. This ground would preferably be a scientifically boring flat spot anyway. Another is the mechanical systems on *Judith* make it difficult to ensure an interference-free environment for instruments to operate. Even for cameras, the obstruction of the *Judith Booster* makes it impossible to take a full panorama with a single camera. There is too much of a chance of the booster crashing into or blowing off the camera when it took off, especially if it is of the Imager for *Pathfinder* (IMP) type of deployable mast. Finally, the lander is unlikely to survive *Judith*’s launch, scratching any extended missions afterwards.

The inability to place scientific instruments on *Judith* led to the decision to place the entire microbiology and geological instrument load on *Christa*. For a long time, *Christa* even carried the sample module. This turned out to be a dubious idea because it makes it quite difficult to design *Christa* with this item on her back. *Christa* will still carry a lot of the empty sample containers during the landing, if not all of them.

The dual lander conclusion results in an interesting organizational foible: much of the engineering is concentrated on *Judith*, while *Christa* is a heavily scientific, but otherwise run-of-the-mill Mars rover, if there ever was such a thing. Because of this, the scientific and engineering aspects are much more clearly delineated on this mission than most multiple payload missions, and it would therefore make an awful lot of sense to bid the entire rover out to principal investigators, perhaps even as a piggy back *Mars Scout*, *Discovery* or *New Frontiers* mission.

4.2 *Christa Rover* Constraints

The conclusion of the dual lander arrangement leads to a desire to model *Christa* in the *Mars Challenger* study to the level of ground contact, figure out what the constraints on her are and use them to estimate the performance abilities of the rover that will result based on what has flown before and what can reasonably be expected. This results in a disappointing performance, because conceptually *Christa* was restricted to “stock” *Exploration Rover* performance. As an engineering exercise, this is not so easy, but by restricting the rover of this paper to the power and range/day capabilities of an *Exploration Rover*, it is pretty much a guarantee that the real *Christa* will complete the mission with time to spare. Also, easier mission requirements are needed to reliably adhere to a reasonable schedule and budget.

According to Chapter 3, the total payload of the hover crane modified *Exploration Rover* lander is 420kg. The rover and everything she carries will need to fit in this mass. The following numbers incorporate the estimated sample module based on the peak performance of the *Judith Booster* to give a number for the actual rover:

420.0kg *Christa* at landing with all sample containers
424.3kg *Christa* with 4.32kg sample load representing maximum performance of *Judith*
416.4kg *Christa* with no samples or empty containers
174kg *Exploration Rover* for comparison
775kg *Science Laboratory* for comparison

The design point mission is that *Christa* lands so far away from *Judith* that there won't be a whole lot of time to do much after it arrives. This distance is based on 360 usable roving days at 0.1km per day, for a distance of 36km.

For a variety of reasons, mostly that she has the most precedent, the author has not done much work to characterize the design of the *Christa Rover*. However, the author has characterized a number of design requirements based upon the lander's configuration and mission requirements:

- The *Christa Rover* is packed very flat at entry. This, fortunately is not an unprecedented situation for the rocker-bogie suspension JPL family of rovers to date. *Sojourner* and *Exploration Rover* both had extreme volume constraints, and *Science Laboratory* is expected to as well in its efforts to stay within its lander, the largest that can qualified by similarity to *Viking*.
- The use of the Rocket Assisted Descent system of *Exploration Rover* heritage is expected to produce just under 3g of accelleration for 4.3 seconds. This offers plenty of energy for "gravity" mobility deployments. While this would be a first (if not employed on *Science Laboratory*), the technique is shown to be feasible by thousands of aircraft (including the *Shuttle*, although it has not employed it in flight) and is easily ground testable, especially if the mobility deployments can be performed at 1g. Qualifying the rover structure would add two centrifuge tests in the deployed configuration, one for *Christa*'s qualification model, and one for *Christa* herself. Still, centrifuge testing is considerably easier than for *Exploration Rover* and *Sojourner*, whose qualification model, named *Marie Curie*, was accidentally tested to failure (safety factor 1.58 at the failure; the test was scheduled to a safety factor of 2.0.)[3] *Sojourner* needed to survive 33g on any axis, and so was tested on the six orthogonal axes. *Exploration Rover* needed to survive 40g. While gravity deployment requires more centrifuge testing, it would save on pyros, motors, and the thermal/vac environmental testing of the same. Finally, in support of the gravity deployment strategy, our extant rocker-bogie rovers "stood up" by locking their front wheels and driving their back wheels, without any motors required in the actual suspension components.[4] During a non-environmental test, *Sojourner* was unable to stand because some of her engineering sensors still needed calibration. A technician lifted the rover by her suspension to complete the deployment, suggesting that *Sojourner*'s wheels can gravity deploy as designed.[5]

4.3 *Christa* Performance Requirements

The standard landing scenario has *Judith* and *Christa* landing 5000m distant from each other over terrain that can be traversed at 100m per day. This results in a 50 day trek and is within the capabilities of an *Exploration Rover*. Improvements are expected between the *Exploration Rovers* and the *Christa Rover*, even if the *Science Laboratory* rover is cancelled (*Science Laboratory* is pioneering the advances for hover crane landing, managed energy entry and long range mobility.) The longest allowable separation between *Judith* and *Christa* assumes that 360 days are available for traverse. This comes to 36km, which should be easily achievable as a 3sigma goal, even with ballistic landers.

4.4 *Christa* Instrumentation Requirements

Christa's instrumentation requirements are centered around a few focused objectives needed to ensure the success of the mission given the chosen ballistic landers. The author is certain that long range rover navigation can be developed and flight qualified more cheaply than highly accurate landers (and is more likely to recover some costs in a commercial technology transfer.) Also needed are instruments and tools for the evaluation, retrieval, selection, qualification (ASQ) and storage of samples for return. The instruments have four major objectives:

1. Provide information required for short term navigation ("hazard avoidance" in current parlance) using on-board autonomous modes
2. Provide information required for long term navigation as determined by the decisions of the operations team on Earth
3. Examine sample sites; retrieve, examine, select, qualify and store samples
4. Be able to record and track macroscopic events, such as dust devils, dust slides, and *Judith*'s ascent (currently beyond the capabilities of an *Exploration Rover*.)

4.4.1 Short Term Navigation

The *Exploration Rover* basic instrumentation is adequate for navigation and geological purposes, however, improved imagery would enhance the prospects of long range navigation. The possibility of navigating autonomously for the better part of a day at 400m/hr for a four hour shift, followed by an extensive visual investigation and download leads to the possibility of 1-2km per day long range traverses when assisted by an operations team on Earth.

The basic dead reckoning techniques, including inertial navigation, are woefully inadequate for rover navigation. A rover, at the least, needs to process images as she drives in order to avoid wiping out on impassible terrain. Both the lack of speed, and the chaotic environment make it impossible to mathematically model a navigation solution far in advance, such as for spacecraft, and to a lesser extent, aircraft.

Short Term Navigation is the designer’s term for what is currently called hazard avoidance, and is referred to this way because it will probably soon mean more than dodging rocks and avoiding cliffs, but actual visual reckoning and correction independent of inertial references and odometry.

The first short term navigation cameras on the *Sojourner* are unacceptably slow. To save power (the cameras used 0.75W), the imaging elements were read directly by the rover computer and took 53 seconds to process one frame. They had a mass of 0.04kg, and a 127.5 * 94.5deg / 768 *484 pixel field of view.[5]

The 'cams on *Exploration Rovers* were all built from a common imaging element and interface standard, but with different optics built around each type. There were two Navcams, six Hazcams, one DIMES camera, and three scientific cameras: the two Pancams and Microscopic Imager. These had a mass of 0.27kg and used 3W, and took 5.2sec to process a 1024*1024 pixel frame.[6]

The latest space qualified camera usable for rover navigation is the 1MP (1024*1024) Malin Mars Descent Imager (MARDI) camera[7], which is capable of taking a full frame every two seconds or one interlaced 256kP frame every half second. It has a power demand of 3.5W and a mass of 0.6kg. It has flown to Mars in the *Polar Lander* and another is on its way in the *Phoenix*.

The enhanced *Science Laboratory* version of MARDI is identical from the objective lens to the focal plane, but uses more modern electronics capable of capturing five 1600*1200 pixel frames each second and storing them in a 256MB cache.[8] These capabilities, combined with efficient visual reckoning navigation software, should be able to allow navigation at the power limited speed (in the ballpark of 1.5km/hr.)[9] Unfortunately, a press release during Round Two indicates that *Science Laboratory*’s MARDI has been cancelled.

For short term navigation, *Christa* would need four or six cameras, two forward, two aft, and one on each side if another type of turn/pivot safety "whisker" sensor will not do. The MARDI's are large, heavy, power hungry, and have a relatively narrow field of view. Carrying six or more of them would be very onerous. It is therefore likely that the MARDI would only be employed for forward navigation, and MER Hazcams (with upgraded electronics) would be used for side and rear coverage.

The unqualified concept for short term navigation is to have onboard software automatically set a path to follow that avoids hazards and moves efficiently towards the destination. The navigation software would rethink this path every few metres, much as a human driver unconsciously does. A better human comparison is the mogul skier bouncing down a chaotic pattern of packed snow piles on a steep run. A skier doing the run knows where he is going, but does not have every mogul planned out at the start of the run.

While driving, *Christa* picks out high contrast features, such as the edges of rocks or shadows in clefts, which are easy to find and track from frame to frame in high speed video. She would range them and predict a range rate and path in the camera frames based on her current driving plan. This allows the rover software to easily make corrections, thus reckoning visually, rather than inertially, much like a human would. Our mogul skier's semi-conscious immediate plan of reckoning is probably on the order of six metres of distance and two to three seconds of time, about what is called for when navigating through highly chaotic terrain at 30-50km/hr. The performance of *Christa*'s navigation need not be this drastic, but a speed of 1-2km/hr should be achievable in qualification runs. A challenge to expect in the development of such a solution is one common to our proverbial mogul skier: confusion caused by shadow and lighting. Driving near sunset and sunrise is therefore unwise, but is already unlikely due to power limitations.

4.4.2 Long Term Navigation

For long term navigation, there would be dual purpose instruments used both for science and navigational purposes. The *Exploration Rover* Pancam is adequate for the task, but the new Malin MastCam for *Science Laboratory* would be preferred. The Mastcam is capable of taking video and so can watch high speed macroscopic events. This capability is needed for *Christa* to record and track *Judith*'s ascent. The public, as well as the engineers, are probably going to want a video of this spectacular event.

Compared to the Pancam, the Mastcam is a monster, with a mass of 1kg and power demand of 13W when taking images (about quadruple those of a Pancam.) It has a still resolution of (1600*1200), a video resolution of 1280*720, a 256MB RAM buffer, an 8GB Flash buffer, telephoto zoom and focus,[10] basically as good as the latest high-end consumer video cameras.

Whatever cameras are used for science observations and long term navigation, the process for *Christa* in a long range roving mode (i.e. getting to *Judith*) would look like this:

- *Christa* receives a command sequence from Earth, which includes a goal or series of goals for final destination waypoints, and any local orbital map updates needed by her navigation system for the day's driving (assuming they are supported by the navigation system.)
- *Christa* sets off on the day's navigation, driving according to her abilities until she either has reached her destination, is stumped on how to get any closer to it, or reaches the scheduled time of day to stop driving.
- Along the way, *Christa* uses short term navigation images to correct her reckoning and avoid hazards.
- Once *Christa* has stopped driving, she executes an imaging and science sequence, which may include the automatic deployment of her instruments on a nearby rock or unusually colored patch of soil. This sequence will need to be modified on an occasional, rather than daily basis, to accommodate a specific target, or a strange change in the shape of the horizon, such as a nearby object, or more distant crater rims or tall hills.
- The sequence data is downlinked in the evening, just after the "night shift" operations team begins its duties on Earth.
- The operations team develops the command sequence for the next day.
- Rinse and repeat. It is quite likely that most of the housekeeping and science command scripts will be recycled and only slightly modified for the next day.

In a scenario where forward visibility is poor due to terrain blockage and a significant increase in mobility over the *Exploration Rover* standard is needed, the ability to program *Christa* with orbiter mapping data (from such instruments as MOLA, MOC, HiRISE, and MARCI) is a must. In this manner, *Christa* can expect to see a feature much as a human expects the next town or gas station, and use it to correct its overall navigation once it is in view.

4.4.3 Sample Handling

This section provides only summary information. Further information is provided in Chapter 7.

Sample handling and qualification stem from the viewpoint of protecting Earth's biosphere from potentially harmful Martian life. The approach to dealing this is to equip *Mars Challenger* with sufficient instrumentation to detect life that may be harmful (Astrobiological Sample Qualification, ASQ)

Christa's biological instruments and investigations are going to be applied both in active in-situ investigations searching for life biology, and in qualifying samples of geological or paleontological interest as safe for return to Earth. It is likely that *Christa*'s instruments will also look for escaped Earth life to determine if our planetary protection policies are (or were) adequate.

The author defines the *Laboratory* instruments as ones that examine samples in a controlled environment internal to the spacecraft carrying it, in this case, the *Christa Rover*. The central instrument is the CIMBRLI ("Kimberly") environmental slide microscope. Experiments attempt to produce a response in a sample detectable to instruments. *Laboratory* investigations test a specific hypothesis on a particular sample, setting requirements for and adhering to the constraints of the experiments and instruments carried. The only investigation examined in this document is that of Astrobiological Sample Qualification (ASQ), which is to ASQ how likely a sample is to contain undetected life which is harmful to Earth's biosphere, a rather encompassing objective. There are probably hundreds of specific investigations that could be performed, many of which are needed for flight qualification.

The *Christa Laboratory* promises to be a small nightmare for engineering, as the internal handling system, chambers, and consumables are very complex. To prevent spurious results, every last Earth microbe must be destroyed or expurgated from the *Laboratory* items which come into contact with Martian samples. The difficulty of this was demonstrated by *Apollo XII*, which brought back a *Lunar Surveyor* camera for examination. After sterilization efforts, and years in the vacuum of space, the sealed unit still had viable Earth microbes inside it...ones that could not have been introduced by the astronauts as it was hermetically sealed prior to launch and was not disassembled until after it got back. Such stringent sterilization requirements may affect the launch vehicle selection, as some pads and fairings have better accommodations for such requirements than others.

Lab Instruments:
- CIMBRLI slide microscope: *Challenger* Imager for MicroBiological Research and Laboratory Investigations.
- Gas Chromatograph
- Mass Spectrometer (distinguishes label isotopes, such as Carbon-14, Potassium-40 and Argon-36.)

Lab Experiments:
- The Grinder (grinds samples in an inert gas environment to allow analysis of unoxidized material)
- Sample Sterilizer (used for experiment control samples)
- Medium Growth and Release Kit

The robotic arm for *Christa* needs to be much longer than the *Exploration Rover* equivalent. *Christa*'s sample container ports will be clustered around the end of the rover which has the arm, impeding the placement of solar panels and suspension components. Even so, the arm will need to reach all of them. *Christa* doesn't need to carry all eighteen sample containers, but it is a good idea. The heritage of the *Christa* arm tools is being eroded by program changes to *Science Laboratory*, some of which indicate a breakdown in the relationships between Jet Propulsion Laboratory and the contractors for the tools. The Mini Corer and the Rock Abrasion Tool have been cancelled for *Science Laboratory*, despite the fact that two of the latter have flown: one on each *Exploration Rover*. The Mini Corer has been deleted from *Christa*'s baseline as it is a difficult system and would be expensive to develop without the heritage from *Science Laboratory*.

Arm Instruments:
- Alpha/Proton/X-Ray Spectrometer (APXS)
- Mossbauer Spectrometer (not in baseline)
- Malin MAHLI (not in baseline)

Arm Tools:
- Rock Abrasion Tool (RAT)
- Mini Core Drill (not in baseline)
- Bucket
- Cleft Scraper
- Sample Container Grapple

Deck/Mast instruments:
- MastCam (mast)
- Thermal Emission Spectrometer (mast/periscope, not in baseline)
- ChemCam (mast, not in baseline)
- Weather Laser (deck)
- Weather Station (deck)

It is quite obvious that *Christa* will not be able to carry all desired instruments, as totaled, they would exceed the science payload of *Science Laboratory*, a craft almost twice as large and making a bigger leap over *Exploration Rover* in science payload to rover mass than it is in its lander performance.

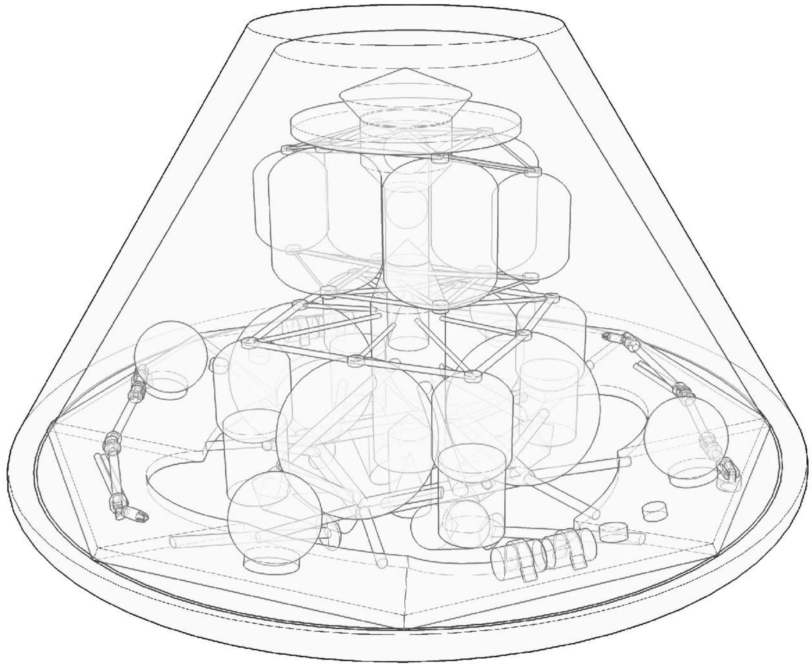
Scientific instrument mass mitigation details are in Chapter 7 (more specifically section 7.4). There are options for reducing camera mass that would sacrifice *Christa*'s mobility performance. It should be possible to provide adequate mobility performance with *Exploration Rover* cameras, especially since *Christa*'s basic mission is to match, not exceed *Exploration Rover* mobility. With improvements in the electronics, *Exploration Rover* camera optics and imaging chips should perform well enough to drive at power limited speeds. The best mass saving option that would still retain adequate performance is to read imaging data directly into one electronics box from several different cameras. If this box were equipped with the ability to receive commands from navigation software to bin only the areas and resolutions needed for short range visual reckoning, it may be possible to save image processing power, thus reducing electronics mass and power use further for a given speed. *Exploration Rover* itself, with a common electronics module for all of its cameras, is half way to achieving this goal already.

4.5 Unique Equipment for Sample Return

Christa begins the process of sample return in its science operations phase. As such, it carries many of the empty sample containers. *Christa* will be able to qualify sample sites and do all the necessary destructive tests on qualification samples, while *Judith* sensors and MAHLI cameras will conduct sample "acceptance". The primary reason for the latter is to be able to reconstruct sample evidence damaged during the trip to Earth by using pre-launch images from *Judith*.

5 *Judith Booster*

Figure 5-1 The *Judith Booster* (version 0710)



5.1 Introduction

The *Judith Booster* is the centerpiece of the *Mars Challenger* mission. In trading cost, reliability, and performance considerations, it was realized that no matter the budget of *Mars Challenger*, the reliability of the *Judith Booster* could not be compromised. By the phase of *Judith Booster* ascent, the public excitement for this first ever ISRU interplanetary ascent could have been building up for two years. *Judith* must work. *Judith* is also at the top of the mission, with each kilogram of hardware translating into four or more under the fairing of the booster from Earth, so compromising performance for cost was not an option either. How then can the mission stay under the contest budget cap, be perfectly reliable, and return lots of samples?

Judith version 0710 is the main difference between *Mars Challenger* and *Mars Challenger II*. The development of the original concept stayed with oxymethane throughout. Between the contest Rounds One and Two deadlines, the author decided upon the use of oxybenzene for a human mission design. In August of 2007, oxybenzene was also selected for *Judith* in an effort to dovetail the ISRU and propulsion analysis. Benzene is an aromatic hydrocarbon, ring shaped with the formula C_6H_6. Because of the reduced hydrogen:carbon ratio, the hydrogen needed is seriously reduced. The price for this is increased combustion temperature, reduced specific impulse, and unequal volumes of fuel and oxidizer. The oxybenzene propulsion approach used for *Judith* is designed to have minimal impact on the original design, and is likely to change as the concept is further pursued.

5.2 *Judith* Description

Judith is a *booster*: it is a launch vehicle designed to launch a payload from Mars to an escape trajectory with a C3 energy of $7 km^2/sec^2$, which is not a job for a "spacecraft" in any traditional sense of the word. The hardware design and operations will be built around the premise of booster operations, rather than spacecraft operations.

Judith ascends from Mars using two stages, both of which use pressure-fed propulsion systems burning locally supplied oxybenzene propellants at a mixture ratio of 1.5:1 and a chamber pressure of 145 psia (1000kPa). It is intended to launch a sample module with a complete mass of up to 63kg from the surface of Mars. The following table describes the mass estimates used to validate the booster's performance.

Added to *Judith* for *Mars Challenger II* was a properly analyzed pressurization system. Helium pressurization is used for both stages. The first stage uses four 40L composite overwrapped pressure vessels which are basically cut down versions of PSI's 80446 helium tank, veteran of the A2100 commercial satellite and MESSENGER mission to Mercury. The second stage uses two. The system was sized using a real gas properties tool provided by the University of Idaho. The helium is assumed to conform to LOX temperatures once injected into the LOX tank, which probably makes this system much larger than it needs to be. The impact of this system is what caused most of the drop in performance from *Judith* version 0702.

Once launched, of the structures of the booster hang from a central tube 450mm in diameter for all of the separating interfaces, and narrowing to 250mm between the second stage tanks. Before launch from Mars, the booster will be cantilevered from the bottom plate inside the lander's equipment deck. This is probably adequate because when launched from Earth, when the most severe loads environments will be experienced, *Judith* is almost completely empty. The structures depicted will probably stabilize better upon entering the Martian atmosphere, the second most severe loads environment (not by much.) Finally, during ascent from Mars, the air is much thinner and induced accelerations are very low compared to Earth launch and Mars entry environments. This is not to guarantee that the flight design is depicted, since a detailed analysis of whether these structures are actually adequate has not yet been performed.

Table 5-1

Judith Booster Component Mass Estimation							
19 October 2007							
	Number	Each	Landing	Launch	**Landing**	**Launch**	**Burnout**
Sample Module							
Sample Module Heatshield	1	10.00	10.00	10.00			
Sample Module Backshell	1	10.00	10.00	10.00			
Sample Containers Landed	18	0.20	3.60				
Sample Containers Launched	18	0.20		3.60			
Samples	18	0.24		4.32			
Total					**23.60**	**27.92**	**27.92**
Cruise Stage					**Performance**		
RCS Props	1	4.50	4.50	4.50			
Props					**4.50**	**4.50**	**0.05**
RCS tank	1	1.50	1.50	1.50	Isp	2200	
RCS system	1	2.00	2.00	2.00	Delta-V	144.84	
Solar Power	1	4.00	4.00	4.00			
Batteries	3	2.00	6.00	6.00			
Computers	3	2.00	6.00	6.00			
Guidance Instrumentation	3	1.00	3.00	3.00			
Separation System	2	5.00	10.00	10.00			
Remaining Structures	1	5.00	5.00	5.00			
Total					**42.00**	**42.00**	**37.55**
Stage Payload					**23.60**	**27.92**	**27.92**
Stack Mass					**65.60**	**69.92**	**65.47**
Second Stage							
LOX	2	233.70		467.40			
Benzene	2	155.80		311.60			
Props					**0.00**	**779.00**	**7.79**
Hydrogen Seed	4	14.36	57.44				
Ascent Tanks	4	11.50	46.00	46.00	**ISRU%**		
Insulation	4	3.00	12.00	12.00	**7.374%**		
Top Structures	1	5.00	5.00	5.00	Isp	2984	
Bottom Plate	1	10.00	10.00	10.00	Delta-V	4379.06	
Batteries	4	2.00	8.00	8.00			
Separation Systems	0	5.00	0.00	0.00			
Thrust Tube	1	10.00	10.00	10.00			
Motor	1	11.50	11.50	11.50			
Fixed Motor Mount	1	2.00	2.00	2.00			
Reaction Control System	0	4.00	0.00	0.00			
Hydrazine RCS props	0	4.50	0.00	0.00			
Hydrazine Tanks	0	1.50	0.00	0.00			
Helium Tank	2	6.80	13.60	13.60			
Helium Charge	2	17.60	35.20	35.20			
Total					**210.74**	**932.30**	**161.09**
Stage Payload					**65.60**	**69.92**	**69.92**
Stack Mass					**276.34**	**1002.22**	**231.01**

First Stage							
LOX	2	397.10		794.20			
Benzene	2	264.70		529.40			
Props					**0.00**	**1323.60**	**13.24**
Hydrogen Seed	0	25.69	0.00				
Ascent Tanks	4	13.20	52.80	52.80	**ISRU%**		
Insulation	2	5.00	10.00	10.00	**0.000%**		
Base Plate	1	30.00	30.00	30.00	Isp	2941	
Thrust Tube	1	15.00	15.00	15.00	Delta-V	2021.86	
Outboard Motor Head Cage	4	2.00	8.00	8.00			
Outboard Motor Thrust Angle	4	5.00	20.00	20.00			
Outboard Motor Wiggle Angle	8	1.00	8.00	8.00			
Helium Tank	4	6.80	27.20	27.20			
Helium Charge	4	17.60	70.40	70.40			
Outboard Motor TVC Actuators	4	1.00	4.00	4.00			
Centre Motor Mount	1	2.00	2.00	2.00			
Separation System	1	5.00	5.00	5.00			
Motors	5	11.50	57.50	57.50			
Total					**309.90**	**1633.50**	**323.14**
Stage Payload					**276.34**	**1002.22**	**1002.22**
Stack Mass					**586.24**	**2635.72**	**1325.36**
Judith Booster Total					**586.24**	**2635.72**	**N/A**
					ISRU%	**2.732%**	
Ascent Delta-v					**6400.92**		
Ascent Payload					**7.92**	**0.30%**	

5.3 *Judith* Performance

Normal Ascent: 4200m/s initial ascent 2200m/s second maneuver: 27.92kg Sample Module (7.92kg of sample containers)

Judith's current performance were drawn up using the following tools and assumptions:

- The motor concept was evaluated using the Air Force Specific Impulse Calculator, AFAL, a one dimensional isentropic flow simulator developed, at least in part, by Curtis Selph independently of the After Columbia Project. The principles are and described in detail in Rocket Propulsion Elements, 7th edition by George P. Sutton and Oscar Biblarz (John Wiley & Sons, 2001) Chapters 3 and 5.
- Benzene was added to the AFAL propellant database from data contained in the 87th CRC Handbook of Chemistry and Physics. Since the values for formation enthalpy in this handbook tend to be higher than those in the AFAL database, the Isp may be slightly optimistic.
- The ascent trajectory to Low Energy Orbit was developed using a two degree of freedom simulator called TASS, for Trajectory Analysis Spreadsheet, a tool developed by After Columbia. There was insufficient time in Round Two to repeat the analysis with the oxybenzene propellant and blowdown effects.
- The injection maneuver was developed using the vis-viva energy formula with a generous assumption for maneuver impulse loss.

5.3.1 Normal Ascent Operations

Judith takes off with all five motors of the first stage burning. The first stage depletes after about 4 minutes (228.8sec assuming the chamber pressure is regulated at a constant 145psia, the blowdown effect of the pressurization system has not yet been analyzed.) The second stage uses one motor and operates for about twelve minutes (673.3sec assuming continuous full pressure.) The second stage conducts two maneuvers. The first inserts the booster and sample module into a low energy parking orbit, while the second, much shorter maneuver, allows the sample module and cruise stage to escape Mars and head back to Earth.

5.3.2 Ascent: Single Motor Inoperative (SMI)

Judith had a Single Motor Inoperative mode until version 0611. Detailed study over the course of *Mars Challenger* revealed that this capability was simply too expensive and risky to implement. The required power redundancy and high thrust motors made the lander too massive. There were also large operational problems that the cranes would need to be designed for, making them heavier. The biggest problem was that the booster would take off sideways into the dead motor. It is obvious from Figure 2-1 that deck equipment impedes such an approach, and the remaining motors stand a good chance of hitting the deck itself. To compound the volume problems, the motors need to gimbal an awful lot to accommodate the squat booster's center of gravity and turn to the slanted ascent attitude, even though it can be controlled by off-loading the tanks on the side of the dead motor. They started bumping into the first stage tanks and wanted to be lower and further outboard in the booster design, causing them to bump into the heatshield and either the ground or landing legs (at least the designer could have chosen which!)

Version 0701 cancelled SMI and tucked the motors further up beside the tanks where they are now.

5.3.3 Rescue From Mars LEO

The possibility of launching *Judith* "merely" to Low Energy Orbit (LEO) over Mars is likely if either sample qualification fails (life is discovered), or *Judith* does not have enough performance to return the desired sample payload to Earth. In this contingency, a mission to rescue the sample module from Mars orbit is undertaken. Depending on the circumstances, it may need to sterilize the module and cruise stage, or merely complete the ejection maneuver to return it to Earth, most likely both if such a mission is needed.

5.4 Propellant Tank Development Process

Note: Illustrations and photographs that do not have endnote references came from the Tank Data Sheet for the tank illustrated, which are available at www.psi-pci.com.

Mars Challenger had hoped to employ existing propellant tanks for this mission. Pressure Systems Incorporated (now part of ATK) has been building tanks since 1963 and has a huge catalog of tanks that may be considered. PSI tanks come in three flavours:

Figure 5-2: all titanium construction (typically hot forged, solution treated, quenched and aged 6Al-4V alloy, which if possible, is weld stress relieved after assembly.) This particular tank is PSI 80375, four of which were used in *Judith* 0702's second stage. It is currently used as the main fuel tank for the *Iridium* phone satellite, where it is launched filled with hydrazine. For *Mars Challenger*, it was launched empty from Earth and filled with propellant after arriving on Mars.

Figure 5-3: full carbon fibre reinforced composite overwrapped titanium liner, a method currently exclusive to pressurant tanks. The welded titanium liner provides the hermetic seal, while composite overwrap bears the pressure stresses. This example is PSI's 80446, which is used as the main lander helium tanks for *Judith*. The lander's cryocoolers, and booster's smaller bottles are charged from these tanks. The second stage of *Judith* 0710 uses tanks of similar appearance to this one, but with the operating pressure and actual size somewhat larger than the titanium tank shown in Figure 5-2. These second stage tanks carry the hydrogen, and as a result, require an aluminum liner since titanium is severely embrittled in the prescence of hydrogen.

Figure 5-4[12]: titanium construction with carbon fibre composite overwrapped cylinder and all-titanium heads. This method is exclusive to relatively large, moderate pressure tanks with cylindrical sections of significant length. The heads are made of hot forged, solution treated, quenched and aged 6Al-4V titanium alloy (one tank uses spinformed heads), and the cylindrical liner is made of annealed titanium sheet at the same thickness as the heads. This provides a robust hermetic liner, upon which is laid the composite overwrap which bears the pressure stresses of the cylindrical section. This example is the enormous PSI 80434, the largest tank made by PSI.

Unfortunately, titanium is not compatible with hydrogen transport because it is vulnerable to embrittlement. Because of this, and the heavy mass of *Shuttle* and *Apollo* dewar type hydrogen tanks, entirely new tanks have to be developed from scratch and qualified for this mission. A fully composite overwrapped aluminum alloy (exact composition has not been selected, but it will be selected for cold workability and used in the annealed condition) liner with a diameter of 625mm, a length of 780mm, 2:1 oblate ellipsoidal heads and a capacity of 216L was specified. *Exploration Rover* had specified small tanks of this type for its cruise stage hydrazine. It is a pity they didn't work. They failed most likely because they were welded using a tungsten inert gas process[14], rather than the more reliable (for aluminum) friction stir method. This tank is small enough that fifth tank can fit on the cruise stage to accommodate boiloff losses during the outbound cruise.

5.5 Motor Development Process[15]

Currently the motor is at the development phase of a one-dimensional isentropic flow study with no efficiency factors placed on it. The reason the simulation numbers were accepted at face value is because the differences which affect efficiency tend to cancel each other out. The AFAL simulation tool can get exhaust compositions wrong, and this is especially the case with monopropellants. Hydrazine performs very badly in AFAL when compared to real motors because it decomposes into too much hydrogen and nitrogen, and not enough ammonia. Bipropellant numbers are more reliable.

- thermal losses to the chamber walls, tends to decrease performance
- ablative liner mass flow, tends to increase performance
- pressure-fed, no turbine or parasitic losses, no effect on performance vs. AFAL result, but most reference engines are pump-fed
- exhaust composition is modeled as frozen at the throat, in reality it works closer to equilibrium in the nozzle, especially in high expansion ratio motors
- AFAL propellant database uses enthalpy of formation numbers which are often quite a bit lower than the actual values. AFAL LOX, but CRC butane was used in this simulation.

The pitch or yaw moment caused by a failed motor acts as a backup technique for detecting a motor failure and for sorting out bad instrumentation data. This is acceptable in Mars' low gravity and thin air and with *Judith*'s powerful guidance system. This is not an option for Earth launch vehicle first stages because aerodynamic forces would tear the booster apart.

The motor selected is a pressure-fed 3450N (774.9lbf) unit operating at 145psia (1000kPa) chamber pressure, with a nozzle exit/throat area ratio of 25:1 at a specific impulse of 2984m/s (304.2sec) in space, and 2941m/s (299.8sec) on the Martian surface. This is a very small motor by booster standards and should be easily developed. To the best of the author's knowledge, no oxybenzene motors exist, but the Marqhardt R-40A hypergolic motor used as the *Shuttle*'s RCS thruster is closest in size. An ablative liner is used because the motor is between the minimum size where regenerative cooling is effective (approx. 300kN) and the maximum size where radiative cooling works (estimated at about 500N for oxybenzene.)

The motor development program can proceed from where it is here in the following steps:

- Detail drawing of the flight motor chamber and nozzle's axisymmetric profile by analysis
- Detail drawing of a test motor to operate at the testing environment pressure (i.e. sea level, test facility, or testbed aircraft altitude) using the same methods
- Detail drawing of a suitable injector
- 2 and 3 dimensional CFD modelling of the above, with potential modifications as required
- Construction of a heavyweight ground test version with adequate margins to survive many starts (including rough starts) and hours of operation, with a flange bolted interface to the injector, thus allowing many iterations of the injector design if required. It would also be able to survive such undesirable effects as combustion vibration, combustion instability, hard start, chuffing, and intentional upsets of the exhaust flow to test recovery properties. It will probably be externally cooled to save on ablative materials.
- Feedback of heavyweight ground test results into the flight motor design stress analyses to optimize the design to handle flutter and transient loads
- Construction of a flight-weight test environment version
- Testing of the test version to verify flutter and transient performance. The preferred testing environment is a high altitude aircraft, such as *Proteus* or *White Knight* (Scaled Composites aircraft), which can easily accept slung pods with motor and propellant, as well as the small thrust loads of this motor.
- Construction of a flight build version for ground environmental testing. The nozzle would be cut down if needed for functional testing after completion of qualification environmental tests (the accelerations and vibrations of launch from Earth and landing on Mars, plus 50%).
- Optional: Construction of a flight build motor, including the mission nozzle, and an upper stage for it to operate (can be the mission build *Judith* second stage) that can be used to boost a small satellite willing to take the risk, say from a *Falcon 1* or *Pegasus* booster. In this manner, other mission hardware can be exposed to space. Most appropriately, a university-based satellite (or perhaps several based on the CalPoly *CubeSat* standard) intended for the exploration of Earth's charged particle belts would be launched, as the charged particle radiation environment is one of the most difficult to test on Earth. It is likely that several appreciative *CubeSat* satellite operators could be found for this type of launch. A reasonable charge would defray, but not offset the cost of such a launch.

5.6 Guidance Development

The performance of the *Judith* guidance system is absolutely paramount to the success of *Mars Challenger*. It faces the following major challenges beyond what normal boosters face:

- It has to be tiny. Even if a booster of this small size were launched from Earth, the mass of a typical guidance system would be onerous, so much so that versions of *Delta II* and *Taurus* still use unguided spinning solid kick stages. The estimate is 2kg based on currently available embedded industrial computers.
- It has to be fault tolerant and reliable, more so than on Earth based boosters, where there is local and radio access to the guidance system. These are not available on Mars. Three computers are provided.
- It has to be separate from the ground operations computers. While always the case for Earth boosters, this is unexpected for a spacecraft.
- It has to be testable after landing on Mars. The ground operations computers need to be able to simulate all practical booster and environmental inputs to the guidance system while on Mars during a simulated ascent, especially in case irreplacable instruments fail during the mission.
- It has to be programmable. Many of the hardware failure scenarios require system flexibility. It is likely that few of the modes for all survivable hardware failures can be qualified prior to launch from Earth under any practical shedule and budget, and it is also likely that there are unknown survivable hardware failures,

and (like *Apollo XIII*), there are failures thought to be unsurvivable that later prove to be survivable after all (i.e.: Single Motor Inoperative, Part Deux.)
- It has to be sterile. Sterilization techniques have caused component level failures in flight hardware before, and was a major factor in the failure of *Ranger* series spacecraft back when the techniques of planetary exploration were new. Inspection is no longer possible once the unit is sealed, and this fact is one of the reasons it has to be fault tolerant and testable after landing. One possible idea is to use a pressure jacket. The case itself would be evacuated, while the pressurized jacket would ensure there is a negative internal pressure, even in the vacuum of space. This would prevent any microbes inside the case from getting out through leaks, probably for several years.

5.7 Launch Support Requirements

The basic launch support requirements of hardware integration (looked after on Earth) and propellant delivery to the launch site are discussed elsewhere. This section is dedicated more to the information, and testing requirements to support *Judith*'s launch from Mars. Add to this that there will probably be an enormous *Judith* fan base monitoring preparations via the Internet (After Columbia Project already has a great deal of experience doing this.) Not only would this create a public presence, it also provides a potential resource that can be utilized to identify and attack problems, such as fine examination of an autonomous series of high resolution pictures taken by the *Christa Rover* during a walk around inspection (this is a two-edged sword of course, serious input needs to be sorted out from uneducated ramblings and those seeking their two minutes of fame without doing any real work.)

5.7.1 Information Requirements

The *Judith*, as a booster, must be checked out like one. Like boosters on Earth, it will experience Flight Readiness and Launch Readiness Reviews, and be given a go for launch after mission controllers have been polled. The main difference is that the block house is about a billion times as far away. The following phases of the mission can introduce survivable damage to the *Judith* booster, most likely survivable if it is known and quantified. The only space mission treated like this so far is the *Shuttle*, where a similar process is used to evaluate the *Orbiter*'s readiness to descend back to Earth.

- Launch from Earth
- Earth/Mars cruise anomalies
- Landing on Mars
- Fuel Plant operations
- Sample integration operations
- Martian weather

The following general types of information need to be gathered while on the surface. Following in parenthesis is whether or not it needs to be gathered in real-time.

- Synoptic data of ascent simulation run (delay acceptable)
- Ascent simulation run status (real-time)
- Booster health parameters (some real-time, some delayed)
- High resolution data of ascent control mechanism checks, such as valves, gimbals (delay acceptable)
- High resolution weather event information (delay acceptable)
- High resolution photographs of the landing site (delay acceptable)
- High resolution inspection photographs and audiographs (delay acceptable)
- Data about samples that may affect *Judith* performance (delay acceptable)
- Fuel plant operation status (real-time and/or alarm modes)
- Fuel plant operational engineering data (delay acceptable)
- Fuel and oxidizer loading status (real-time and/or alarm modes)
- Fuel and oxidizer load detailed data (delay acceptable)
- Post-propellant load photographs and audiographs (delay acceptable, but real-time and/or alarm modes during inspection process.)

5.7.2 Support Requirements for the First Launch From Mars

Excepting propellant manufacturing and fuelling (which has its own chapter), the *Judith* may be rather demanding of other supporting hardware, most of which are required for Earth-based boosters. These include:

- Inspection points; getting cameras and other sensors into places that are not normally visible, such as inside a motor or along propellant lines in the *Judith* structure.
- Hazard clearing; perhaps digging out a drift under a nozzle is required to provide ground clearance for motor start, or perhaps *Judith* and its lander are askew on the surface and need to be brought closer to the vertical.
- Sample integration; getting the samples into the booster
- Special non-destructive evaluations; if composite overwrapped tanks are ultimately chosen, it would be useful to rule out liner/overwrap separation. Also, by using ultrasonic sensors, it may be possible to much more accurately determine the propellant quantities prior to launch.
- Pressurant; this service is backwards from the conventional arrangement for boosters. *Judith* provides helium to the fuel plant from tanks on board the booster.

5.7.3 The Cranes

Two "big" cranes are envisioned, each capable of lifting 20kg at a maximum height of 5m and a maximum radius of 5m (across the lander plus 1.5m.) To accommodate this, they are articulated with two lengths 2.5 metres long and are budgeted at 20kg each. They are required for:

- Inspecting the *Judith Booster* for damage
- Lifting the sample containers to the top of the *Judith Booster*
- Moving the heatshield of the sample module out of the way so samples can be integrated

The ones depicted are smaller than these due to time constraints on analysis and 3D modelling.

5.7.4 Instrumentation

Each of the *Judith* cranes are equipped with the following instrumentation.

- Microscopic Imaging (Malin MAHLI): An instrument currently intended for use on *Science Laboratory*, this instrument, ironically, is insufficient for *Christa*'s scientific needs. It is however, perfect for inspecting the surface of the *Judith Booster*. It is equipped with automatic focus and Z-stacking/range mapping and capable of a maximum resolution of 12 microns/pixel.
- ULTSI: <u>U</u>ltrasonic <u>T</u>ank and <u>S</u>tructure <u>I</u>nspection: An ultrasonic transponder which will be able to test for propellant quantity, pressure (as a sanity check for suspect pressure transducers), and gross tank defects. It may also double as a seismograph.

5.7.5 Tools

The cranes are required during normal missions to unpack the *Judith Booster*. The booster will be optimized to ascend from Mars, but on the way there, ascends from Earth inverted and descends to Mars rightside up at about triple the load factors that will be experenced during the ascent it was designed for. The booster may be packed into the lander with dunnage structures analogous to the stryrofoam standoffs television sets are packed into their shipping boxes with. This is unlikely, since the booster is launched empty (even a good proportion of the empty sample containers will be on *Christa*) and ascends full of samples and propellants.

The basic tool is the "hand" interface with the mechanical and probably electrical elements of the other devices the crane manipulator uses. The basic rotating actuator will be compatible with the standard hex socket fasteners, enabling the crane, with the help of its built-in MAHLI camera, to tighten and loosen screws. Other tools envisioned include:

- Thermographic imager: Would be able to inspect tank composites and insulation. Not in baseline because it might just be useless with the external insulation in place.

- Sample container sealer: To improve the integrity of collected samples for return to Earth, they will be packed into containers intended to survive (with the help of impact shock absorbers built into the sample module) a recovery scenario where the parachutes fail to open. It is expected to be a cannelure crimp or resistance seam weld operation.
- Bucket: The standard issue terrain clearing tool may be needed to mitigate the effects of dust or sand drifting. Traditionally, Earth boosters suffer from ground effect feedback. This is still a problem on Mars, and affects hovering landers. The plume bounces back at the vehicle, and can throw debris with it.
- Compressed Air Blower: This device interfaces with the fuel plant compressed Martian air supply and will be used to blow dust off the solar panels, and possibly off interesting rocks or clasts near the *Judith* landing site

5.8 Sample Module

Figure 5-6: Sample Module

This is a dumb (as in no computer) lander designed to enter Earth's atmosphere at up to 12000m/s at a relatively steep entry angle to minimize weather and targeting error. Its primary recovery mode will be mid-air catch by helicopter, but will be designed to survive impact under its parachute. Impact without its parachute will break the sample module, but probably not the sample containers. With the laboratory ASQ (including growth media followed by examination to 0.5 micrometres) and acceptance examination of samples for Martian life down to the 12.5 micrometre resolution, it is very unlikely that any of these samples will contain undetected Martian life. Also, such undetected Martian life is likely to be on board outside sample containers. The concern for sample survival through parachute failed impact is the preservation of the samples from Earth based microorganisms, and not a concern for planetary protection. It is desirable in the event ASQ fails; it should be possible to launch another mission to implement sample module and container exterior sterilization, probably after *Judith* has launched the sample module to Mars orbit.

The sample module consists of a 70deg toriconical heatshield (the 'lid' for most of the mission), which includes two tool grapple points. The base of the module includes a high temperature steel strap and clampband for securing the heatshield to the base. Unlike the plastic strap used for the sample module separation mechanism, this is one that must survive entry at Earth. The parachute drogue is a ringsail, and followed up by a ram air parasol to slow descent for airborne capture and prevent sample damage if the module lands. There will be an ability to program the main parasol not to deploy if the weather is going to be stormy over the recovery site. This will ensure that the module isn't blown out of the recovery area by storm winds on its parasol. The resulting impact will damage the aeroshell and samples, but not breach the individual containers. Nearly complete reconstructon of broken samples should be possible from *Judith*'s MAHLI ASQ acceptance images taken before they are sealed into the containers.

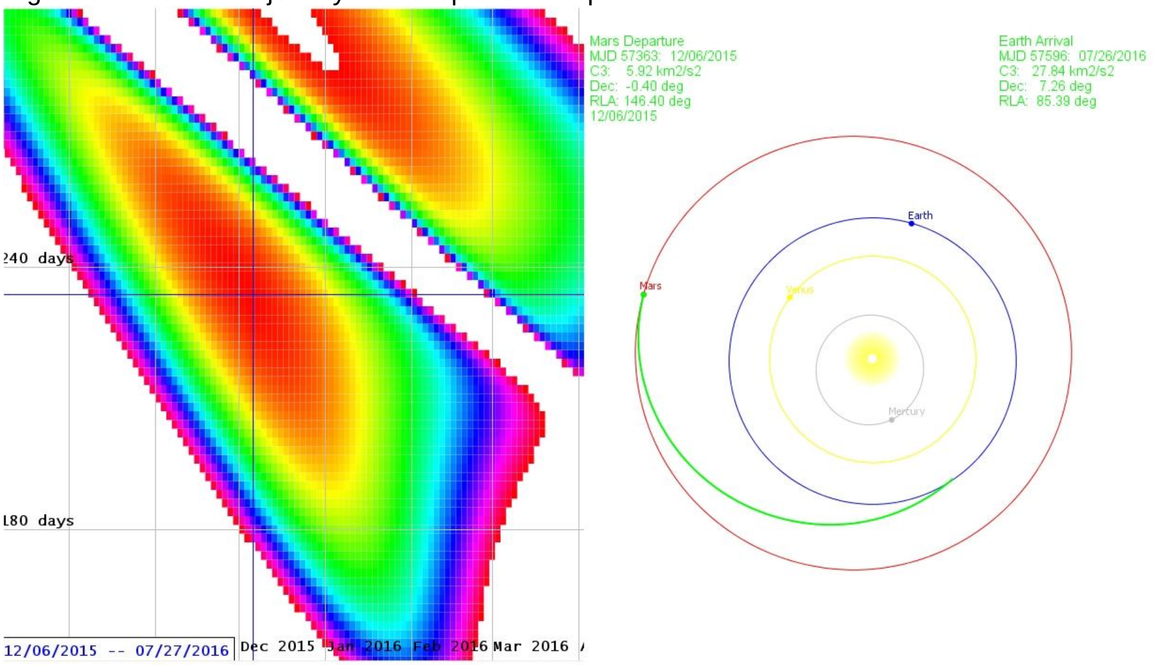
The sample module uses a specific plastic strapped clampband interface to the Earthbound cruise stage (which consists of a mass optimal combination of gallium arsenide solar cells and lithium thionyl chloride primary batteries, a single PSI 80228 or 80467 propellant tank, a redundant set of RCS thrusters capable of correction translations, and the *Judith* ascent computer set.) The cruise stage is in turn attached to the *Judith* second stage.

5.8.1 Sample Containers

The sample module payload dropped dramatically since Round One because of the new pressurization system. The total tank volume was also reduced, as well as the Isp. This version carries more propellants than *Judith* version 0702, but this is more than offset by other factors. The sample module now carries 18 containers instead of 42. The payload, including both samples and containers, is 7.92kg. With all the sample containers aboard, this allows 4.32kg in net samples, or 240g per sample container

5.9 Return Trajectory

Figure 5-7: Return Trajectory Porkchop and Path plots



AstroJava.com Judith Booster Launches Samples to Earth

Landing on Earth is a lot easier than landing on Mars. Because of this, *Judith* launches the sample module on a trajectory optimized for departure energy. It is capable of launching the sample module anywhere inside the red sweet spot of this porkchop plot, a 2 month launch window. The Type I trajectory is selected to speed the trip and shorten the overall mission. The depicted trajectory launches on 6 December 2015, and reaches Earth on 26 July 2016.

5.9 Expected Direction

The anticipated performance of *Judith* has tended to go down with each design iteration, as more and more fidelity was added and certain design decisions were made. It would appear that, the oxybenzene propellant combination suffers from having too low a specific impulse and does not completely fill equal volume tanks. The best performing propellant option is probably oxyethylene. Oxymethane suffers from requiring a large amount of hydrogen, on the same order as the produced propellants' by volume. Oxybenzene suffers from a relatively low Isp and differing fuel and oxidizer volumes. The optimum appears to be in between them. The next iteration, if done, will attempt to use oxyethylene.

6 Propellant Production

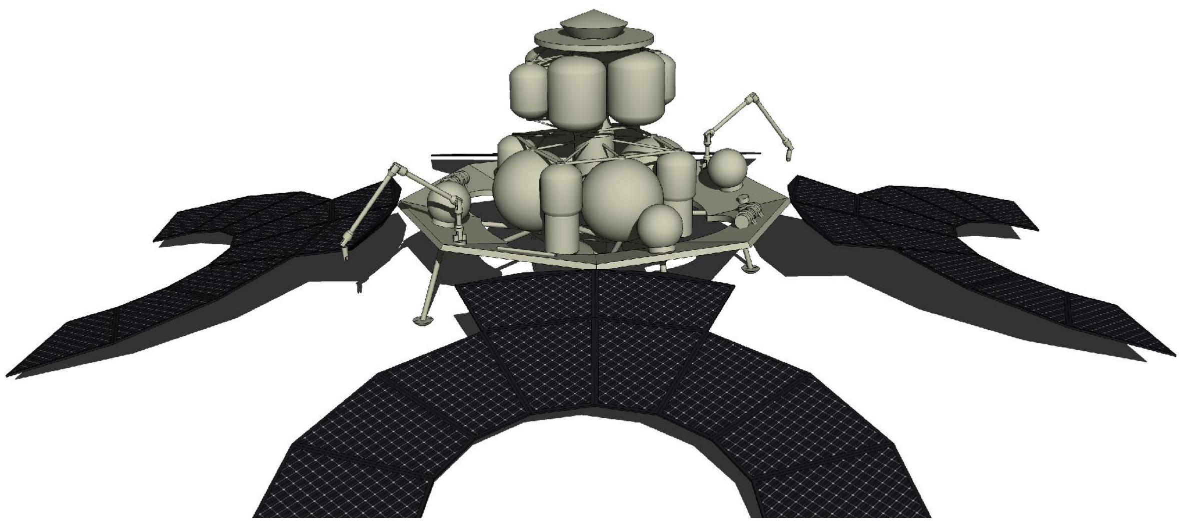


Figure 6-1: Deployed View of *Judith* 0710

6.1 Introduction

In-Situ Resource Utilization is, quite simply, the use of local, as opposed to imported, resources in the accomplishment of a mission goal. It goes beyond using simply environments, such as in aerobraking, gravity slingshots and solar pressure, to actually retrieve and process material. It also should not be confused with component level repair, closed cycle life support, and staged logistics.

The decision to use oxybenzene instead of oxymethane is the main distinguishing factor of *Mars Challenger* and *Mars Challenger II*. Instead of 1842kg of oxymethane propellant produced from 168kg of seed hydrogen, 2107kg of oxybenzene propellant is produced from only 57.4kg of seed hydrogen. This had a dramatic impact on the design, and a less dramatic impact on the performance because of oxybenzene's reduced specific impulse. As mentioned in Chapter 5, most of the performance impact was an inevitable result of a realistic pressurization system designed between *Judith* version 0702 and version 0710.

To size the system, one of the two redundant fuel plants should be able to independently produce all of the needed propellant in 360 shifts with two-thirds of the lander's full power. The power safety factor This corresponds to a normal mission return at the December 2015 opportunity, and has about 80 days of timeline margin.

The latest electrical estimate came back asking for an overhaul of the illustrated solar power system. There was insufficient time left for *Mars Challenger II* to incorporate this estimate into the design. See section 6.8 on Solar Power for the details.

6.2 Launch Operations and Ascent From Earth

Seed hydrogen based ISRU has some complications on the launch pad, which will have the sad reality of interacting with the pad requirements for planetary protection sterilization. The following factors will be present, and probably add several million dollars to the cost of the launch service:

- a need for super clean/sterile fairing air and surfaces (probably Class 100 and VC 7 cleanliness standards for those who are familiar with them.)
- a need for hydrogen tanking of the *Judith Booster* on the pad, or
- continuous uninterrupted cooling from before encapsulation until T minus four minutes (requiring lots of electricity and unusual ground support equipment.)
- a desire for subcooled (below boiling point) liquid hydrogen
- an interruption of the fairing environmental control would cause a disproportionate delay in launch to verify or re-establish sterile conditions and replenish lost *Judith* hydrogen
- uncertainty in the exact mass at launch, something which launch service providers don't like

Launch is expected to expected to input extra heat into the seed and make-up hydrogen supplies through solar and earth thermal radiation exposure, launch vibrations, aerothermal heating and acoustics. The extra cryocooler and space radiators of version 0702 are not required. Instead, an extra hydrogen tank is provided inside the Christa Can, the makeup tank. The makeup take allows about 18% of the total supply of liquid hydrogen at launch to boil away without any impact on *Judith*'s supply when she lands.

The increased heating caused by launch will last between two and eight hours, depending on whether the single shift correction described in Chapter 2 is executed. Based on the cryogenic experience of space telescopes, it should be possible to reduce the heat input to the *Judith Booster* during cruise to less than a watt without much difficulty. The total boiloff margin provided is 13.3kg. To maintain a reserve all the way to Mars, the heat input needs to be reduced to 0.317W or less. While not unprecedented, for a mission of this type, it could be quite a challenge.

6.3 Cruise

The cruise configuration of *Mars Challenger II* has been essentially overhauled since the original *Mars Challenger* submitted for Round One. Based on Lockheed Martin Centaur Documentation (LDCK), and the expense of developing the gas management devices proposed for the original, the designer has decided upon using settled venting and transfer techniques. Because the makeup tank isn't perfectly vertical in the Can, it needs internal tubes and pickups to make sure it is getting the right state of hydrogen (gas or liquid) for settled operations (venting and transfer.) A settled venting operation begins with RCS thrusting, once venting has started, the impulse exerted by the venting should be enough to keep the seed hydrogen settled in the tanks. These impulses will obviously need to be accounted for in the cruise maneuver plan.

The settled transfer happens during the approach to Mars. The tanks in the *Judith Booster* receive liquid hydrogen from the makeup tank. The makeup tank is closed and allowed to pressurize, while the *Judith* tanks are vented to reduce their pressure. Once the transfer valves are opened, the liquid hydrogen will flow naturally from the makeup tank to the *Judith* tanks without the use of pumps.

6.4 Entry, Descent, Landing

Landing is also expected to cause hydrogen boiloff, but not as bad as launch and cruise. Once on the surface, ISRU begins immediately. If there is sufficient hydrogen after cruise, what is left in the make-up tank will be fed into *Judith*'s tanks and allowed to boil at as low pressure as possible, allowing the hydrogen in the tanks to be subcooled prior to entry. The tanks will also be at a relatively low pressure, which is allowed to increase during the EDL sequence. There will be a minimum pressure to ensure tank stability.

6.5 ISRU Operations

For *Mars Challenger II* version 0710, there was a lot more analysis to determine practice as well as theory. Many concepts appear to be fundamentally simple at first, but as soon as rigor is applied, the elegance disappears and one winds up producing a sixty page report instead of a simple formula. A problem with *Mars Challenger* was tank volume management. Ideally, a hydrogen tank needed to be emptied before propellant was put into it. *Mars Challenger* compromised somewhat by putting methane into first stage tanks before they were empty of hydrogen. This is not possible with benzene or oxygen.

Benzene/hydrogen compatibility is likely, but unknown, and since the benzene required is of lower volume than oxygen, oxygen becomes the volume critical propellant anyway. A spreadsheet was made to analyze and illustrate the progression of ISRU on the surface of Mars and is reproduced as Appendix B. Also included in the analysis was an assumption that a significant amount of hydrogen would boil off in all tanks, being tapped off for the ISRU plant.

6.5.1 Chemical Reactions[16a]

Reverse Water Gas Shift:
(1) $H_2 + CO_2 \rightarrow CO + H_2O$

The reagents are the seed hydrogen and carbon dioxide from the Martian air. The products are carbon monoxide and water. It requires a catalyst (iron/chrome or copper/alumina) and input heat to operate at about 600K. It absorbs about 822J/kg of heat energy, which is not very much. The equilibrium constant of this reaction is problematically low, so it must be combined with a condenser and membrane separator to be effective. The condenser separates the least volatile part of the four part mixture, water. The remaining three components, hydrogen, carbon dioxide, and carbon monoxide are separated in the membrane separator. The carbon dioxide and hydrogen are returned to the RWGS reactor, while the carbon monoxide is used in the next step.

Electrolysis Reaction:
(2) $2H_2O \rightarrow 2H_2 + O_2$

Fortunately, the Electrolysis reactor separates the products by producing one at each electrode. The hydrogen is fed back into the hydrogen supply, while the oxygen is liquified and put straight into an ascent tank. The unit itself will use potassium hydroxide (KOH) as an electrolyte salt. This means that a small amount of water will be wasted in the unit, and that the KOH concentration will need to be carefully regulated, favoring as a reactor with as small a water capacity as one can get away with. The reaction uses 13.5kJ/kg of electrical energy, dominating the power requirements for the chemical processes.

Fischer-Tropsch 5.2 Reaction:
(3) $2H_2 + 4CO \rightarrow C_2H_4 + 2CO_2$

This reaction produces at least 1086J/kg of heat, which means that it can be thermally coupled to the RWGS reactor to provide heat for it when both reactors are running at the same time. This will defray, but not eliminate, the electrical requirement of the RWGS reactor (the fuel reactor needs the products from the RWGS reactor, so the RWGS reactor must start first.) The number 5.2 may be unfamiliar: the designer has used it to specify the exact Fischer-Tropsch reaction from Pioneer Astronautics' MAHOSS document.

Reactions (3) and (4) are combined into a single reactor called the fuel reactor.

Zeolite Benzene Reaction:
(4) $3C_2H_4 \rightarrow C_6H_6 + 3H_2$

This slightly endothermic reaction (requires 211J/kg of heat) reacts ethylene into benzene and hydrogen. The hydrogen is fed back into the hydrogen supply for the RWGS reactor and the fuel reactor itself.

It is convenient for analysis purposes to combine certain chemical reactions into processes which can be expressed as a single reaction. The most obvious is to do this to the entire ISRU fuel plant:

ISRU Process
(5) $6H_2 + 12CO_2 \rightarrow 2C_6H_6 + 12O_2$

A rough estimate of the amount of energy required is 5.4kJ/kg, which is the electrolysis energy assuming that each hydrogen atom passes through the electrolysis reaction twice. After accounting for the mixture ratio difference, it amounts to 7.5kJ/kg. From the propellant estimate of 2107kg, a total of 15803kJ

(4390W-hr) is needed for the chemical processes. This isn't a whole lot compared to the power requirements of the physical processes.

This produces oxybenzene propellants at a mixture ratio of 2.46:1, which is far higher than the 1.5:1 used by the propulsion system. A lot of LOX is therefore vented as excess. This feature of oxybenzene ISRU should be remembered for human missions, where this excess LOX could be a handy source of life support oxygen for the crew (a human mission using oxybenzene will probably use a mixture ratio of 2.1:1 with turbopump engines and properly proportioned tanks, leaving less, but still a significant amount of excess LOX.)

Fuel Process
(6) $6H_2 + 12CO \rightarrow C_6H_6 + 3H_2$

This is the combined Fischer-Tropsch and zeolite reaction. It is exothermic with a heat output of 875J/kg, just enough to satisfy the RWGS reactor if the pair are well coupled and well insulated. It allows 53kJ/kg of heat leakage.

6.5.2 Air Compression

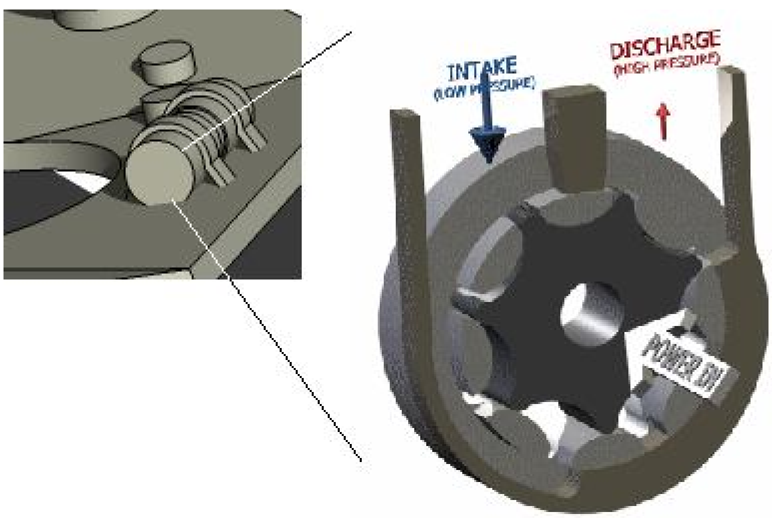


Figure 6-2: StarRotor Compressor operation: for 7 rotations of the outer rotor, the inner rotor rotates 8 times. The parts are sealed by close clearance, they don't actually touch during normal operation. There is a parallel gearbox with synchronization gears. Anyone who gets into the nitty gritty of atmospheric ISRU will soon discover that the chemical reactions, while key, are not the major part of the challenge.

The compressor needs to take in Martian air at a highly variable handful of Pascals and increase the pressure to 100psia (931kPa), requiring a compression ratio of about 750:1. 3070kg of air needs to be compressed for ISRU purposes, plus a small amount for solar panel blowing gas. This translates into about 157500 cubic metres. Assuming 6 hours of compressor operation over the course of a 360 day ISRU phase, the capacity needed is 1.22m3/min, or 43.1 ACFM/min. The sort of earthly air compressor you can buy at a hardware store with this performance is about the size of a phone booth. This compressor is assumed to operate at 60,000rpm (really fast), and is made of 5 stages at 3.76:1 each. If actually designed, the compressor should be about the same size since the higher compression ratios will prefer the earlier stages because of heat of compression issues and greater internal leakage in the smaller high pressure stages. This positive effect is counterbalanced by the fact that the 750:1 compression ratio assumes isothermal conditions, which in practice is a fantasy, especially for a small high-speed compressor like this one. The estimated mass of the compressor is 1.8kg and it is going to be a major pain to keep it cool during operation. The estimated mass of the compressor, complete with cooling jacket and heat exchanger, is 4.0kg.

The cryocooler compressor and cold head are estimated based on this compressor's basic analysis. The estimated dimensions are 125mm diameter by 250mm long. The analyzed dimensions are 86mm diameter by 117mm long, not including the cooling jacket. The 250mm diameter estimate of the LOX liquefier includes the receiver tank.

Based on the electrical efficiency of earthly compressors (by mass, doubled), it requires about 20,000 W-hr to compress 1kg of Martian air, or about 29,000 W-hr for each kg of complete propellant.

6.5.3 Liquefaction

The liquefaction of the LOX is relatively easy, but electricity intensive. LOX boils at 90K. The cryocooler performance is based on Cryomech model compressors

O2
Cooling a kilogram to 90K: 121kJ
Liquifying a kilogram: 213kJ
Total: 334kJ
Total electricity: 7829kJ/kg or 2175W-hr/kg

This is based on the certified performance of a Cryomech AL300/CP970 operating at 80K (which actually uses 23.44 W of power per Watt of heat lift.) Going for the ISRU compressor is the much colder heat sink (233K vs. 308K) and warmer cold end requirement (90K vs. 80K), and the fact that all of the heat lift is assumed at the same efficiency, which is unlikely to be the case. About 1330.7kg of LOX needs to be liquefied (a bit more than the actual LOX load to account for azote boiloff.) This translates into an average of 1554W-hr/kg of overall propellant.

The total electrical requirement per kg of completed propellant is almost 35,000 W-hr per kg. For a 360 day ISRU phase, this asks for almost 205,000 W-hr per day. This is well beyond the current solar power system design, which is still based on estimates from *Judith* 0701.

6.5.4 Tank Management: An Unexpected Hassle

See also Appendix B

The problems of tank management have been very much mitigated by the adoption of oxybenzene propulsion, but they are still present. *Mars Challenger II* also adopted a more agressive reuse program for the landing propulsion system tanks:

- All propellants, intermediate products, and seed hydrogen are mutually exclusive. None can be mixed in the same tank.
- The LPS tanks liquid sides are used for the interim storage of water. A maximum of 24.6L is required in each of two tanks. More may be used for power management reasons.
- The gas sides of two LPS tanks will be used as the receiving tanks for each of the two air compressors
- The gas sides of the other two LPS tanks will be used as the receiving tanks for each of the two helium compressors.

The helium receiving role is particularly important, because the main pressurant tanks are charged to 4500psia and are not expected to drop below 3000psia before launch from Mars. The high pressure side of the cryogenic cooling system is only about 200-250psia. If the helium receiving volume of the cryocooler system is insufficient, the high pressure side's pressure will drop as the cryocooler cools down, because the helium will concentrate in the cold head, where it is denser because of the low temperature. Either the cryocooler efficiency will drop, or the system will need to be recharged from the pressurant system. This recharge gas would then be vented and lost as the cryocooler warmed up when not in operation. The typical Cryomech system does not have a receiving tank, indicating that the volume in the internal pipes, heat exchangers, external hoses and cold heads are sufficient for these cryocoolers. Because *Judith*'s cryocooler is an gas cooled design (Cryomech compressor modules are oil cooled), it is likely that the inherent receiving volume for *Judith*'s cryocoolers are probably sufficient. Specifying reuse of the LPS tanks as receiving tanks of for the helium compressors is a precaution.

6.5.5 The Effects of Azote

Azote is a term to describe the inert portion of an atmosphere (from the Greek for "no life"), and was the original word for nitrogen coined by Antoine-Laurent Lavoisier in c1774.[16a] Prior to the discovery of argon and the other noble gasses in the 1890s, "nitrogen" included argon and the noble gasses. The noble gasses were discovered because John William Strutt (better known as Lord Rayleigh) found a small difference in the density of atmospheric nitrogen (or azote) produced by eliminating oxygen, water vapor and carbon dioxide from the air, and pure nitrogen produced by chemical reactions.[16b] This set the stage for William Ramsay and Morris William Travers to discover and fill the noble gas column, which was missing from the periodic table at the time.[16c]

Martian azote forms only 4.3% of the martian atmosphere. Of this, about 63% is nitrogen and 37% is argon. The way the *Mars Challenger* and *Mars Challenger II* ISRU systems work, these components are not as easily sorted out as is the case with other ISRU designs (most of which use sorption or cryogenic compressors which ignore azote gasses.) In this system, the azote would wind up in the liquid oxygen. The boiling point of argon is 87K vs. the 90K of liquid oxygen. This means that both nitrogen (boiling point of 80K) and argon will boil from a LOX tank maintained at a pressure and temperature between the vapor pressure curves of LOX and liquid argon. The azote gasses will act as a coolant for the LOX in the tank. There may be some liquid argon left in the tank at lift off. Since argon is chemically very inert (only lighter noble gasses neon and helium are more inert than argon), it will not pose any problem for the operation of the motor. To confirm this, the argon impurity in the LOX can be controlled during the motor's qualification tests.

The martian atmosphere contains about 0.4% combined of water vapor, oxygen, carbon monoxide, and methane. All but one of these gasses occur in the ISRU system and will not be a problem. Methane is in the parts per million proportion and will not be significant.

6.6 Operations

The operations team has the stressful misfortune of having to operate on a day that is 24 hours and 39 and a half minutes long while still living on a planet with a 24 hour and zero minute day. It is unlikely that their families will telecommute to Mars with them, even though their bedside clocks may need to be hacked to tick just a bit slower. The following assumes this has been done, and is written from the perspective of *Judith*'s workday.

- *Judith* operations "night shift" crew formulate a strategy for the days operations, making plans for necessary inspections and maintenance operations based on booster health feedback.
- Around sunrise, the communications pass begins (probably 2 hours per day). It is most likely that *Christa* science and navigational data exchange would dominate UHF orbiter links, so most of *Judith* communications would be through its direct to Earth high gain antennas. As the communication system is dual string, it may be possible to use two different channels at once and transfer twice as much data, as long as enough bandwidth is available on Deep Space Network (or equivalent) channels. *Judith*'s more direct-to-earth approach is also easier to implement for a stationary lander than for a rover.
- The most important part of the communications pass will be tank pressure information, and any changes in pressure relief and check valve statuses, which may indicate an overpressurization. Overpressurization is devastating, not because of tank damage, but because it means a propellant resource has been lost through pressure relief valves. That resource is most likely to be hydrogen. Venting just 26.6g of hydrogen means losing at least a kilogram of propellant for lift-off.
- As the sun rises, more electrical power becomes available. The batteries are charged and the ISRU system begins to come on line according to the night shift's current management plan.
- Command upload will probably include instructions regarding automated inspection by one or both (probably just one) of the cranes using the Malin Mars Hand Lens Imager (MAHLI). This is likely to take priority behind one of the fuel plants in terms of electrical demand. There may also be changes to the ISRU managment plan (such things as the draw pressures of each LH2 tank and the receiving tanks for finished or intermediate ISRU products, as well as which ISRU processes are running.)
- Hopefully, there will be an evening communications pass, and a capability (probably through a resource other than the Deep Space Network) to detect alarm states continuously (all day, every day, evenings, weekends, holidays, etc.) An alarm state (such as a pressure relief valve popping) would be communicated via a semaphore carrier signal, possibly to a relay (perhaps even bounced passively off Mars' moons), and contain, at most, four bits of information. Unless the problem is with the high gain communication system on *Judith* (and the other communication system is unavailable) this signal should be readable using a lower gain asset than those that typify the Deep Space Network.

- During the night, *Judith* is mostly shut down, keeping the computers running (one running, one standby of the ground operations set) and perhaps circulation of coolants to reject built up compression heat.

6.7 Launch Preparations

The Launch Preparation Plan essentially details the steps necessary to get from the end of the ISRU phase, when all of the propellants have been produced, to the moment of launch.

- Sample qualification/acceptance (See Chapter 7)
- Sample Module heatshield installation and inspection
- Sample Module integration and mass measurements ("integration" means the determination that the sample module load and configuration are compatible with ascent, not the physical installation of the module. For Earth launches, this is an eight month paper trail making sure, among other things, that the satellite will not fall off the booster during ascent.)
- Movement of propellants between tanks (the post-ISRU configuration has the right propellants in the right tanks, but not in the right amounts)
- Ultrasonic determination of exact ascent propellant quantities and mass balance
- Correction of propellant tanking, if necessary
- Securing of lander components that have any hope of surviving launch
- Positioning and programming of *Christa* to record the launch using Mastcam
- Positioning of orbital assets to support launch (such as *Telecommunications Orbiter* or *Reconnaissance Orbiter*.)
- Launch
- *Christa*'s post-launch inspection of the *Judith* lander and playback of ascent coverage

Ground operations would include Flight Readiness and Launch Readiness Reviews, much as launches from Earth already do.

6.8 Solar Power

The decision to go with solar power was obvious. Nuclear power is too politically expensive. The engineering requirements of a nuclear reactor for this mission is too expensive, even without the political problem. Radioisotope heat sources necessary (even while operating the compressors via directly shafted "steam" turbines) would produce a thermal management nightmare during the outbound cruise. Add to all this that the any nuclear materials need to remain contained during any conceivable disaster, including Mars entry and ascent failures. Solar power is a no-brainer.

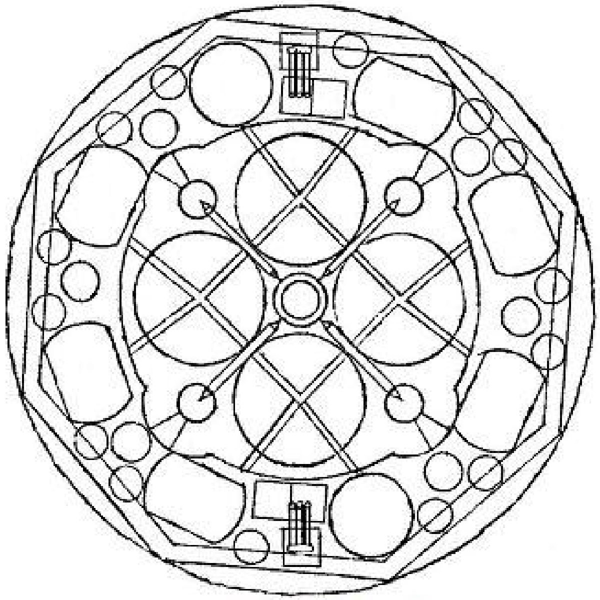
The solar electrical system for *Judith* is enormous. The 32 panels shown in figure 6-2 generate 150W of peak power each. This results in a 4800W system, peak power, which is not *quite* adequate vs. the design estimates. Version 0702 adds one panel to each of the 8 "worms" of panels, increasing the peak power to 6000W.

The analysis accomplished for Version 0710 asks for a peak power of 26000W. Clearly, this could be a bit of a problem.

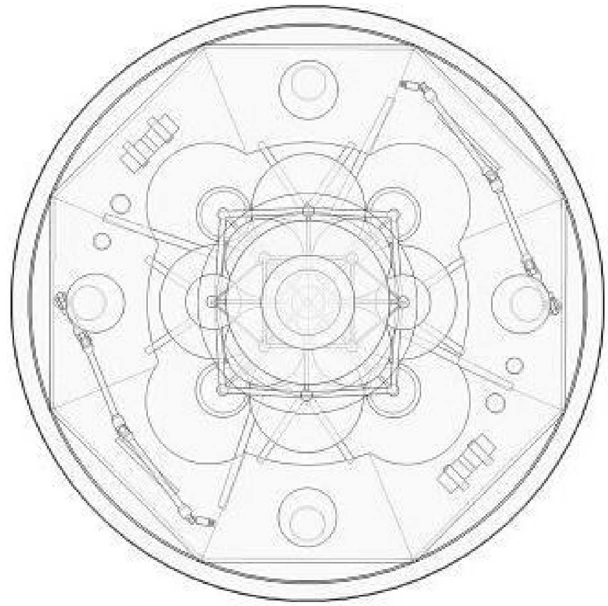
6.9 Expected Direction

Overleaf: Figure 6-3

This pair of images shows the extreme degree of refinement which occurred in the fuel plant. The compressors were properly analyzed and sized to fit the mission (they got a lot smaller). It also shows the dramatic impact of the pressurization system analysis (it got a lot bigger and the main helium tanks were moved to the booster itself). The 3D model does not yet have the motors for the landing propulsion system. The many small circles on the drawing for *Judith* version 0701 are these Star 8 and MR-104 motors. Note also the larger deck cutaways to accommodate *Judith*'s ascent motors lift-off clearance needs.



Mars Challenger Judith 0701



MARS CHALLENGER II Judith 0710

Judith, once again, is a booster, not a spacecraft. The lander it came in is a spacecraft designed to be a launch site. This type of mission is unprecedented, even when compared to the *Luna* series sample return missions and the *Apollo* piloted spaceflight. Most of this operational personality stems from In-Situ Resource Utilization. The rest comes from the designer's risk assessment, and assessment of the "risk budget" for this type of mission. On a cost scale, this is a flagship mission, and there is little avoiding that. *Pathfinder* demonstrated how a successful low cost mission can rapidly turn into a flagship mission via the public perspective. On the scale of public influence, *Mars Challenger*'s flagship status is a certainty (or it should be thus assumed.) As a result, mission risk has been attacked using multiple strategies, including ISRU itself. ISRU eliminates the mission phases of destination orbital rendezvous and multiple launches from Earth needed to make a non-ISRU sample return mission of this scale work at all, and preferred for smaller conventional sample return missions. *Mars Challenger* goes beyond this to reduce the risk of ISRU itself, and of sample return missions in general.

From the original report: "The latest compressor estimates are far smaller than the numbers in this report, so suddenly, there is room available in *Judith*, as well as some wiggle room in the mass budget. Version 0703 would probably add two tanks to the hover propulsion system, to add some margin to the situation with propellant tank management. If the electrical estimates come down, it may lose the recently added solar panels as well."

There was no Version 0703, since the design effort was not restarted until August 2007 (version 0708.) The compressor has now been properly analyzed for volume management, but obviously needs higher fidelity thermodynamic and fluid dynamic analysis before its mass and power consumption estimates become reliable. The direction of the electrical estimates have been in the opposite direction and the solar power system of Version 0710 is currently broken. The next version would improve the air compressor detail before revising the solar power system, since the air compressor's power consumption estimates are the dominant item on the power budget. Because of the impact of air compression, it makes little difference what propellant combination is selected, however propulsion system factors would lead us to explore oxyethylene in the next version by simply eliminating the zeolite reaction from the current ISRU design.

7 Astrobiology

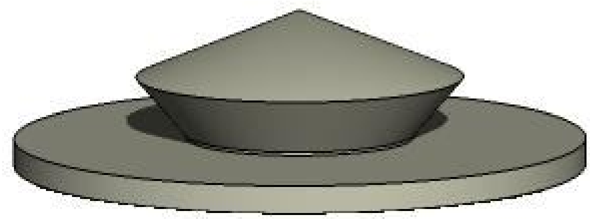


Figure 7-1: Sample Module and Cruise Stage: The standard load is 18 samples of 240g each.

7.1 Introduction

This chapter explores the rather dubious prospect of cramming a microbiology mission potentially more ambitious than that of *Science Laboratory* into a rover about half as large. Obviously *Mars Challenger* should concentrate on the lightest and least expensive method of ensuring the safety of Earth's biosphere from undiscovered potentially harmful Martian life. The strategy is called Astrobiological Sample Qualification, or ASQ. The author's conclusion is that the only (not just the lightest and cheapest) way to do this is to make sure that it isn't there in the first place.

The concept of qualifying and accepting samples for return to Earth follows the pattern of qualifying and accepting spacecraft to fly into space. All other considerations are about protecting samples from Earth lifeforms in order to have high scientific integrity. The requirements for that greatly exceed the needs of outbound planetary protection according to current NASA policies and international treaty.

In a nutshell, detecting or not detecting life on Mars is the only return planetary protection measure used on *Mars Challenger*.

7.2 What is Life?

Sample handling and qualification stem from the viewpoint of protecting Earth's biosphere from potentially harmful Martian life. The approach to dealing this is to equip *Mars Challenger* with sufficient instrumentation to detect life that may be harmful. This is defined as active biology of one of the following four types:

- Macroscopic life: These are multicellular, visible life forms capable of being seen by the naked eye, or in *Christa*'s case, Mastcam and MARDI/Hazcam cameras. Encountering this type of life is very unlikely.
- Microscopic life: Includes protozoa, bacteria, algea, fungus, and other single cellular life that may need a microscope or other experiments to detect. Christa's CIMBRLI instrument and growth stimulant experiments are the primary means of qualifying sample sites as free from microscopic life.
- Viruses: Viruses store their genetic information in Deoxyribo Nucleaic Acid (DNA) or Messenger Ribo Nucleaic Acid (mRNA) and require other life to reproduce, making them very difficult to detect for a carefully sterilized rover instrument, as well as making it difficult to classify them as life. They are also too small for reliable microscopic imaging. As an Earth contamination hazard, viruses form both the greatest and hardest to detect form of life and will probably form the critical requirements of the sample qualification instruments. Polymerase Chain Reaction (PCR) investigation should be able to detect viral DNA and mRNA.
- Prions: Prions are malformed proteins which are able to self-replicate by stealing resources from a living cell's ribosomes. The most well known is the one that causes Bovine Spongiform Encephalopy (better known as "Mad Cow Disease") and Variant Kreutzfeld-Jacobs disease. This prion apparently originated in the cannibalistic feeding of cows by British farmers who used feeds containing rendered bone meal. Our experience both in the lab and on the farm indicate that it is very unlikely that we will find viable prions on Mars, that it is unlikely they can be qualified out of samples, and that it is unlikely they will significantly pollute the biosphere if released on Earth, as they would need to be compatible with Earth life.

Christa's biological instruments and investigations are going to be applied both in active in-situ investigations searching for live biology, and in qualifying samples of geological or paleontological interest as safe to return to Earth. If a site close enough to the location of a previous landed mission, *Christa* should be sent after *Judith*'s launch to look for escaped Earth life in order to determine if our planetary protection policies are (or were) adequate.

7.3 Sample Qualification Methodology

At a site where samples are selected for return, one of the samples will be examined in great detail to rule out that it contains life. This qualification sample goes through a series of investigations. The CIMBRLI microscope (qv) examines raw sample material, material that has been through the growth or PCR lab to stimulate life that may be in it. In the process, the qualification sample is destroyed. Samples which will actually be returned are laboratory examined using the cleft scraper and visually using the MAHLI instruments (see Chapter 5) on the *Judith* lander.

7.3.1 *Christa Laboratory* Experiments, Instruments, and Investigations

The author defines the *Laboratory* instruments as ones that examine samples in a controlled environment internal to the spacecraft carrying it, in this case, the *Christa Rover*. The central instrument is the CIMBRLI ("Kimberly") environmental slide microscope. Experiments attempt to produce a response in a sample detectable to instruments. Laboratory investigations test a specific hypothesis on a particular sample, setting requirements for and adhering to the constraints of the experiments and instruments carried. The only investigation examined in this document is that of sample qualification, which asks how likely a sample is to contain undetected life which is harmful to Earth's biosphere, a rather encompassing objective. There are probably hundreds of specific investigations that could be performed, many of which are needed for flight qualification.

The *Christa Laboratory* promises to be a small nightmare for engineering, as the internal handling system, chambers, and consumables are very complex. To prevent spurious results, every last Earth microbe must be destroyed or expurgated from the Laboratory items which come into contact with Martian samples. The difficulty of this was demonstrated by Apollo XII, which brought back a Lunar Surveyor camera for examination. After years in the vacuum of space, the sealed unit still had viable Earth microbes inside it...ones that could not have been introduced by the astronauts, as it was hermetically sealed prior to launch and was not disassembled until after it got back. Such stringent sterilization requirements may affect the launch vehicle selection, as some pads and fairings have better accommodations for such requirements than others. A possible method would be to find (or engineer) an extremophile-hunting protozoa or other microorganism. This microorganism would destroy the hardiest “bugs” which would survive normal sterilization procedures. Afterwards, this “hunter bug” would be easily destroyed by normal sterilization, leaving the *Christa Laboratory* perfectly clean. Such methods might not be necessary, since *Viking* and *Phoenix* instruments were indicated by control measurements as being perfectly sterile.

Lab Instruments:

- CIMBRLI slide microscope: If it must have an acronym, CIMBRLI ("Kimberly") for Challenger Imager for Microbiological Research and Laboratory Investigations should do nicely. Automatic slide preparation with dust samples and possibly nutrient solutions will accompany this environmental microscope. The imaging area will be in a small altitude chamber capable of simulating Earth-like temperatures and pressures. The imager itself does not need to be fast and slide handling mechanisms can pan the sample around inside for a high resolution mosaic. It will probably consist of the standard *Exploration Rover* CCD with custom optics and upgraded electronics. Adjustable focus and automatic z-mapping (features of MAHLI) is desirable, as at the intended resolution of 0.5 micrometres per pixel, focusing an entire grain of sand is unlikely. Several lighting modes can also be incorporated (i.e.: an light emitting diode (LED) kit that includes LEDs of various spectra combined with filter wheels.) The environmental chamber will include purge and sterilization functions. This instrument is very important to sample qualification and is the core of the microbiology investigations on *Christa*, as its progenitors have been on Earth for two centuries. The Malin Mars Hand Lens Imager (MAHLI) has a maximum resolution of 12.5 micrometres[17] The *Exploration Rover* Microscopic Imager, at 30 micrometres per pixel (no color, no lighting) is the first space "microscope".[18] MECA on *Phoenix* will be the first slide microscope on Mars, achieving a resolution of 2 microns.[18b] CIMBRLI is expected to form about 5kg of mass and up to 20W of power use (not counting separate experiments.)
- Gas Chromatograph and Mass Spectrometer (GCMS): On *Viking*, this was actually one investigation with two sensors. Mass spectrometers produce an electrical or magnetic field, ionize atoms and pull them into the electrical field around a corner to a detector. Where the atom hits the detector identifies its charge-to-mass ratio, and therefore the element and isotope. The mass spectrometer, invented by

Francis William Aston in 1919[18c], has been in use on planetary spacecraft since the beginning of the space age, and is used by orbiters, landers, and deep spacecraft to identify whatever matter is in the area, even in the hard vacuum of deep space. Gas Chromatography identifies organic compounds by light emission signatures, and requires hydrogen. This hydrogen supply is the only factor that favors putting such a device on the immobile *Judith*. This does form the possibility of having *Christa* "refuel" a gas chromatograph from *Judith*'s supply, but it would be very difficult to implement.

Lab Experiments:
- The Grinder: This simply grinds up an acquired rock sample to increase the reaction area of experiments that rely on biological or chemical reactions. The reason this is required for any such investigations other than on straight dust, is because Martian dust is highly oxidized. The grinder will require an inert gas supply (such as helium or argon) to prevent the same effect from interfering with lab experiment results. It also pays to examine the Grinder chamber's atmosphere after grinding a sample, in case it has released gasses while grinding.
- Sample Sterilizer: The sterilizer introduces a mechanism, probably ionizing radiation, intended to destroy any lifeforms in a sample to provide a control sample for medium growth experiments. If a medium growth experiment produces the same response in both sterilized and unsterilized samples, it concludes that sterilization had no effect on the experiments outcome and that the response is probably was not biological. The sterilizer chamber would also look for reactions during sterilization, as in biology, many methods of sterilization cause cell membranes and other biological structures to break down, and also causes histamine reactions in lifeforms with immune response. The products of these responses should be detectable, and also pre-sterilization and post-sterilization microscopy should show differences too.
- Medium Growth and Release Kit: Using the experience of in-situ extremophile research at sites in Antarctica, Iceland, Greenland, the Northwest Territories in Canada, and in a wide number of desert locations, this set of growth and release investigations is analogous to petri dishes in Earth labs and similar investigations on *Viking*. Because the majority of Mars analog research applicable to these sorts of investigations have occurred since the launch of *Viking*, the author believes, very much unlike for the landers, that the *Viking* heritage for this kit is probably useless. The designer possesses only an introductory knowledge of extremophile microbiology, and will make no further comments about what this kit may entail.
- Polymerase Chain Reaction (PCR): PCR is currently used by medical and criminal investigation laboratories to grow trace amounts of nonliving DNA to testable proportions (i.e.: for virus and bacteria strain identification and DNA finger printing.)

7.3.2 Arm Instruments, Experiments, and Tools

The robotic arm for *Christa* needs to be much longer than those on the *Exploration Rovers*. The reason for this is because the arm needs to be able to reach all the sample containers carried on *Christa*. *Christa* will land with all eighteen sample containers, so that she will be able to select samples before first encountering *Judith* on the surface.

Arm Instruments:
- Alpha/Proton/X-Ray Spectrometer (APXS): This German instrument has become the staple of Mars surface materials research over the last ten years (*Sojourner*, *Mars 96*, *Beagle 2*, and both *Exploration Rovers* carried it, *Science Laboratory* plans to.) It operates by emitting alpha particles from a cesium source and then reading emitted and reflected alpha particles, protons, and x-rays for characteristic signatures. Even though it is off the shelf, it is impossible to make cheap or on a short schedule, as it requires about a year of ground truth calibration. It must be deployed in physical contact to a test site to be effective.
- Mossbauer Spectrometer (not on board in baseline version): This device was a specialized instrument for detecting iron bearing minerals using gamma rays, and used in much the same manner as APXS on the instrument arms of the *Exploration Rovers*. It is unlikely that *Christa* would carry one, especially if the secondary Terra Meridiani site is selected (possible because the hematite "blueberries" discovered by Opportunity may contain protenoids or other pre-animate matter as accretion nuclei.)
- Malin MAHLI (on *Judith*): The Mars Hand Lens Imager (12.5 micrometre per pixel, LED monochromatic lights and filters, automatic Z-scanning and mapping into single complete image with range plot overlay) is under development by Malin Space Science Systems for *Science Laboratory*. For *Christa* it might be overkill because CIMBRLI will be able to do many of the same investigations (although they would take a

lot longer, they would be much more thorough.) MAHLI forms the core of the sample acceptance imaging on *Judith*.

Arm Tools:
- Rock Abrasion Tool (RAT): Essentially the rock hammer of the *Exploration Rover*, this tool grinds away a thin layer of the surface of a rock to get at the unweathered material within. It also had a brush for sweeping dust and grinding debris away. With *Christa*'s longer arm, it may be possible to use this last feature on solar cells.
- Core Drill (not on board baseline version): Drills a section out of a rock in order to take deep samples. The core can be laid upon a deck tray and examined using arm and mast instruments, placed in the *Laboratory* and experimented upon. A qualification sample is unlikely to be in shape to be returned to Earth after being investigated in the *Laboratory*. Analogous to spacecraft development on Earth, a second sample would be drilled out and "acceptance tested" for return using only arm and mast instruments (including *Judith*'s MAHLI cameras.) This drill would be able to retrieve cores up to 20cm deep.
- Bucket: A simple backhoe-like dirt scoop. For both simplicity and flexibility, particle size filtering can be implemented as a deck tool (most likely, an investigation would like to examine small clasts, sands, and dust first, then examine pebbles (or blueberries) around 10mm using CIMBRLI before putting them in the Lab Grinder to see if there is anything organic inside.
- Cleft Scraper: Field experience on Earth indicates that extremophile life likes to hide in the clefts of rocks, where it is mostly protected from the elements. This tool would reach into a cleft and "swab" it for a small sample which can then be tested via media growth, PCR and CIMBRLI imaging. The cleft scraper is also the main tool for handling microscope slides outside the laboratory.
- Sample Container Device: The sample container is about 180mm in diameter. A common device would be used to grapple both its lid and the container itself.

7.3.3 Mast and Deck Instruments

- ChemCam (not in baseline): A remote sensing laser spectrometer planned for *Science Laboratory* as a mast sensor. Aiming at a location up to 9m away, it fires a small, but powerful laser to vaporize and ionize a bit of material at that location, and then uses a narrow angle spectrographic camera to read the resulting emission spectra. It will most likely be used to examine locations that can't be reached by the rover it is carried on. It is not applicable to ASQ and is therefore not carried on *Christa*, yet.
- Thermal Emission Spectrometer (not in baseline)[19]: The first edition of this instrument was carried on *Global Surveyor* (the orbiter), while each *Exploration Rover* carried a smaller version. It works by measuring infrared radiation signatures. Its optics are sensitive to temperature, and so were contained in the *Exploration Rover* Warm Box. The necessary periscope formed the structure of the *Exploration Rover* mast. Problems with deck instruments shading solar panels are already anticipated and such a sensor would be best arranged differently, either with local heaters or RHUs, or with a periscope that retracts for periods when the rover is on the move and using all available electrical power for propulsion and imaging.
- Weather Laser (deck): A laser pointing up (either stabilized in the vertical position or with compensation in its electronics) is combined with a non-imaging spectrographic camera to measure atmospheric opacity and identify dust constituents. It is necessary to characterize the weather for *Judith*'s ascent, and this is a good way to estimate upper level winds. Identification of dust constituents can lead to an estimation of which minerals tend to get transported by dust storms, and therefore provide data about how dust storms develop by comparing them with orbital measurements of potential sources.
- Weather Station (deck): Basic meters to measure wind direction and speed, temperature, barometric pressure, and sunshine are common on landers and rovers. *Judith* will also have one (or two) for engineering purposes.

7.4 Limitations

It is quite obvious that *Christa* will not be able to carry all of these instruments, as totalled, they exceed the science payload of *Science Laboratory*, a craft almost twice as large and making a bigger leap over *Exploration Rover* in science payload to rover mass than it is in its lander performance. It therefore helps to identify the priorities:

- CIMBRLI: The microscope offers the best return for detecting life, and is therefore indispensable.
- Growth Experiment: If undetected life is present in a sample that won't grow under Mars conditions, but will grow in Earth-like conditions, it is dangerous. Life that does not grow under Earth conditions is safer. Simulating Earth conditions will lead to the detection of life that will grow under Earth conditions. This instrument should be considered indispensable.
- PCR: Viruses are potentially harmful to Earth life, so we need to ASQ if they are in the samples. PCR is our best hope of detecting them.
- Mini Corer/RAT: It may be possible to combine these tools.
- Cleft Scraper: As the best shot at finding life at a site without doing major damage to it, the cleft scraper offers a more secure site qualification. For a simplistic sample return mission equipped with ASQ, every tool can be dropped except for this one.
- APXS: an easy-to-use spectrometer capable of identifying organic material is required. It is possible that the designer has his spectrometers mixed up, and there is a better one for the job.
- Cameras: See Chapter 4 for details

7.5 Landing Sites[20]

Usually, a lander mission does not select landing site this early in the design, but two selections are required by the contest rules. The author has gravitated towards those that are most likely to contain current or fossil life. The selected sites are Marte Vallis and Terra Meridiani

7.5.1 Marte Vallis[21]

The first consideration for selecting a landing site is altitude. The reason is that a lander trying to stay within the *Viking* qualified capabilities can't land just anywhere, unless it is really light and fluffy (i.e. ballistic coefficient of 25kg/m^2 or less.) This rules out Tharsis (which is relatively boring volcanic plateau), and Noachis (the ancient highlands are some of the most scientifically interesting parts of Mars.) Altitude is also important to ISRU, because the thinner the air is, the harder it is to compress. The first impression is Hellas Basin, which is a good spot to land from the viewpoint of scientific interest. It used to be flooded with water, and has interesting areas near the edges where the flooded plain hasn't been covered by lava. Hellas Basin is up to 8km below reference altitude. The downside is that it is too far south and does not get enough sunlight for *Mars Challenger II*.

Marte Vallis is close to the equator, has lander friendly territory, and resides at almost 3km below reference altitude. What is most interesting about it is that it possesses flood areas cutting through very recent (Amazonian era) lava flows, suggesting recent, if not current, water activity. The reason for the lack of chemical indicators is likely due to the low residence time of water in the area.

7.5.2 Terra Meridiani[22]

Terra Meridiani is the area where *Opportunity* landed and now roves. The site *Mars Challenger* is interested in is northeast of the hematite area *Opportunity* is in; about 300km northeast of *Challenger Memorial Station*. This allows the possibility of *Christa* traveling to *Challenger Memorial Station* or to a surface rendezvous with *Opportunity* after *Judith* launches. This extended mission would allow us to investigate how well Earth life fared in the Mars environment, and against the sterilization measures used for *Exploration Rovers*. It is speculated that *Opportunity'*s numerous blueberries may contain proteinoids or prions at their cores. Extensive sedimentary activity is evidenced there as well, and there is a variety of both old and new terrain, as Mars winds blow material away.

7.6 Expected Direction

There could be some difficulty in cramming the entire ASQ payload onto *Christa*, but it should be possible if the engineering team remains focused on that task. More importantly, the scientists need to stick to the ASQ payload and not add extras. The loading down of missions is not acceptable in the sort of cost and performance limited environment *Mars Challenger* (or any other sample return mission trying to squeeze under $1200M.)

8 Conclusions

8.1 It is possible to do a Mars sample return mission for under $1200 million.

Several new technologies are needed, or need to be adapted from non-space technology. The existing basis of landing technology can support a sample return mission if it is carefully managed. The multiple lander per Earth launch approach is an excellent way to reduce the cost of missions requiring higher landed masses, and also to reduce the costs of individual missions. There is the possibility of launching two *Science Laboratory* class rovers from a single *Ariane 5* equipped with a SPELTRA adapter. Each such mission would have its own cruise stage, and therefore be able to select its own landing site.

8.2 It won't be easy.

There are a lot of challenges *Mars Challenger* still needs to overcome in its design phase before it can be selected as a mission. What you see here is the work of two people, although using the knowledge of many. This limitation is why the design is not yet complete, and also why the quality of the work is inconsistent. The full design, development, launch and operations of this mission will require the effort of a variety of disciplines and hundreds of people. This report is intended to set that project on the best course, not to be the definitive volume on robotic sample return. After Columbia Project hopes that the readers of *Mars Challenger II* will be able to depart with a better understanding of how best to accomplish the task of returning samples from Mars, and a higher hope about humanity's future in the new frontier of space.

Endnotes

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3. Mishkin, pp. 158

4. Mishkin, pp. 120

5. Mishkin, pp. 190

6. *Sojourner*, http://starbase.jpl.nasa.gov/archive/mpfr-m-apxs-2-edr-v1.0/mprv_0001/document/rcinst.htm when accessed

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9. Miller et. al., pp. 4

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11. Malin et. al., pp. 1

12. Tam et. al., pp. 4

13. Tam et. al., pp. 8

14. Alexander, pp. 9

15. Sutton, Biblarz, Chapters 3, 5, 8, 9, 10, 17, and 20

16. Collaudin et. al., pp. 7

16a. *MAHOSS*

16a. Azimov, pp. 7

16b. Azimov, pp. 21

16c. Azimov, Chapter 3

17. Edgett et. al., pp. 2

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18c. Asimov, pp 53

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21. Hartmann, Chapter 31

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Appendix A: Compliance Matrix

The following is a twenty-seven point assessment of *Mars Challenger* against the stated requirements of the MarsDrive contest, done much as After Columbia would if we were responding to a Request For Proposals or Announcement of Opportunity with an actual mission bid.

1. Place a scientific payload on Mars	The scientific payload has been named Astrobiological Sample Qualification, or ASQ, and is specifically designed to provide the information necessary for the safe return of samples. Chapters 4, 5, and 7 have instrument details.
2. Collect geologic and astrobiological samples	This goal has the dedicated mission element, the *Christa Rover*. In this manner, samples from an enormous area (square kilometres) can be selected for return. See Chapter 4.
3. Use local Martian resources to produce a quantity of propellant (methane, LOX) to allow the collected samples to leave the surface and return to LEO.	The sample return module, booster, fuel plant and lander have been named *Judith*. This point is both general and contains specific propellant combination and return contamination strategy which are, according to later points, open to the contestant to decide. *Mars Challenger* uses oxybenzene propellants and has selected astrobiological sample qualification (ASQ) as its return contamination strategy. See points 13,18, and 19 for booster and ISRU details.
4. The mission may be accomplished using any variety of interplanetary transfer. It should also be launched using existing or near-term launch vehicles.	*Mars Challenger* is launched using a single dedicated commercial ascent service and is final only from its 1.2m class adapter. *Atlas V* 541 has been selected and described, but *Mars Challenger* is compatible with *Delta IV-H*, and *Ariane 5 ECA*. There are larger *Atlas V* and *Ariane 5* launch vehicle configurations available as well. *Proton* is probably not available because the pad does not support operations with liquid hydrogen, a propellant production consumable. Both the booster and rover elements are launched on this service, and use a common cruse stage. They separate during Mars approach and land using separate landers. *Judith*'s lander is based on *Viking* heritage and *Science Laboratory* design. *Christa* uses the aeroshell, parachute, and terminal stop motors of an *Exploration Rover*, augmented by a *Science Laboratory* style hover crane touchdown system. The rover drives to the booster during the concurrent sample collection and ISRU phases. The *Judith Booster* injects the sample module and accompanying cruise stage directly to an Earth return trajectory. The sample module is recovered in the air, but has several fallback options, depending on the landing site weather. See Chapters 2, 3, and 5.
5. Choices of both trajectories and launch vehicles should be thoroughly discussed.	Chapter 2 contains the complete discussion of the outbound leg, while Chapter 5 contains the discussion of the return leg. *Atlas V* was selected because its user information is the most detailed of all commercial boosters. Final booster selection would follow an Request For Proposals (RFP) process to address outstanding launch support problems (liquid hydrogen and payload sterility.) Both forward and return trajectories are Type I transfers to minimize cruise exposure and maximize surface time on Mars.

6. The mission must specify a target and backup landing site...	Marte Vallis is the primary landing target because it has the most recent major outflow channels and lander friendly territory. The new flows discovered by *Global Surveyor* are in high altitude, high latitude Noachian highlands, and are inaccessible because of the terrain (such concerns highlight the need for crew exploration.) The second selection is Terra Meridiani. The site is approximately 300km northeast of *Challenger Memorial Station*, the landing site of *Exploration Rover Opportunity*. *Global Surveyor*'s Thermal Emission Spectrometer revealed several wide areas of hematite deposition in Terra Meridiani. This site is a different one from where *Opportunity* landed. There are several indications both from *Opportunity* and *Global Surveyor* that the entire area was once a seabed. Landing *Mars Challenger* there could allow that question to be answered. After *Judith*'s launch, *Christa* can be sent to *Challenger Memorial Station* with the goal of investigating if any terrestrial organisms piggybacked on *Opportunity*, and how well they fared on Mars. There are also a number of interesting rover engineering experiments that can be done in this case.
7. ...and the ability of the proposed lander to touchdown at both sites must be demonstrated.	The difficulty of landing on Mars is a factor in many decisions, including the decision to use two landers. Both landing sites are at about 1500m below mean surface elevation and have large clear areas where a pilotless lander can be expected to land with limited ability to assess terrain hazards. Both landers rely on qualification by similarity to *Viking* tested hardware with exception to touchdown and hazardous terrain avoidance. Here they picked up where *Exploration Rovers* laves off, extending DIMES (Descent Imaging Motion Estimation Software) to include hazardous terrain avoidance. Both landers, within the context of this exotic frontier, can be described as "conventional". Chapter 3 has the complete report on the landers.
8. The mission should adequately protect against he contamination of collected Martian samples by Terrestrial organisms.	The forward contamination requirements for scientific integrity exceed those stipulated by NASA policy and international treaty. *Mars Challenger*'s approach is to sterilize the entire payload stack to "ten-count", or *Viking* level sterility. (Most martian missions are "hundred thousand count".) Sample containers, sealers, the CIMBRLI lab and associated consumables, container grapples, *Judith*'s MAHLI cameras and other sample handling equipment are sterilized to "zero-count" standards. Operational procedures both in preparation and after launch prevent zero-count equipment from being exposed to ten-count areas. A failure of astrobiological sample qualification because of a terrestrial organism would be a disaster. Chapter 7 addresses these issues.
9. The mission should be equipped with instrumentation appropriate for the scientific exploration of Mars.	Many of *Mars Challenger*'s engineering remote sensors are appropriate to the exploration of Mars and will be used as such. ASQ is a goal heavily linked to scientific objectives. Together, *Judith* and *Christa* carry all of the capabilities of the *Exploration Rovers* and *Science Laboratory* with exception to the Miniature Thermal Emission Spectrometer, Mossbauer Spectrometer, and ChemCam laser spectrometer. *Christa* will carry the second slide microscope to land on another planet, along with 21^{st} century editions of *Viking* laboratory experiments. Astrobiology is discussed in Chapter 7. Geology is a secondary objective.
10. Equipment mobility.	*Christa* is a rover sized between an *Exploration Rover* and the *Science Laboratory*. Proposed mobility hardware is the heritage Bickler system of rocker bogie suspension, in-wheel motors and turn actuators. This system is common to all Mars rovers to date, including *Science Laboratory*. The mobility of previous rovers was limited by "brain power", not solar power. *Christa* is a stand-alone vehicle with independent direct-to-Earth and UHF relay communications, as well as an separate operations team. Chapter 4 is the *Christa Rover* chapter, and contains the complete mobility discussion.

11. Manipulation equipment.	*Christa* is equipped with a Honeybee Rock Abrasion Tool, cleft scraper, soil bucket, and sample container grapple on its arm, along with a deck slide preparation kit. *Judith* is equipped with the sample container grapple, sample sealer, and an air gun (which operates off the ISRU compressed air and azote boiloff supply) on each of its two cranes. The air gun's design application is blowing dust from the solar arrays. See Chapters 4 and 7.
12. Scientific astrobiology measurements.	The Astrobiology Sample Qualification (ASQ) payload is the primary payload of the *Christa Rover*. It is equipped with the CIMBRLI environmental microscope and the *Christa Laboratory*. Details are in Chapter 7.
13. Propellant for Earth return must be created using indigenous Mars resources, in whole or in part.	*Judith* uses four chemical reactions (in three reactors) and three thermodynamic reactions, local carbon dioxide, stored liquid hydrogen, and closed-loop helium to generate 2107kg of oxybenzene propellants, 2047kg of which is Martian material. *Mars Challenger II* has been refined to include a properly analyzed compressor and the expected impact of Martian azote, or inert atmospheric constituents. Chapter 6 contains the ISRU design.
14. Complete Mission Cost	*Mars Challenger* is based on previous Mars missions and attempts to use as much existing technology as possible. The expense of a Mars mission of this type is the use of new technologies, and where those expenses come from is the flight qualification of the new hardware. This couples the mission cost to the mission objectives. One of the biggest mission objectives, in terms of cost impact, is simply landing on Mars. It is important to stay within the existing *Viking* tested technology base in order to meet the goal of $1200M or less. There was insufficient time and manpower to detail and source *Mars Challenger* to the point of a detailed cost analysis. Based on Mars missions that have flown before, with sufficient control of mission objectives and mass, it should be possible to fly this mission on a budget of $1200M and a six year schedule.
15. Sample Quarantine and Containment	See Chapter 7. *Mars Challenger*'s approach is to use the ASQ payload to determine that samples to be sent back are free from life that has the potential of harming Earth's biosphere. This objective forms the mission's entire scientific payload. Beyond this, containment is with the objective of isolating the samples from terrestrial life, not vice versa.
16. Sample Grab Mechanism	There are tools intended to be used on returned samples, and an additional set which are used for ASQ. Chapter 7 has the details. *Christa* includes the sample module grapple and sample bucket. Site qualification tools include the cleft scraper and rock abrasion tool. The cleft scraper has the ability to manipulate a CIMBRLI slide outside the *Christa Laboratory*.
17. Astrobiology Experiment Equipment/Techniques	*Christa Laboratory* includes the CIMBRLI chamber, which is able to simulate Earth-like conditions, adjoining chambers for growth experiments, and an oven for pyrolytic experiments. The laboratory uses four instruments for determining the composition of samples being experimented. The CIMBRLI microscope, gas chromatograph, mass spectrometer, and Alpha Particle X-Ray Spectrometer. The last instrument has been arm mounted on previous missions. If *Christa* needs to have one operate under lab induced environmental conditions, it may need to carry it there instead of the arm, or carry two such instruments.
18. Mars Ascent Vehicle	The sample return booster is named *Judith* and is capable of launching a 24kg sample return modules, approximately 4kg of which are samples. The return ascent is a direct insertion with less than one full coast orbit. Chapter 5 is the chapter on *Judith*.
19. In-Situ Propellant Production (specifics on techniques and amounts produced.)	*Judith* ascends using 2107kg of oxybenzene propellants produced with the use of 58kg of earth supplied hydrogen, and 3070kg of compressed Martian air. The excess martian air is needed to provide additional carbon, leading to a lot of oxygen venting, and also because Martian air contains about 4.3% of useless inert constituents. See Chapter 6 for further details.

20. Aerocapture and Landing Mechanisms	*Mars Challenger* uses the standard NASA 70deg toriconical heatshield and disk-gap-band parachutes qualifiable by similarity to systems tested during the *Viking* program. Both landers employ a combination of flight qualified solid motors and monopropellant hydrazine propulsion in a two step landing phase. *Judith*'s lander retains its backshell, while *Christa* is landed on its wheels using a hover crane approach similar to that of *Science Laboratory*. See Chapter 3.
21. Light Element Geochemistry	*Christa* carries a gas chromatograph, alpha particle x-ray spectrometer (APXS), and mass spectrometer. It should be possible to identify the composition of most soils and rocks examined using these instruments, especially after the ground truth of return samples is used to calibrate the accumulated data. See Chapter 7 for details.
22. Weathering History	While not specifically armed for the task, both *Christa* and *Judith* are very well equipped to study rock and environment weathering history. *Christa*'s CIMBRLI microscope, rock abrasion tool, and lab sample grinder can be used in such investigations. *Judith*'s air gun and MAHLI may also be useful. The air gun is "ten-count" biological standard, and therefore can't be used on samples selected for return to Earth. See Chapter 7 for details.
23. Residual Organics	*Christa* carries a gas chromatograph, alpha particle x-ray spectrometer (APXS), and mass spectrometer, which will be able to identify carbon-based compounds in the environment. See Chapter 7 for details.
24. Iron Redox State	The authors do not understand this requirement, nor how it might relate to astrobiological sample qualification. It does sound as though this requirement has to do with distinguishing various flavours of iron oxides, the calling of the Mossbauer spectrometer carried on the arms of the *Exploration Rovers*. This instrument was one of the founding members of the Cornell *Athena* geological exploration payload, the *Exploration Rovers* are based on. It is not a part of *Christa*'s ASQ kit, but might be added, volume, mass, power, and cost permitting.
25. Magnetic Fraction	The authors do not understand this requirement. Within the designer's understanding are the things such as magnetic permeability, to distinguish ferromagnetic from paramagnetic materials. The author is also familiar with superdiamegnetism and the operation of non-ferrous scrap metal sorters that use the eddy current principle. As this is of little consequence to the ASQ requirement, *Christa* is not equipped with specific instruments. As part of her navigation package, *Christa* does carry a directional magnetometer to see if compasses are any good for local area navigation where a magnetic field is present. Mars does not possess a global magnetic field, but some local magnetic fields have been detected by orbiters.
26. Interplanetary Dust Particles	*Mars Challenger* focuses on the requirements of astrobiological sample qualification and the engineering requirements of a sample return mission. As such, it has no specific investigations for interplanetary dust particles. They are unlikely to be distinguishable from indigenous Martian dust on the surface, and *Mars Challenger* does not carry detectors or impact panels for cruise. For the qualification of a piloted mission's safety, there is data from *Pioneer*, *Voyager* and other planetary flyby missions. Such a requirement can best be explored by a *Stardust*-like mission flown on a free-return trajectory such as one a piloted mission might use during an abort.
27. Oxidant	*Viking* had a labeled release experiment test positive for both an exploratory sample and a similar control sterilized sample. It is uncertain whether this reaction was caused by biological activity or a chemical reaction caused by reactive material. *Christa*'s advantage is the CIMBRLI microscope, which will be able to visually examine such samples at detail fine enough to reveal bacteria, reaction precipitates or voids. See Chapter 7 for instrument details.

Appendix B: Tank Management Analysis

Mars Challenger II
Judith 0710A
Tank Management Analysis
After Columbia Project 2007

		Second Stage				First Stage				Landing Propulsion System*				Cruise			
Substance	Density	1	2	3	4	1	2	3	4	1	2	3	4	LH2			
Volume		216.0	216.0	216.0	216.0	367.0	367.0	367.0	367.0	32.0	32.0	32.0	32.0	216.0			
Water(H2O)	1.000	216.0	216.0	216.0	216.0	367.0	367.0	367.0	367.0	32.0	32.0	32.0	32.0	216.0			
N2H4	1.000									32.0	32.0	32.0	32.0	216.0			
LH2	0.070	15.1	15.1	15.1	15.1									15.1			
Benzene (C6H6)	0.865			186.8	186.8			317.5	317.5								
LOX	1.140	246.2	246.2			418.4	418.4										
Step																	
Earth Launch	Total																
Substance	LH2	H2O	LOX	C6H6	LH2	LH2	LH2	LH2	GHe	GHe	GHe	GHe	N2H4	N2H4	N2H4	N2H4	LH2
Mass	68.04	During settled venting,			13.61	13.61	13.61	13.61					32.00	32.00	32.00	32.00	13.61
Volume	972.00	Gas port must remain			194.40	194.40	194.40	194.40					32.00	32.00	32.00	32.00	194.40
% Full	90.00%	Uncovered			90.00%	90.00%	90.00%	90.00%					99.99%	99.99%	99.99%	99.99%	90.00%
Arrival	LH2	H2O	LOX	C6H6	LH2	LH2	LH2	LH2	GHe	GHe	GHe	GHe	N2H4	N2H4	N2H4	N2H4	LH2
Mass	57.76	Boiloff allowance is			11.55	11.55	11.55	11.55					32.00	32.00	32.00	32.00	11.55
Volume	825.12	0.0428	Kg per day		165.02	165.02	165.02	165.02					32.00	32.00	32.00	32.00	165.02
% Full	76.40%				76.40%	76.40%	76.40%	76.40%					99.99%	99.99%	99.99%	99.99%	76.40%
Settled Transfer	LH2	H2O	LOX	C6H6	LH2	LH2	LH2	LH2	GHe	GHe	GHe	GHe	N2H4	N2H4	N2H4	N2H4	LH2
Mass	57.76				14.36	14.36	14.36	14.36					32.00	32.00	32.00	32.00	0.30
Volume	825.12				205.20	205.20	205.20	205.20					32.00	32.00	32.00	32.00	4.32
% Full	76.40%				95.00%	95.00%	95.00%	95.00%					99.99%	99.99%	99.99%	99.99%	2.00%
Empty LH2 Tank 1	LH2	H2O	LOX	C6H6	LH2	LH2	LH2	LH2	LOX	GHe	C6H6	GHe	Water	Water	Water	Water	Jettison
Mass	40.82	0.00	418.00	209.80	0.00	13.61	13.61	13.61	418.00	98.00	209.80						
Volume	583.20	0.00	366.67	242.54	0.00	194.40	194.40	194.40	366.67		242.54						
% Full	67.50%	0.00%	99.91%	66.09%	0.00%	90.00%	90.00%	90.00%	99.91%		66.09%						
Empty LH2 Tank 2	LH2	H2O	LOX	C6H6	LOX	LH2	LH2	LH2	LOX	LOX	C6H6	C6H6	Water	Water	Water	Water	
Mass	25.70	0.00	997.60	405.60	161.60	0.00	12.85	12.85	418.00	418.00	209.80	195.80					
Volume	367.20	0.00	875.09	468.90	141.75	0.00	183.60	183.60	366.67	366.67	242.54	226.36					
% Full	56.67%	0.00%	92.11%	63.88%	65.63%	0.00%	85.00%	85.00%	99.91%	99.91%	66.09%	61.68%					
Empty LH2 Tank 3	LH2	H2O	LOX	C6H6	LOX	LOX	LH2	LH2	LOX	LOX	C6H6	C6H6	Water	Water	Water	Water	
Mass	12.10	0.00	1328.00	577.30	246.00	246.00	0.00	12.10	418.00	418.00	295.60	281.70	Dumping LOX				
Volume	172.80	0.00	1164.91	667.40	215.79	215.79	0.00	172.80	366.67	366.67	341.73	325.66					
% Full	40.00%	0.00%	99.91%	90.93%	99.90%	99.90%	0.00%	80.00%	99.91%	99.91%	93.12%	88.74%					
Empty LH2 Tank 4	LH2	H2O	LOX	C6H6	LOX	LOX	C6H6	LH2	LOX	LOX	C6H6	C6H6	Water	Water	Water	Water	
Mass	0.00	49.20	1328.00	820.50	246.00	246.00	186.50	0.00	418.00	418.00	317.00	317.00	24.60	24.60			
Volume	0.00	49.20	1164.91	948.74	215.79	215.79	215.61	0.00	366.67	366.67	366.47	366.47	24.60	24.60			
% Full	0.00%	38.44%	99.91%	99.85%	99.90%	99.90%	99.82%	0.00%	99.91%	99.91%	99.86%	99.86%	76.88%	76.88%			
Empty Water	LH2	H2O	LOX	C6H6	LOX	LOX	C6H6	C6H6	LOX	LOX	C6H6	C6H6	Water	Water	Water	Water	
Mass	69.00	0.00	1328.00	820.50	246.00	246.00	186.50	69.00	418.00	418.00	317.00	317.00	0.00	0.00			
Volume	79.77	0.00	1164.91	948.74	215.79	215.79	215.61	79.77	366.67	366.67	366.47	366.47	0.00	0.00			
% Full	36.93%	0.00%	99.91%	88.19%	99.90%	99.90%	99.82%	36.93%	99.91%	99.91%	99.86%	99.86%	0.00%	0.00%			
Mars Launch	LH2	H2O	LOX	C6H6	LOX	LOX	C6H6	C6H6	LOX	LOX	C6H6	C6H6	Water	Water	Water	Water	
Mass	0.00	0.00	1328.00	889.50	246.01	246.01	164.78	164.78	417.99	417.99	279.97	279.97					
Volume	0.00	0.00	1164.91	647.33	215.80	215.80	190.50	190.50	366.66	366.66	323.67	323.67					
% Full	0.00%	0.00%	99.91%	74.11%	99.91%	99.91%	88.19%	88.19%	99.91%	99.91%	88.19%	88.19%					

*Landing Propulsion System Tanks, Fill Factor Requirement accounted for in “full” state