PERMANENT ROBOTIC BASES IN THE SOLAR SYSTEM

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Abstract

One way to portray the evolution of space exploration is as a sequence of overlapping eras, each succeeded by an era embodying more complexity and more mature objectives. One model (Stone) suggests that we are currently in the third era, and that the focus of the fourth era will be the evolution from occasional visits to permanent bases, supporting the continuous presence of robots and/or humans. Another term applied to this is "outposts," used in the traditional terrestrial sense to suggest a continuous presence, e.g. a base of operations, beyond the edge of settled civilization. The new thing about applying the outpost notion to space exploration is that the presence may be robotic—initially or permanently—rather than human. Table 1 provides some idea of the potential richness of the outpost concept.

Examples of Possible Outposts

- The poles of Mars – look carefully for water, evidence of life, and evidence of climate changes
- Olympus Mons on Mars – continuously monitor and study the solar system's largest volcano and search for evidence of recent volcanic activity
- Mars' Great Valley, Valles Marineris – search for water and understand the tectonic origins of this huge rift valley
- The Lunar Terminator Regions – set up and operate observatories that could give early warning of asteroids that might endanger Earth
- "L2" – an orbit around the sun that allows an unobstructed view of the entire universe—the full sky—every year and hence is an ideal place to do long-term astronomy in space, to look for planets and signs of life outside the solar system, and possibly, to provide communications-relay capability between Earth and the other planets
- Near Earth Asteroids, asteroids passing near the Earth - to take up residence and study how they're constructed and might be used, or diverted if they become a threat
- The Asteroid Belt – Beyond Mars, to study the raw materials of the planets
- "Ice Station Europa" – penetrate Europa's frozen ocean and carry out a campaign to look for life beneath the ice
- Titan – Saturn's largest moon, and the only one in the solar system with a thick atmosphere, rich in organic chemicals, to study the hidden surface and search for the missing link between organic chemistry and life

The remainder of this paper explores in more detail the idea of permanent robotic bases—robotic outposts—and some of the engineering and technological questions associated with them.

The Eras of Space Exploration

The first era of space exploration could be said to have focused on just being able to get there: During the 1960s the challenge was learning to design, build and operate spacecraft which could actually go somewhere else in the solar system. During the second era—roughly the 1970s and 1980s—the challenge was to find out what was there when we arrived. To do that we built large spacecraft with as large a suite of sensor systems as we could manage and as much data return as we could manage. The third era, which might be said to have begun early in this decade, is focused on going frequently, landing and bringing back samples, and factoring cost into the mission design equations.

Figures 1a, 1b and 1c exemplify the first three eras, and Table 1 contrasts some important aspects of the second era against those of the present, or third era.

Table 1: Second and Third Era Characteristics [1]

Second Era	Third Era
Individual Projects	Programs of Linked Projects
Large, Comprehensive Observatories	Small,. Focused Systems
Global Scale Exploration	Local Scale Exploration
Remote Sensing	In-situ Sensing

The next era—or fourth era—will, we believe, be characterized by the establishment of continuously operating bases (many people use the term "outposts") elsewhere in the solar system. Table 2 suggests some of the key differences between the present era and the next.

Table 2: Third and Fourth Era Characteristics [1]

Third Era	Fourth Era
Episodic Surface Activities	Continuous Cooperative Operation
Localized Mobility	Long Range Mobility
Limited Power	Sustained, Substantial Power
Limited Communications	Continuous, High-Bandwidth Network Communications
Resources brought from Earth	Using in-situ Resources

Figure 1a The First Era: Getting There

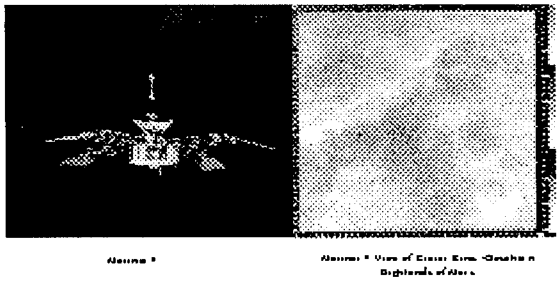


Figure 1b The Second Era—Finding Out What's There

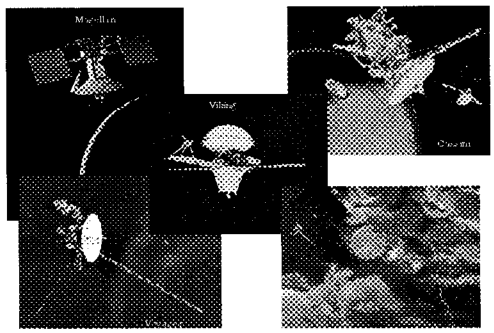


Figure 1c The Third Era: Going often, Landing and Bringing Samples Back

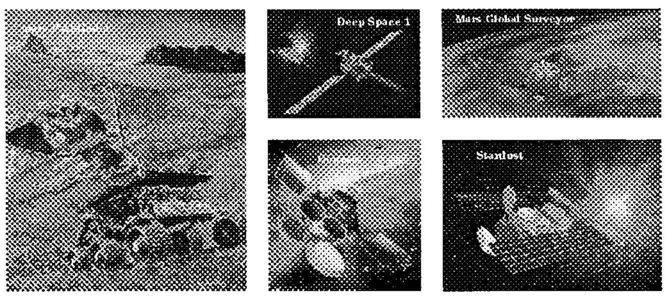
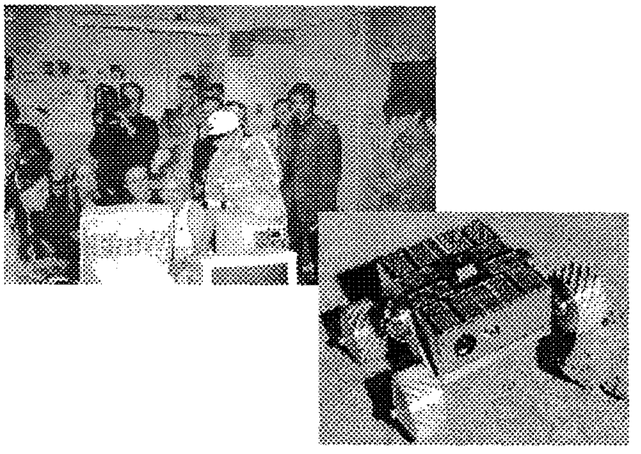


Figure 2 Towards the Fourth Era - Public Engagement: Students in Helsinki Operating a Rover (Rocky 7) in the Mojave Desert over the World-Wide Web



The Case for Continuous Presence

The general rationale for establishing an outpost is:

- Compelling scientific, engineering, economic or other rationale for permanent, continuous presence of robots, and/or humans, consistent with NASA's basic challenges
- Exciting, dramatic, dynamic place to be ("Engaging")
- Utilizable resources to boost self-sustainability
- Stepping stone to elsewhere
- One reason for Human outpost: High probability human-enabled science required

A more specific, summarized rationale for establishing an outpost on Mars:

- Mars Outpost Science Workshop (3/99) validated the concept from scientists' points of view, identified need for further study
- Many possible scientific reasons for continuous presence including rigorously investigating sites:
  - With compelling evidence of past (or present) life, and / or
  - Which are complex, with compelling evidence of past (or current) water, and/or
  - Where we find planetary processes, requiring long-term study.
- Application of scientific techniques requiring continuous relatively high power levels (e.g., drilling) or techniques not amenable to long sample transit times (e.g., "wet" chemical or biochemical analysis), etc.
- Existence of the water and life mysteries, climatological dynamics, dramatic terrain, as well as level of general knowledge and interest, make Mars an engaging place

Finally, long term continuous presence will give people here on Earth the opportunity to truly participate in the exploration process, in the fashion suggested in Figure 2.

Siting Outposts

No matter where in the solar system we choose to place robotic outposts, the selection of site or orbit will more than likely require Third–Era type visits to reduce risk and maximize likely return on investment.

Arguments associated with Mars Outpost site selection are:

- Many potential sites, given current knowledge (or lack thereof) regarding best place to find compelling evidence of life and/or water, and/or geologically revealing terrain,
- Such factors being equal, secondary operational factors may become extremely important (e.g. ease of communicating with Earth, and Mars orbit with its relatively high pressures of CO_2),
- Selection of specific site(s) probably should await increased knowledge provided by current Mars Programs—especially MGS, future Mars Surveyors, and ESA's Mars Express Mission; e.g. site selection for first Outpost site(s) could take place with much greater confidence (at least with respect to water and geology) as early as 2005 if these missions complete their objectives successfully, and
- It could be proposed that Mars Surveyor Program establish a new Program Objective: provide recommended site(s) for Mars Outpost(s) in 2007.

Designing and Developing Outposts

Before a robotic outpost can begin continuous operations aimed at meeting its scientific exploration and/or engagement objectives, many "precursor" activities must take place to reduce risk and increase the probability of success.

These may generally be categorized as:

- Design information acquisition,
- Technology/systems validation, and
- Infrastructure emplacement.

Long before the outpost begins operation, sufficient site-specific "design" information must be acquired to allow intelligent choices of technologies, systems concepts, and designs. Once these choices are made, some or all of them may require demonstration and/or validation, up to and including long-term operation in test modes at the actual future outpost site.

Finally, some of the needed infrastructure that enables outpost operations may need to be in place and verified as operational before actual outpost operations begin.

- Static or on-site infrastructure identification (note that some of these capabilities could be partially or completely mobile)
- Static utilization asset identification (i.e., the elements needed to achieve scientific, engineering and engagement objectives)

Outpost design is necessarily very location-dependent, but can be thought of as comprising the following elements:

- Establishment of site characteristics, and
- Identification of transportation/mobility assets.

Some idea of these notions may be inferred from Table 3, which lists information needs and design elements for a genetic Mars Outpost.

Table 3 Generic Robotic Mars Outpost Design Architecture ("Inventory" of possible elements of Outpost Design)

Site Characteristics

- Hazard-free Landing / Ascent Zone?
- Propinquity to Engaging Location(s)?
- Optimal Observing Location?
- Desirable Energy Characteristics?
  - Insulation
  - Wind
  - Thermal
- Existence of in-situ Resource(s)/Raw Materials?
- Shelter?
  - Wind
  - Dust
  - Radiation
  - Shadow

Transportation / Mobility Assets

- Transport to / from Mars Orbit
  - Navigation Beacon(s)
  - Hazard Free Landing/ Ascent Zone
  - Comm (See Base Comm)
- "Local" Mobility Assets
  - Aerial Vehicles
    - On-Board Nav.
    - On-Board Comm
    - Payload
      - Instruments / Imagers / Analysers
      - Deployment capability / Deployable Units
      - Sampler(s)
    - Power
    - Propulsion
  - Surface Vehicles
    - On Board Nav.
    - On Board Comm.

- Power, Propulsion, etc.
- Payload
  - Instruments / Imagers / Analysers
  - Deployment Capability / Deployable Units
  - Sampler(s), e.g. portable drill
- Manipulation
  - Construction
  - Repair(?)

- Subsurface_Mobility Assets
  - e.g., moles, crevasse crawlers

Static Base Infrastructure

- Base_Nav
  - Transportation Support
  - Mobility Support
- Base Comm To / From:
  - Earth / Earth-Mars Transit
  - Mars Orbit
  - Mobility Assets
  - Other Outposts
- Energy Conversion / Storage
  - Power for Base Infrastructure
  - Recharge Transportation Assets
  - Power for Base Science / Engagement Assets
- Resource Production
- Command / Control / Computing
  - Autonomous Local Operations
    - Planning, Dispatching, Monitoring
- Maintenance / Repair / Construction
  - Shelters (Assets under Repair, Materials)
  - Materials
  - Materials Handling / Processing
  - Manipulation / Assembly / Disassembly
    - Infrastructure Asset Repair
    - Base Science / T/ E Asset Repair
    - Transportation / Mobility Asset Repair

Static Base Utilization: Science / Technology / Engagement

- Science Support Assets
  - Sample Analysis Laboratory

- Data Analysis / Info. Extraction Computing

- Base Experimentation / Engagement
  - Technology Demos / Tests
  - Instruments
  - Imaging
  - Sampling (e.g., Drills, windborne dust collectors)

Certain key systems and capabilities may be needed for any outpost in a given location, irrespective of what specific scientific, exploration or engagement objectives it is intended to accomplish. This irreducible minimum set of key systems might be termed the "backbone" of the outpost; "backbone" outpost technologies might be a good place from which to start to construct outpost technology programs.

A preliminary cut at the "backbone" for Mars surface outposts is given in Table 8.

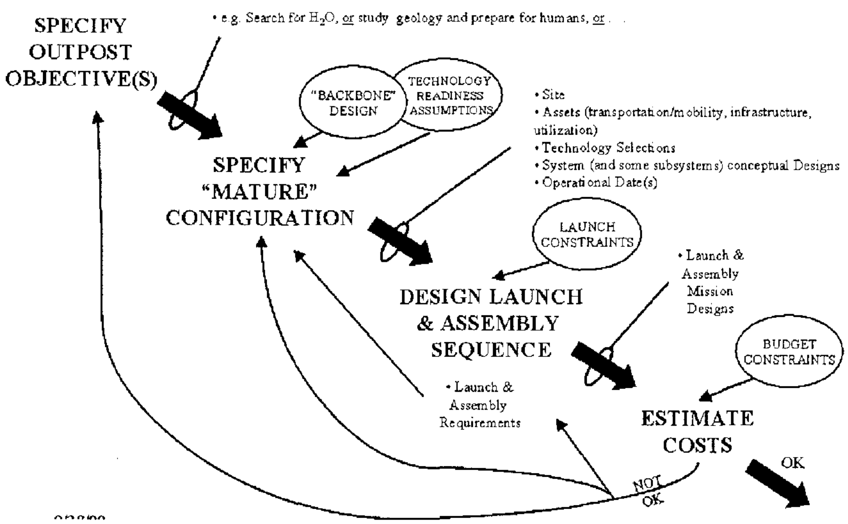
Table 4: Outpost "Backbone"

Site Characterization:	• Hazard-free landing zone; knowledge of radiation, Insulation, wind, thermal environments; knowledge of topology (e.g. natural shelter)
Transportation:	• Nav Beacon(s), Lander Comm
Static Infrastructure:	• Comm to/from Earth • Energy Conversion / Storage • Command / Control / Computing (autonomy)

Given the fact that an outpost must more than likely be established and supported by several missions rather than one,* the "launch and assembly sequence" design becomes an integral part of the outpost design process, as indicated in Figure 3.

* Self-replicating, self-sufficient, or otherwise completely autonomous outposts are beyond the purview of this paper.

Figure 3 Outpost Conceptual Design Process



Technical Challenges

One key to placing outposts on Mars is the existence of an adequate communications infrastructure. Figures 4a through 4d show how we might evolve a Mars communications network.

Figure 4a Mars Network Evolution [2]

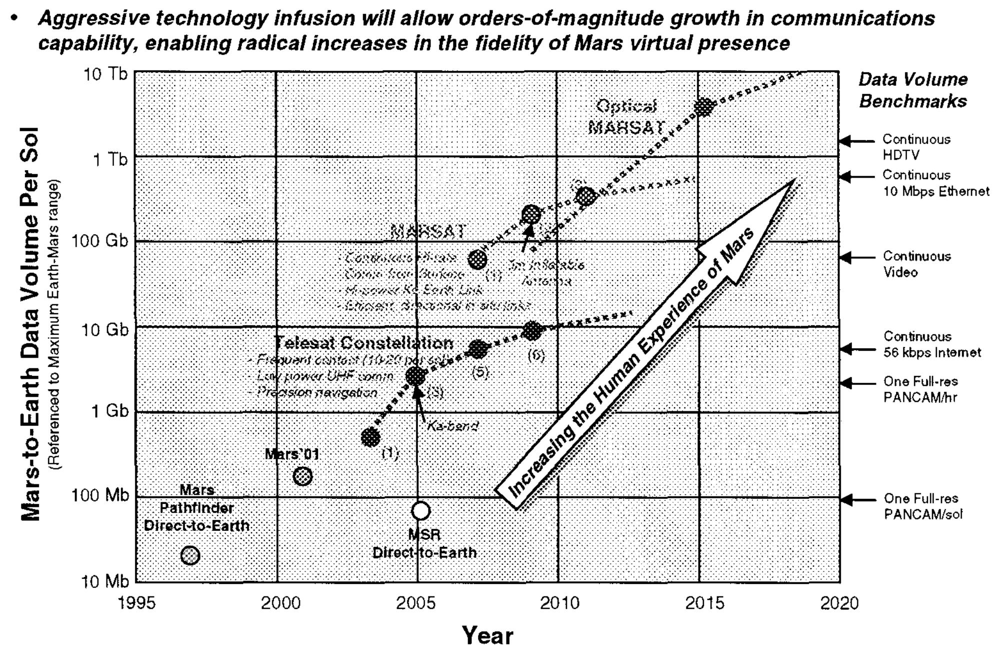


Figure 4b Mars Infrastructure Today

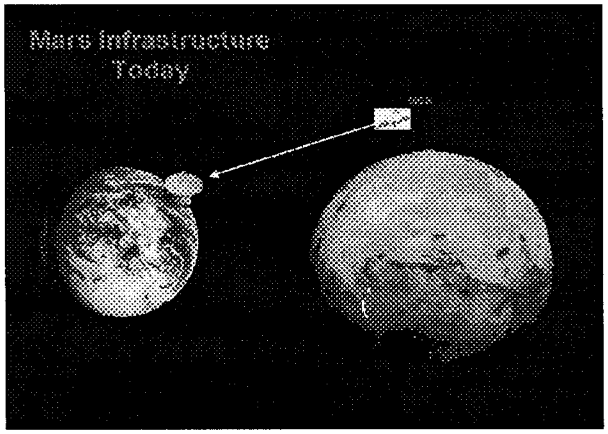


Figure 4c Mars Infrastructure c. 2005

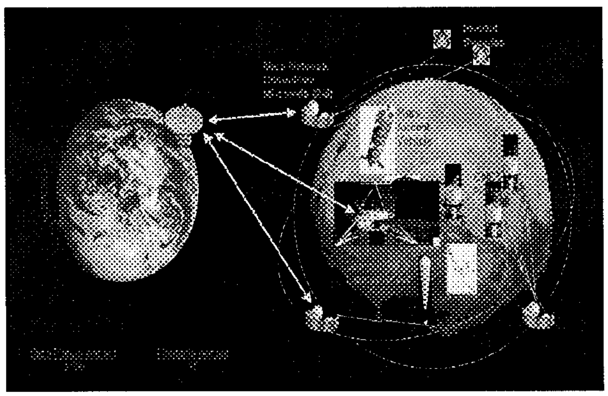
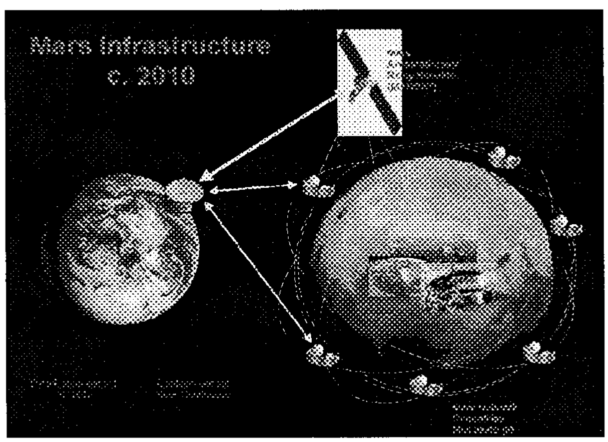


Figure 4d Mars Infrastructure c.2010



Some key technological challenges in addition to communications capability include precision landing (see Figure 5a for one current concept for Mars' landings); in-situ science instrumentation (one concept for a highly miniaturized, multifunction, analytical instrument, capable of being carried by a small surface rover, is shown in Figure 5b); mobility (current concepts for Martian surface mobility, sub-surface mobility and aerial mobility are shown in Figures 5c, 5d and 5c); in-situ resource utilization (Figure 5f shows an artist's conception of an "oxygen factory" utilizing Martian atmospheric CO_2; other concepts exist for production of fuel, e.g. Hydrogen from sub-surface water or water ice).

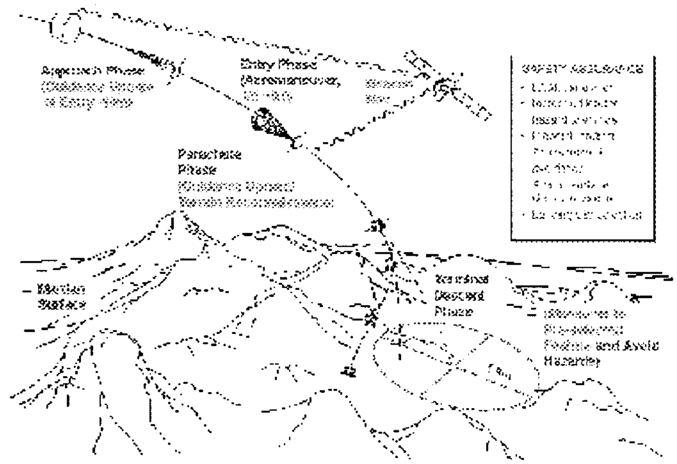


Figure 5a Precision Landing: Mars '07/'09 and Beyond [1]

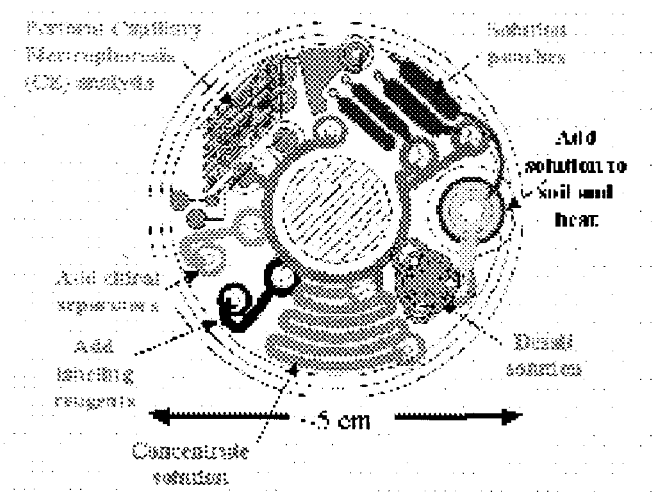


Figure 5b Biochemistry Lab in a Teacup [1]

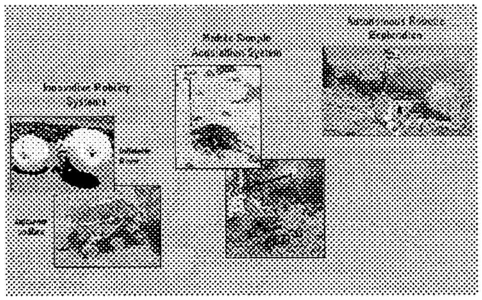


Figure 5c Surface Mobility Roadmap: Unlocking the Secrets of the Red Planet [3]

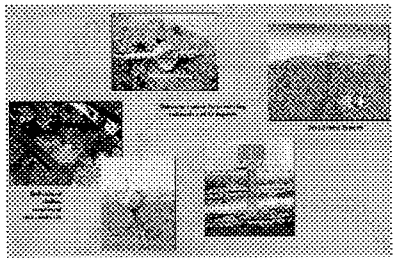


Figure 5d Subsurface Mobility Roadmap: Accessing the Subsurface of Mars with Innovative Robotic Techniques [3]

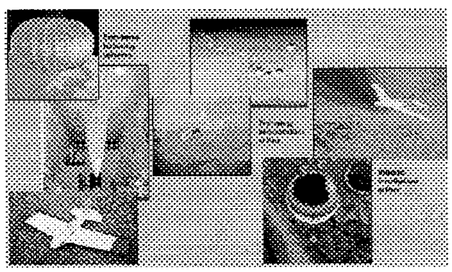


Figure 5e Aerial Platforms Roadmap: Bridging the Gap between Orbital and Surface Platform Data [3]

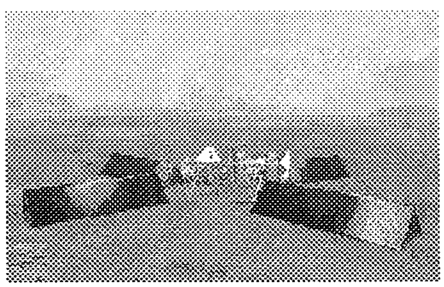


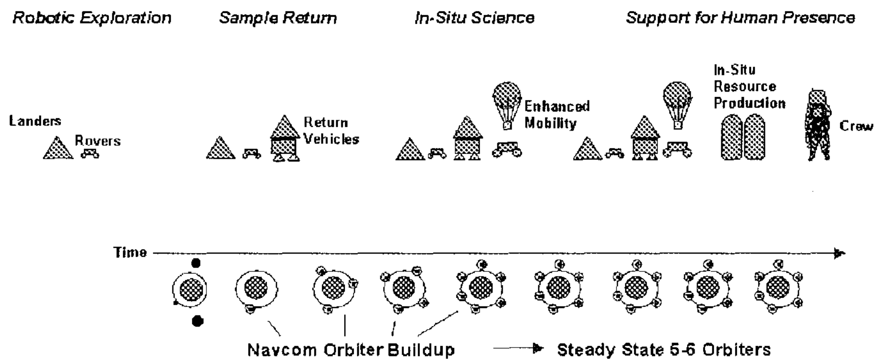
Figure 5f In-situ Resource Production Unit

And, of course, one of the biggest overall challenges of the fourth era, the era of continuous presence, is to apply the right mix of logistics science, technology development, and risk management to achieve the necessary longevity and reliable operations, without substantially greater budgets than we have today….

Outpost Evolution

While not all human-mission scenarios for going to places such as the Moon, Mars, libration points, asteroids, etc. currently involve precursor robotic outposts, most current studies tend toward approaches wherein human crews arrive only after robotic missions have reconnoitered and prepared the site. Figure 6a suggests in a very general way how a Mars robotic base—or outpost—might logically evolve into the landing site for a human mission by carrying out precursor functions such as detailed-site characterizing and resource stockpiling. Also shown is the accompanying buildup of needed navigation and communications infrastructure.

Figure 6a Mars Outpost Evolution toward Human Exploration



Figures 6c through 6f on the next page show how such a Martian site might look as it evolves from the first rover landing to the presence of a human crew.

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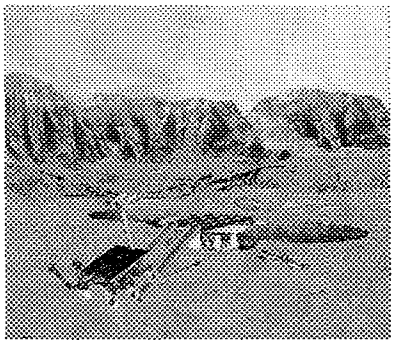

Fig. 6b Outpost at First Rover Landing

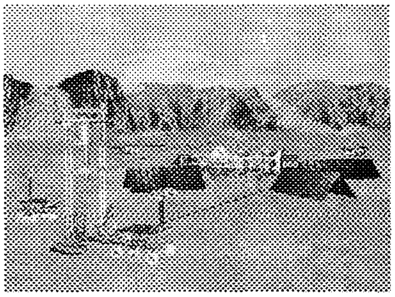

Fig. 6d Outpost Conducting Distant Exploration

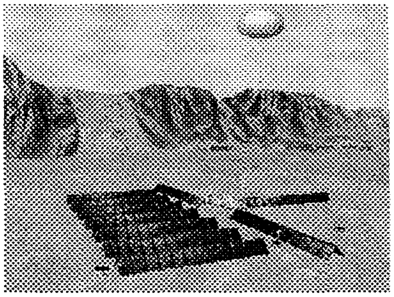

Fig. 6d Outpost Conducting Distant Exploration

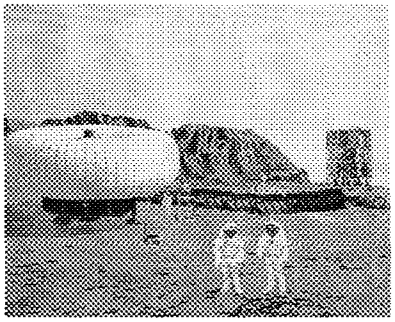

Fig. 6e Outpost with Humans

Conclusions

Permanent robotic bases, or outposts, on the surface of Mars, or elsewhere, belong to the future; the transition from today's third era efforts—to survey, land and return samples—into continuous presence awaits advances in longevity of robotic systems, in-situ science capabilities, precision landing, high-bandwidth interplanetary communications, in-situ mobility systems, and, probably, in-situ resource utilization. But work is progressing in all of these areas, and a decade from now we may well see the beginning of the fourth era. And, not too long after that perhaps, the coming of humans to bases made habitable through the efforts of outpost robots.

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References

1. Edward C. Stone, "The Role of Robotic Outposts in Establishing a Permanent Presence in Space," Carl Sagan Memorial Lecture, American Astronautical Society, 1999 National Conference, Nov. 16, 1999.
2. Charles D. Edwards, JPL, private communication.
3. James A. Cutts, JPL, private communication.