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Mars Exploration Study Workshop II

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Preface

The Mars Exploration Study Project was undertaken by the Exploration Programs Office (now the Planetary Projects Office) in response to the strategic planning initiatives of the Associate Administrator for Exploration, NASA Headquarters in the summer of 1992. The purpose of the study, as viewed by the Associate Administrator for Exploration, was to establish a vision for the human exploration of Mars which would serve as a mechanism for understanding program and technical requirements that would be placed on a precursor lunar exploration program being developed by the Office of Exploration (The First Lunar Outpost). Emphasis was placed on determining the commonality between the Mars and Moon exploration programs to help ensure that total costs for both programs would be minimized and that the lunar program would not contain dead ends which would be difficult or expensive for the Mars program to correct if both programs are carried out sequentially.

The study team chose an approach that emphasized the important aspects of Mars exploration without consideration of the lunar capability. Because Mars exploration is inherently more complex than initial lunar exploration programs, it was considered important to identify the characteristics required for Mars so the evolution of a FLO-like lunar program that would optimize the programmatic interactions could be planned. The result, toward which the study is progressing, is a coherent view of Mars exploration which is valuable in its own right as well as being useful for the integrated programmatic view.

From the outset, it was clear that the Mars study would progress most effectively in an atmosphere of openness to new ideas from outside of NASA. Although most of the study activities represented in the work and in this report have been produced by NASA employees, active interchanges between the study team and non-NASA researchers have been encouraged and many "not-invented-here" concepts have been included in the study.

The workshop summarized by this report was held on May 24-25, 1993 at the Ames Research Center. It gathered the NASA study team and a group of non-NASA Mars exploration enthusiasts in an environment which allowed and even encouraged criticism. This report provides an overview of the status of the Mars Exploration Study, materials presented at the workshop, and discussions of open items being addressed by the study team. In particular, the design reference mission (DRM) was reviewed and focused. The workshop advanced a DRM that significantly reduces the perceived high costs, complex infrastructure and long schedules associated with previous Mars scenarios. The strategy enhances the mission return, improves the safety of the crew, and reduces or eliminates many of the obstacles associated with conventional strategies. This review of the DRM is believed to be an essential step in improving our understanding of technique, risk and cost. In addition, three teams were assembled to address issues of cost, dual-use technologies, and international involvement. It was believed that the definition of the DRM would allow these issues to be addressed in a more coherent manner.

The current phase of the Mars Exploration Study is expected to be complete in December, 1993, when a comprehensive technical report will be assembled.

This workshop was successful primarily due to the efforts of Nancy Ann Budden, who coordinated the meeting content and logistics from Houston, as well as Geoff Briggs, Doug O'Handley, and Larry Lemke at Ames Research Center who provided local workshop coordination and support. The Mars Study Team reviewed the manuscript with particular inputs from Stan Borowski, John Connolly, Andy Gonzales, Lisa Guerra and David Weaver. David Black and Mary Cloud at the Lunar and Planetary Institute provided support for the outside participants. This paper is Lunar and Planetary Institute contribution number 820.

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Section I. Mars Exploration Workshop II:

The Premise for Mars Exploration

I. The Premise for Mars Exploration

A. The Rationale and Objectives for Mars Exploration

In August, 1992, the first workshop of the Mars Exploration Study Team was held at the Lunar and Planetary Institute, in Houston, Texas. It was the purpose of that workshop to address the "whys" of Mars exploration, to provide the top-level requirements from which the Mars exploration program could be built (Duke and Budden, 1992).

The workshop attendees identified the major elements of rationale for a Mars exploration program as:

- Mars is the only planet beyond the Earth-Moon system where sustained human presence is believed to be possible.

- The technical objectives of Mars exploration are to understand the planet and its history, in part to better understand Earth; and to understand what would be required for a permanent human presence there.

- The political environment at the end of the Cold War may be conducive to a concerted international effort that is appropriate and may be required for a sustained program. There would be political benefits from a cooperative program.

- The technical capabilities are available or on the horizon, such that commitment to the program will both effectively exploit previous investments, but also contribute to advances in technology.

- The goals of Mars exploration are grand, will motivate our young, benefit technical education goals, and excite the people and nations of the world to excel.

- In comparison with other classes of societal expenditures, the cost of a Mars human exploration program is modest. Many of the benefits of a human exploration program are indirect or intangible. Further analysis is needed to help quantify the benefits of Mars exploration, so that compelling arguments can be made to the public and leaders of those nations who might participate in a Mars exploration program, to justify the expenditures that will be required.

Reflecting the conclusions of the workshop, the Exploration Program Office (ExPO) adopted as the technical goal for the Mars exploration program: "Verify a way that people can inhabit Mars." Derived from this goal are three objectives: (1) Conduct human missions to Mars; (2) Conduct applied science research to use Mars resources to augment life-sustaining systems; and (3) Conduct basic science research to gain new knowledge about the solar system's origin and history. Conducting human missions to Mars is required to accomplish the exploration and research activities, but contains the requirements for the safe transportation, maintenance on the surface of Mars and return of a healthy crew to Earth. The surface exploration mission envisions approximately equal priority for applied science research - learning about the environment, resources, and operational constraints that would allow humans eventually to inhabit the planet; and basic science research - exploring the planet for insights into the nature of planets, the nature of Mars' atmosphere and its evolution, and the possible past existence of life. These more detailed objectives are shown in Table 1 and form the basis for defining the required elements and operations for the Mars exploration program.

B. The Reference Mission

1. Purpose of the Reference Mission

The reference mission serves several purposes. First, it provides a mechanism for diverse technical personnel to collectively integrate their definition and design efforts around a baseline strategy. This allows people with innovative concepts to compare their approach on a direct basis. It is particularly important to establish a set of mission accomplishments that must be met by alternative scenarios. This is a major step in documenting the expected benefits of the exploration program. Second, it allows the formulation of a technically credible approach, with appropriate documentation of the technical and programmatic risks, which can form the basis for defensible cost estimates for the program. Previous studies of Mars missions have been associated with rather high costs, but with little visibility into the assumptions and approaches to developing the costs. Developing the reference mission provides a starting point for cost analysis, which can identify important programmatic or technical problems whose solution can reduce the overall cost and risk of the program. Likewise, the reference mission provides a basis for analyzing the importance of technology development and new data which can be gathered in advance of the human exploration mission design. Finally, the reference mission provides a basis for understanding potential cooperative approaches to conducting the mission.

Table 1.
Mars Exploration Program Technical Objectives

<u>Conduct Human Missions to Mars</u>
a. Land people on Mars and return them safely to Earth
b. Demonstrate the capability of people to effectively perform useful work on the surface of Mars
c. Demonstrate the ability to support people on Mars for two years or more at a time
d. Demonstrate the ability to support people in space for periods of time consistent with Mars mission opportunities (2-3 years)
e. Demonstrate that space operations capabilities including communications, data management, and operations planning can accommodate both routine and contingency mission operational situations; and understand abort modes from surface or space contingencies
f. Determine the characteristics of space transportation and surface operations systems consistent with sustaining a long term program at affordable cost
<u>Conduct Applied Science Research to Use Mars Resources to Augment Life-Sustaining Systems</u>
a. Catalogue the global distribution of life support, propellant, and construction materials (hydrogen, oxygen, nitrogen, phosphorous, potassium, magnesium and iron) on Mars and of the Moons Phobos and Deimos
b. Demonstrate effective system designs and processes for utilizing in-situ materials to replace products that otherwise would have to be provided from Earth
<u>Conduct Basic Science Research to Gain New Knowledge About the Solar System's Origin and History</u>
a. Demonstrate the capacity for robotic and human investigations to gain significant insights into the history of the atmosphere, the planet's geological evolution, and the possible evolution of life
b. Determine whether Mars, the Martian system, or Earth-Mars transits are suitable venues for other science measurements

2. Reference Mission Overview

The mission objectives of the reference mission adopted for this study include: (1) Define a robust surface mission, supporting crews on the surface of Mars for 500-600 days. This is in contrast to previous mission studies that have adopted short stay times for the first or first few human exploration missions. The investment in the systems that are necessary to get humans to Mars is large and similar for either short or long duration stays; therefore, the large benefit gained by extending the stay time should be cost-effective; (2) Provide an operationally simple approach. Because an integrated mission in which a single spacecraft is launched from Earth and lands on Mars to conduct the long exploration program is not feasible, it is necessary to determine the simplest and most reliable set of operations in space or on the surface of Mars to bring all of the necessary resources to the surface where they are to be used; (3) Provide a flexible implementation strategy. Mars missions are complex, so that multiple pathways to the desired objectives have considerable value in insuring mission success; (4) The approach must balance technical, programmatic, mission, and safety risks. Mars exploration will not be without risks; however, the risk approach will be an important element in the acceptability of the mission concept to the public and leaders.

The provision of a robust surface capability is basic to the reference mission defined in this study. The surface capability provides a comfortable, productive and safe place for the crew. This, in turn, changes the perspective with respect to previous studies. Whereas in previous studies, many mission contingencies resulted in aborts (direct returns to Earth), another option exists in this reference mission, namely, abort to Mars' surface. This allows the mission design to focus on the surface capability, not on the provision of redundant systems to be used in the unplanned and relatively improbable event of system failure in flight. The robust surface capability is implemented through the split mission concept, in which cargo is transported in manageable units to the surface and checked out in advance of committing crews to their missions. This approach provides a basis for continued expansion of capability at the outpost through the addition of modules to the original systems. The split mission approach also allows the crews to be transported on faster, more energetic trajectories, minimizing their exposure to the space environment.

The reference mission is depicted in Figures 1a and 1b. The 2007 and 2009 launch opportunities were selected for this study because they are reasonable target dates for a program initiated in the decade of the 1990's, but also because they represent the most energetically difficult opportunities. A mission designed for those years will be easier in later years. For example, where the trans-Mars and trans-Earth crew transfers in the 2009 opportunity are 180 days, in the easier 2019 opportunity they are 120 days each way for the same transfer vehicle design. In the first opportunity, 2007, three cargo missions are launched on minimum energy trajectories direct to Mars, without assembly or fueling in low Earth orbit. The first payload is a vehicle in which the crew will return to Earth after their exploration, which is left in Mars orbit. The second payload is a surface habitat and ascent vehicle. The third payload contains the crew's ascent vehicle and a mixture of other elements of the surface systems and consumables. The ascent vehicle is landed dry (except for hydrogen to be used as a reactant) and is fueled through production of methane and oxygen from the Mars atmosphere. All are checked out and the ascent vehicle is verified to be fueled before the crew is launched from Earth. At the second opportunity, 2009, the crew is launched. They land in the habitat in which they have ridden from Earth, without a rendezvous in Mars orbit. After their stay on Mars, they use the previously landed ascent vehicle to return to orbit, rendezvous with the Earth return vehicle, and return to Earth. In the second launch window, two additional cargo missions also are launched, which provide backup or extensions of previous capabilities. For example, a second Mars ascent vehicle is landed and a second Earth return vehicle is placed in Mars orbit, providing two redundant means for each leg of the return trip. Subsequently, one piloted mission and two cargo missions can be launched at each opportunity.

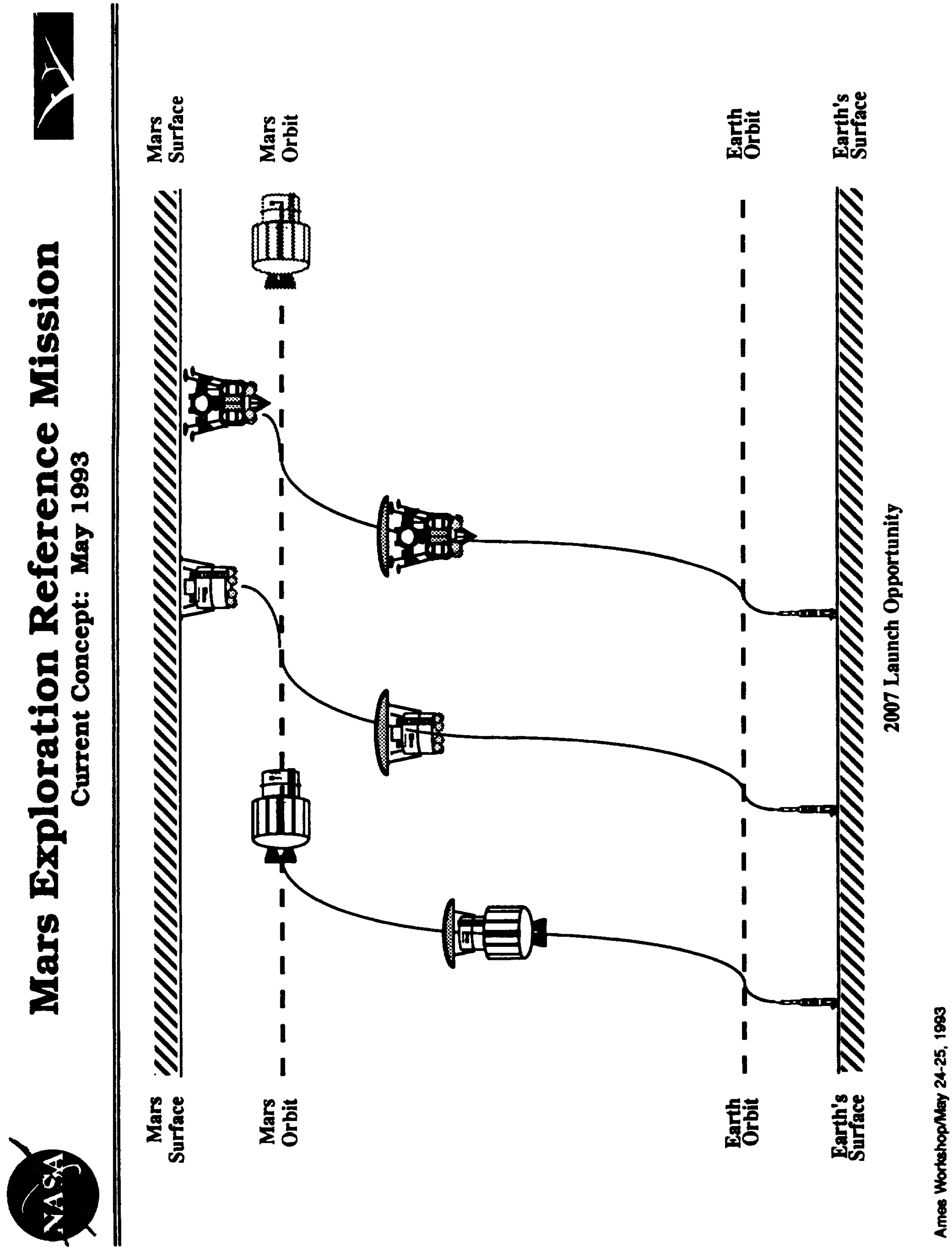

Figure 1a. Mars Exploration Reference Mission Current Concept: May 1993 — [D. Weaver]

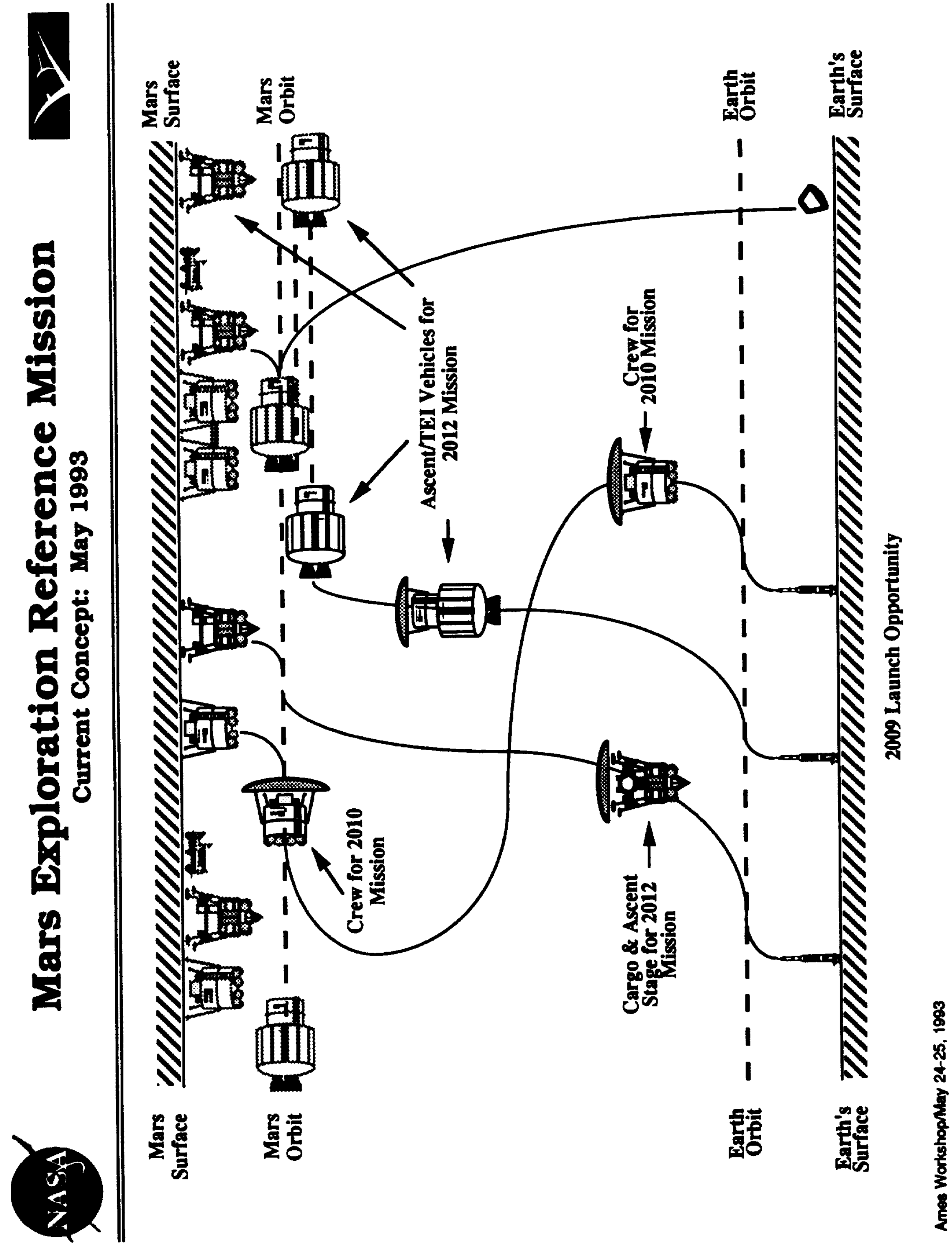

Figure 1b. Mars Exploration Reference Mission Current Concept: May 1993 — [D. Weaver]

The major distinguishing characteristics of the design reference mission, compared to previous concepts, include: (1) No low-Earth orbit operations, assembly or fueling; (2) No rendezvous in Mars orbit prior to landing; (3) Short transit times and long surface stay times for the first and subsequent crews exploring Mars; (4) A common heavy lift launch vehicle, capable of transporting crew or cargo to space, and capable of delivering needed payload with a total of 4 launches for the first human mission and three launches of cargo and crew for each subsequent opportunity; (5) Exploitation of indigenous resources from the beginning of the program, with important performance benefits and reduction of mission risk; (6) Availability of abort-to-Mars'-surface strategies, based on the robustness of the Mars surface capabilities.

C. The Surface Mission

1. Surface Mission Overview

The principle was established at the beginning of the Mars Exploration Study that the technical benefits of Mars exploration would be heavily weighted toward those things that people could constructively accomplish on the surface of the planet. Although the trip there and back will be rigorous and will require substantial planning and good use of technology to reduce risk, the vast majority of the important exploration tasks are those that are accomplished on the planet's surface. For that reason, emphasis in this study has been placed on the definition of the surface system. As few previous studies have addressed these surface mission issues in depth, surface mission concepts are not as advanced as space transportation issues. But the resolution of the surface mission issues is essential also to the space transportation question, because they tend to dominate the requirements for transportation of hardware and crew to Mars' surface.

(a) Implications of Mission Objectives

There are typically a set of difficulties that arise in defining and justifying a particular set of surface mission activities. These arise from an interaction of what is desired versus what is feasible. This requires that the final definition be approached either from both perspectives simultaneously or iteratively. Both techniques will be used in this study. Probably, at this point in the reference mission design, the set of surface activities is too demanding, and will have to be scaled back somewhat. The first step in this process is to analyze in more detail the implications of the mission objectives that have been adopted (Table 1).

(1) Conduct human missions to Mars

From the point of view of the surface mission, this implies that the capability for humans to live and work effectively on the surface of Mars must be demonstrated, with several sub-objectives. These include defining a set of tasks of value for humans to perform on Mars and providing the tools to carry out the tasks; supporting the humans with highly reliable systems; providing a risk environment that will maximize the probability of accomplishing mission objectives; and providing both the capability and the rationale to continue the surface exploration beyond the first mission. This then requires a set of functional capabilities on the surface, including habitats, surface mobility systems, and supporting systems such as power and communications systems.

(2) Conduct applied science research to use Mars resources to augment life-sustaining systems

This objective will require that an assessment be made of the location and availability of specific resources, such as water; and that effective systems designs be developed and demonstrated to extract and utilize indigenous resources, including operating the systems beneficially. As demonstrations, there are opportunities to use indigenous resources in the life support system, in energy systems as fuel or energy storage, and as propellant for spacecraft. These may develop into essential systems for the preservation of the outpost as the outpost evolves. To the support facilities identified in the previous paragraph must be added exploration systems (orbital or surface), resource extraction and handling systems and additional systems for recycling water and air and producing food.

(3) Conduct basic science research to gain new knowledge about the solar system's origin and history

This will require that a variety of scientific explorations and laboratory assessments be carried out on the surface of Mars, both by humans and robots. The science problems will not be assessed completely at any one site, so this requirement implies considerable crew member mobility and transportation systems to support exploration, as well as the specialized tools required outside the outpost to collect and document materials and the facilities inside the outpost to perform analyses.

(4) Surface System Definition Philosophy - Safety Philosophy

The ability to define a robust surface capability that supports the reference mission objectives requires that a design approach be accepted which balances performance, risks, and costs. It is evident that the priorities that must be established for the surface mission, as for the entire mission are: (1) The health and safety of the crew is the top priority for all mission elements and operations; Life-critical systems are those absolutely required to insure the crew's survival. Life-critical systems will have two backup levels of functional redundancy; if the first two levels fail, the crew will not be in jeopardy, but will not be able to complete all mission objectives; (2) Completing the mission as defined, to a satisfactory and productive level(mission-critical). Mission critical objectives will have one backup level; and (3) Completing additional, possibly unpredicted (mission-discretionary) tasks which add to the total productivity of the mission. Mission discretionary systems will not jeopardize the crew if they fail, but need not have a backup. The backup systems may be provided by either real redundancy (multiple systems of the same type) or functional redundancy (systems of different type which provide the required function). Recoverability or repairability by the crew will provide yet additional safety margins.

This risk approach provides a framework for defining the overall surface system, which is robust with respect to safety and performance. The strategy adopted for the principal Life-Critical systems of the reference mission is shown in Table 2.

Table 2.
Principal Functions of Life-Critical Systems and Safety Strategy

	Primary	**Backup #1**	**Backup #2**
Habitable volume	Habitat #1	Habitat #2	Pressurized Rover
Air and water	Life Support System #1	Life Support System #2	Consumable Cache
Power	Power Unit #1	Power Unit #2	Power Unit #3
Food/food preservation	Supply #1	Supply #2	Emergency Supply

In the reference mission, a habitat and pressurized rover are delivered and checked out prior to the departure of the crew on the first human mission. The crew arrive in a second habitat. Each habitat is equipped with a life support system capable of providing for the entire crew for the duration of their surface stay. The concept of a life-support cache (Figure 2) is derivative from the objective/assumption that indigenous resources will be extracted and utilized in the strategy from the beginning of the program. The reference mission thereby utilizes a system to produce methane, oxygen and other consumables from Martian resources, and verifying these caches prior to the crew departing from Earth. In the reference mission, all food is brought from Earth. An experimental bioregenerative life support system capable of producing a small amount of food is included as a mission-critical element; however, the crew will not depend on it for their sustenance. In earlier versions of the reference mission, an energy cache was considered as the second backup to the power system. However, such a backup apparently requires too large an initial power system, if it is to be manufactured on the required schedule, and has therefore been replaced by a redundant power system.

2. Principal Elements of the Surface Mission

(a) Surface Mission Objectives

(1) Science Objectives

The principal science objectives for Mars exploration is determining:

- Is Mars a home for life - in the past, present or future?

This set of objectives will combine field and laboratory investigations in geology, paleontology, biology and chemistry. The underlying assumption is that these problems will not have been solved by previous robotic Mars exploration programs and the optimum manner to solve them is through judicious use of humans at Mars as field geologists and laboratory analysts.

- What are the origins of the planet Mars and what does it tell us about Earth?

This set of objectives involve geology and geophysics, atmospheric science, meteorology and climatology, and chemistry. They will also require iterative sampling of geological units as well as monitoring of a global network of meteorological stations. The global network will most likely be established by robotic elements of the program.

- What resources are available on Mars?

The location and general accessibility of resources on Mars will be determined by the series of robotic missions; however, in detail, understanding the extent and utility of the resources may require the presence of humans. The first missions will require that resources be extracted only from the atmosphere, which is well-enough known for that purpose. Subsequent missions may utilize other resources, including indigenous water. The resource discovery and verification of accessibility will require investigations in geology, atmospheric science and chemistry.

The targeted investigations to be carried out from the Mars outpost depend on an increasing range of accessibility from the outpost by humans and automated rover/sample collectors. A general geological map of the region of the outpost site should have been prepared by robotic missions prior to selecting and occupying the initial site. Field investigations carried out by crews on Mars will address detailed questions requiring access to varied terrain and rock types. The reference mission includes provision for two pressurized rovers, eventually allowing traverses of up to 500

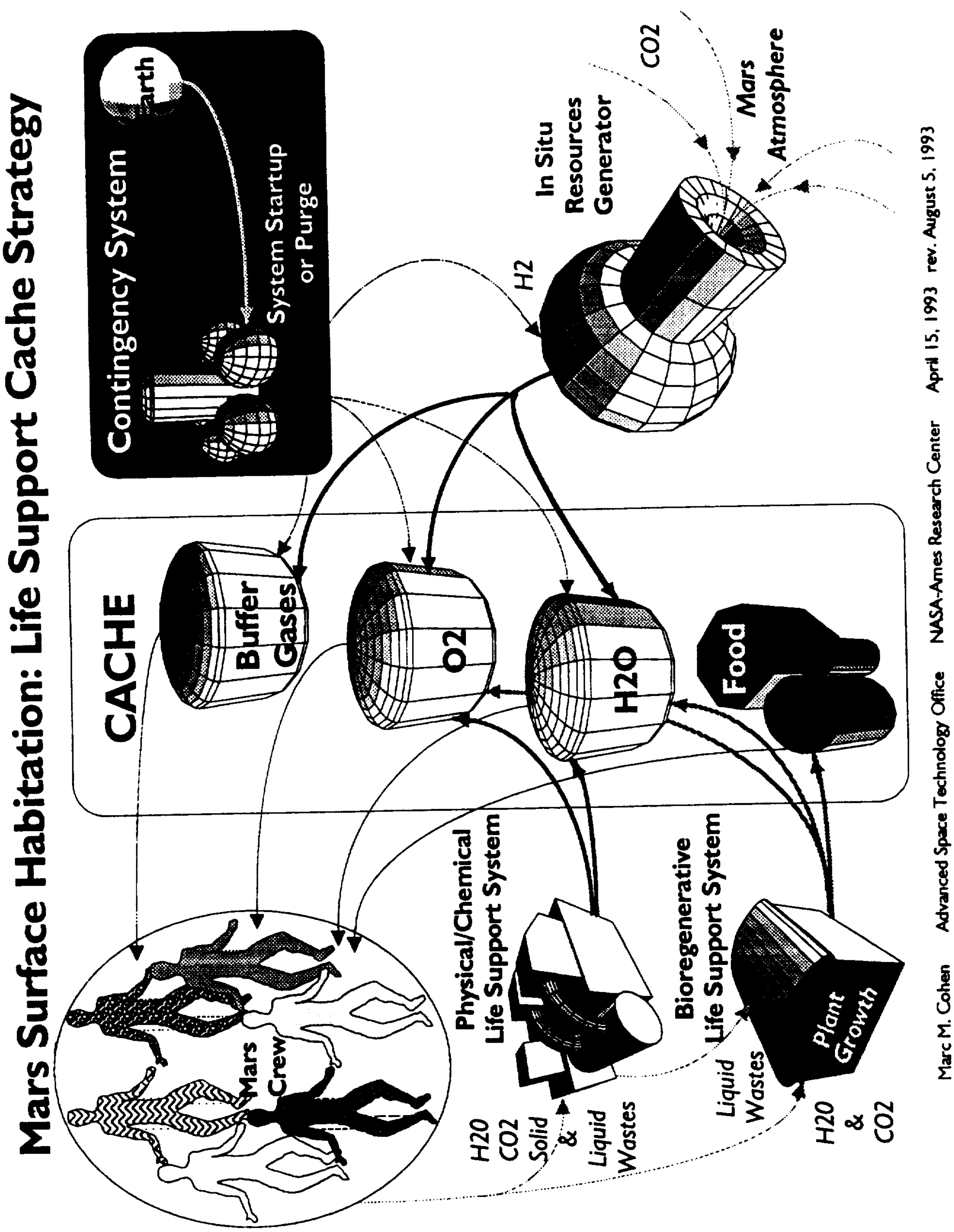

Figure 2. Mission Design Logic
Mars Surface Habitation: Life Support Cache Strategy — [M. Cohen]

kilometers range from the outpost. It also includes three smaller, instrumented rovers which can be teleoperated as necessary to document and collect samples for analysis in the outpost laboratory or for return to Earth.

(2) Habitation objectives

The habitation objectives of the Mars outpost include:

- Insuring that Martian habitability is not fundamentally limited by uniquely Martian characteristics such as low gravity, absence of a magnetic field, soil toxicity, or the radiation environment.

- Demonstrate that self-sufficiency can be achieved on the local scale of a Mars base. This includes the provision of a reasonable quality of life and reasonably low risk for the human crews.

- Implementation of an experimental biologically regenerative life support system.

- Determine the potential for expansion of base capabilities using indigenous resources.

- Investigate the biological adaptation to Mars over multiple generations of representative plant, animals and microbial species.

- Assay the volatile inventory of Mars to identify regions where they are readily available to humans.

These habitation objectives are aimed at establishing the feasibility and approach required to move beyond the exploratory phase toward the development of long-term activities on the planet. They influence the selection of elements that are included in the surface systems, including habitats, mobility, life support, power and communications systems.

(b) Surface Mission Timelines

A possible timeline for the surface mission is shown in Figure 3. This timeline is illustrative of the considerations that must go into defining logistics and capabilities of the crew on the surface. It represents the current level of thinking on the surface strategy to be employed. Key considerations for this effort include: (1) The size of the crew. For the reference mission, a crew of 6 has been adopted. (2) The length of the surface stay. Six hundred days has been accepted as the reference mission baseline. This is consistent with the capabilities of the reference transportation system strategy, in which crew transit times are between 120 and 180 days. (3) The mobility available. It is assumed that two pressurized rovers are available. These could allow traverses to distances of 500 kilometers from the outpost, when confidence in the systems and operations had been gained. (4) The allocation of crew time to external activities (Extra-habitat activity = EHA) and internal habitat activities (IHA). The assumption is that each time an exploration sortie is made that considerable post-sortie analysis and planning would be undertaken before the next sortie. (5) The amount of time required for maintenance and repair. This is a key consideration and a technology driver for these missions. To the extent that crew time is used for maintenance and repair, it will not be available for productive exploration and analysis. (6) Provisions for emergencies. For example, the possibility that a solar particle event will interfere with planned activities must be considered. (7) Overhead, recreational, and defined physical conditioning time must also be

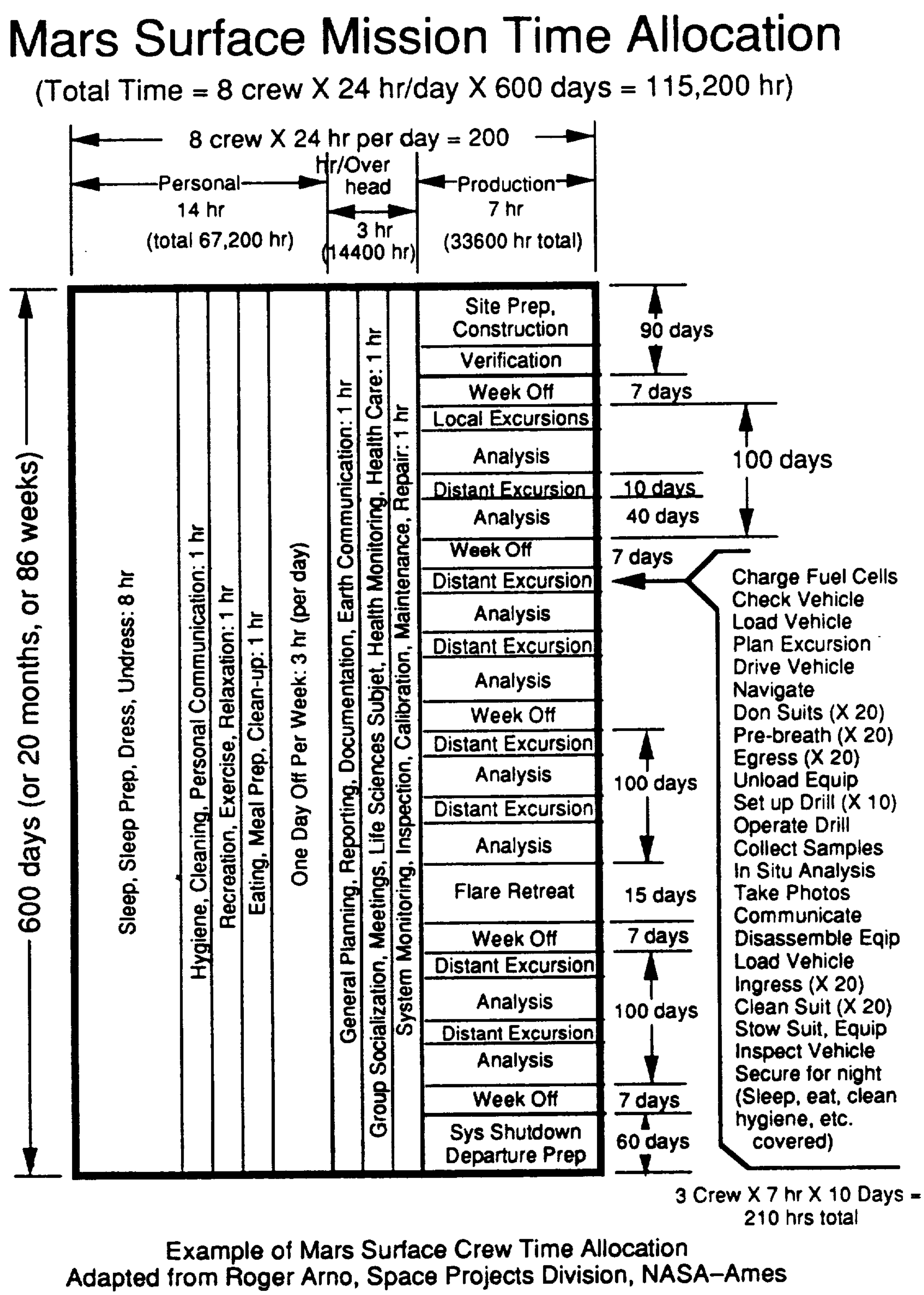

Figure 3. Example of Mars Surface Mission Crew Time Allocation — [M. Cohen]
(Note: This calculation was based on a crew of eight while the reference mission uses a crew of six)

considered. These are reasonably well understood, except for the amount of exercise needed to maintain fitness in a 1/3-g environment. These amounts of time are also dependent on what is needed to maintain optimum levels of crew performance.

(c) Human Factors and Crew Size

Humans are the most valuable mission asset for the Mars exploration program, and must not become the weak link. The requirement that humans spend on the order of 600 days on the surface places unprecedented requirements on the people and their supporting systems. Once committed to the mission on launch from Low Earth Orbit, the crew must be prepared to complete the full mission without further resupply from Earth. Their resources are either with them or have already been delivered to or produced on Mars. No further resupply is available and return to Earth in substantially less time than the nominal mission is not possible. Crew self-sufficiency is required because of the long duration of their mission and by the fact that their distance from Earth impedes or makes impossible communications and control from Earth. The crews therefore need their own resources (skills, training) and specialized support (systems) to meet the new challenges of the missions. However, unlimited resources can not be provided within the constraints of budgets and mission performance, so tradeoffs must be made between cost and comfort, as well as performance and risk. Because the objectives of the missions are to learn about Mars and its capability to support humans in the future, there will be minimum level of accomplishment below which a viable program is not possible. Survival of humans on the trip there and back is an insufficient program objective.

Basic human survival factors for the crew include adequate shelter, including radiation protection; breathable, controlled, uncontaminated atmosphere (in habitats, suits, and pressurized rovers), food and water, medical services, psychological support, and waste management. In the 4-6 month transits to Mars, the chief problems will be on maintaining interpersonal relationships needed for crew productivity, and maintaining physical and mental conditioning in preparation for the surface mission. On the surface, the focus of crew concerns will turn to their productivity in a new and hazardous environment. The transit environment is likely to be a training and conditioning environment, the surface environment is where the mission-critical tasks will be done. Mental health as well as physical health will be crucial to accomplishing the mission.

Within these parameters, there are a number of areas that will require attention (Table 3). These are generally well known as questions; what is not as clear is how serious many of them are as problems, and how much effort is required to reduce the risks they present to the mission to acceptable levels. For a thorough analysis of the issues involved, see NASA Advisory Council Aerospace Medicine Advisory Committee (1992).

For long-duration missions, with inevitably high stress levels, the trade-off between cost and crew comfort must be weighed with special care. The development of high quality habitats and environmental design features are critical to assuaging stress and increasing crew comfort — conditions that will greatly increase the likelihood of mission success. Providing little more than the capability to survive invites mission failure.

Not all amenities need be provided on the first mission. The program should be viewed as a sequence of steps which, over time, will increase the amount of physical space on the surface, increase the amount of free time by the crew, increase the amount of crew autonomy, improve the quality of food, increase access to privacy, increase the quality and quantity of communications with Earth. In addition, experience in Mars surface operations may reduce some of the stresses associated with the unfamiliarity of the environment.

The quality of life can be facilitated by access to indigenous resources. In the near term, use of indigenous resources reduces some of the mission risks (creation of caches, use of local resources for radiation shielding). In the long term, use of local resources may allow more rapid expansion of usable space. Achieving the capability to produce water and oxygen may have physical and psychological benefits over continued recycling. For example, reducing limitations on water utilization for hygiene purposes will be psychologically supportive. The ability to grow food on site also has a psychological effectiveness. The psychological impacts of these developments is difficult to quantify, however real the effects may be.

Table 3.
Human Factors Study Topics*

1. Shelter/air	9. Crew autonomy
2. Water	10. Privacy
3. Food	11. Leisure, recreation and entertainment
4. Health monitoring and maintenance	12. Adaptation to gravity variations
5. Psychological support	13. Exercise
6. Communications	14. Human-machine and automation interaction
7. Rest, relaxation and sleep	15. Human-robotic partnership
8. Crew factors (size, skill mix, organization)	

*For description of topics, see: Clearwater, Y. and Harrison, A. (1990), Crew Support for an Initial Mars Expedition, *Journal of the British Interplanetary Society*, vol. 43, pp. 513-518.

The number of crew to be taken to Mars is an extremely important parameter for mission design, as many of the systems used (e.g. habitats) will scale directly to the number of crew. A progress report was given on the Ames Research Center's study of the minimal size crew needed to achieve the combined science and habitability objectives of the Mars surface mission. For this study it was assumed that crew health and safety are of first priority in successfully achieving the mission objectives and that the surface system design requirements for operability, self-monitoring, maintenance and repair will be consistent with the identified minimum number of crew persons. This was done in a top-down manner (objectives=>functions=>skills=>number of crew members+system requirements) as the systems have not been defined in a bottoms-up manner based on an operational analysis of the system.

A workload analysis was carried out assuming that the crew's available time would be spent either in scientific endeavors or in habitation-related tasks. It was assumed that individuals have weekday schedules similar to a normal life regime:

Sleep	8 hours
Hygiene	1 hour
Meals	2 hours
Exercise	1 hour
Rest and Relaxation	3 hours
Work	9 hours

The crew was assumed to have weekends free from work, except for essential tasks and chores which could be carried out in less than 5 hours per crew member. From these analyses, lists of required skills were developed, which are generalized in Figure 4. At a summary level, the five most relevant technical fields required by the exploration and habitation requirements include mechanical engineer, electrical and electronics engineer, geoscientist, life scientist, and physician/psychologist. It is assumed that these are important enough that they should be represented by a specialist, with at least one other crew person being cross-trained as a backup.

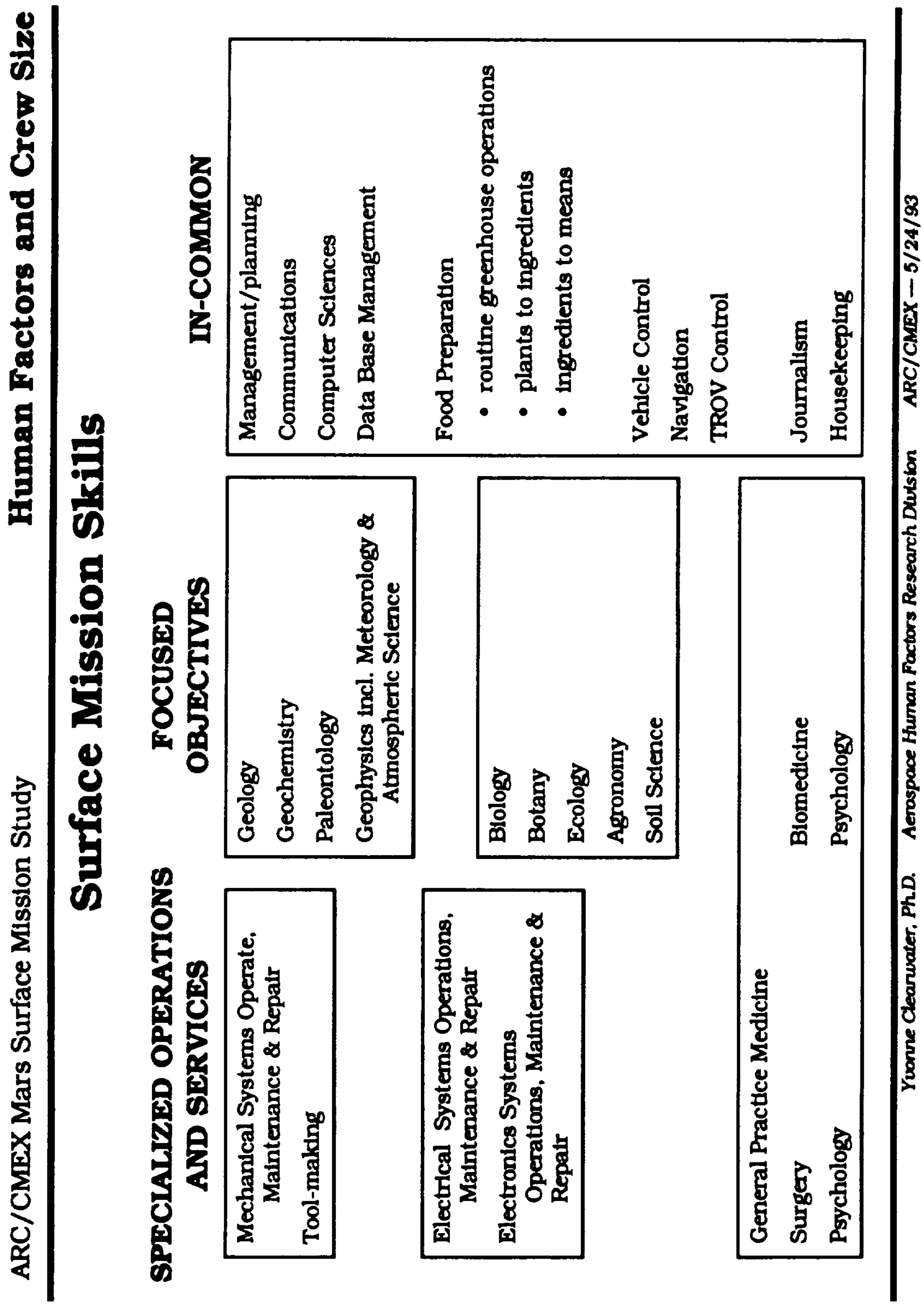

Figure 4. Surface Mission Skills — [Y. Clearwater]

A wide variety of tasks would have to be handled by each crew member, including support tasks as well as tasks of command and communications. It is assumed that technical individuals would be cross-trained for these responsibilities.

The result of the functional analysis indicates that the surface mission can be conducted with a minimum crew size of five, based on technical skills required. However, loss or incapacitation of one or more crew could significantly jeopardize mission success. Therefore, a minimum crew size of seven or eight may be required to address the risk issues. Currently, the reference mission is built on the assumption of a crew of six.

There is an immature understanding of the manner in which the crew would be supported by intelligent robots and automated systems. The work load analysis indicates that the total amount of time spent in the field (on EHA by foot or in a rover) by a crew scientist will be 10-20% of the amount of their time on Mars. Thus, it appears that automated or teleoperated rovers, capable of extending the effective field time by crew members, will be a good investment from the point of view of total mission productivity. Progress being made currently in telerobotic operations of a rover in the Antarctic environment can be translated directly to Mars exploration capability.

(d) Mars Surface Habitat

The Mars surface habitat must provide for the safety and health of the Mars crew for 600 days on the surface as well as providing operational capability for conducting both IHA and EHA tasks. The habitation capability will be unprecedented in the space arena and has little precedent on Earth. The level of experience and theoretical understanding is small. However, it is clear that the maintenance of human physical and psychological health for a long-duration mission of this type must be given higher priority than for other space missions, if only because there is no escape once the mission has been entered. More specifically, the habitat element must:

- Provide an appropriate living and working environment

This requires that it be demonstrated that people can effectively live and work on the surface of Mars for extended periods of time, both in and outside of the habitat. Habitability of the surface systems, their interconnectability, and the effectiveness of the support systems to control the environment are critical. The supporting systems must work reliably for the duration of the crew's surface mission, to maintain a livable environment, and maintain effective crew performance for that period of time. The risks must be shown to be acceptable, and the operations capabilities – including communications, command, and control, data management and local operations planning – must be able to accommodate both routine and contingency/emergency operations.

- Develop the capability to use Mars resources to reduce the dependence on Earth supply

Sources of needed resources must be located in places where they are accessible to the outpost. The most needed resources are consumables (N_2, O_2, H_2O). Once found, processes must be developed to extract them, separate and purify those to be used, and deliver them to the habitat or other places of use.

- Provide a set of systems which can sustain humans in a reasonably Earth-like environment

These systems include a life support systems capable of maintaining crews for the mission duration and beyond, in the case of failure of the crew to be able to return to Earth on the planned schedule. This can be augmented by experimental systems, such as the bioregenerative life support system.

- Provide caches of consumables on the Mars surface

These are required prior to arrival of the crew, therefore they must be created by automated devices; however, they will continue to be replenished and possibly increased during the crew's visit.

- Provide safety, reliability and robustness through functional redundancy of the support systems.
- Allow ready access to the surface for undertaking exploration objectives.

A further requirement on the surface architecture is that the system be expandable to allow the assets launched on three consecutive launch opportunities to be assembled at the outpost location.

The Ames Research Center study team (Cohen, 1993) has made the argument that the prime importance of the surface mission will make it imperative that the surface habitat system be designed specifically and totally for use on the surface. They argue that functionality of a space vehicle and a surface habitat will be incompatible. Thus, they disagree with a basic premise of the current reference mission that the crew will be transported to the Martian surface in their transit habitat, which will augment the surface habitation already delivered to the surface robotically. If the crew is landed in a short-term crew lander, there are significant implications from the requirement that they transfer from the lander to the habitat in a short period of time, thus requiring that they land in a physical condition that is suitable to that transfer. This in turn, could dictate an artificial gravity space transit vehicle or other equally severe requirements. Thus, the implications on total mission design and cost is severe. This disagreement needs to be tested in additional trade analysis and studies. For the current reference mission, it is assumed that the transit habitat can be taken to the surface and is usable as habitable volume by the crew. It is probably acceptable that the habitat be designed for the surface mission, with modifications to conduct the space transit, rather than vice-versa; this may not be true for systems such as the life support system, for which zero-g operation is the more demanding.

Operability of the surface habitat will depend upon achieving a new level of human / machine / environment interaction. In general, the crew will need to be able to carry out their operations with minimal concern for housekeeping functions, which will be managed by automated systems, and may have some degree of control by the ground. The crew must be equipped to manage the systems for all contingencies requiring short-term responses, say less than an hour, because of the inability for control from Earth due to communication times. However, even in these areas, machine control of fault detection and automated safing will be available.

The habitat must be considered as a system, not just a structure. Even for the first human mission there are two structures that must be functionally linked, the habitat that is delivered to the surface prior to the arrival of the crew, and the habitat that is landed with the crew. Subsequent missions can add capability to the initial outpost, and all systems must be designed to be functionally integrated on the surface. The nature of the physical connections between habitat structures is an area that requires more discussion and focus. Options include hard-docking of habitat structures, which would require transportability and adjustability of the structures on the surface; flexible pressurizable links between structures; pressurized rovers linking several structures; or space-suited movement between structures. These tradeoffs must be considered explicitly in determining the evolution pathway for the surface outpost.

Habitat design issues can begin to be understood if the habitat functionality is allocated to Life-Critical, Mission-Critical, and Mission-Discretionary functions (Table 4). The ability of designs to meet these criteria will be a significant part of the selection process by which the habitat is chosen.

A set of preliminary requirements has been advanced for the habitat element by the Ames Habitation Group (Cohen, 1993). These requirements are not yet completely compatible with the reference mission, but form the basis for further discussion.

Table 4.
Life-Critical, Mission-Critical, and Mission Discretionary Functions

MISSION 1	OBJECTIVES		
		Habitation	
RISK LEVELS	Science	Living & Working Environment	Life Support & ISRU
Life-Critical	• None	• Survival in habitat • Mental and physical health • Proximity EVA (<2 km)	• Open-loop consumables from cache for 600 days • Energy generation
Mission-Critical	• Proximity Operations (<2 km) rovers and EVA	• Productivity • Sustained, reliable human performance	• P/C life support • Cache Restoration • Energy Production
Mission-Discretionary	• Local Operations (<100 km) rovers and EVA	• Recreation • Extended time off duty • Access to greenhouses • Access to rover "garage"	• CELSS: Waste, CO_2, O_2, and food • Inflatables • Fuel Production

A reference habitat has been studied at the Johnson Space Center (Figures 5 and 6). The definition of the Mars habitat concept is sensitive to many mission parameters, including its relationship to the space transportation system as well as the objectives of the surface mission. The key drivers and assumptions in defining the habitat are listed in Table 5.

Landing on Mars in the transit habitat, as defined in the reference mission, is a significant issue which requires more work. The argument against this approach is that the primacy of the surface requirements will cause any scars taken to address a transit mission requirement to not trade well against alternatives where the surface and transit functions are separated. However, from the point of view of the crew, there are several positive affects of the single habitat approach:

- The crew can operate the habitat element on its way to Mars, thus eliminating a concern of immediately relying on a surface habitation element that has been dormant for two or more years.
- The crew does not have to perform any strenuous physical tasks immediately on landing on Mars; they have time to adjust to the new gravity environment over a safe period of time.
- The crew can have a full complement of consumables at hand.

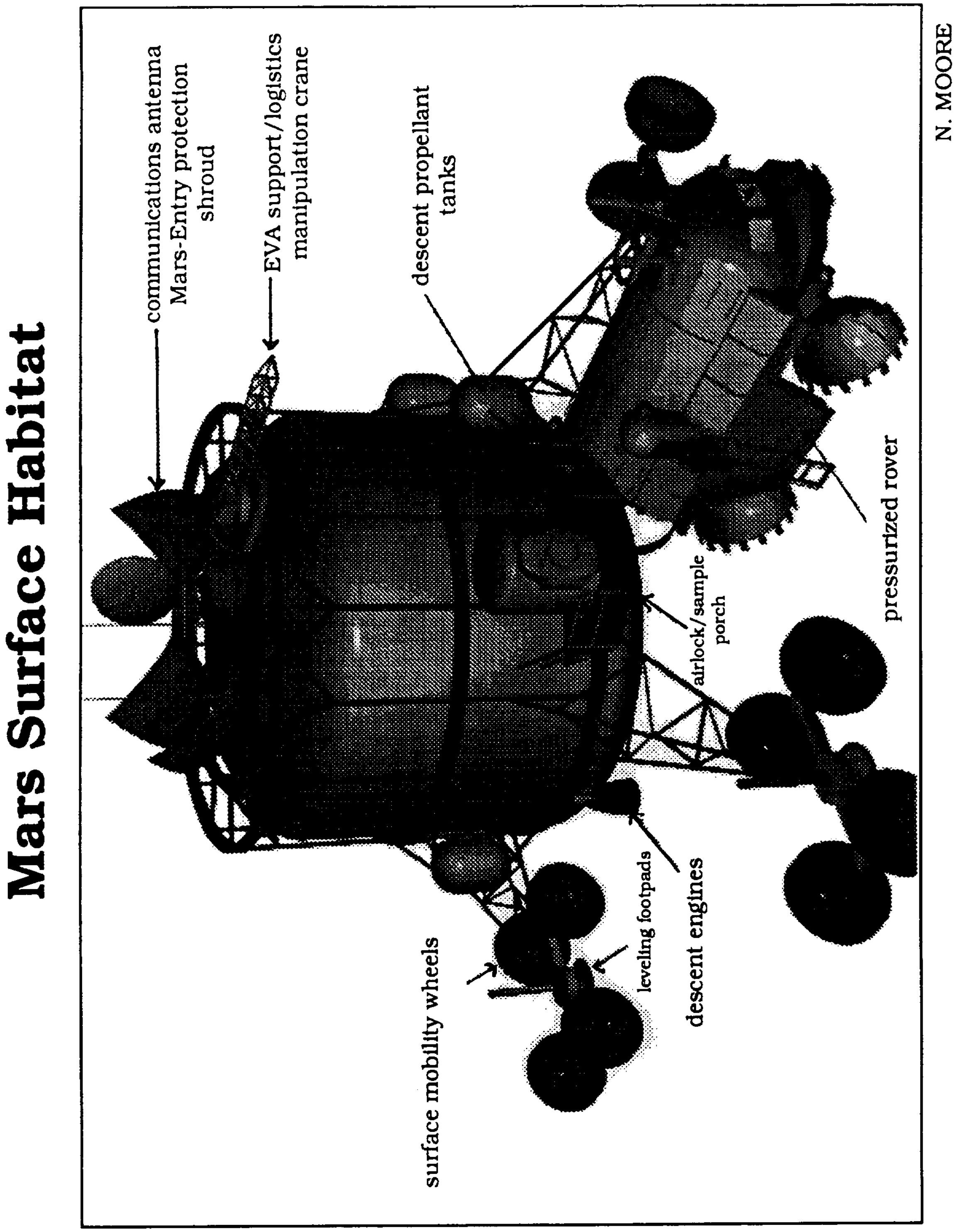

Figure 5. Mars Surface Habitat — [N. Moore]

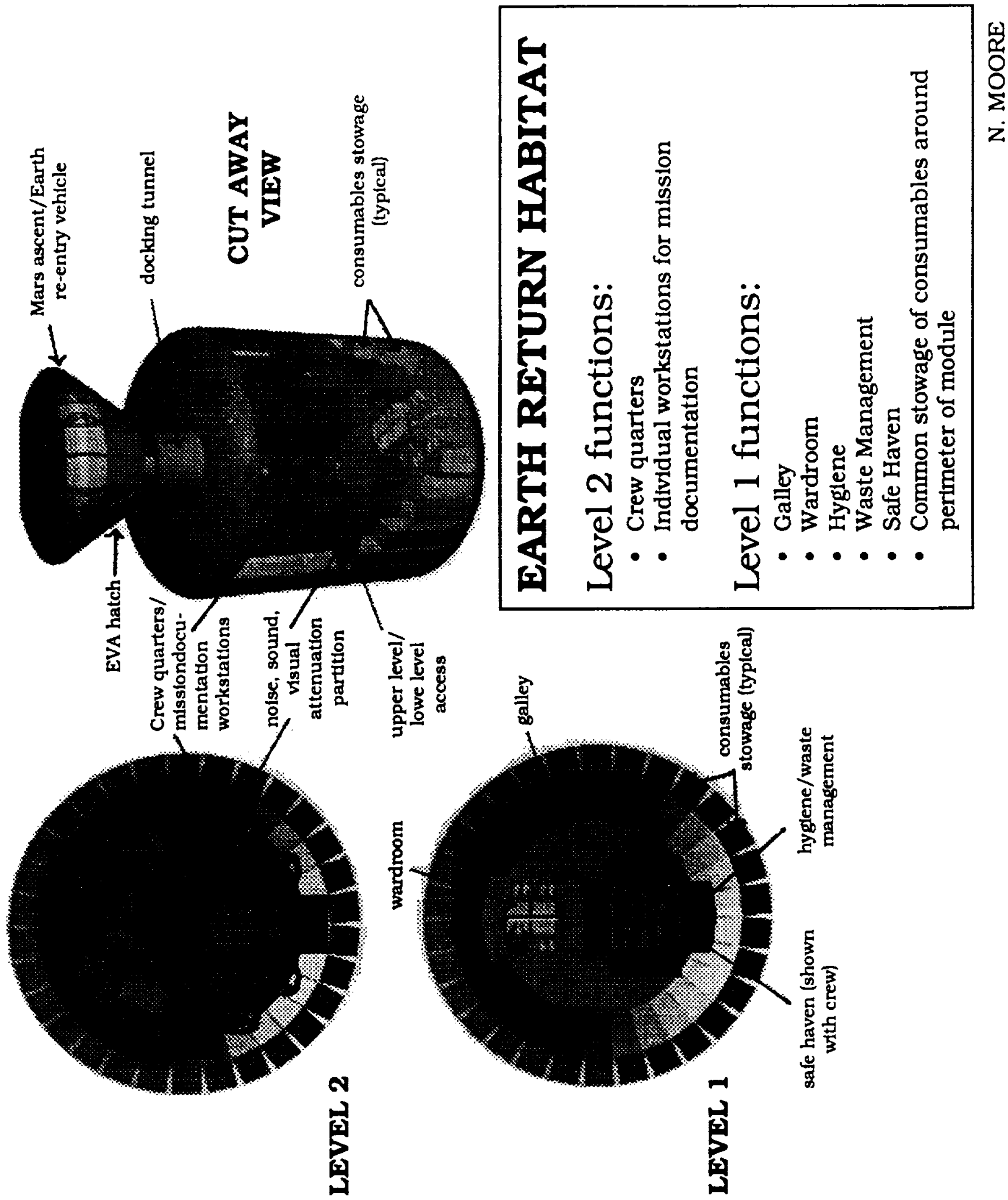

Figure 6. Earth Return Habitat — [N. Moore]

- The crew can take benefit from the habitat delivered in the previous cargo mission, which could be hooked into the system in about 10 weeks.
- Crew training is minimized (only one habitat style); training can occur in flight.
- Crew transfer in Mars Orbit is not needed.
- Artificial gravity is not necessary, since the crew will have time to adjust to the gravity of Mars before performing strenuous work.

Table 5.
Driving Requirements For Habitation Conceptual Design

- The capability for surface exploration drives the allocation of space in the habitat for science and support of the remote operations.
- A direct launch for a crew of 6 from Earth to Mars in a single habitat, constrained to 50 metric tons.
- The length of the mission phase for each habitat drives the consumable requirement. Crew size drives the free volume as well as equipment and consumables.
- The habitat must accommodate the surrounding environment
- Landing several piloted missions at the same site implies a need for functionally connecting the habitats, probably with pressurized connecting links or hard docking.
- Requirements for food, air and water are fairly well known; most air and water will be recycled.
- Uncertainties of the environment (gravity, radiation) remain.
- Interfaces with the transportation system, e.g. integration of lander and habitat power systems, are yet to be defined.
- Mass reduction is an objective.
- Common designs for surface and transit habitats or with lunar habitats are desirable from the point of view of reducing Mars development and operations costs, and mission risk.

Three concepts were studied to compare outbound/surface habitat configurations with Earth return habitat configurations. In the current scenario, the Earth return habitat is parked in low Mars orbit and rendezvous with the crew ascending from the surface (Table 6). Concept A consists of a 9.5 m diameter vertical cylinder with two habitated floors separated by a bulkhead. A single element would suffice for the return mission element returning from Mars. The 7.5m design would require additional cargo and consumables to meet the 600 day surface stay. Concept C is a 6m diameter element. Two or three of them would be required for the surface stay, but single elements would be adequate for the transit legs of the mission. This is a minimal habitat, but was considered interesting enough to put some additional work into the effort.

Table 6.
Mars Habitation Concepts

	Outbound/Surface			Earth Return	
Concept	**Outbound No.**	**Surface No.**	**Pressure Shell Dimensions**	**No.**	**Pressure Shell Dimensions**
A	1	2	9.5m dia. x 3 m high	1	9.5 m dia. 3 m high
B	1	2	7.5 m dia. x 6 m high	1	7.5 m dia. x 6 m high
C	1	2-3	6 m dia. x 6 m high	1	6 m dia. x 6 m high

A mass estimate was made for a Concept C habitat (Table 7) used as a surface habitat. Two surface interface concepts were also studied. The first case is that of a mobile habitat which can dock with more than one other habitat, providing a pressurized link. The other concept is to provide mobility to the lander, in which the landing legs are used as mobility devices. This would allow two habitats, landed perhaps two kilometers from one another, to be moved and connected for easy crew IHA access. The landing separation may be dictated by the risk associated with the impact of an aborted cargo landing, rather than environmental problems of blowing dust or sand. This is a subject for further analysis.

Table 7.
Mass Analysis of Mars Mission Surface Habitat

	Current Estimate
Life support	6.0 mt
Crew accommodations	22.5
Health care	2.5
Structures	13.0
EVA	2.0
Electrical power distribution	0.5
Communications and information management	1.5
Thermal control	2.0
Power generation	2.0
Attitude control	2.0
Crew	0.5
Spares/growth/margin	7.0
Radiation shielding	---
Science	TBD
Total Estimate	61.5 + TBD

There are many elements of uncertainty that remain in the definition of the surface habitat (Table 8). The issue of integrating the transit habitat with the surface habitat is described in the Surface-Transit Habitat Integration section below.

Table 8.
Habitat Issues and Work to be Accomplished

- Human research needs: low gravity and radiation effects; long duration crew performance in isolation and confinement
- Mars research needs: contamination effects of Mars soil, dust, and atmosphere; human contamination of Mars
- Technology needs: lightweight structures and electronics, long shelf life consumables, high reliability components, closed life support systems; crew health systems
- Mass uncertainties: structural analysis of habitat structure is planned to reduce uncertainty
- Surface habitat mobility: docking/berthing of surface habitat elements
- Commonality: degree of common design of surface and Earth return habitats
- Logistics: resupply of surface habitat for future crew missions
- Crew size: need to define crew size based on cost, performance, and risk analyses
- Risks: an analysis is needed to define all major risks to crew and mission
- Mars ascent crew module: can it be sized to augment the Earth return habitat on the return trip
- Earth descent crew module: can it be common with the Mars ascent crew module

(e) Life Support Systems

The life support system for the Mars surface is an integral part of the architecture of the mission, and must be viewed both in term of its requirement to maintain the health and safety of the crew as well as to prepare for eventual self-sufficiency of a Mars outpost. Solutions to design issues must also keep in mind limitations of the delivery systems. The life support system for extended duration systems must minimize consumable supply and resupply from Earth. Approaches that address this requirement include the utilization of indigenous resources and creation of caches of consumables, and highly regenerative systems that reuse consumables brought from Earth. The availability of consumables in the Martian atmosphere, and potentially from surface or subsurface deposits, can influence the degree of closure that is adopted for the system.

A conceptual life support system architecture is presented in Figure 7. Indigenous resources (oxygen, nitrogen, water) are extracted from the Martian environment and provide caches of consumables for the life support system as well as providing fuel and oxidizer for the space transportation system. For the first mission, all food and a supply of hydrogen will be transported from Earth. An experimental bioregenerative life support system capable of providing a fraction of the food could allow some of the food brought from Earth to be retained in the food cache.

The proposed approach to producing oxygen and other gases from the atmosphere consists of pumping Martian atmosphere through a reactor, removing the inert nitrogen and argon (about 2% of the total) and reacting the carbon dioxide with hydrogen brought from Earth to produce methane and oxygen. Enough methane and oxygen is produced to propel the ascent vehicle from the surface to orbit. Table 9 gives an overview of the requirements. The consumables are modeled according to a requirement to provide for a 6 person crew for 600 days on the surface, with no recycling.

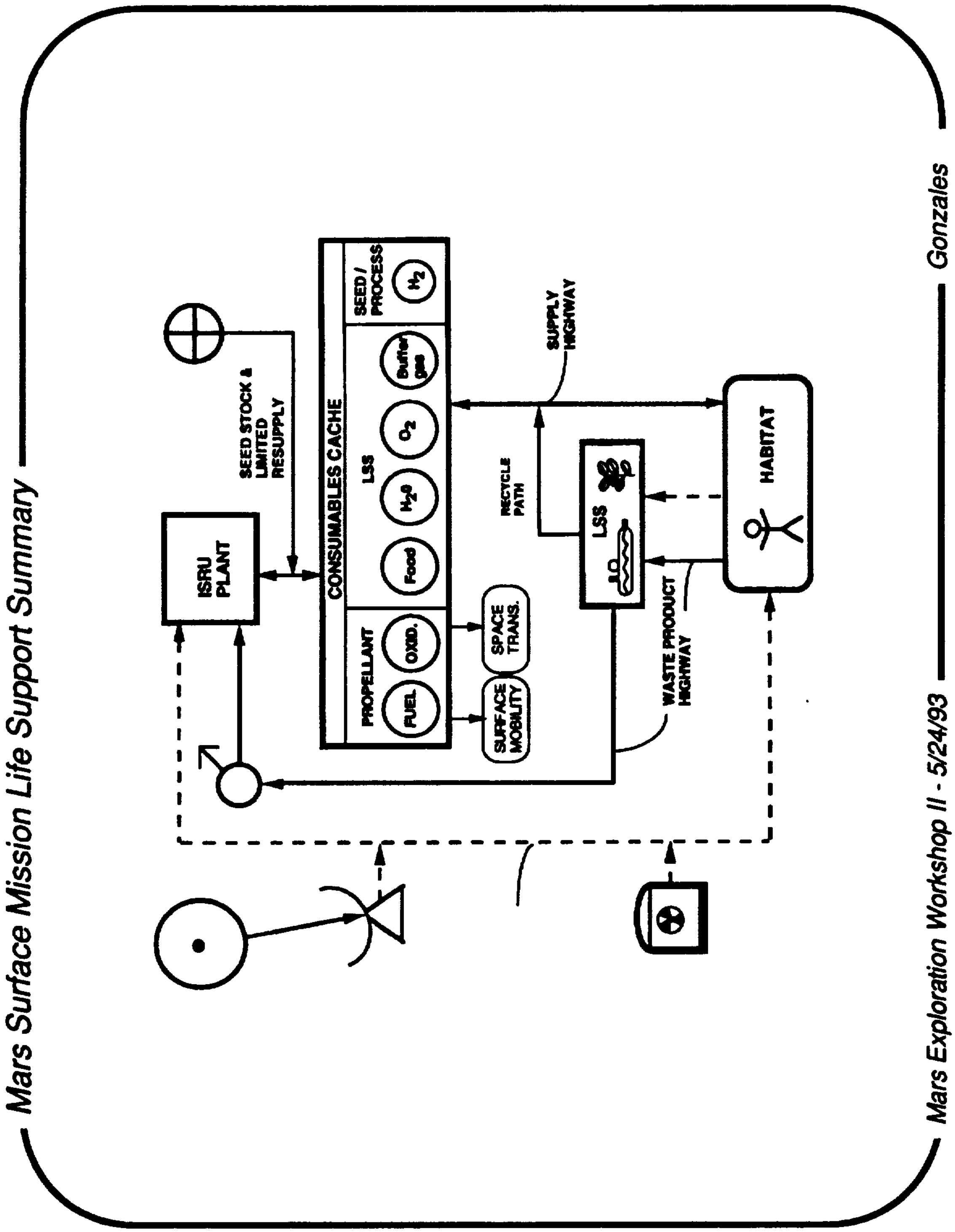

Figure 7. Cache-Based LSS Architecture — [A. Gonzales]

Table 9.
Atmospheric Volatiles for Propulsion and Consumables for the Life Support Cache

	Quantity Required (metric tons)	Amount of Atmosphere Required (metric tons)
Methane, fuel	5.6	16
Oxygen, oxidizer	19.4	26.6
Oxygen, air	0.8	1.1
Nitrogen and Argon, air	1.2 – 3.2*	50 – 150*
Potable water	14	---
Oxygen, for potable water	12.4	17.4
Water, hygiene	120	---
Oxygen, hygiene water	106	146
Hydrogen, methane	4.2	Earth
Hydrogen, potable water	1.5	Earth
Hydrogen, hygiene water	13	Earth
Food, dry	2.2	Earth

* The range depends on the atmospheric pressure adopted for surface habitats and the inert/oxygen ratio. Requirements for inert gases are significantly less if low pressures are adopted.

The above table indicates that a quantity of Earth-supplied hydrogen is required to "seed" some of the reactions which process the indigenous Mars resources. The Sabatier Process, well known on Earth, follows the reaction CO_2+4H_2--->CH_4+2H_2O. Water produced in the reaction would be either stored in the cache or dissociated to form hydrogen and oxygen. Oxygen would be stored in the fuel or life support cache, and hydrogen would be recycled into the Sabatier reactor. The table shows that there is a general balance of the requirements. If enough water is produced to provide for the potable water cache and a 600 day reserve of breathing gas, and the oxidizer requirements for the transportation system, enough byproduct nitrogen and argon should be available for the consumable cache. It may not be feasible to have a complete cache of hygiene water available at the start of the first mission.

For the long-term system, a hybrid physio-chemical (P/C) and bioregenerative (BR) life support system is proposed(Fig. 8). The BR system can produce food as well as revitalize air and purify water while operating as a buffer with significant inertia. The P/C system can be modulated to provide short term control and can be used concurrently with the BR system when caches require filling. The combination of the two provides flexibility and introduces independent design diversity.

There are costs associated with the robustness of the life support system. Table 10 gives mass and volume comparisons for various combinations of P/C and BR systems and ISRU systems. The analysis includes tankage, expendables, spares and integration. Masses and volumes for P/C system are based on Space Station Freedom level technology. A packing density of 70 kg/m^3 was assumed, unless otherwise known. Consumables, spares and expendables were sized for 800 equivalent days (33% contingency).

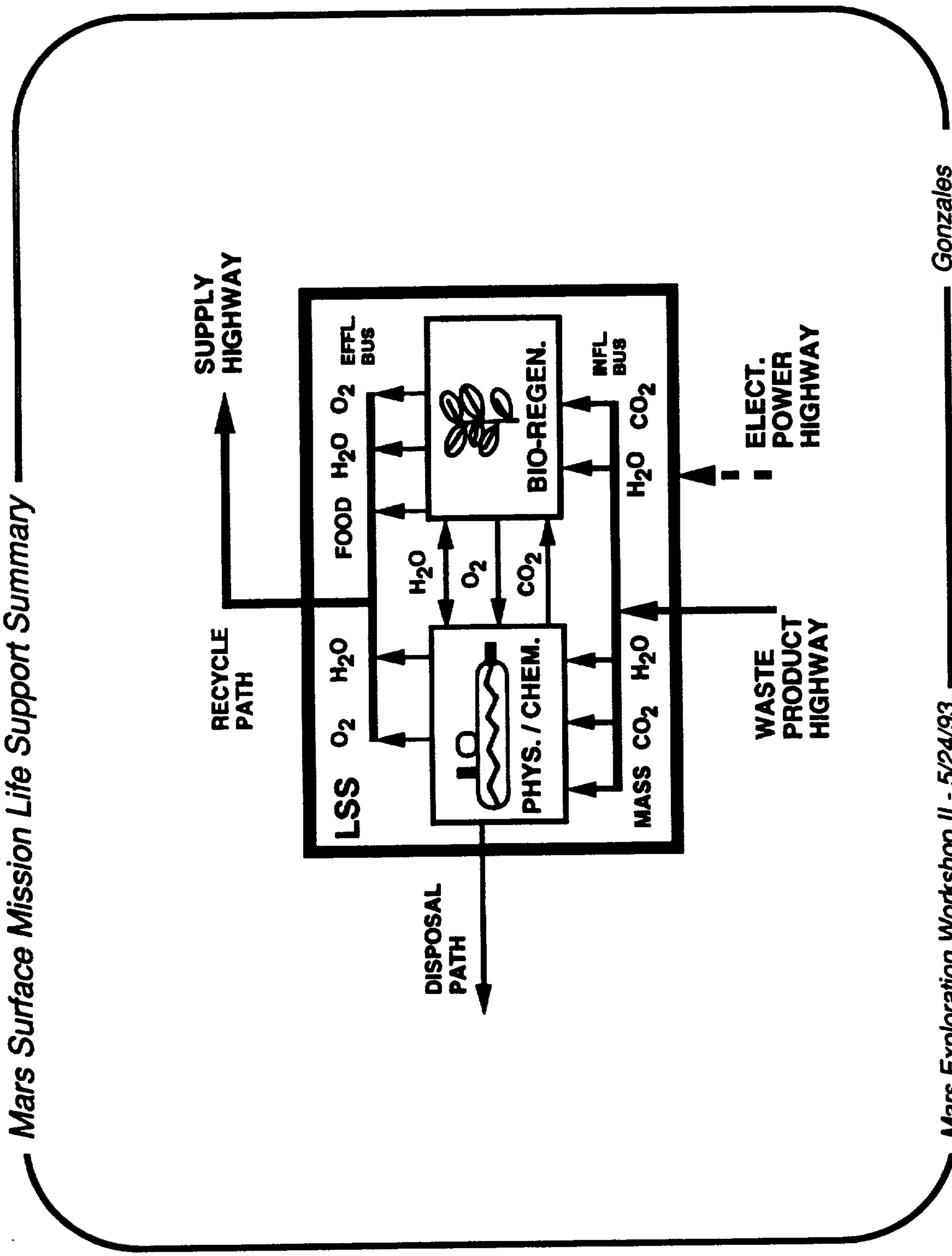

Figure 8. LSS Process Distribution — [A. Gonzales]

Table 10.
LSS Architecture Mass, Volume and Power Comparisons

Architecture	Function Redundancy Levels	Mass (Mt)	Volume (m^3)	Power (kW)*
Open loop	1	180	290	0
100% P/C with ISRU cache	2	60	470	7
100% BR with ISRU cache	2	60	410	60
Hybrid 100% P/C and 100% BR with ISRU cache	3	80	600	67
50% P/C and 50% BR with ISRU cache +200 days consumables from Earth	2+	90	540	37

* Power above open loop case.

The large power requirements associated with the bioregenerative system are due to the assumption that all lighting will be artificial. Natural Martian sunlight may be sufficient to grow some crops at a lower level of productivity than on Earth. However, new types of transparent, but highly insulating greenhouse material will be necessary, and new approaches to radiation shielding may be required.

In general, it is believed that satisfactory P/C or bioregenerative systems can be made available for the Mars outpost. The major question is whether adequate power can be made available within the limitations of the space transportation system. Because of the power requirements of the bioregenerative life support system, it may be necessary to defer the complete activation of that system to the second or third mission. It would be important to begin the testing of the BR system on the first mission, but perhaps at a 10% of food requirements level.

For the reference mission, the following characteristics will be assumed:

- ISRU - produce consumable cache of water, oxygen, pressurization gases sufficient that a 600-day supply of consumables exists at all times. These caches will be produced and verified before the first crew departs Earth.

- A 800 day supply of dry food will be transported from Earth on a cargo mission. Additional backup supplies will be transported with the crew.

- The bioregenerative system will be sized and delivered with the capability to provide nearly 100% of food, air, and water life support requirements. Initially it will be operated at a reduced capacity, traded down to 25%, limited by crew time utilization. As additional missions are sent to Mars, operation of the BR LSS will be ramped up towards the 100% level. At this stage it will be fully providing the second level of functional redundancy to the overall LSS.

(f) ISRU System

The ISRU system has been described in the previous section. It will provide fuel and oxidizer for the Mars ascent vehicle and will provide for the caches of life support consumables - water, oxygen and pressurization gases. In early reference mission concepts, it was proposed that the ISRU system also produce an energy cache, in the form of additional CH_4 and oxygen to run electrical generators or fuel cells. It was found that the power required to create this cache was excessive due to the compounded inefficiencies of cache production, storage and reconversion. The mass of the storage capacity required for the cache exceeded the mass of a redundant power system. Therefore, a redundant power system was chosen over an ISRU energy cache.

There are several detailed trades that have been made in defining the ISRU system. The basic system for producing methane is described in the previous section. In the process that produces the required amount of methane (5.6 t), only 11 t of oxygen is produced. Because the total required amount of oxygen (combined as water) that must be produced to meet all requirements is 32 t, additional processing capacity is needed. This can be done either by running the Sabatier processor in a manner that throws away methane as it produces water, adding a unit to reclaim hydrogen from methane, or bringing an alternative unit to convert CO_2 directly to oxygen. Zirconia membrane capable of reducing CO_2 to CO and O_2 have been operated for long durations in the laboratory environment and could be effective in the Martian environment.

Power for ISRU requires on the order of 1 kW for each ton of oxygen produced in the 17 months between the landing of the ISRU unit and the launch of the crew. Thus, approximately 25 kW of power are needed for the ISRU application. As some of the technology (e.g. Sabatier reactors) are common to life support and ISRU systems, there may be a resultant decrease in mass for an integrated system. Furthermore, the propellant production must be carried out prior to departure of the crew from Earth, while the life support system must operate while the crew is on the surface. Thus, there may be opportunities to time-share the power system for the two applications, thus reducing the total mass of the emplaced power system.

(g) Mobility

Mobility on several scales is required by people operating from the Mars outpost. Any time the crew is outside of the habitat, they will be in pressure suits, and will be able to operate at some distance from the habitat, determined by their capability to walk back to the outpost. They may be served by a variety of tools, including rovers, carts and wagons. On a local scale, perhaps beyond a kilometer from the outpost and less than ten, exploration will be implemented by unpressurized wheeled vehicles. Beyond the safe range for EVA walkback, exploration will be undertaken utilizing pressurized rovers, allowing explorers to operate for the most part in a shirtsleeved environment, and performing EVA's as they deem necessary.

The requirements for long range surface rovers were presented at the workshop. Requirements to be placed on the rover included: (1) a radius of action of up to 500 km in exploration sorties that allow 10 work days to be spent at a particular remote site, and (2) the speed of the rover should be such that less than half of the excursion time is appropriated for travel. Each day, up to 16 person-hours would be available for extravehicular activities. The rover is assumed to have a nominal crew of two persons, but be capable of carrying four in an emergency. Normally, the rover would be operated only in the daytime, but could conduct selected investigations at night.

A conceptual rover vehicle design was presented (Figure 9) (Lemke). The major subsystems of the implementation include: (1) Cabin/structure; (2) life support; (3) EVA; (4) Power; (5) mobility; and (6) science. The life support system includes dehydrated food, with the water produced stored and condensed in a dehumidifier; storage of Oxygen; CO_2 scrubbed with a regenerative molecular sieve. An airlock must be provided to support EVA. The rover will contain a science package as well, but the details have not been defined.

Mars Surface Mission Mobility

PRESSURIZED ROVER CONCEPTUAL DESIGN (p.1 of 3)

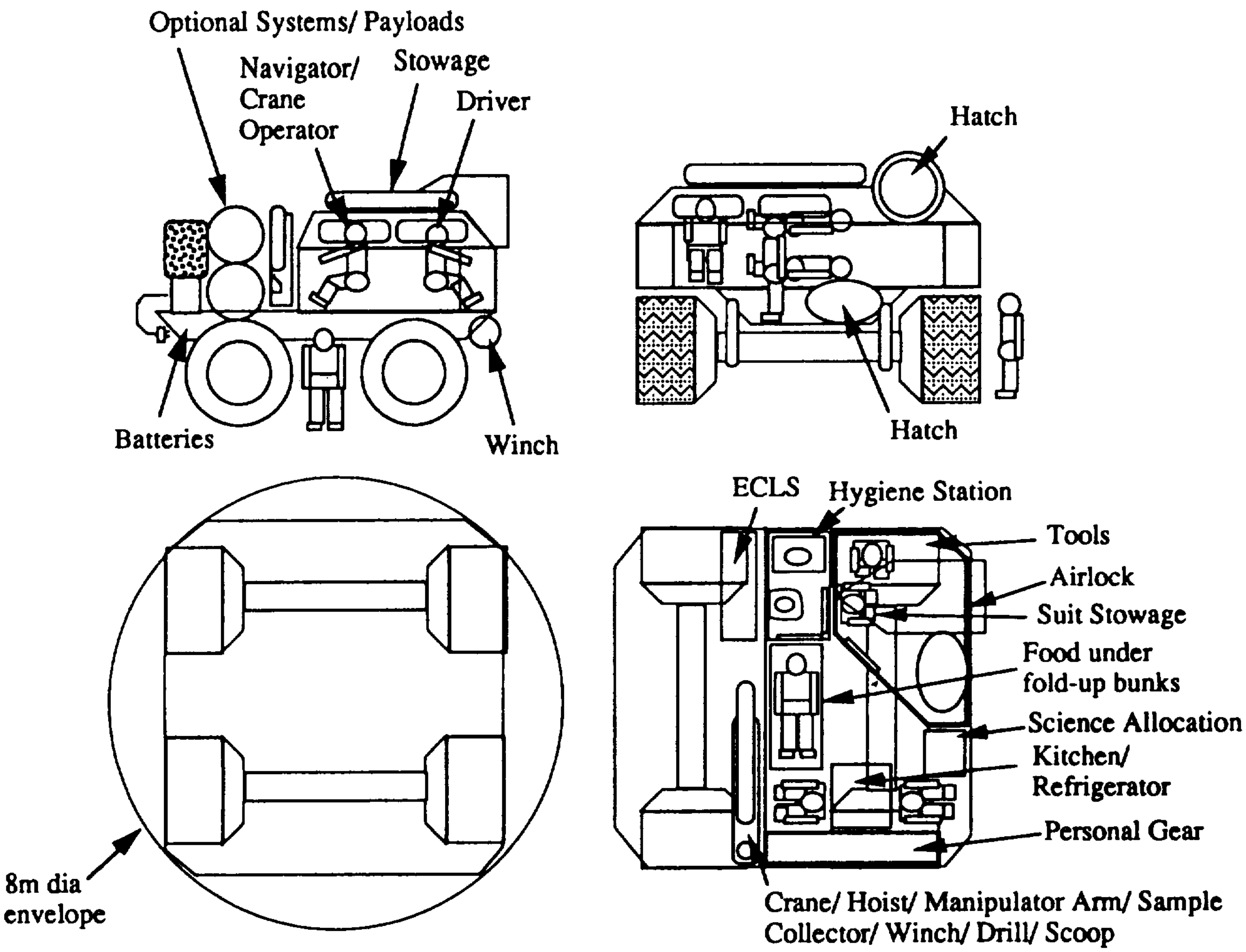

Figure 9. Mars Surface Mission Mobility
Pressurized Rover Conceptual Design — [L. Lemke]

Two major issues have emerged. The first is whether to power the rover with a nuclear system (dynamic isotope power system) or a chemical system. The above referenced concept has a power requirement of 40 kWe while moving and 5700 kWe-hrs total, and is within the range of DIPS; however, there is no requirement for continuous power (when the rover is not in use) and there may be hesitancy to proliferate nuclear systems. Three chemical systems have been considered (H_2-O_2; CH_4-O_2; CO-O_2). All appear to be feasible if tankage mass and volume can be accommodated. Methane-oxygen engines possess the best combination of mass and volume. The second issue is whether wheels or legs or tracks should be used. Wheels are the leading option, representing a compromise between mass, efficiency, technical risk and operational safety. Propulsion efficiency does not uniquely discriminate between options. Tracks are not particularly valuable on Mars, based on terrain types observed in Viking images. The theoretical attributes of legs are attractive, but not yet demonstrated technologically.

Not discussed in this workshop, but nevertheless important, are two other classes of robotic vehicles, unpressurized utility vehicles which can carry people or cargo, and robotic scientific exploration vehicles. The unpressurized utility vehicles would find use in local exploration around the outpost; they could be driven by crew members or could be teleoperated from the outpost. The robotic science vehicles would be long-range vehicles, capable of traversing hundreds of kilometers or more under autonomous, teleoperated, or telepresent control, making observations and collecting samples for return to the surface outpost for analysis.

(h) EVA Systems

The Mars missions will place new, unique requirements on ways of doing EVA and will thus require new innovative approaches and strategies for accomplishing EVA exploration to meet these requirements. Mars EVA system objectives are twofold:

- To enable the astronaut to perform exploration, support, and maintenance operations external to the base or shelter in the geographical and climatological environments of Mars;
- To enable the astronaut to accomplish EVA tasks and objectives efficiently and safely while minimizing physical and mental stress and fatigue.

EVA tasks consist both of constructing and maintaining the habitat, and conducting a scientific exploration program encompassing geologic field work, sample collection, and deployment, operation and maintenance of instruments. Any EVA system must perform these tasks with the critical functional elements of a pressure shell, atmospheric and thermal control, communications, monitoring and display, and nourishment and hygiene. Balancing the desire for high mobility and dexterity against accumulated risk to the explorer is a major design driver on a Mars EVA system.

Because of the unique challenges for a Mars EVA program, (frequency and duration of sorties, quick turn-around times, necessary dexterity and mobility, dust and abrasion) a fresh strategy for interfacing the crew with the surface is required. Three concepts were suggested at the workshop: independent, umbilical, and roving EVA systems (Buckley, 1993).

The independent EVA system is a modified Apollo approach, allowing some regeneration of consumables and battery recharging to reduce weight.

The umbilical EVA system transfers air and fluid consumables from a transport vehicle, through an umbilical, to the crew member, with a back-up PLSS used for short tasks not suitable for an umbilical.

The roving EVA system (REVAS) would consist of a shirt-sleeve environment roving suit system to be used for major science and exploration tasks. A pressurized vehicle equipped with dexterous arms, telepresence and virtual reality technologies, window, lights and cameras, would enable the crew inside to traverse, observe, test and sample the exterior Mars environments, both hostile and benign.

The advantages and disadvantages of the three systems were discussed in terms of comfort, fatigue, suit operating pressures, mobility, dexterity, bulk, technological complexity, and risk.

(i) Power Systems

The Mars surface outpost has a number of diverse requirements. Table 11 presents the current analysis of requirements for a habitat for a crew of 6, including the P/C life support system. Table 12 presents an analysis of the power requirements for ISRU production of water, fuel, oxygen and buffer gases. The amounts produced are generally consistent with the requirements called out in Table 9. The mobility power requirements are shown in Table 13. A possible power profile is given in Figure 10, which shows some periods when up to 100 kWe of power is required, with nominal steady state for the habitat of about 60 kWe.

Table 11.
Surface Habitat Power Estimates

Estimated Habitat Power Requirements for a Crew of Six (kWe)			
Element	**Mode**		**Notes:**
	Nominal	**Emergency**	
CELSS	37.00	9.00 *	Open Loop in Emergency Mode
Thermal Con Sys (TCS)	2.20	2.20	
Galley	1.00	0.50	Emergency values
Logistic Module	1.80	1.80	derated from nominal
Airlock	0.60	0.60	where deemed
Communications	0.50	0.50	appropriate
Personal Quarters	0.40	0.10	
Command Center	0.50	0.50	Values adapted from
Health Maint. Fac. (HMF)	1.70	0.00	NAS 8-37126,
Data Mgt Sys	1.90	0.80	"Manned Mars System
Audio/Video	0.40	0.10	Study"
Lab	0.70	0.00	
Hygiene	0.70	0.35	
Total	**49.40**	**16.45**	

* Adapted from MTV LSS trade study, Dall-Bauman, EC7

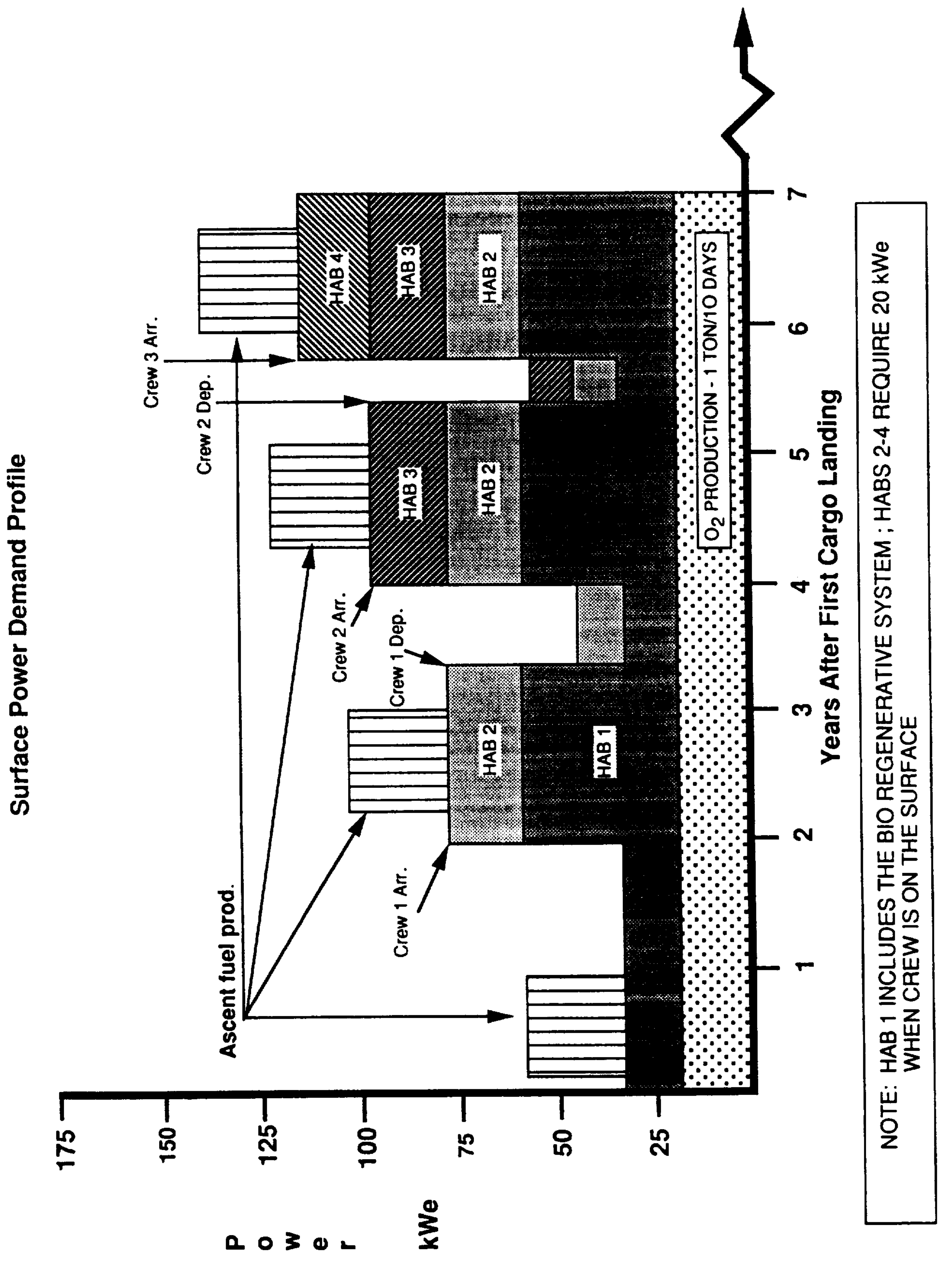

Figure 10. Surface Power Demand Profile — [B. Cataldo]

A number of issues guide the selection of a power systems strategy. These include the risk considerations, which require that mission critical functions have two level redundancy and life critical functions have three. The surface power systems should have 15+ year lifetimes, to allow them to service the three mission opportunities with good safety margins. Transportation power systems should have 6+ year lifetimes to minimize the need for replacement over the program lifetime. There are logistics objectives, including reducing the deployment and setup time of power systems, reducing the power system maintenance tasks, and providing interconnectability between power elements delivered on different flights. The power requirements for producing and maintaining life support caches can be met early, which reduces the boiloff of imported hydrogen and leaves the power system to meet the requirements of the habitat life support systems. The mobile systems ultimately require power systems capable of providing 1000 km (out and back) mobility.

Table 12.
Resource Production Power Requirements

Resource Production Parametrics					
	Resource Mass (mt)			Energy Consumed MWH	Kilowatts Required
Element	Import H_2	Qty. Prod.	Excess CH_4	CO_2 Processing	5000 hr Prod Period
Water Cache	3.20	14.40	6.40	1.41	0.28
Fuel per ascent	0.00	26.50		2.46	0.49
CH_4		5.80	0.60	0.00	0.00
O_2		20.70		80.30	16.06
Oxygen cache	0	3	0	36	7.20
Buffer gas cache	0	2	0	20	4.00
Total	3.20	45.9		140.17	28.03

Table 13.
Mobility Requirements (for Power)

Pressurized Rover • 2-3 crew • 500 km radius range • 5 days out - 10 days at site - 5 days back • Crew alternate on monthly sorties	10 kWe
Unpressurized Rover • 15-20 km radius range • 3 hours out/3 hours back plus 4 hours at site • Primary operation - daily, daytime only	4 kWe
TROV • 500-1000 km radius range • Reconnaissance, exploration and science • Day/night operation possible	4 kWe

The strategy adopted for the reference mission includes a primary and backup SP-100 class nuclear reactor with dynamic conversion. Each of these systems is capable of producing 100 kWe. The habitat is provided with a photovoltaic/energy storage system (Ge/As photovoltaic with regenerative fuel cell) capable of supplying a third level of redundancy for life critical functions. This could begin at 10 kWe and grow to 50 kWe over the three mission set.

A 10 kWe DIPS is favored by the power system experts for the pressurized rover. The DIPS can also provide an additional steady power source for the habitat in an emergency. However, if methane and oxygen are being produced by a robust power system, use of fuel cells or even internal combustion engines may be effective in an integrated system, and the diverseness of power systems reduced.

Mass and volume requirements for the selected power systems are shown in Table 14. If the photovoltaic system is able to track the sun (more complex operation), its mass can be nearly halved, at the expense of additional operational risk.

Table 14.
Surface Power System Characteristics

Power System	Type	Mass Estimate	Volume (m^3)
Main	100 kWe SP-100 reactor with dynamic conversion	13 mt (less deployment)	42
Backup	Same	Same	Same
Backup	50 kWe Ga/As with RFC	32.5/17.5 mt (non-track vs. track)	1020/490
Emergency	10 kWe DIPS	Use Pressurized Rover Power System	

The photovoltaic system does not trade well against the SP-100 as a backup. The main argument for utilizing the PV system is that it should not have similar failure modes to the nuclear system. This is an area where future trades and experience will determine the proper solution. It should be noted that in this strategy, the use of an energy cache has been deleted and there is no surface vehicle use of the methane production capability. The economics of this would change if a local supply of water (hydrogen) becomes accessible.

3. Systems Engineering and Integration of Surface Systems

The totality of systems required to make the surface exploration mission successful is of broad scope. The key elements are indicated in the icons presented in Figure 11. The key to a successful Systems Engineering and Integration approach is to systematically relate the functioning of each of the systems both in concert with the other systems and with respect to the goals and objectives of the program. Therefore, a successful SE&I will be able to link each system and its requirements to every other system (including space transportation, ground operations, etc.) and the program requirements, in a manner that optimizes the whole with respect to some combination of performance, risk, schedule and cost.

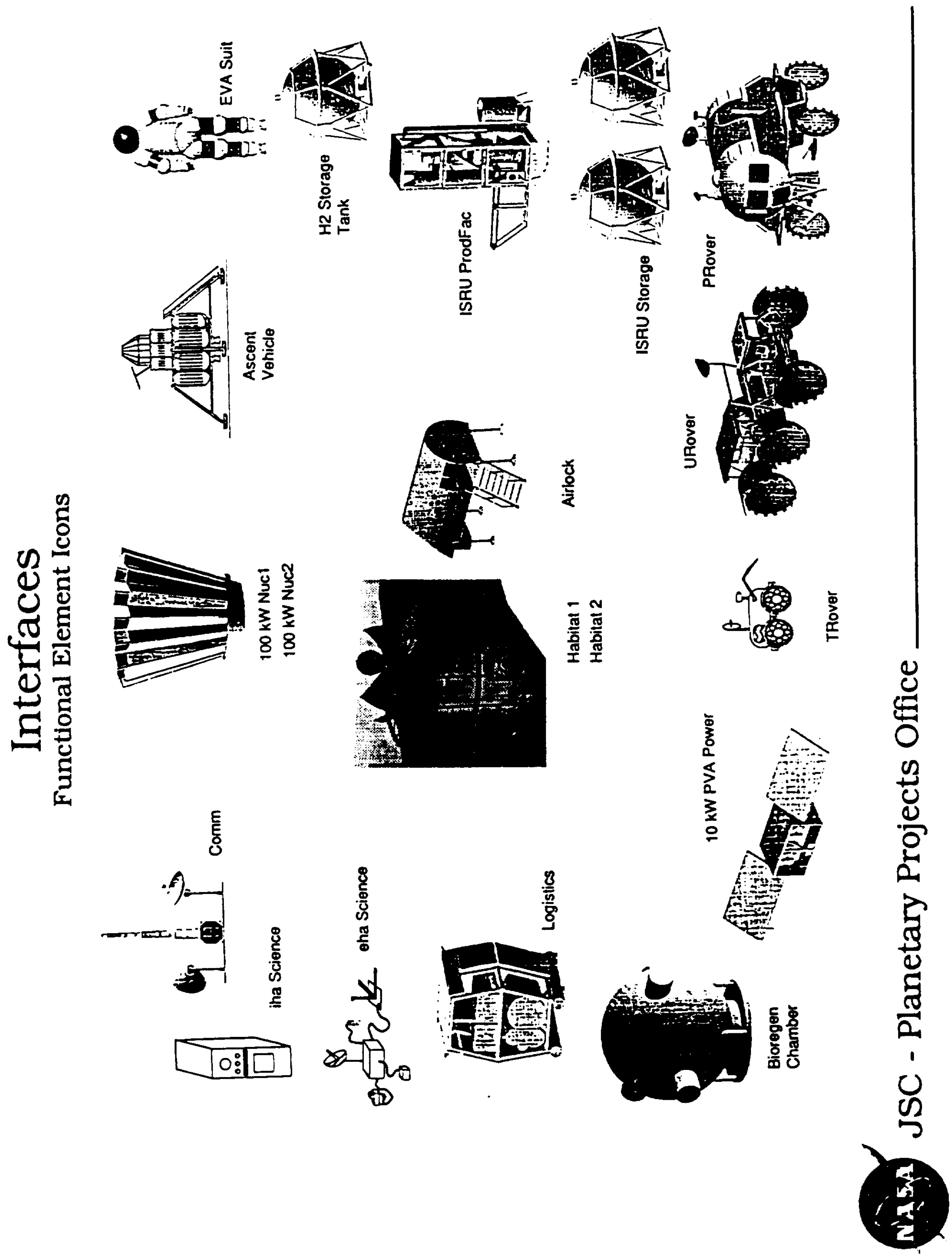

Figure 11. Functional Element Interfaces — [J. Connolly]

In order to do this, the surface systems integration team has taken the Goals and Objectives of the Mars exploration program and the preliminary mission design concept, and has made functional allocations to each of the surface system elements.

An example is given in Figure 12, where the functions for a telerobotic rover are defined. Analysis of these functional relations allows an understanding of any areas of confusion or overlap, deficiencies of stated requirements, and appropriate levels of functional redundancy. Matrices of functionality against surface system elements, such as that in Figure 13 are useful. These are then used to identify interfaces and allocate any missing functions. An example of a schematic interface problem is shown in Figure 14, where the data interfaces are depicted between the various surface elements. The result of this process eventually will be a set of requirements on each of the surface elements which can be used to derive the optimum system and subsystem designs. In addition, the SE&I analysis will include consideration of mission effectiveness models, whereby tradeoffs of functions can be made between various systems, and risk analyses. Software tools are currently appearing in the marketplace to allow these analyses to be highly automated.

The reader is directed to the working papers of the workshop for more detail on these issues.

In order to complete the SE&I analysis, it is important to have a Surface Reference Mission, which is a subset of the overall reference mission that deals with the surface. The purpose of the Mars reference mission SE&I activity is to integrate the components of the reference mission in order to give an additional measure of reality to the mission cost estimates that will be made in the next stage of program definition. This reference mission defines the order in which surface elements are brought to Mars and activated. Table 15 gives the surface reference mission functional capabilities:

Table 15.
Surface Reference Mission Functional Capabilities

- The surface system is delivered by cargo space transportation system and robotically emplaced.
- The capability to return to Mars orbit exists on the surface.
- Habitation and resource utilization functionality is established on the surface.
- Systems are activated by Earth-control and remotely checked out.
- Systems are continuously operated and monitored from Earth when human crews are not present.
- Laboratory functions and backups to life-critical functions are established on the surface.
- Mobility capability is established and equipment to accomplish science objectives is delivered.
- Prior to crew launch, the readiness of all surface functions are verified; accommodations are made to revive any functions which have been lost or degraded.
- The crew performs a complete checkout of the surface systems and performs all required maintenance and repair actions.
- Science and exploration objectives are performed: IHA science, local science, regional science, and global science.
- Science data is transferred to investigators on Earth
- Prior to departure, crew checks out ascent element and surface systems and performs required maintenance and repair
- Surface operations are transferred to Earth control upon crew departure.

TELE-ROBOTIC ROVER FUNCTIONS

- Maintain Mission Productivity
  - -Thermal Protection on the Mars Surface
    - Waste Heat Collection
    - Heat Rejection to Environment
    - Temperature Monitoring and Control
  - Provide Mars Surface Communications
    - Earth to Rovers
    - Habitat to Rovers
    - EHA to Rovers
  - Provide Mars Surface Data Management
    - Systems Monitoring and Control
    - Data Archiving
- Reconnoiter Future Locations for Mars Exploration
  - -Exploring via Telepresence
    - Cleaving Rocks
    - Augering Holes
    - Trenching
    - Raking and Sieving
    - Drilling
- Survey / Utilize Mars Surface Resources
  - Terrain Mapping
  - Recommend Future Locations for Mars Exploration
  - Sounding
  - Preparing Samples for Analysis
  - Deploying Instruments
  - EHA Sample Storage and Processing

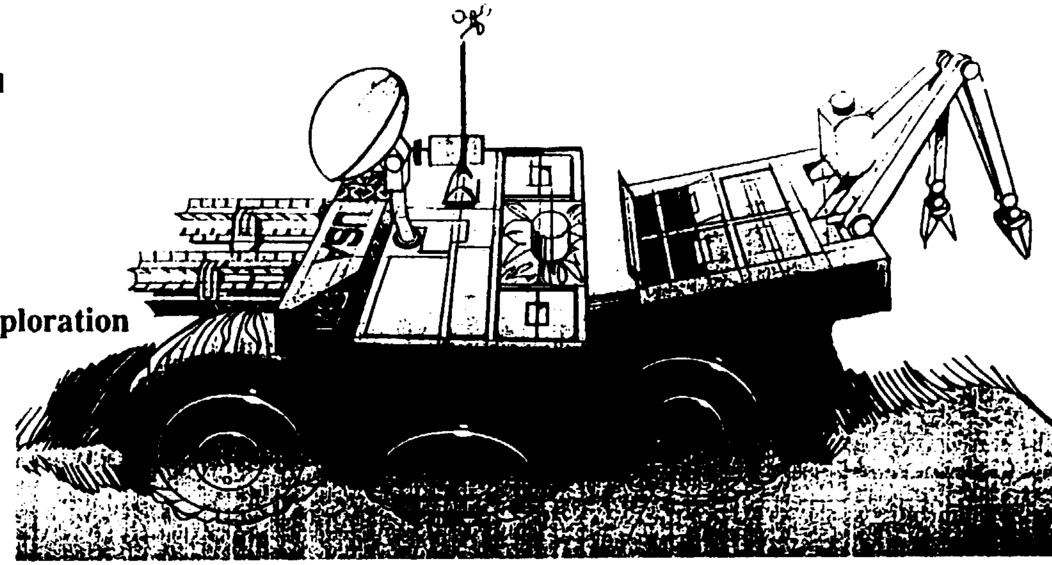

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Figure 12. Tele-Robotic Rover Functions — [J. Connolly]
(one of 16 functional elements)

Mars Study Mission Functions

Function	Element: Prec	Ascnt	TRov	URov	PRov	Suit	ISRU	Com	Powr	Hab	Lab	A/L	ehaS	ihaS	Plants	Log
Perform work on Mars surface																
Keep people alive on Mars for two or more years																
• Provide consumables					P	P				P	P	P			P	
- Food					P	P				P	S				P	
- Water					P	P				P	P				P	
- O2 and other gasses					P	P				P	P	P			P	
- Medical support (health maintenance)										P	S	P				
• Provide shelter					P	P				P	P	P			S	
- regulate temperature					P	P				P	P	P			P	
- regulate pressure					P	P				P	P	P			P	
- regulate atmospheric composition					P	P				P	P	P			P	
• Provide waste management					P	P				P	P				P	
• Provide power					T				P							
• Radiation protection on the Mars surface					P					P	P					
- GCR Protection					P					P	S					
- SPE Protection					P					P	S					
- Protection during EHA																
• Life support on the Mars surface					P	P				P	P	P			P	
- Atmosphere Revitalization					P	P				P	P				P	
Contaminant Removal					P	P				P	P				P	
Maintain gas composition					P	P				P	P				P	
Replenish oxygen					P	P				P	P				P	

NOTE: P = Primary Function, S = Secondary Function, T = Tertiary Function

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Figure 13. Functional Allocation Matrix — [J. Connolly]
(one example taken from an 8-page report)

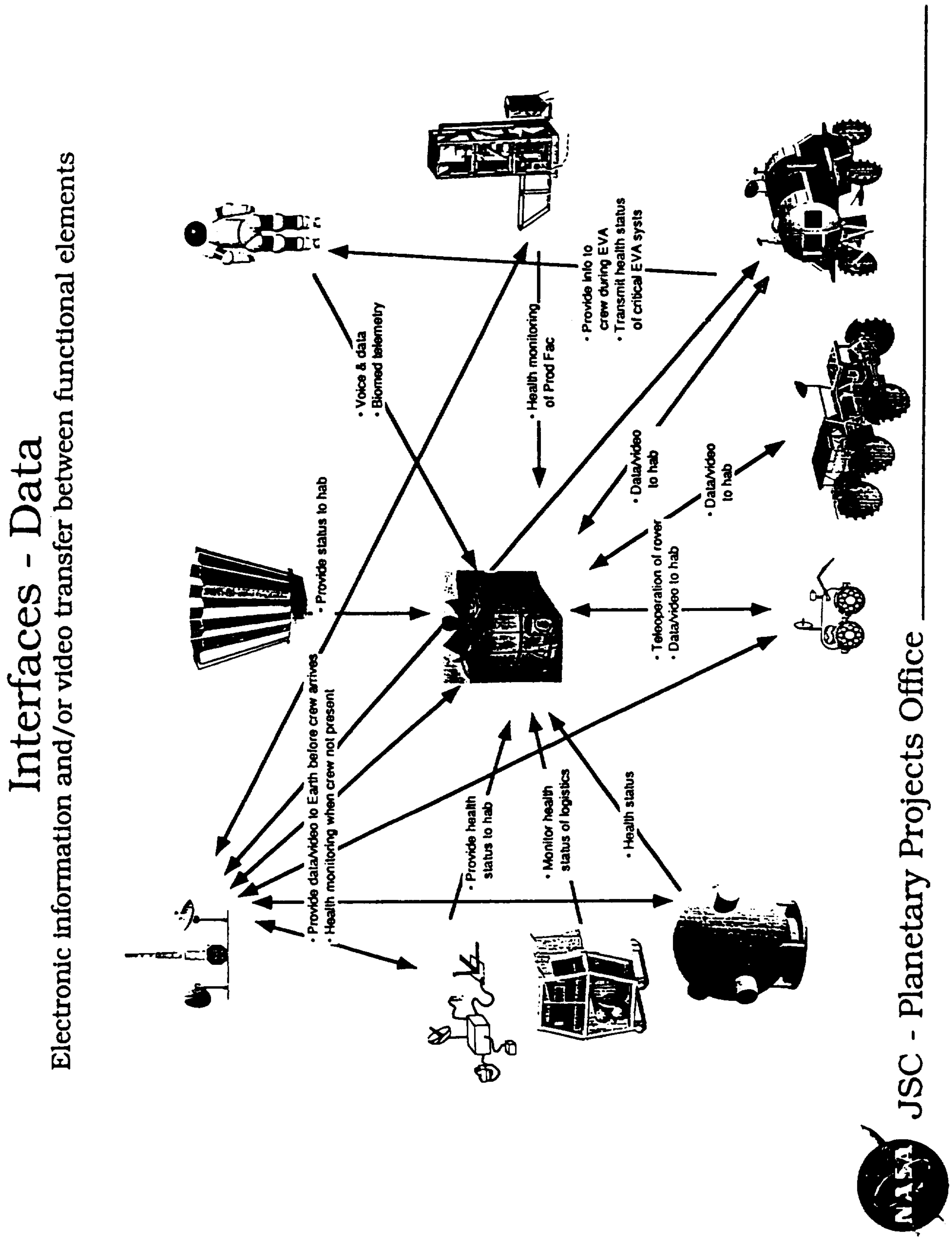

Figure 14. Interface Diagram—Data — [J. Connolly]
(1 of 8 interface categories)

Table 16 defines the reference mission implementation for the first four landings, encompassing the initial buildup of the Mars base, the time period between launch opportunities, and the first 600-day crew mission.

Table 16.
Sequence of Functions Performed by Mars Landers in Mars Exploration Reference Mission

Landing 1

- One of the first three launches has delivered a transit habitat and trans-Earth stage to Mars orbit
- Deliver ascent vehicle, ISRU plant, nuclear power system, backup photovoltaic power system, hydrogen cache, pressurized rover, bio-regenerative life support system, teleoperable rover and communication system plus consumables and science equipment.
- Deploy communication system.
- Deploy 100 kW nuclear system >500m from lander, using telerobotic rover.
- Deploy backup photovoltaic power system.
- Deploy ISRU plant; initiate operation to produce liquefied methane and oxygen; propellants stored in ascent vehicle.
- Deploy biochamber; connect to habitat as appropriate.

Landing 2

- Deliver habitat, backup 100 kW nuclear power supply, teleoperated rover, consumables and science.
- Deploy nuclear power supply with teleoperable rover .
- Activate habitat and check out (from Earth).
- Monitor operation of ISRU methane production facility until ascent vehicle is full; then fill Nitrogen/Argon and breathing oxygen caches.
- Go/no-go for launch of crew from Earth - system health monitoring; crew maintenance plan prepared; propellant and storables cached; early science results from teleoperated rovers; check out return vehicle and habitat.

Landing 3

- Deliver crew and habitat, EVA equipment, consumables, spares and science equipment.
- Crew acclimates to Mars surface.
- Check out first habitat and perform necessary maintenance.
- Perform connection of first and second habitat, as appropriate.
- Activate bio-regenerative life support system to begin producing food and recycling air
- Commence IHA activities, including science, habitation and housekeeping/maintenance. At conclusion of surface stay, load ascent vehicle, verify launch readiness, verify readiness of trans-Earth system, transfer surface assets to remote Earth operation, and depart Mars.

Prior to First Crew Landing

- The base is monitored from Earth for system health. Maintenance items are recorded and the crew spares manifest is added to accommodate maintenance and repair actions.
- The ISRU plant has operated to produce and maintain 5.7 mt of Methane and 20.8 mt of LOX, both stored in the ascent vehicle tanks; 14.4 mt of water, 3.0 mt of oxygen and 2.0 mt of Nitrogen/Argon, which are stored at and used by the bio-regenerative life support system.
- Telerobotic rovers are used for science missions, base maintenance and monitoring.

[• Two cargo missions are launched prior to the crew to support the SECOND crew mission. The assets contained on these landers are available for use by the first crew in the event of catastrophic failure of the initially emplaced elements.]

First Crew Landing

- The Crew Vehicle consists of a transfer habitat which is capable of both microgravity and Martian gravity operations, EVA equipment, consumables, spares and science equipment.
- The crew checks out the original surface lab and performs any maintenance necessary to ensure habitability.
- The crew activates the bio-regenerative life support system and begins food production and atmosphere recycling.
- The crew's transfer habitat is towed to the habitation area and docked to the lab and bio-regenerative life support system.
- IHA science activities commence.
- Both pressurized and unpressurized rovers are available for EHA crews to perform science sorties of progressively longer duration and distance:
  - — local science
  - — regional science
  - — global science
- At the conclusion of the nominal 600 day stay, the crew returns samples to the ascent vehicle, verifies ISRU propellant load, transfers the base to remote Earth operation, and initiates Mars launch.

D. Space Transportation

The space transportation system consists of a trans-Mars injection (TMI) stage, a biconic aerobrake for Mars orbit capture and Mars entry, a descent stage for surface delivery, an ascent stage for crew return to Mars orbit, an Earth-return stage for departure from the Mars system, and an Earth crew capture vehicle (a la Apollo) for Earth entry and landing. As mentioned earlier, the reference program splits the delivery of elements to Mars into cargo missions and human missions, all of which are targeted to the same locale on the surface and must be landed in close proximity to one another. The transportation strategy adopted in the Mars DRM eliminates the need for assembly or rendezvous in low-Earth orbit of vehicle elements and requires a rendezvous in Mars orbit only for the crew in preparing to leave Mars. The transportation strategy also emphasized the use of common elements in order to avoid development costs and to provide operational simplicity. Thus, a modular space transportation architecture resulted. A complete detailed description of the space transportation architecture would be beyond the scope of this paper. Instead, below is described an overview of each of the major elements in the space transportation function. References are provided to the more detailed system descriptions, where available.

1. TMI Stage

The TMI stage (used to propel the spacecraft from low Earth orbit onto a trans-Mars trajectory) employs nuclear thermal propulsion. Nuclear thermal propulsion was adopted for the TMI burn because of its performance advantages, its advanced, previously demonstrated state of technology development, its operational flexibility, and its inherent mission and crew risk enhancements. A single TMI stage was developed for both piloted and human missions. The stage is designed for the more energetically demanding 2009 human mission and then used in the minimum energy cargo missions to throw the maximum payload possible to Mars. In the human missions, the TMI stage uses four 15,000 lb. thrust NERVA derivative (NDR) engines (Isp = 900 seconds) to deliver the crew and their surface habitat/descent stage onto the trans-Mars trajectory. After completion of the two-perigee burn Earth departure, the TMI stage is disposed of in interplanetary space on a trajectory that will not re-encounter Earth or Mars over the course of 10^6 years. The TMI stage used with the crew incorporates a shadow shield between the NDR engine assembly and the LH_2 tank in order to protect the crew from the radiation from the engines that build up during the TMI burns.

As shown in Figure 15, the same TMI stage is used in all cargo missions. The transportation system can deliver approximately 65 metric tons of useful cargo to the surface of Mars or nearly 100 tons to Mars orbit (250 x 33,793 km) on a single launch from Earth atop a heavy lift launch vehicle that has the capability of lifting 240 metric tons to low Earth orbit (407 km). The TMI stage for cargo delivery only requires the use of three NDR engines, so for cost and performance reasons one engine is removed from the piloted mission stage, as is the shadow shield as it is not required in the absence of the crew on these flights. For a thorough description of the TMI stage and the trades associated with its use in the Mars DRM, see *Borowski*.

2. Mars Orbit Capture and Descent Stage

Mars orbit capture and the majority of the Mars descent maneuver is performed using a single biconic aeroshell. The decision to perform the Mars orbit capture maneuver was based upon the fact that an aeroshell will be required to perform the Mars descent maneuver, no matter what method is used to capture into orbit about Mars. Unlike past mission concepts employing aerocapture, however, where the Mars entry speeds have been high, and the mission profile required a post-aerocapture rendezvous in Mars orbit with another space transportation element, the Mars DRM has neither of these features. Thus, the strategy employed was to drive toward the development of a single aeroshell development that can be used for both the MOC and descent maneuvers. Given the demands on a descent aeroshell of the Mars entry and landing requirements, the delta's to permit aerocapture are considered to be modest.

The descent stage itself, employs four RL10-class engines, modified to burn LOX/CH_4, to perform the post-aerocapture circularization burn and to perform the final ~500 m/se. of descent prior to landing on the Mars surface. The use of parachutes has been assumed to reduce the descent vehicle's speed after the aeroshell has ceased to be effective and prior to the final propulsive maneuver. A single common descent stage has been assumed for the delivery of both the surface/transit habitats as well as the ascent vehicle and other surface cargo. The descent vehicle is capable of landing ~65 metric tons of cargo on the Mars surface. When delivering crew, this number is reduced because of the limitations of the TMI stage to deliver the same payload to the higher-energy trajectory required for the crew.

3. Ascent Vehicle

The ascent vehicle is delivered to the Mars surface atop a cargo descent stage. It is composed of an ascent stage and an ascent crew module. The ascent stage is delivered with its propellant tanks empty. However, the descent stage delivering the ascent vehicle includes several tanks of seed hydrogen for use in producing the nearly 30 metric tons of LOX/CH_4 propellant for the nearly 5,600 meters/second required for ascent to orbit and rendezvous with the previously deployed Earth-return vehicle. The ascent vehicle also uses two RL10-class engines, modified to burn LOX/CH_4. The crew rides into orbit in the Earth Crew Capture Vehicle (ECCV) or in a dedicated ascent capsule. The ECCV is similar to an Apollo Command Module and is eventually used by the crew to enter Earth's atmosphere and deliver the crew safely to a land landing. An ECCV would have the necessary heat shield for Earth re-entry. Thus, as in Apollo, it would be heavier than a dedicated ascent module for delivering the crew to Earth orbit. However, unlike Apollo, the ascent propellant is produced in situ, thereby substantially muting the impact of the heavier ECCV for ascent. The advantages of using the ECCV for ascent lies in the ability to eliminate a separate system development and the safety/maintainability associated with the crew having access to the ECCV during their entire surface stay, as well as their Earth-return transit.

4. Earth-Return Vehicle

The Earth-return vehicle is composed of the TEI stage, the Earth-return transit habitat, and the ECCV (if the ECCV is not the ascent crew module). The TEI stage is delivered to Mars orbit fully fueled, where it loiters for nearly four years before being used by the crew in returning to Earth. It uses two RL10-class engines, modified to burn LOX/CH_4. Again, these are the same engines developed for the ascent and descent stages, thereby reducing engine development costs and improving maintainability. The return habitat is effectively a duplicate of the outbound transit/surface habitat used by the crew in going to Mars, less the substantial stores of consumables in the latter habitat.

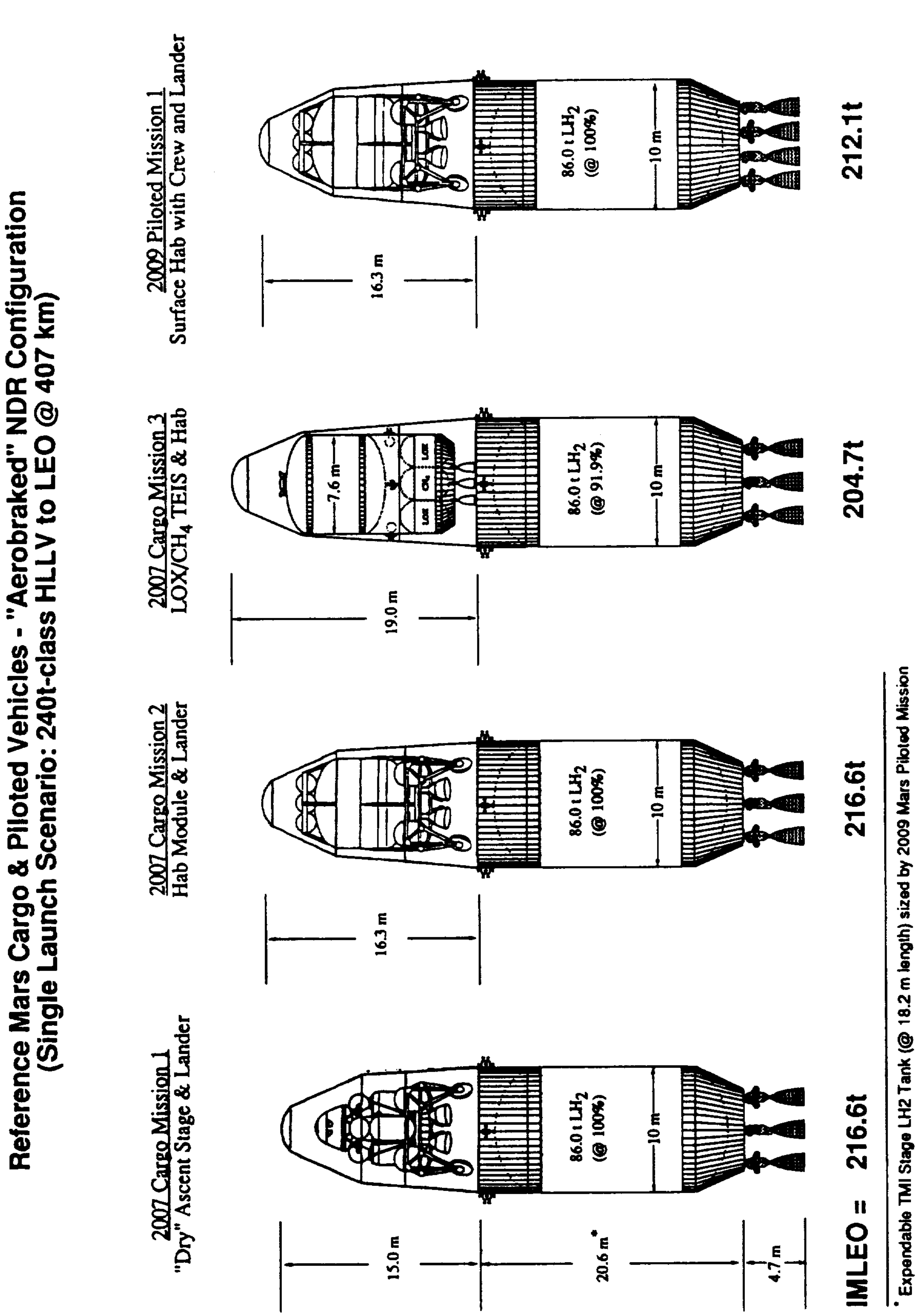

Figure 15. Reference Mars Cargo and Piloted Vehicles — [D. Weaver]

Section II. Mars Exploration Workshop II:

Issues for Mars Exploration

II. Issues for Mars Exploration

A. Surface-Transit Habitat Integration Issues

In the initial concept for the reference mission, the objective to design a 50 metric ton habitat for the surface and a 25 metric ton habitat for the Earth return transit was adopted. Analysis has shown these numbers to be quite hard to achieve using historical approaches for crews of six. On the surface, more than one habitat can be linked in the nominal mission in order to provide adequate volume, consumables and reserves. For the space legs, all resources must be contained within the habitat. Three historical estimates of a habitat capable of supporting six people for 180 days were reviewed (Table 17). It was concluded that masses of 50 metric tons were more likely achievable than 25 metric tons. However, it was agreed that the use of newer technology and more specific attention to return habitat functionality could lower the mass somewhat. This is an important issue, as the mass of the returning spacecraft has the highest leverage on initial mass in low Earth orbit of any element of the Mars mission.

Table 17.
25mt Earth Return Transit Habitat Assessment

Data Source	Mass Estimate	Volume
MSFC	48.2 mt	330 m3
JSC	46.5 mt *	250 m3
Boeing	52 mt (Extrapolated with contingencies)	350 m3

The Johnson Space Center habitat team considered that their Concept C surface habitat design could be split approximately in half, yielding a 35 metric ton space transit habitat.

B. Space Transportation Issues

The Space Transportation System required for the Mars reference mission includes the following elements.

- Launch from Earth to orbit using a common Heavy Lift Launch Vehicle (HLLV) capable of lifting about 225 metric tons of payload to Low Earth orbit. This vehicle sizing was chosen initially because it had also been selected for the First Lunar Outpost initiative studied last year by the Exploration Programs Office at the Johnson Space Center. The shroud size is 10-14m x 30m.

- The upper stage on the HLLV takes the payload directly from Earth launch to Trans-Mars insertion, without stopping for any operational function in low Earth orbit. Thus, the entire system must be "human-rated."

- The upper stage chosen for trans-Mars insertion is a nuclear thermal stage with an Isp of 900 sec, which is jettisoned post-TMI.

- An aerobrake is used to conduct an aerocapture maneuver at Mars. Because the trajectories are low or relatively low energy conjunction class trajectories, such aerobrakes are within current design understanding with little new technology required. The aerobrake is utilized for aerocapture rather than the nuclear stage because it is the same aerobrake used for descending to the surface, and gives no mass penalty, whereas the nuclear stage presents operational difficulties at Mars.

- The same aerobrake used to aerocapture to a high Mars orbit, is then used to decelerate and land the payload on the surface. Using this integrated approach allows approximately 60 tons of surface payload to be landed on Mars for each HLLV launch from Earth.

- The piloted Mars Ascent Vehicle is delivered automatically to the surface and fueled using an indigenous propellant plant that is integral to the lander that carries the MAV.

- A separate cargo mission delivers a fueled (methane-oxygen) Trans-Earth injection stage to Mars orbit in the first opportunity, where it waits for the crew to come up from the surface at the end of their mission.

- At the end of their surface stay, the crew rendezvous' with the Trans-Earth injection stage in high Mars orbit, then returns home.

This scenario is simpler than previous mission concepts, in that it eliminates LEO assembly and eliminates Mars orbit rendezvous before descent. Also, it equalizes the requirements on the Earth to orbit launch vehicle for both cargo and crew, and for the aerobrake on entry and landing on Mars. Finally, it preserves an element of commonality with current lunar mission designs, in the areas of landers, space transportation system stages, and surface habitats. It is relatively spare in its use of HLLV's; only four launches are needed to undertake the first human landing on Mars.

However, it also depends on the development or demonstration of several new technologies, including nuclear thermal propulsion, Mars aerocapture, in-situ propellant production, and automated rendezvous and docking (on ascent).

Several issues have arisen during the course of the study:

- The size of the HLLV is beyond the scale of any existing Earth to orbit launch vehicle. The creation of a new HLLV is viewed as a very expensive proposition and perhaps a budgetary "show-stopper" because it must be committed to early in the program. For that reason, an analysis was performed of the potential use of a half-sized launcher. It was demonstrated that such a concept is reasonable; however it would require approximately twice as many launches, and would imply some level of operations in low Earth orbit. Because of the relatively large amounts of propellant that must be carried to LEO to launch the reference missions, it is probable that the mission can be split into cargo and propellant flights, with refueling on orbit. However, this vehicle also does not currently exist, although there is some chance that the Russian Energia launcher could be configured for this use. If the vehicle has to be developed by the United States, it is felt that the tradeoff between size and cost would favor the largest feasible launch vehicle. Therefore, the 225 metric ton launcher is retained for the reference mission.

- It was adequately shown that the same aerobrake could be used for both Mars capture and Mars descent. The descent aerothermal environment is less severe than that of aerocapture. However, the high ballistic coefficient of the lander causes high landing velocities. Designs with parachutes for slowing descent may be required. Packaging of the Mars lander inside of biconic aeroshells was also addressed (Figure 16). It appears that any of the lander/ascent concepts can be fit into a 10 m diameter by 15m long envelope, which appears to be adequate for cargo payloads as well.

Biconic Brake Envelope Sizing for Lander/Ascent Stage

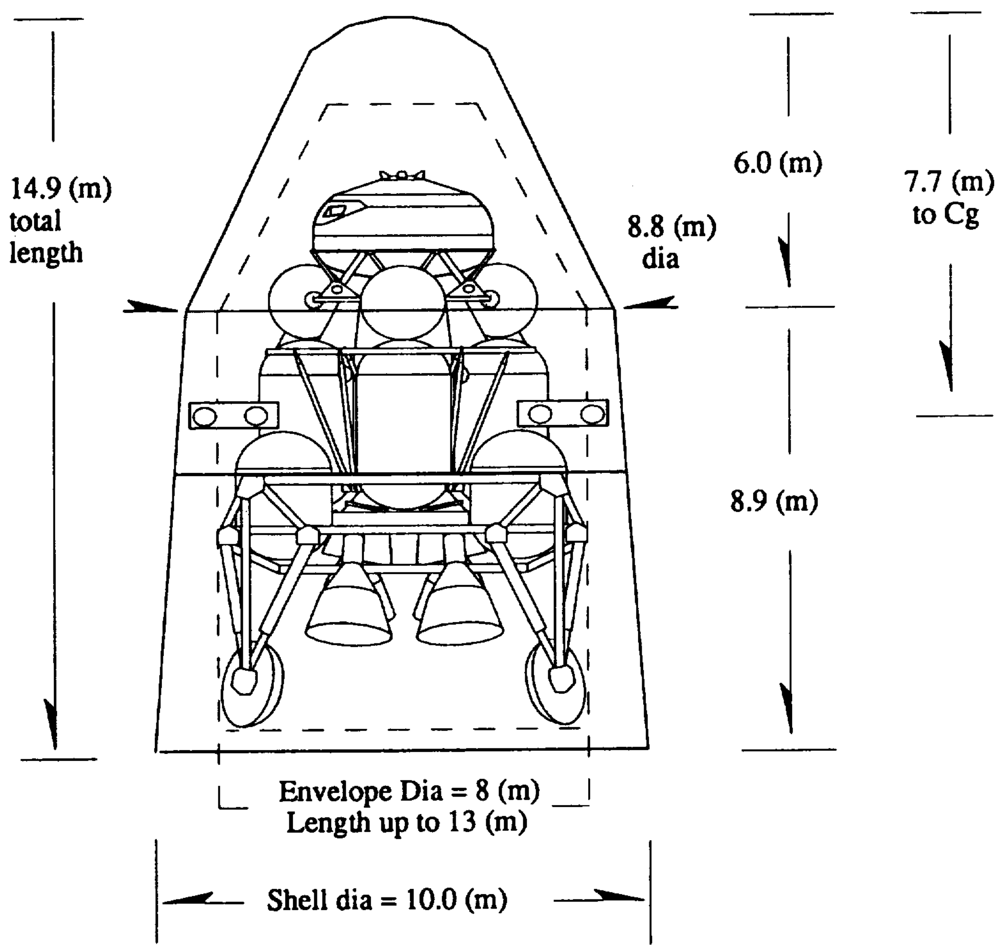

Figure 16. Biconic Brake Envelope Sizing for Lander/Ascent Stage — [G. Woodcock]

- The use of indigenous methane in the ascent vehicle improves overall performance for the mission, by replacing propellant that otherwise would have to have been delivered to Mars' surface. The leverage of the methane production on space transportation system performance is maximized by using a high Mars parking orbit. It might be further increased by increasing the mass of the lander with respect to the TEI stage. Designs have not been investigated which combine ascent vehicle space with the transit vehicle space in providing for crew accommodations. Methane production facilities also be gained from its use in the life support consumable production also influence surface mobility vehicle performance, and the robustness of the life support system caches. However, additional work on integration of the ISRU system with other surface activities remains needed. Growth of the system through time could result in further performance improvements and enlarged caches resulting in greater safety for subsequent crews.

- The nuclear stage proposed by the Lewis Research Center could be designed around any of the four reactor options studied in 1992 (Figure 17). Work done in Russia is especially promising, with the possibility of higher Isp (~950) at a thrust/weight of about 3.0 (for a 15 klbf engine) being a possible development target. Disposal of the NTR stage at Mars has been recognized as a requirement. If the stage is inserted into a 1.19 AU circular orbit, it will take on the order of 1.7 km/sec delta V from Mars orbit, significantly less (~0.4 km/sec) if disposal is along the interplanetary trajectory but without the circularization burn. There are a number of issues of risk and performance that have yet to be worked out. Table 18 gives the Lewis Research Center's recommendations for NTR in the reference program. Among their recommendations is to consider dual mode NTR systems which provide electrical power for the transfer vehicle and refrigeration for cryogen storage, which can reduce insulation requirements. Another issue for future trades is the extent to which utilizing NTR for Mars orbit insertion and return to Earth improves the mission and reduces the number of transportation elements. The answer to this is not yet clear cut. Although there are three different propulsion modes in the reference mission (NTR, aerobrake, methane-oxygen chemical systems), all three would still exist in the LeRC proposal, albeit in different forms.

Table 18.
Reference Scenario Observations and Recommendations (for NTR)

CARGO PILOTED / EARTH RETURN STAGE MISSIONS:
• The NTR has a "very mature" technology database. It has already been tested (Rover/NERVA) at the thrust, specific impulse, and burn duration levels required for a piloted mission to Mars. The CIS technology is potentially better!!
• Clustered (2 to 4) lower thrust (15 to 25 klbf) NTR engines are suitable for present "no MEV/no TEI propellant" split sprint, Mars mission scenarios.
• With perigee propulsion, a "stretched" version of NASA/LeRC's "First Lunar Outpost" (FLO) NTR TLI stage can be used for TMI applications also. IMLEO requirements to deliver 50t of surface payload are ~215-220 t (better than 90% of 240 t HLLV capability).
• Using the NTR for TMI and MOC maneuvers increases the IMLEO to ~232 t for 50 t of surface payload. With disposal, IMLEO ~227 t and surface payload reduced to 39 t due to volume limits with 240 t–class HLLV's (with 10 m diameter tanks). Slush H_2 can also improve performance.
• "Dual Mode" NTR systems with refrigeration can reduce boiloff, decrease stage length and increase delivered payload.
• With 120 t–class HLLV, a single launch cargo vehicle can deliver surface payloads varying between 18 t (with disposal) and 25 t (without disposal). The 120 t–class HLLV systems are "mass-limited."

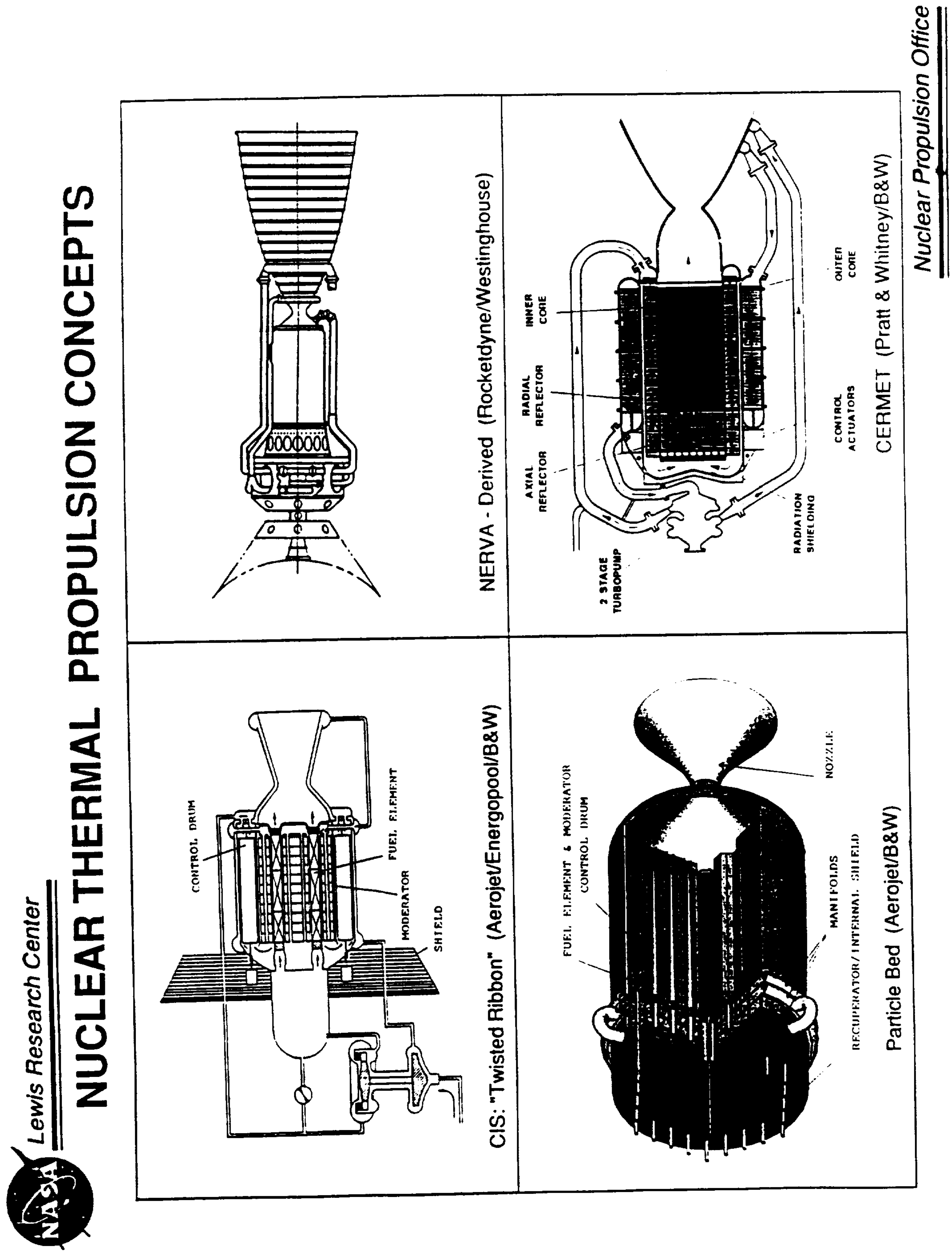

Figure 17. Nuclear Thermal Propulsion Concepts — [S. Borowski]

- The reference mission has a top level approach to risk reduction and safety which appears sound; however, not enough attention has yet been given to recovery modes in the event of life-threatening system failures. Principal focus in this argument is given to various "abort" modes where abort refers to the possibility of returning directly to Earth without going to the surface of Mars. This is a traditional abort implementation mode for interplanetary human flights (Apollo), but is a strategy that is diametrically opposed to the approach of the reference mission, which is aimed at getting to Mars whenever a life-threatening situation arises. However, the approach of having an integral abort mode for each onboard system failure, no matter how unlikely will result in designs similar to previous mission concepts, which could not be afforded. There may be modest changes to the reference approach which can provide additional abort modes that do not now exist. These would presumably have the effect of lowering risk, perhaps at some performance decrement or cost growth. The solution to this discussion is more precisely formulated risk analyses and mitigation strategies that meet the objectives of the reference mission philosophy.

- There are various arguments that the whole approach to the space transportation system is flawed. In particular, Gordon Woodcock, an outside reviewer, has argued strongly for a nuclear or solar electric propulsion-based transportation system. This argument emphasizes that NEP/SEP is more likely to evolve to a system of low recurring costs to support a long term Mars development program; could be competitive for the first mission; has greater commonality with the overall architecture of other space activities; would introduce new technologies which would be multiuse, including providing near-term uses terrestrially; has the potential for improving the safety of deep space transportation; and has moderate development risk. His analysis can be found in the working papers presented at the workshop.

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NASA Advisory Council Aerospace Medicine Advisory Committee (1992), *Strategic Considerations for Support of Humans in Space and Moon/Mars Exploration Missions: Life Sciences Research and Technology Programs*. National Aeronautics and Space Administration, Washington, D.C.

Duke, Michael B. and Budden, Nancy Ann, NASA Johnson Space Center, "Results, Proceedings and Analysis of the Mars Exploration Workshop," JSC-26001, August 1992.

Section III. Mars Exploration Workshop II:

Working Group Discussions and Papers

III. Working Group Discussions and Papers

In addition to reviewing the reference mission approach to Mars exploration, workshop participants were asked to address three "cross-cutting" issues: cost, dual use technologies, and international cooperation. Each working group was asked to generate a white paper to capture the content of their deliberations. These discussions were not intended to provide definitive analysis or answers to the issues, but to provide guidance to the mission analysis team that could be used in focusing or revising the reference approach.

Because the topics of discussion were different for each working group, the products differ accordingly.

The working group on cost assembled their own set of questions to address, and proceeded to convene a "mini" workshop" with presentations and discussion. Their white paper summarized both the presentations and the discussion.

The working group on dual use-technologies created a matrix to display how Mars mission technologies could have both space and terrestrial applications.

The international cooperation working group wrote a white paper based on the recent IACG meeting and the workshop discussions.

The following products resulted from the three working groups:

A. Cost Working Group

1. Agenda and Purpose
2. Discussion Questions
3. "Cost Credibility"

B. Dual-Use Technology Working Group

1. "Opportunities for Dual-use Technology in Mars Exploration"

C. International Cooperation Working Group

1. "Building International Cooperation for Mars Exploration"

A. COST CREDIBILITY

Cost Working Group
Hum Mandell, Chair
Mars Exploration Workshop II
May 24-25, 1993

PREMISE

In an environment where perception can quickly become reality, the current perception and reality are that support for human exploration of Mars has waned since its peak between 1989 and 1992. While there are many reasons for this, chief among them are the failure of the previous administration and NASA to rally Congressional support and the subsequent change of administration. There are other factors, some created by misinformation, which will inhibit or preclude the reintroduction of human exploration of space to the national agenda.

One major misperception to be confronted is the cost of the venture. During the "90-Day Study," NASA management had little concern for the costs of human exploration. The project leader assumed that the "Space Exploration Initiative" was high enough on the national agenda to render cost secondary. Only at the end of the study were cost estimates generated. The results would have demanded a doubling or tripling of the current NASA budget for up to thirty years. Development costs exceeding $200 billion were common across the several alternatives considered. Even the most optimistic proponents of the programs became concerned over these magnitude of the estimates. Ultimately, when the results were presented to NASA management, the detailed cost estimates were quickly recalled and embargoed.

But the damage was done. The perception abounded, throughout NASA and the external community, that costs of up to $500 billion would be required to implement Moon and Mars exploration. Had the study been concerned with cost from the outset, two things could have been done to produce more affordable missions: first, less ambitious architectures could have been analyzed; and second, the parameters of the cost models employed (which reflect the manner in which business was done in NASA at that time) could have been modified to reflect a less expensive management paradigm.

Since the end of the "90-Day Study" NASA has made a few attempts to correct the misperceptions of prohibitive cost. However, in the current political climate of mistrust, and with the questioning of NASA's credibility, the opportunity to convey the message that there are affordable options for Mars exploration may be difficult to create.

If human exploration is to be returned to the national agenda, NASA must create and capitalize on just such opportunities. And the process must begin with the restoration of trust between NASA and the policy making bodies governing the future of space appropriations.

Two questions become immediately apparent. First, what must NASA do to regain credibility? And, second, once credibility is achieved, how can the subject of human Mars exploration be restored to the national agenda?

It is the premise of this white paper that proving the affordability of human flight to Mars must begin with correcting the self-created misperception that costs will reach hundreds of billions of dollars. It has been successfully demonstrated that missions costing only tens of billions of dollars are feasible. However, these costs may be achieved only under conditions of major change to the architectures of the Ninety Day Study, and to the management paradigm employed by NASA in the development of human spacecraft.

MARS IS AS AFFORDABLE NOW AS IT WILL EVER BE

There are two sides to affordability: the supply of resources, and the demand which is created by the venture. If the two are in balance, the venture is affordable. NASA must attack both sides of the equation, of course, but the supply side, while it may be influenced, is less controllable than the demand side.

Influencing the Supply

The supply of resources to NASA has reached a plateau, at somewhat less than one-half the peak values reached during the 1960's. Unless major events occur that are beyond our current capability to predict, that supply should remain relatively constant for the foreseeable future.

NASA can influence the supply of resources both by restoring its credibility, and by positively influencing national economic factors, such as the creation and preservation of aerospace industry jobs. The current strategy to restore credibility begins with small projects (those costing less than $100M and of 2-3 years duration). These small, well defined projects must have direct application and value to human exploration, and must demonstrate new management techniques and paradigms. If successful, these projects should aid in the restoration of confidence in NASA's ability to successfully perform programs. They will also provide beneficial engineering and scientific information for future human explorations.

However, space exploration strategies depending on the increase of national resources must be avoided. Considering the national budget deficits, the likelihood of increasing NASA funding in the near term is extremely remote.

A possibility does exist for the acquisition of resources from outside sources, such as other government agencies and foreign governments. Appendix 1 identifies some of the additional costs and concerns associated with a multinational exploration program. Therefore, the strategies of exploration program management must also include the leveraging of these resources and a consciousness of the additional costs such participation may incur.

Influencing the Demand

There are two ways to influence the demand for resources. One is to reduce the program content or eliminate certain capabilities of the mission spacecraft and surface equipment. This has traditionally been the NASA's first action to reduce costs.

But there is a better, if possibly harder, means of reducing demand; reduce costs by changing the ways in which NASA designs, acquires, and operates space hardware. This involves cultural changes requiring both dedication and a new set of skills.

The balance of the supply of resources against the demands of exploring Mars is probably as favorable today as it will be any time in the future. Today, the only substantial degree of control by NASA is on the costs, or the demands for resources, of the venture. And a major possibility for savings is in the reduction of the developmental costs, through the use of low-cost management processes. In addition, the operational costs of subsequent space programs must be sharply reduced.

Additionally, there exists today both a knowledge base and a momentum for the human exploration of Mars. NASA and the nation have invested a great deal of time and effort in this venture which, if lost, will be difficult to recapture in the future. Therefore, it is extremely risky to pursue strategies predicated on waiting years to begin human exploration. While it is inevitable that humans will explore Mars, it is not similarly inevitable that Americans will participate in the mission. If the United States loses its current momentum, on the likely-false hope that the budgetary picture will improve in the future, this country will lose a major opportunity, at least for this generation, and very possibly forever. As a result, the United States must find ways to reduce costs so that this venture may be undertaken in the coming years.

REDUCING COSTS

Architectures

The mission architectures utilized during the "90-Day Study" were very rich in content, and included significant investments in infrastructure for both the Moon and Mars, as well as expanding the Low-Earth orbit infrastructure. Linking the logic of lunar and Mars explorations carries with it the hazards of compounding the negative probabilities of both ventures. If the Moon is introduced before Mars, then the success of the Mars venture becomes totally dependent on the success of the lunar program.

Proposed architectures should be highly exclusive, providing only needed capabilities at the times they are required, incrementally phasing from the first modest needs of exploration to the later needs of colonies.

A proposal has been made that the two ventures be unlinked, and that Mars be given priority. An architecture is proposed which develops the basic capabilities for exploration based first on the needs of the Mars exploration. Requirements associated with the Moon may be added as relatively low cost increments to the costs of the Mars exploration spacecraft and surface systems.

Cultural Change

It has been demonstrated analytically that the strongest influence on program costs is the culture of the developing and operating organizations. This influence, relatively speaking, is more dominant than any other predictive cost parameter, including the size or performance of the mission vehicles.

While a treatise of cultural change is far beyond the scope of this paper, it is clear, however, that if there is to be further human exploration of space, it must be done more economically, and that the major means for achieving economies needed is change to the management paradigm.

The Direction for Cultural Change

Change must have direction to be effective in reducing costs. A significant amount of research has been done to determine "benchmarks" for the low-cost organizations of the future. This research has determined that under specific sets of conditions, costs may be reduced by factors of at least six below the costs of programs developed with traditional NASA spacecraft program management practices.

The benchmark conditions are many, but most influential is the relationship between the public sector and the private contractor community. Benchmarks require that NASA state its requirements in terms of the performance it wishes to achieve, and allows the competitive private sector to satisfy those functional requirements. Contractor rewards must be expressed and distributed in terms of results achieved, unlike current practices which base rewards on the evaluation of "paper" products or on the performance of the government to "manage the contractor". Contract changes must be reduced or eliminated. Technologies must be ready by the time the program development begins. Costs and budget availability must match. And, while less directly controllable by NASA, stable funding is essential. NASA also needs to examine non-traditional acquisition approaches; for example, the purchase of commercial launch services based on a fixed price per pound of payload to orbit. By undertaking these types of cultural changes and innovative acquisition and management practices, NASA can substantially reduce the costs traditionally associated with aerospace systems.

Benchmark Example

To begin restoring credibility, projects must demonstrate, from start to successful completion, that the principles of low cost management are not only conceptually feasible, but are capable of being employed by NASA. An insight into the potential magnitude of the cost reductions can be gleaned from the example of Space Industries Inc. and their Wake Shield Facility.

NASA has already successfully managed small, low cost projects, such as the Wake Shield project developed by Code C, with a small contractor, Space Industries Inc. (SII). SII embraced an explicit philosophy to address basic requirements in the simplest and most cost effective manner. SII implemented that philosophy by deliberately choosing the technical processes and management style implemented to undertake this project. These choices included some departures from those of "traditional" aerospace contractors, such as: a focus on performance requirements rather than technical specifications; the elimination of "non-essential" requirements; a "design-to-operate" approach that allows the intended use to drive the design; use of a small, matrixed personnel corps in a simplified organizational structure; streamlining of management, documentation, testing and other procedures; and use of non-aerospace sources for fabrication and assembly. Moreover, there was an awareness that success was predicated not only on new procedures, but by a conscious acceptance of this management philosophy by the entire SII team. Ultimately, the proof was in the results. When the technical requirements from this project were entered into traditional NASA cost models, the estimates produced were six times as large as the actual costs experienced.

REBUILDING CREDIBILITY

Credibility will be difficult and time-consuming to rebuild. Even if the current space station redesign effort is successful, there will be lingering doubts about NASA's ability to manage large programs, and fear that Mars exploration will be unaffordable. While there is no "quick fix", there are positive steps NASA can undertake. Initially and immediately, NASA would benefit from successfully executing the redesigned space station, within cost and schedule projections. Beyond that, NASA must effectively execute the small projects discussed above. There is, however, a legitimate concern that success with such projects as Lunar Scout is too small to convince Congress that NASA is capable of the large undertaking of human exploration. Performing a few small programs under a low-cost management paradigm is unlikely to constitute sufficient "proof" for key decision makers and skeptics. How then does NASA span the gap between successful small projects and desired large programs?

Scaling from Small Programs

One proposal is to pursue programs of intermediate size, between the small $100 million class and the $1 billion class. These would demonstrate NASA's ability to take on programs of both greater dollar value as well as technical and management complexity, and thereby provide further confidence that the principles of low cost management can indeed be scaled to large programs.

The criteria for selecting these intermediate sized "bridging tasks" programs must include their relevance to the main objective, i.e., human exploration of Mars. They should provide challenge, and yield useful technologies. They must be done quickly. They must be successful.

Candidates for this category of mission can include Mars sample returns, the landing of in situ resource utilization demonstration units on the Moon and Mars, the landing of large scientific payloads on the Moon and Mars, and the deployment of communications networks around Mars. A list of organizational attributes for these bridging tasks is included in Appendix 2. Any of these candidates could be performed for a few hundreds of millions of dollars employing the benchmark management paradigm.

<u>Other Concerns on the Road to Credibility</u>

As an adjunct to that process of rebuilding cost credibility, NASA must also build its constituencies. It is widely believed that there is national support for NASA to continue the human exploration of space. But this support must be identified, motivated and demonstrated.

Once demonstrated, NASA must carry its message to its paying customers, the United States taxpayers. It must demonstrate that there will be wide direct and indirect benefits to the national economy. It must demonstrate where the funding will be spent, and where jobs will be created.

CONCLUSION

Beyond bridging tasks and constituency building, NASA has significant work to do. Some is immediate, such as learning to say "No" when project funding is cut without a corresponding reduction in content. This type of discipline will minimize the unrealistic cost commitments that have destroyed NASA's cost credibility. It means NASA may have to forgo certain projects because decision makers will not support the true estimated cost; but it will help NASA shed the perception that they are merely showing the nose of the camel with its projects and cost estimates. Moreover, NASA must establish throughout the agency, regardless of center or headquarters code, common near- and long-term objectives and priorities. Once done, NASA must simply focus on the objectives, eliminate the superfluous drains on agency resources, perform projects within the ability of the current NASA budget, and be successful at delivering what it promises. If it can do these things, NASA can proudly reclaim its place as the Federal Government's premier "can-do" organization.

<u>Cost Working Group Participants</u>

Hum Mandell, Chair	NASA/JSC
Beth Caplan	NASA/JSC
Mike Duke	NASA/JSC
David Weaver	NASA/JSC
Nancy Ann Budden	NASA/JSC
Lisa Guerra	SAIC
Tom Bonner	SII
Larry Lemke	NASA/ARC
Geoff Briggs	NASA/ARC
Bill Huber	NASA/MSFC
Gordon Woodcock	Boeing
John Clark	NASA/LeRC
John Connolly	NASA/JSC
Paul Campbell	Lockheed

COST WORKING GROUP
Exhibit I

1. Agenda and Purpose

Purpose: To begin the *enabling* process of proving that human flights to Mars are affordable *now*.

Agenda

Introducing Cost Credibility, The Need	*Mandell*
Lower Cost Mars Missions	*Guerra*
Understanding the Uncertainties in the Costs	*Guerra*
Lower Cost Exploration Missions	*Caplan*
Benchmarking: Rules of Organization	*Mandell*
Benchmarking: Cost Reduction Analysis (SII)	*Mandell*
How It Is Done in Practice	*Bonner*
Group Discussion • Review/add discussion questions • Generate answers/focusing questions • Identify key points for afternoon presentation	*All*

2. Discussion and Questions

- What are the cost opportunities and penalities associated with a multinational program?
- How can costs be distributed amongst international partners with the intent of cost reduction? What are the risks associated with such an approach?
- Which Mars mission technologies pose cost and schedule risk? How can they be developed or paid outside a Mars program? Where should the balance be established between "dual-use" mission technology for benefit to the economy and current state of the art ("off-the-shelf") technology for cost savings?
- How can R&D for a Mars program be distributed among NASA Centers without creating additional integration and administrative cost for the program?

COST WORKING GROUP
Exhibit 2

Cost Impacts of International Participation

While there are opportunities for cost savings through international participation, there are also potential additional costs?

- May have costs for communication, travel, and interfaces
- Requires clean interfaces to keep additional costs low
- Need to identify benefit (cost/benefit) of international participation
- Assess the impact of international "trade blocks" on an international mission
- While total mission cost might be greater, cost/nation would be less programmatic risk
- Need to trade off "in-line" tasks with tasks that add mission performance (e.g./surface systems & experiments) as options for international participation

COST WORKING GROUP
Exhibit 3

Organizational Characteristics for Bridging Tasks

What are the characteristics required for potential "bridging tasks"?

- Establish and maintain a change in organizational culture, rather than being dependent on the orientation and beliefs of prevailing management
- Must have a reasonable scale/complexity
- Must have shared objectives
- Must have challenging mission
- Overcome psychological barriers and positively motivate people/organizations
- Tasks must have useful products
- Must be in-line with long-term objectives
- One person in charge with the responsibility, authority and accountability
- "Green fields"--new organizations at new locations with new ways/culture
- If new org at new location is not possible, establish skunkworks at centers that report through unique management chains
- "Can do", imperative-driven organization to replace slow, ineffective bureaucracy
- Produce more product with the same number of people (Less paper, more product)
- Change project management regulations and rules
- Eliminate/waive procurement regulations

B. DUAL-USE TECHNOLOGIES AND MARS EXPLORATION

Dual Use Technologies Working Group
Barney Roberts, Chair
Mars Exploration Workshop II
May 24-25, 1993

"Dual use" technologies are defined as those which can find early application in non-project activities (terrestrial, other space), but which are also needed for a space project. They are generally emphasized by the current national administration which desires to improve American quality of life through investments in new technology. Space programs are not spared this requirement. A project strategy that emphasizes the creation of dual use technologies, besides consistency with this current trend in Washington could 1) more easily generate funds through increased cooperation and joint-venturing; 2) provide smaller projects which could be more easily funded; 3) provide for a "step-by-step" approach to the Mars Mission; 4) provide a stimulus to the local and national economies; and 5) foster an increase in space advocacy.

"Dual-use" was further loosely defined as a project with any level of cooperation between government and non-government entities which would produce useful products for both entities. Levels of funding needed from each entity for a project was not discussed. It was recognized that the useful information from a technology project could flow from government entities outward, from non-government entities into the government, or in both directions.

The group took as its charge to 1) choose a set of dual-use technology categories with which to work, 2) provide technology examples within each category, and 3) provide both terrestrial and space applications for each technology. The group began by listing technology category candidates using a brainstorming technique. A final set was approved by consensus. The group then used a "round-robin" technique to produce likely technologies in each category along with their terrestrial and space applications. Some discussion took place over the merits/demerits of these ideas. However, the group did not feel charged to fully critique these ideas but charged only to create a usable set from which future discussions could be held.

The group listed and worked with ten Mars Mission-related dual-use technology categories. These can be found in the ten tables which follow. These categories are:

Propulsion	Human Support
Communication & Information Systems	Power
In Situ Resource Utilization	Structures & Materials
Surface Mobility - Suits	Science & Science Equipment
Surface Mobility - Vehicles	Operations & Maintenance

These categories were then associated with a total of fifty-four technology areas along with their applications. The space applications are found in the right column and the terrestrial applications are found in the left column.

Constructing such a table was a valuable exercise since it illustrated that many of the Mars Mission technologies and their space applications do have a connection to terrestrial (economic) use. This "dual usage" can have a favorable effect on both the local and national economies in the USA. In addition, a broader use of space technologies in the commercial arena heightens the potential for building a more favorable opinion of space activities among the public, among business people, among educators and politicians. In other words, it could increase the constituents who are favorable to space activities and space expenditures.

Dual-Use Technology Working Group Participants

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Alan Adams	NASA-MSFC
Teresa Buckley	NASA-ARC
Robert Cataldo	NASA-LeRC
Jack Schmitt	Consultant
Thomas Polette	LESC
Nathan Moore	LESC
Gary Moore	U of Wisconsin
Robert Zubrin	Martin Marietta
Robert Zimmerman	RAND
Woody Lovelace	LaRC
Andrew Gonzales	NASA-ARC
John Mankins	NASA-HQ

Table 19. Dual-Use Technologies: Propulsion

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Dual-Use Technologies: Propulsion

Terrestrial Application	Technology	Space Application
•Nuclear Reactors •Weapons & Nuc Waste Disposal •Hi-Efficiency Heat Engines (Turbines, Thermo-Structural Integrity) ←	•High-Temp Materials	•NTR •Aerobraking
•Clean-Burning Engines (H2/O2) ←	•Hi-Efficiency Cryo Refrigeration	•Propellant Maintenance
•Higher Performance Commercial Launchers ←	•Methane/O2 Rocket Engines	•ISRU-Based Space Transportation

Note: Technology "Spin-In" = →
"Spin-Off" = ←
"Both" = ↔

Table 20. Dual-Use Technologies: Communication and Information Systems

Futron

Dual-Use Technologies: Comm./Info Sys.

Terrestrial Application	Technology	Space Application
•Communications (Hi-Def TV Br'dcast)	← •Ka Band, or Higher	•Telepresence: Vision and Video Data •Interferometers: Raw Data Trans.
•Entertainment Industry •Commercial Aviation	↔ •Machine-Human Interface	•Control Stations •System Management
•Communications •Archiving	↔ •Data Compression/Info Processing •Large Scale Data Mgt Systems	•Interferrometers: Raw Data Trans., Info Processing •System Management, Expert Data •Archiving/Neural Nets

Note: Technology "Spin-In" = →
"Spin-Off" = ←
"Both" = ↔

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Table 21. Dual-Use Technologies: In Situ Resource Utilization

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Dual-Use Technologies: ISRU

Terrestrial Application		Technology	Space Application
•Mineral Analysis, Yield Estimation - Deep Mine Vein Location and Tracking •Wall and Ceiling Integrity	←	•Advanced Sensors	•Mineral Analysis, Yield Estimation Surface Mineral Analysis and Resource Location
•Deep Mine Robotic Operations • Mining • Beneficiating • Removal	↔	•Advanced Robotic Mining	•Surface Mining Operations • Mining • Beneficiating • Transportation
•Improved Automated Processing; Increased efficiency	↔	•Automated Processing: Advanced FDIR	•Remote, Low-Maintenance, Processing
•Reliable, Low-Polution Personal Trans. •Regenerable Energy Economies •Small, Decentralized Power Systems for Remote or 3rd World Applications	←	•Alternative, Regenerable Energy Economies • Methane/O2 • H2/O2	•ISRU Based Engines •Regenerable Energies •Hi-Density Energy Storage
•Environmentally-Safe Energy Production	←	•Space-Based Energy Generation & Transmission	•Surface Power Gen & Beaming

Note: Technology "Spin-In" = →
"Spin-Off" = ←
"Both" = ↔

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Table 22. Dual-Use Technologies: Surface Mobility - Suits

Futron

Dual-Use Technologies: Surface Mobility-Suits

Terrestrial Application		Technology	Space Application
•Hazardous Materials Clean-up •Fire Fighting Protection and Underwater Eqpt.	←	•Lightweight, Superinsulation Materials	•Surface Suits: Thermal Protection
•Robotic Assisted Systems •Orthopedic Devices for Mobility Impaired Persons	↔	•Robotics •Mobility Enhancement Devices and Manipulators	•Robotic Assisted Suit Systems
•Hazardous Materials Clean-up •Fire Fighting Protection and Underwater Eqpt.	←	•Dust Protection, Seals, Abrasive Resistant Materials	•Surface Suits: Outer-Garment
•Haz-Mat Clean-up, Underwater Breathing Gear	↔	•Light-Weight, Hi-Rel, Life Support	•Portable Life Support for Surface Suits
•Remote Health Monitoring	←	•Portable Bio-Med Sensors and Health Eval. Systems	•Surface EVA Crewperson Health Monitoring
•Hypo-Hyper Thermal Treatments •Fire Fighting Protection and Underwater Eqpt. •Artic/Antartic Undergarments	←	•Small, Efficient, Portable, Cooling/Heating Systems	•Surface Suits: Thermal Control Systems

Note: Technology "Spin-In" = →
"Spin-Off"= ←
"Both" = ↔

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Table 23. Dual-Use Technologies: Surface Mobility - Vehicles

Futron

Dual-Use Technologies: Surf Mobility - Vehicles

Terrestrial Application		Technology	Space Application
•ALL-Terrain Vehicles •Research (Volcanoes) •Oil Exploration	◄►	•Mobility	•Surface Transportation •Humans •Science Eqpt •Maintenance & Inspection
•Reactor Servicing/Hazardous Applications	◄►	•Robotics & Vision Systems	•Teleoperated Robotic Systems
•Earth Observation, Weather, Research	◄—	•Super-Pressure Balloons (110,000ft -Earth Equiv.)	•Mars Global Explorations
•Efficient, Long-Term Ops, Lo-Main. •Machines in Artic/Antartic Environments	◄—	•Tribology	•Surface Vehicles •Drive Mechanisms •Robotic Arms •Mechanisms
•Helicopters, Autos	◄►	•Variable SpeedTransmissions	•Surface Vehicles
•Automated, Efficient Construction Equipment	◄—	•Multi-Purpose Construction Vehicle Systems and Mechanisms	•Robotic Construction and Set-up Equipment

Note: Technology "Spin-In" = —►
"Spin-Off" = ◄—
"Both" = ◄►

Table 24. Dual-Use Technologies: Human Support

Futron

Dual-Use Technologies: Human Support

Terrestrial Application		Technology	Space Application
•Stored Food •US Army •NSF Polar Programs	←	•Long-Life Food Systems •W/HI Nutrition •Efficient Packaging	•Efficient Logistics •Planetary Bases •Long Space Flights •Space Stations
•Improved Health Care •Sports Medicine - Cardio-Vascular •Osteoporesis - Immune Systems •Isolated Confined Environs/Polar Ops •Non-Invasive Health Assessments	←	•Physiological Understanding of the Human/Chrono-Biology •Understanding of Psyhco-Social Issues •Instrumentation Miniturization	•Countermeasures forLong-Duration and/or Micro-g Space Missions •Health Management and Care
•Health Care •Disaster Response •US Army	↔	•Long-Term Blood Storage	•Health Care for Long-Duration Space Missions
•Office Buildings ("Sick Building Syndrome) •Manufacturing Plants	←	•Environmental Monitoring and Management	•Environmental Control for •SpaceCraft Cabins •Planatery Habitats •Press. Rovers
•Contamination Cleanup •Waste Processing	←	•Waste Processing/SCWO •Water Purification	•Closed Water Cycles for •SpaceCraft Cabins •Planatery Habitats •Press. Rovers
•Long Life Clothes •Work Clothes in Haz Environ •US Army	←	•Advanced Materials/Fabrics	•Reduced Logistics Thru Long-Life, Easy Care Clothes, Wipes, Etc. •Fire Proof/Lo-Out-gassing Clothes
•Efficient Food Production	↔	•Advanced Understanding of Food Production/Hydroponics	•Reduced Logistics Thru Local Food Production for •SpaceCraft Cabins •Planatery Habitats

Note: Technology "Spin-In" = →
"Spin-Off" = ←
"Both" = ↔

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Table 25. Dual-Use Technologies: Power

Futron

Dual-Use Technologies: Power

Terrestrial Application		Technology	Space Application
•Batteries/Regen Fuel Cells for •Autos •Remote Ops •DOD •NSF Polar Programs	←	•Hi-Density Energy Storage •Alternate Energy Stor. (Flywheels)	•Reduced Logistics for Planetary Bases •Hi-Rel, Lo-Maintenance Power Systems
•Clean Energy From Space	←	•Beamed Power Transmission	•Orbital Power to Surface Base •Surface Power Transmission to Remote Assets
•Remote Operations •DOD •NSF Polar Programs	←	•Small Nuclear Power Systems	•Surface Base Power •Pressurized Surface Rover •Interplanetary Transfer Vehicle
•Remote Operations •DOD •NSF Polar Programs •Hi-Efficiency Auto Engines	←	•Hi-Efficiency, Hi-Rel, Lo-Main Heat-to-Electric Conversion Engines	•Energy Conversion for Planetary Bases •Low Servicing Hours •Little or no Logistics

Note: Technology "Spin-In" = →
"Spin-Off" = ←
"Both" = ↔

Table 26. Dual-Use Technologies: Structures and Materials

Futron

Dual-Use Technologies: Structures and Materials

Terrestrial Application		Technology	Space Application
•Vehicles •Fuel-Efficient Aircraft •Modular Construction (Homes, Etc)	←	•Composite Materials •Hard •Soft •Advanced Alloys, Hi-Temp	•Cryo Tanks •Habitat Enclosures •Pressurized Rover Enclosures •Space Transit Vehicle Structures
TBD	←	•Super-Insulation •Coatings	•Cryo Tanks •Habitable Volumes
•Large Structures, Hi-Rises, Bridges •Commercial Aircraft •Improved Safety •Lower Maintenance	←	•Smart Structures •Imbedded Sensors	•Space Transit Vehicle Structures •Planetary Habitat Enclosures •Surface Power Systems •Rover Suspensions

Note: Technology "Spin-In" = →
"Spin-Off" = ←
"Both" = ↔

Table 27. Dual-Use Technologies: Science and Science Equipment

Futron

Dual-Use Technologies: Science and Science Eqpt.

Terrestrial Application		Technology	Space Application
•Energy Resource Exploration •Environmental Monitoring, Policing	←	•Spectroscopy •Gamma Ray •Laser •Other	•Geo-Chem Mapping •Resource Yield Estimating •Planetary Mining Operation Planning
•Undersea Exploration •Haz Env Assessments, Remediation	←	•Telescience	•Remote Planetary Exploration
•Environmental Monitoring •Medicine	←	•Image Processing •Compression Techniques •Storage •Transmission •Image Enhancements	•Communication of Science Data •Correlation of Interferometer Data
•Improved Health Care •Sports Medicine - Cardio-Vascular •Osteoporesis - Immune Systems •Isolated Confined Environs/Polar Ops •Non-Invasive Health Assessments	←	•Physiological Understanding of the Human •Instrumentation Miniturization	•Countermeasures forLong-Duration and/or Micro-g Space Missions •Health Management and Care

Note: Technology "Spin-In" = →
"Spin-Off" = ←
"Both" = ↔

Table 28. Dual-Use Technologies: Operations and Maintenance

Futron

Dual-Use Technologies: Operations & Maintenance

Terrestrial Application	Technology	Space Application
←	•Task Partitioning •R & QA in long-term, Haz Env •System Health Management And Failure Prevention Thru AI and Expert Systems, Nural Nets	
←		
←		

We mentioned this area as important, but did not complete. Recommend that we work with Jon Ericson and Bob Savely to get it right.

Note: Technology "Spin-In" = →
"Spin-Off" = ←
"Both" = ↔

C. **BUILDING INTERNATIONAL COOPERATION FOR MARS EXPLORATION**

International Cooperation Working Group (ICWG)
John Niehoff, Chair
Mars Exploration Workshop II
May 24-25, 1993

PREMISE

The sustained exploration of Mars, eventually including the significant involvement of humans, is one of the most challenging goals of the space program. It is apparent that many benefits could be derived from pursuing this goal as an international effort supported by the resources of the global community. It is also obvious that many political obstacles need to be overcome to realize and sustain such a cooperative opportunity. At least two essential ingredients are required to create an International Mars Exploration Program. First, a significant period of time is needed preceding the initiative during which technology/infrastructure investments are made, relevant national capabilities are clearly established, and the ability to cooperate on joint space efforts is successfully demonstrated. Second, a "right" moment is required when capabilities, resources, and national objectives merge to create a consensus opportunity leading to the meaningful, sustained commitment to the initiative.

MARS INTERNATIONAL POLICY AGREEMENT

Perhaps the largest single obstacle today in moving Mars Exploration forward on the world agenda is the lack of any international agreement, either stated or perceived, to serve as a basis for developing the enabling program ingredients outlined above.

In the past, for scientific, economic or educational reasons, political and professional organizations have generated and endorsed high-level policy agreements for the purpose of framing/encouraging the cooperative pursuit of mutual interests. Examples of such ad hoc agreements include deep drilling in the world oceans, exploration of Antarctica, the lunar treaty, and the protocol for planetary protection.

An international policy statement of a similar nature regarding the robotics/human exploration of Mars and endorsed by all spacefaring nations would establish a solid foundation on which to build the prerequisites of a sustained international program. Specific evolving capabilities and cooperative ventures within and among the national space agencies could then proceed with the expectation that these efforts could eventually lead to the implementation of an International Mars Exploration Program.

APPROACH

Given that an international policy statement can be attained to better focus the preparatory activities of national space agencies in anticipation of the "right moment" for a cooperative Mars exploration program, what might such activities be? Important among them are the following tasks:

- Establish an international project design/definition activity to determine the critical technologies and essential infrastructures;

- Refine the understanding of required resources to plan, develop and operate the program;
- Create effective cooperation management structures;
- Demonstrate successful joint efforts in relevant precursor activities and/or missions;
- Develop critical technologies and essential infrastructures;
- Seek commercial interests and participation;
- Build political support for a sustained effort.

Accomplishing these tasks puts all participating countries in a more advantageous position, poised to implement a sustained international Mars exploration program when the typically brief "window-of-opportunity" occurs. This readiness communicates to governments and their administrations, world-wide, that we have done our homework and have a sound plan in place with tested lines of international cooperation ready for action.

ICWG'S ASSESSMENT OF THE MARS DESIGN REFERENCE MISSION

As a start to the first task outlined in the Approach above, the International Cooperation Working Group (ICWG) assessed the current Mars Design Reference Mission (DRM) from the perspective of international participation. Its critique of the DRM can be summarized by a set of Pro versus Con findings.

Pro Findings of the DRM:

- The Mars Exploration DRM contains a set of precursor missions and demonstrations that are favorable from the standpoint of "testing" effective international cooperation prior to the significant commitment of cooperative human exploration.
- The DRM requires a near-minimum number of system elements, which, in turn, yields fewer interfaces (technical and programmatic) than previous mission scenarios.
- Since the DRM uses the split-mission strategy for cargo and crew, and builds Mars surface infrastructure over a period of time, development/deployment of systems is staggered, resulting in more reasonable (lower) annual budgets during all phases of the program.
- The program plan of exploration affords many new development and technology insertion opportunities for various international partners to pursue.
- The sequential deployment of cargo payloads provides full system back-ups to previous deployments (before nominal utilization), hence reducing system failure risks to the crew.

Con Findings of the DRM:

- The Mars DRM demonstrates little or no commonality with a human lunar exploration program (e.g. First Lunar Outpost); hence, little opportunity is taken to leverage development and operations experience from a less challenging, but effective international lunar exploration experience.

- There is a requirement for a very large Heavy Lift Launch Vehicle (HLLV) in order to avoid LEO assembly and staging activities; hence, the DRM ignores the existence and possible cooperative opportunity to use the Russian Energia HLLV. The Energia has sufficient payload capability to limit LEO activities to mating fully ground-integrated payloads with independently launched propulsion stages, i.e., no on-orbit assembly would be required. Furthermore, developing a new HLLV exclusively for the Mars Exploration Program would increase cost, require a new testing phase-in period, have vehicle-unique EIS obstacles because of its size, and increases the impact of launch failures because entire missions would be carried on each HLLV.

- While the number of independent systems are near minimum in the DRM, those that have been chosen invoke a near-maximum in new technologies right from the start. Nuclear propulsion, LOX-Methane chemical propulsion, aerocapture braking, ISRU systems, and advanced life-support systems (including greenhouses) are all part of the DRM. Not only does this put more cost into enabling developments, but it exacerbates the risks associated with international cooperation, i.e. you don't understand the technology well enough to know if your partners are doing a good job in applying it to their part of the development task. It also becomes much more difficult to assist or assume other development tasks if cooperation breaks down, and a critical partner decides to withdraw from the initiative.

- Because of the launch strategy chosen (large HLLV with all ground-integration), complex payload integration activities are required which could be an obstacle to maximum international cooperation in development, testing and integration of system elements. Technology transfer could also be a larger problem with this approach. On the other hand, using smaller HLLV's and utilizing orbital assembly of system elements has its own set of problems from an international perspective. Ultimately, this is expected to be a significant trade-off in the definition and implementation of specific international cooperative agreements.

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Appendix A. Mars Exploration Workshop II:

Summary of Workshop

Appendix A: Summary of Workshop

A. Overview of Workshop

Objectives:

- Review and critique Mars Reference Program assumptions and content
- Evaluate Reference Program from diverse perspectives
- Identify open issues, concerns

Participants:

- Mars Study Team
- Mars consultant Team
- Invited Guests

Format:

- Day One: Presentation of the Mars Reference Mission; Status of the Surface Systems, Space Transportation, and Habitat Subgroups
- Day Two: Discussions and Feedback from the three new Working Groups on International Participation, Dual Use Technologies, and Cost. Status of Subgroup Issues from Day One.

Logistics:

- Date: 24-25 May 1993
- Place: Ames Research Center, Building 262, Room 100

B. Agenda

Mars Exploration Workshop II Agenda

Monday, May 24

8:30 am	Introduction — *M. Duke*
9:00 - 10:00	Overview of reference program — *D. Weaver*
10:00 - 12:30	Surface Mission Issues–Surface Systems Subgroup — *G. Briggs and J. Connolly*, team leads
12:30 - 1:30 pm	Lunch
1:30 - 3:30	Habitat Status-Habitat Subgroup — *A. Adams*, team lead
3:30 - 5:30	Space Transportation System Options — *W. Huber*, team lead
5:30 - 6:30	Discussion and plan for next day
6:30	Stanford University Faculty Club dinner

Tuesday, May 25

8:30 am	General Discussion of Issues
9:30 - 12:00	Working Group Discussion Sessions • International Cooperation • Dual-Use Technologies • Cost
12:00 - 1:00 pm	Lunch
1:00	Mars Abort and Architecture Assessment — *G. Woodcock*
1:30	Stanford International Mars Study — *B. Lusignan*
2:00	Mars Exploration Study Subgroup Reports • Habitation Issues • Space Transportation Issues • Surface System Issues
3:30	Working Group Reports • International Cooperation • Dual-Use Technologies • Cost
5:30	Adjourn

C. Presented Papers

Monday, May 24, 1993, 8:30 am

Mars Exploration Workshop II: Objectives and Agenda	*Mike Duke*
IACG Workshop on International Coordination of Mars Exploration	*John Niehoff*
International Cooperation in the Exploration of Mars (paper only)	*Wes Huntress*
Mars Study Team Reference Mission Overview	*David Weaver*
Mars Surface Mission Study	*Geoff Briggs*
Mars 2008 Surface Habitation Study	*Marc Cohen*
Mars Surface Mission Life Support Summary	*Andy Gonzales*
Mars Surface Mission Mobility	*Larry Lemke*
ISRU	*John Connolly*
Surface Risk and Safety Philosophy	*John Connolly*
Preliminary Power Systems Assessment	*Bob Cataldo*
Mars Surface Mission Human Factors and Crew Size	*Yvonne Clearwater*
Telepresent Science	*Michael Sims*
EVA Systems	*Theresa Buckley*
JSC Surface Systems Work	*John Connolly*
Surface Reference Mission	*John Connolly*
Mars Habitat Working Group Status/Review	*Alan Adams*
Life Sciences Critical Research Requirements	*Paul Campbell*
Reference Implementation Concepts	*Nathan Moore*
Space Transportation Systems Working Group	*Bill Huber*
Nuclear Thermal Rocket Stage Technology Options	*Stan Borowski*
Mars Aerobrake Studies	*Woody Lovelace*

Tuesday, May 25, 1993, 8:30 am

Mars Abort and Architecture Assessment	*Gordon Woodcock*
Stanford International Mars Mission: Executive Summary	*Bruce Lusignan*
Mars Exploration Study Subgroup Reports: Issues	
Habitation Issues	*Alan Adams*
Space Transportation Issues	*Bill Huber*
Surface System Issues	*John Connolly*
Workshop Team Results	
International Participation	*John Niehoff*
Dual-Use Technologies	*Barney Roberts*
Cost	*Hum Mandell*

D. Charters and Questions for Working Groups

Charters for Working Groups on International Participation, Dual-Use Technologies, and Cost

1. Evaluate the reference program from your working group's perspective.

2. Agree upon a prioritized set of studies needed to clarify issues or make needed decisions. The number of topics addressed should be small (perhaps 5 or less), but should be of clear priority. These will become the basis for subsequent definition and trade studies and will be used to define a program if funding is available in FY94.

3. Document the top 5 issues. The product expected of each of the working groups for each issues is:

    - A description of the issue
    - The value of resolving the issue – i.e., its implications on program planning or mission definition; a defense of its priority
    - Recommended options for subsequent study

4. Make recommendations of other personnel who should be involved with working group activities; links to universities, etc.

Questions for Working Groups

International Cooperation Working Group

- How can the current reference program be allocated between several participating countries?
- What changes to the reference program would enhance potential for multilateral participation?
- What other questions do we need to address?

Dual-Use Technology Working Group

- What are the most promising dual-use technologies included in the reference program?
- What mechanisms exist or should be created to validate the dual-use aspects?
- What other questions need to be asked?

Cost Working Group

- What is the cost of the current reference program if existing cost models are utilized?
- How can the actual costs be improved with respect to current cost models?
- What are the cost benefit/penalties associated with a multinational program?
- What other questions need to be asked?

Appendix B. Mars Exploration Workshop II:

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13. ABSTRACT *(Maximum 200 words)*
A year-long NASA-wide study effort has led to the development of an innovative strategy for the human exploration of Mars. The latest Mars Exploration Study Workshop II advanced a design reference mission (DRM) that significantly reduces the perceived high costs, complex infrastructure and long schedules associated with previous Mars scenarios. This surface-oriented philosophy emphasizes the development of high-leveraging surface technologies in lieu of concentrating exclusively on space transportation technologies and development strategies.

As a result of the DRM's balanced approach to mission and crew risk, element commonality, and technology development, human missions to Mars can be accomplished without the need for complex assembly operations in low-Earth orbit.

This report, which summarizes the Mars Exploration Study Workshop held at the Ames Research Center on May 24-25, 1993, provides an overview of the status of the Mars Exploration Study, material presented at the workshop, and discussions of open items being addressed by the study team. The workshop assembled three teams of experts to discuss cost, dual-use technology, and international involvement, and to generate a working group white paper addresssing these issues. The three position papers which were generated are included in section three of this publication.

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