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Mars Pathfinder Status at Launch

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MARS PATHFINDER STATUS AT LAUNCH

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ABSTRACT

The Mars Pathfinder Flight System is in final test, assembly and launch preparations at the Kennedy Space Center in Florida. Launch is scheduled for December 2, 1996. The Flight System development, in particular the Entry, Descent, and Landing (EDL) system, was a major team effort involving JPL, other NASA centers and Industry. This paper provides a summary Mars Pathfinder description and status at launch. In addition, a section by NASA's Langley Research Center, a key EDL contributor, is provided on their support to Mars Pathfinder. This section is included as an example of the work performed by Pathfinder team members outside JPL.

NOMENCLATURE

APXS	Alpha Proton X-ray Spectrometer
ATLO	Assembly, Test and Launch Operations
C_{m_α}	Static stability parameter
DOF	Degree-of-freedom
EDL	Entry, Descent, and Landing
ETR	Eastern Test Range
RAD	Rocket Assisted Deceleration
RHU' S	Radioisotope Heater Unit
α_T	Total angle of attack

MISSION DESCRIPTION

Mars Pathfinder, launching on December 2, 1996 and landing on Mars on July 4, 1997, will demonstrate a low-cost delivery system to the surface of Mars. Historically, spacecraft that orbit or land on a distant body carry massive amounts of fuel for braking at the planet. Pathfinder requires fuel only to navigate to Mars; the spacecraft aerobrakes into the Mars atmosphere directly from Earth-Mars transfer trajectory, deploys a parachute at 10 km above the surface and, within 110 m of the surface, fires solid rockets for final braking prior to deployment of airbags that cushion touchdown. The spacecraft is shown in its cruise configuration in Fig. 1. The Pathfinder Entry, Descent, and Landing (EDL) sequence is illustrated in Fig. 2. After landing, petals open to upright

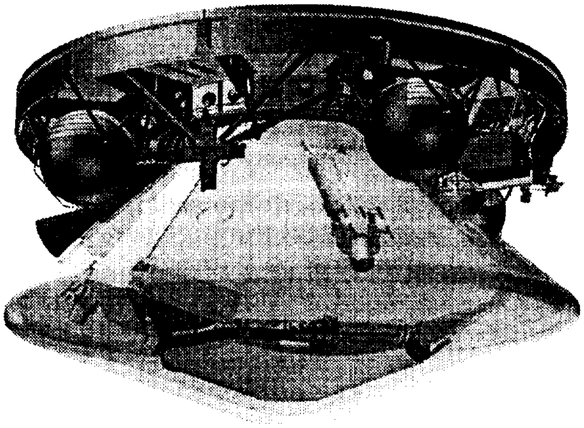

Fig. 1: Mars Pathfinder in Cruise Configuration.

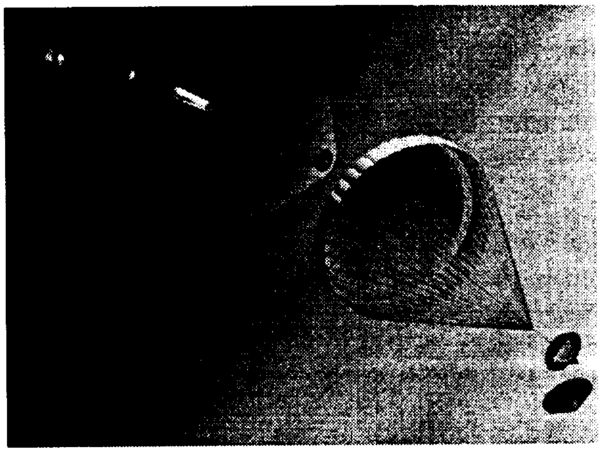

Fig. 2: Mars Pathfinder Entry, Descent, and Landing Sequence.

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the lander, followed by deployment of a small rover and several science instruments.

A major objective of Pathfinder – acquisition and return of engineering data on entry, descent, and landing and lander performance – will be completed within the first few hours after safe landing. In addition, the lander will transmit images of the Martian surface the first day. Next, a rover will be deployed, as early as the first day, to perform mobility tests, image its surroundings, including the lander, and place an Alpha Proton X-Ray Spectrometer (APXS) against a rock or soil to make elemental composition measurements. The primary mission durations for the rover and lander are one week and one month, respectively. However, there is nothing to preclude longer operations.

Pathfinder will also accomplish a focused, exciting set of science investigations with a stereo, multi-color lander imager on a pop-up mast; atmospheric instrumentation for measuring a pressure, temperature and density profile during entry and descent and for monitoring Martian weather after landing; and the rover with its forward and aft cameras and the APXS. The APXS and the visible to near infrared filters on the lander imaging system will determine the elemental composition and constrain the mineralogy of rocks and other surface materials, which can be used to address first order questions concerning the composition of the crust, its differentiation and the development of weathering products. Regular tracking of the lander will allow determination of the Martian pole of rotation, its precession since Viking era measurements, and the moment of inertia, which should allow discrimination between interior models that include a metallic core and those that do not.

The Pathfinder Landing Site selected is Ares Vallis (19.5° N, 32.8° W), which is near the subsolar latitude (15° N) for maximum solar power at landing on July 4, 1997 and is at 2 km below the datum for correct operation of the parachute. The site is in Chryse Planitia a lowland where a number of catastrophic floods from the highlands to the north debouch. It is a "grab bag" site with the potential for sampling a wide variety of different Martian crustal materials, such as ancient crustal materials, intermediate age ridged plains and a variety of reworked channel materials. Even though the exact provenance of the samples would not be known, data from subsequent orbital remote sensing missions could be used to infer the provenance for the "ground truth" samples studied by Pathfinder. Available data suggest the site is about as rocky as the Viking sites, but perhaps a bit less dusty. This site has streamline islands (carved by the flood) nearby and a very smooth depositional surface at Viking resolution, except for small hills and secondary craters.

MARS PATHFINDER SCIENCE OBJECTIVES AND INVESTIGATIONS

The science payload chosen for Mars Pathfinder includes an imaging system, an elemental composition instrument and an atmospheric structure instrument/ meteorology package. These instruments, used in conjunction with selected engineering subsystems aboard both the lander and rover vehicles, provide the opportunity for a number of scientific investigations. The scientific objectives and investigations afforded by Pathfinder include: surface morphology and geology at meter scale, elemental composition and mineralogy of surface materials and a variety of atmospheric science investigations.

The surface imaging system will reveal Martian geologic processes and surface-atmosphere interactions at a scale currently known only at the two Viking landing sites. It will observe the rock distribution, surface slopes and general physiography in order to understand the geological processes that created the surface. This will be accomplished by panoramic stereo imaging at various times of the day as well as before and after the imager deploys omits pop-up mast. Images will be calibrated by observing a flat field target near the imager head and shadowed and illuminated portions of reference or calibration targets. In addition, observations over the life of the mission will allow assessment of any changes in the scene over time that might be attributable to frost, dust or sand deposition or erosion or other surface-atmosphere interactions. The rover will also take close-up images of the terrain during its traverses. A basic understanding of near-surface stratigraphy and soil mechanics will be obtained by imaging (from both rover and lander) rover tracks, holes dug by rover wheels, and any surface depression left by the spacecraft landing.

The Alpha, Proton, X-Ray Spectrometer (APXS) and the visible to near infrared (0.4 to 1 micron) spectral filters on the imaging system will determine the elemental composition and constrain the mineralogy (particularly sensitive to pyroxene and iron oxides) of rocks and other surface materials, which can be used to address questions concerning the composition of the crust, its differentiation and the development of weathering products. These investigations will represent a calibration point ("ground truth") for orbital remote sensing observations. The imaging system will obtain full multispectral panoramas of the surface and any subsurface layers exposed by the rover and lander. Because the APXS is mounted on the rover it will characterize the composition of rocks and soil in the vicinity of the lander (tens of meters), which will represent a significant improvement in our knowledge over that obtained by Viking or that likely to be obtained by the Russian Mars 96 small stations, which deploy the APXS on single degree of freedom arms. The rover-mounted APXS sensor head on Pathfinder will also be placed in holes dug by the rover wheels and against rocks that have been abraded by a rover wheel. Multispectral images are also planned for two sets of magnetic targets distributed at two locations (and heights) on the spacecraft that will discriminate the magnetic phase of accumulated airborne dust. IN addition, a single magnetic target mounted near the imager head will be viewed by a magnifying lens to determine the size and shape of individual magnetic particles. The APXS will also measure the composition and, in particular, the titanium content of dust adhering to magnetic targets at the end of the rover ramps, which is critical for discriminating the various magnetic phases. A rear-facing imager will enable close-up images with millimeter resolution of every APXS measurement site. Between these images and auxiliary information form lander imaging spectra, it is likely that mineralogy can be constrained from the elemental abundance's measure by the APXS.

The atmospheric structure instrument will determine a pressure, temperature and density profile of the atmosphere (with respect to altitude) during entry and descent at a new location, time and season. Measurements of pressure and temperature will be made in a triangular space between the petals at the base of the lander during descent. Redundant three-axis accelerometers will allow extraction of atmospheric density profiles and hence pressure and temperature profiles during entry. Diurnal variations in the atmospheric boundary layer will be characterized by regular surface meteorology measurements (pressure, temperature atmospheric opacity, and wind). Three thermocouples mounted on a meter high mast located on a petal away from the thermally contaminating lander electronics will determine the ambient temperature profile with altitude. A wind sensor on the top of this mast along with three wind socks below it will allow determination of wind speed and direction versus altitude in the boundary layer as well as calculation of the aerodynamic roughness of the surface. Regular sky and solar spectral observations by the lander imager will also monitor dust particle size and shape, refractive index, vertical aerosol distribution and water vapor abundance.

MARS PATHFINDER IMPLEMENTATION STRATEGY

Pathfinder is in a special "cheaper, better, faster" project operating mode, accomplishing a challenging mission at low cost and fixed price, using a "Kelly Johnson"-like skunkworks approach, focusing on a limited set of objectives, streamlining project approaches and attempting to minimize bureaucratic interference. NASA's Office of Space Science is developing Pathfinder. The Advanced Concepts and Technology Office teamed with the Space Science office is developing the Pathfinder rover. Pathfinder is being developed at Jet Propulsion Laboratory in its in-house, subsystem mode.

Some of the major elements of Pathfinder's project implementation strategy are the following:

- Formation of a project team comprised of right, energetic youth and scarred old-timers, extracted form the standard institutional organization, formed into a skunkworks, everyone reporting directly to project management
- Co-location around a Test Bed where testing begin almost immediately
- Necessary up-front planning and design; but, emphasis on early deliveries to provide a long, extensive test program
- Early proof-of-concept testing of new items like airbags and the rover
- Early end-to-end flight/ground interface and functional testing in the Test Bed
- Start of Flight System Assembly and Test on June 1, 1995, 18 months prior to launch
- Concurrent engineering among mission, science, instrument, rover, flight system, ground data system, mission operations, procurement, and product assurance elements of the project
- Emphasis on development of thorough Work Breakdown Structures, Project Integrated Schedules, and cost estimating, monitoring and control processes.

MARS PATHFINDER TEAM BUILDING

First we assembled an excellent, motivated team at JPL. Now that may sound like "Motherhood and Apple Pie", but far and away this is the most important ingredient to Pathfinder's successful approach to date. Pulling high-spirited individuals together, inside and outside JPL, to make up the Pathfinder tam was not a trivial task. With JPL institutional support, key team members were extracted from their home divisions and co-located with

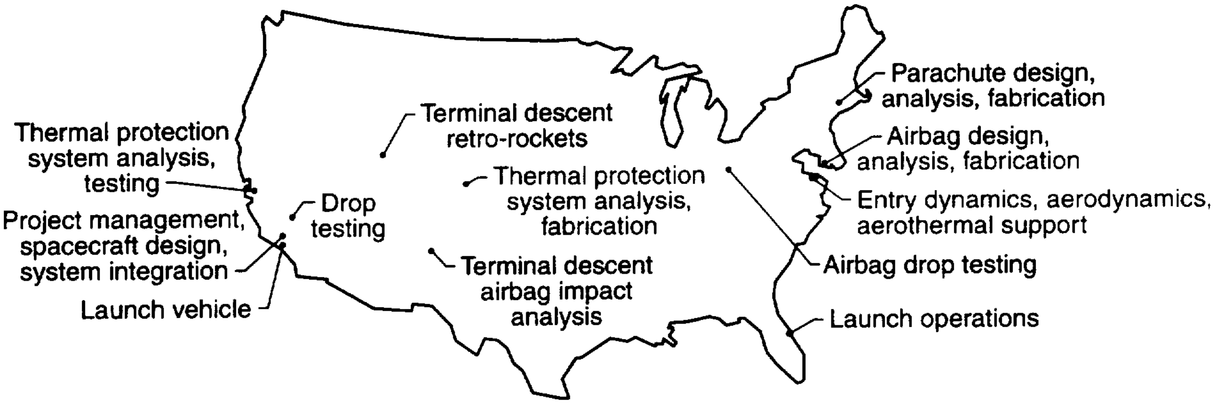

Fig. 3: Mars Pathfinder Distributed EDL Team.

the Project in what is called a "soft projectization mode: where team members remain administratively tied to their home divisions. The team is a mix of bright, ambitious youth and scarred old-timers, all sensitized not only to the technical challenge but very importantly to the need to do this job at a fixed price. All were empowered to produce their product according to their plan.

Not fully appreciated at the start was the degree to which we would need to expand the Pathfinder team outside of JPL in order to bring in the necessary expertise for development of our EDL approach. We knew we had to go outside of JPL for this, but never appreciated at first how much. You could not go to the JPL phone book and look up the names for the Planetary Entry, Descent and Landing Division. We have not had this development expertise at JPL in place since the Surveyor Moon mission in the 1960's – as a matter of fact, no complete planetary landing development technology base was available anywhere in the US.

At Pathfinder start, just bits and pieces of related EDL expertise were scattered about. We scoured the countryside (see Fig. 3) and found this support:

1. Major test facilities and test expertise for early proof-of-concept airbag testing at Sandia National Laboratories
2. Key aged, but contributing Viking engineers and managers and their lessons learned scattered about
3. Excellent, cost-effective atmospheric entry support from NASA's Ames and Langley Research Centers
    - Ames arc jet tested and sized the thickness of the heatshield ablative material
    - Langley performed aerodynamic computations, provided a high-fidelity atmospheric entry analysis, and supplied heatshield design support.
4. Aeroshell design, fabrication and test expertise at Lockheed Martin adapting the Viking design including use of the Viking heatshield ablative material
5. Parachute experience at Pioneer Aerospace adapting mainly their Earth parachute expertise, but starting with the Viking disk-gap-band parachute design and importantly relying on Viking's extensive parachute test experience, especially at high altitudes
6. Extensive expertise at ILC Dover for Pathfinder's major development of the airbags
7. Test facilities and test expertise at the China Lake Naval Weapons Center for rocket drop tests, altimeter tests and cruise stage-backshell-lander separations tests
8. Test facilities and test expertise at NASA's Lewis Research Center Plum Brook Station chamber for airbag drop tests at simulated Mars atmosphere
9. Very importantly, the infusion into the Pathfinder team of a design-test-design-test culture for items like the parachute, the bridle, solid rocket system and the airbags by the above contributors

Design and test consulting and critique came from within JPL, Sandia National Laboratories, Space Industries, NASA's Ames and Langley Research Centers, Lockheed Martin and from numerous consultants. We also interacted with the Russians and the European Space Agency.

JPL is putting the whole EDL system together: performing the system design, orchestrating the EDL tests and simulations, assessing mission risk mitigation, and building the backshell, bridle and lander including its uprighting petals as well as the cruise stage which is jettisoned prior to entry. The full EDL team is listed in Table 1. Each contractor, small to large, got with the spirit of Pathfinder, doing more for less and producing on schedule. Most contracts were fixed price. As an example of the work performed by members of the EDL team, the role of Langley Research Center is discussed in the following section.

LANGLEY'S ROLE

As a member of the Pathfinder EDL team, the Langley Research Center provided definition of the vehicle aerodynamics, six-degree-of-freedom (6-DOF) entry analysis, and support to the aerothermal working group. Langley's involvement with the Pathfinder project spans numerous mission phases including design, test, operations, and postflight analysis. As shown in Fig. 4, this work had a direct impact on several subsystems including the Pathfinder heatshield and flight software. Additionally, through this effort, the entry environment (loading and frequency) was defined for subsystem design, test, and evaluation. The Langley effort was tightly-coupled to work performed at the Jet Propulsion Laboratory, Ames Research Center, and Lockheed Martin. Additionally, coordination with Pioneer Aerospace, developers of Pathfinder's parachute system, was required.

These analyses were required as a result of differences between the Pathfinder mission and its Viking predecessors. While both aeroshells are 70 deg sphere-cones, Pathfinder's atmospheric entry velocity is much higher (7.6 km/s) while its mass and scale are roughly half that of the Viking spacecraft. Additionally, while Viking utilized an active control system and a center-of-gravity position offset from the symmetry axis to achieve trimmed

Table 1. EDL Support Team.

System	JPL
Red Hat Team[1]	JPL, USC, Space Industries, UCLA, CIT, Other consultants
Analysis, Consulting, Review	Space Industries
Aerodynamics	Langley Research Center
Entry Dynamics Simulation	Langley Research Center
Backshell Heating	Langley Research Center
Backshell Interface Plate	JPL
Aeroshell and Heatshield Analysis	Lockheed Martin
Heatshield Analysis Support	Ames Research Center/Applied Research Associates/ Langley Research Center
Backshell Thermal Protection System	Lockheed Martin
Backshell Interface Plate Insulation	Ames Research Center
Multi-Body Descent Simulation	JPL
Parachute	Pioneer Aerospace
Bridle Drop Tests	China Lake Naval Air Weapons Center
Bridle	JPL
RAD System	JPL
RAD Rockets	Thiokol
Airbag Impact Analysis	Sandia National Lab, Rockwell
Airbags	ILC Dover
Airbag Gas Generators	Thiokol
EDL Separations	JPL
EDL Sequence	JPL
Communiations	JPL
RAD Drop Tests	China Lake Naval Air Weapons Center
Initial Airbag Drop Test	Sandia National Lab
Full-Scale Airbag Drop Tests	Lewis Plum Brook Research Center
Parachute Drop Tests	Yuma and Boise Orchard Training Range

[1] Red Hat= Devil's advocates which challenge and question EDL design and test approaches

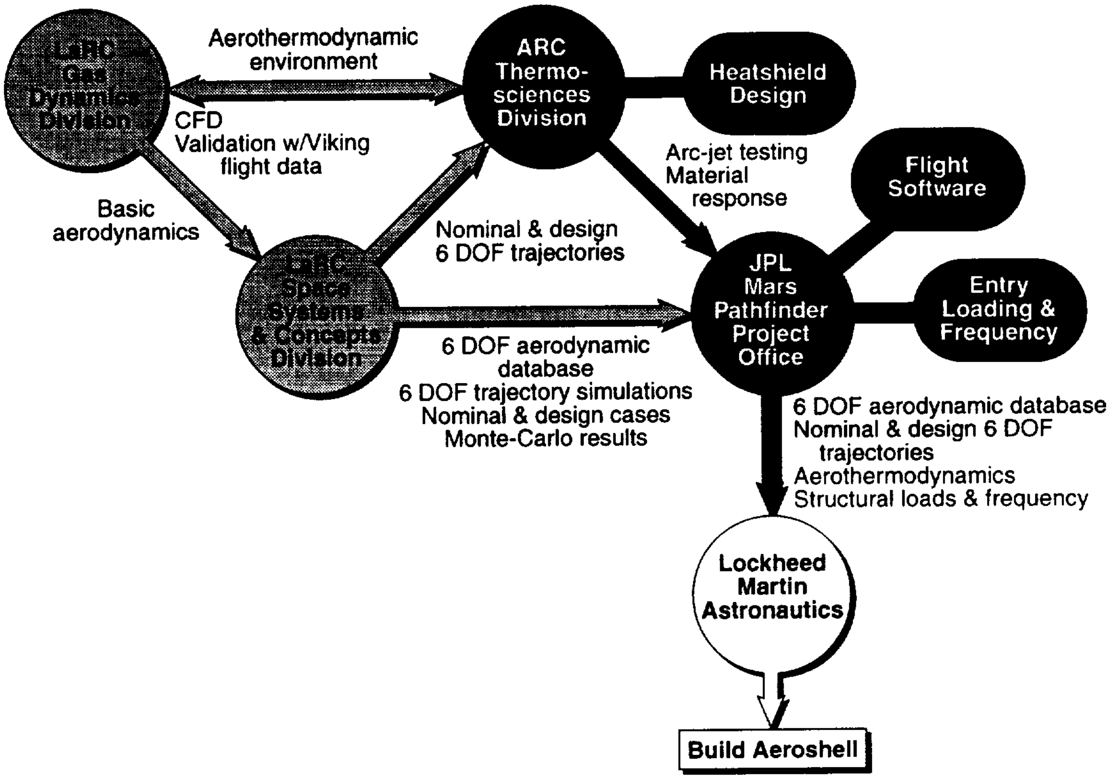

Fig. 4: Impact of Langley Analyses on the Mars Pathfinder Flight System.

flight at approximately 11 deg angle-of-attack, Pathfinder does not rely on active control. Instead, an initial spin of 2 rpm and aerodynamic damping are used to provide vehicle stability about a 0 deg trim angle-of-attack.

In light of these differences, a 6-DOF aerodynamic characteristic assessment[1] and Monte-Carlo trajectory analysis were performed[2,3]. The simulation results demonstrated the flyability of the Pathfinder aeroshell and quantified both the vehicle's aerodynamic stability and the effect which numerous uncertainties (e.g., initial state errors, aerodynamic uncertainties, mass property mispredictions) had upon the nominal mission profile. These analyses were also used by the Pathfinder project office at JPL to (1) address the effect which an initial vehicle wobble, incurred during cruise-stage separation, would have upon the atmospheric flight, (2) quantify the impact of various uncertainties on the parachute deployment conditions and landing footprint, (3) determine how close to the axis of symmetry the center-of-gravity must be maintained (with ballast), and (4) provide information regarding the appropriate vehicle spin rate.

The Pathfinder aerodynamic database[1] was derived from a combination of computational fluid dynamic calculations[4], wind-tunnel, and ballistic range results. Aerodynamic predictions were computed at numerous points along the nominal Pathfinder entry trajectory, spanning an angle-of-attack range of 0-11 deg. Based on these computational flowfield solutions, the static aerodynamic stability of the Pathfinder aeroshell may be estimated. As shown in Fig. 5, two low angle-of-attack regions of static instability are predicted, the first near peak heating (at about 6.5 km/s) and the second at 3.5 km/s. In each of these regions, a small perturbation in the vehicle's angular orientation will increase the angle-of-attack from the trim state. However, since both instabilities are confined to regions of low angle-of-attack, this angular motion is bounded. This behavior is illustrated in Fig. 6 which presents the nominal Pathfinder angle-of-attack profile.

As shown in Fig. 6, the first static instability occurs in the peak heating region. Early 6-DOF Monte-Carlo analysis revealed that angles-of-attack as large as 5 deg (3-σ) may occur in this region[2]. This information was relayed to the aerothermal working group for use in the design of Pathfinder's afterbody thermal protection system[5]. Additional 6-DOF Monte-Carlo entry simulation data included determination of the likely range of parachute deployment conditions[2,3]. As an example, the dynamic pressure and Mach number variations are presented in Fig. 7. Six-DOF Monte-Carlo results were generated numerous times in the

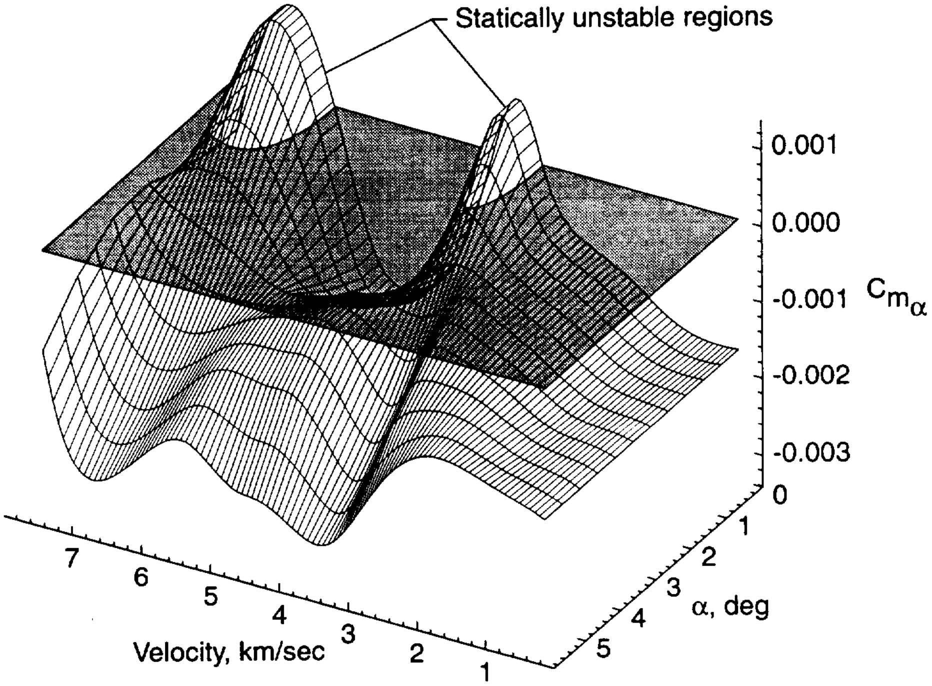

Fig. 5 : Static Stability of the Mars Pathfinder Entry Vehicle.

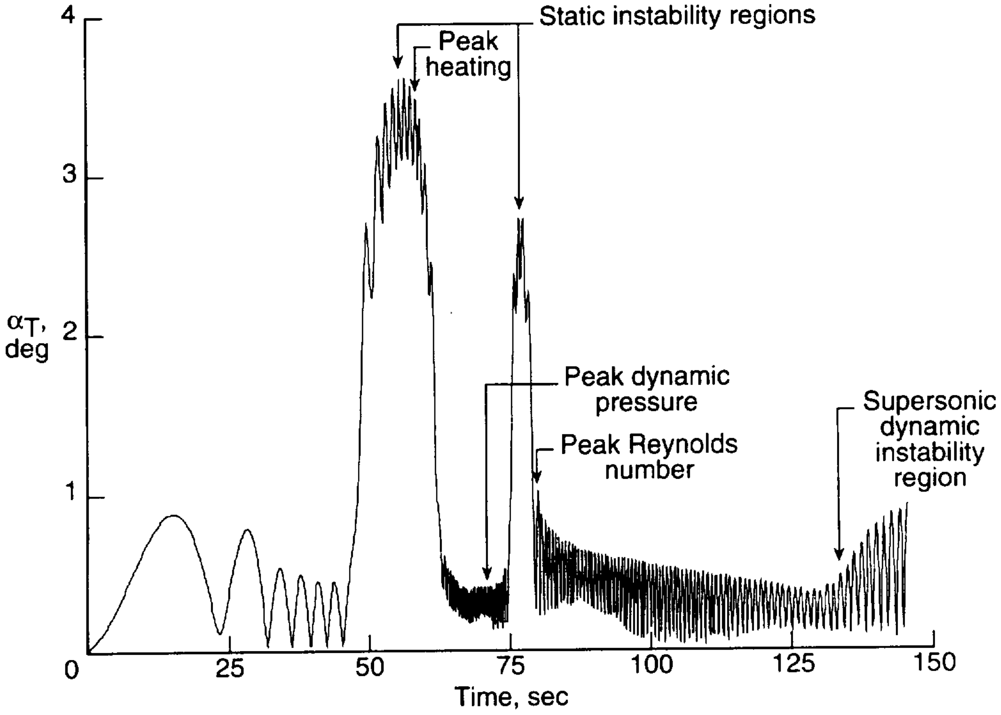

Fig. 6: Mars Pathfinder Nominal Angle-of-Attack Profile.

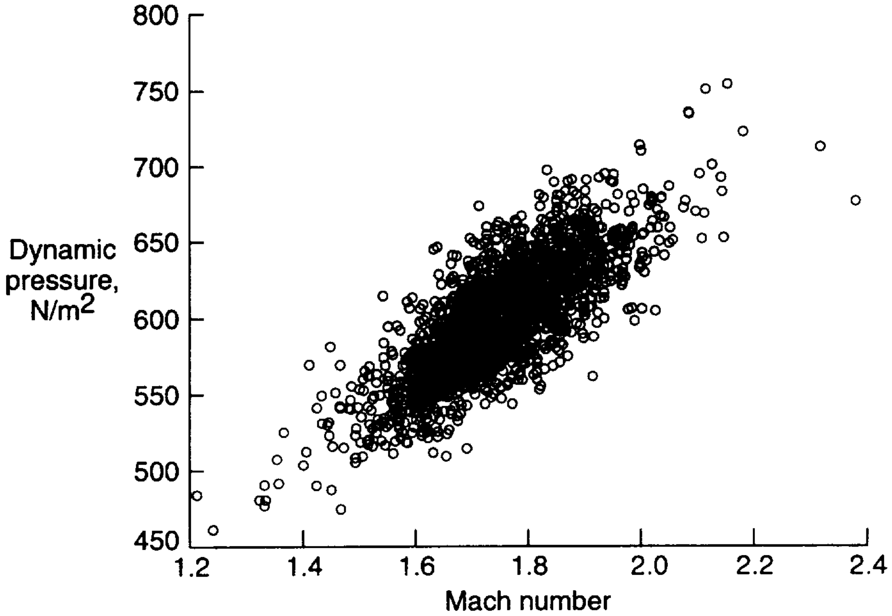

Fig. 7: Parachute Deployment Altitude and Dynamic Pressure Results obtained from Six-DOF Monte-Carlo Simulation.

Pathfinder design, test, and evaluation process. A final prelaunch simulation based on the measured flight system mass properties is scheduled for mid-October, 1996.

The 6-DOF trajectory simulation was roughly validated through comparison with a 3-DOF simulation independently developed at JPL[3]. Because the 6-DOF simulation was viewed as more appropriately describing Pathfinder's entry dynamics, its use has continued in the test and operations phases of the mission. For example, entry loading and frequency profiles determined through 6-DOF simulation were used at JPL to prescribe the appropriate subsystem test environment.

Six-DOF deceleration data is also used within the Pathfinder flight computer to determine the time of parachute deployment (time-to-go). As shown in Fig. 8, this mission event is preceded by comparison of onboard accelerometer measurements with a stored set of 6-DOF deceleration parameters[3,6]. In the event of accelerometer system failure, a fixed-time backup deployment sequence would be initiated[7]. This fixed-time criterion is also based on 6-DOF simulation. System performance has been increased by allowing for updates of the stored deceleration parameters (and fixed-time backup) as late as 8 hours prior to entry[8]. During flight, parameter revisions may be relayed to the Pathfinder spacecraft as a result of improved state estimates (after trajectory correction maneuvers and through more frequent Deep Space Network tracking) and updated atmospheric properties (through use of Hubble Space Telescope observations)[9]. Each of these operational updates requires additional 6-DOF simulation to re-specify the flight software parachute deployment parameters.

Following Pathfinder's landing, the 6-DOF trajectory simulation will be used to provide an initial estimate of the lander location based on a high-fidelity entry state determination analysis. This location will be relayed to the Deep Space Network to initiate lander acquisition. Subsequent use of the 6-DOF simulation capability includes plans for more detailed postflight trajectory reconstruction and flight-derived aerodynamic determination[10].

PROJECT STATUS

All flight system development and test has been completed and we have shipped to Kennedy Space Center at NASA's Eastern Test Range (ETR) for final preps for launch.

Final assembly and test occurs at ETR after installation of the APXS curium source and the rover RHU'S. This includes installation of the flight aeroshell, parachute, RAD rockets, pyros, airbags and the lander flight battery. The RAD rockets, pyros and parachute motor are armed with safing inhibits prior to launch. Spin balance tests, both in the cruise and entry configuration, will be accomplished and then we fuel our tanks with hydrazine prior to final weighing and 3rd stage mating.

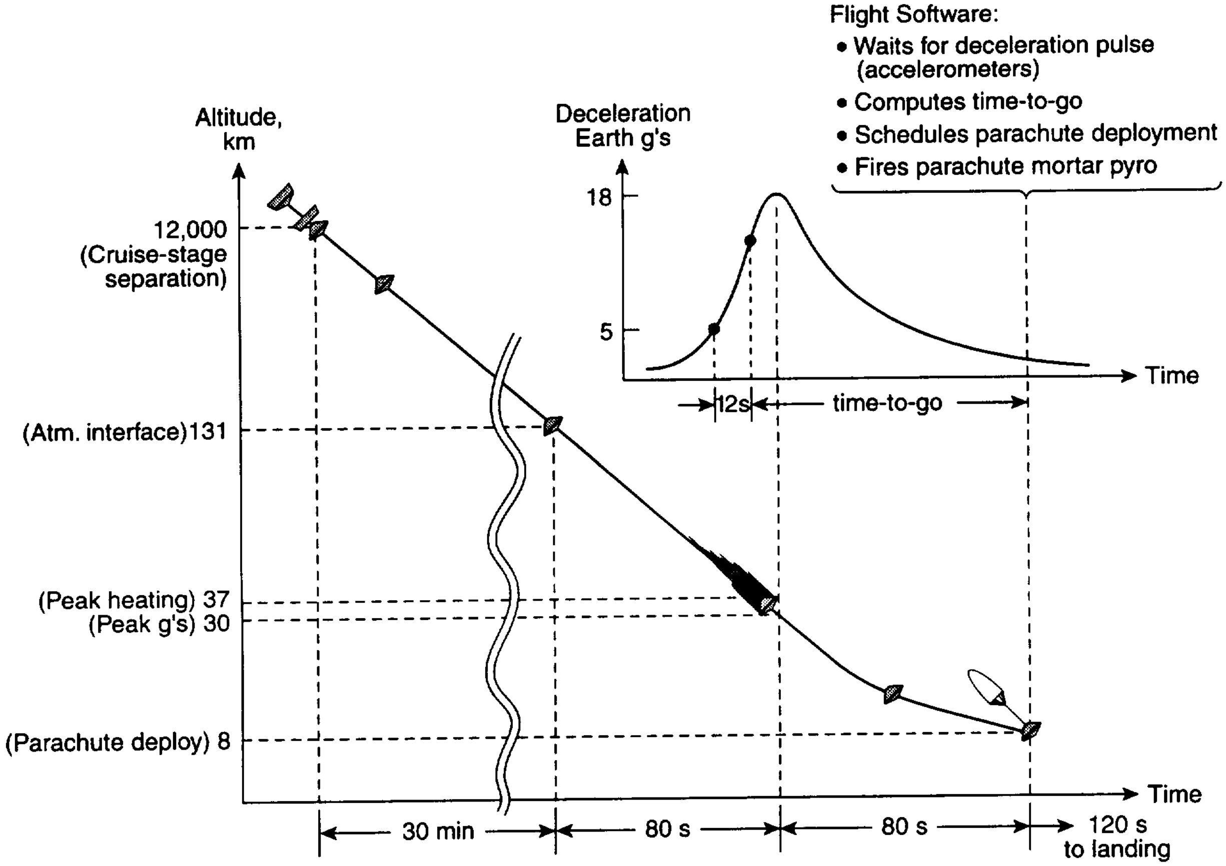

Fig. 8: Flight Software Parachute Deployment Process.

After the above, the flight system on the 3rd stage will be moved to the pad for launch vehicle mating and final processing. In early October, we will have completed final flight system assembly and the entry spin balance test and will be setting up for the cruise stage spin balance test.

Figure 9 shows the flight system after testing the surface operations mode at Mars atmospheric pressure. Figure 10 is a picture of the cruise stage prior to mating with the entry vehicle. Figure 11 is a picture of the flight rover. Figure 12 depicts a painting by the artist Pat Rawlings as to what the night landing might look like. We are on track for launch on Dec. 2, 1996 and, very importantly, we remain within our NASA fixed price cost cap.

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Fig. 9: Flight System After Testing.

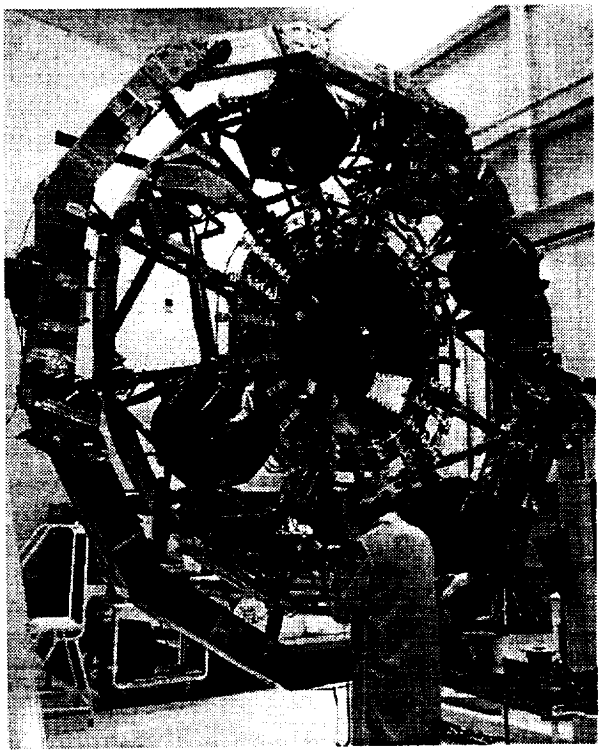

Fig. 10: Cruise Stage.

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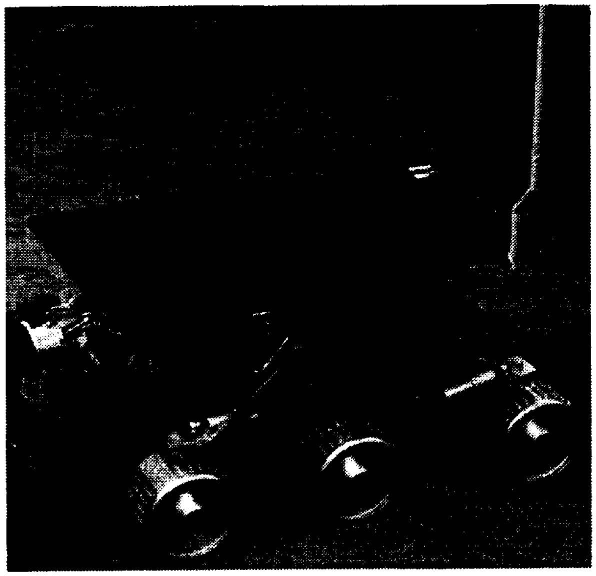

Fig. 11: Rover.

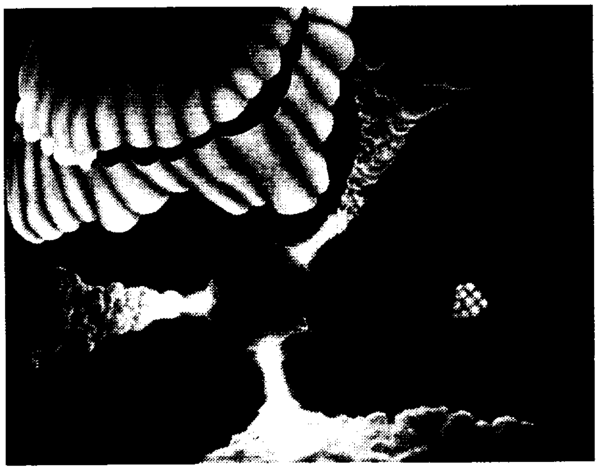

Fig. 12: Landing at Night.

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