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DESIGN OF A SCIENTIFIC PROBE FOR OBTAINING MARS SURFACE MATERIAL

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INTRODUCTION

Background

With the recent renewed interest in interplanetary and deep space exploratory missions, the Red Planet, Mars, which has captured people's imagination for centuries, has again become a center of attention. In the late 1960s and early 1970s, a series of Mariner missions performed fly-by investigations of the Mars surface and atmosphere. Later, in the mid 1970s, the data gathered by these earlier Mariner missions provided the basis of the much-publicized Viking missions, whose main objective was to determine the possibility of extraterrestrial life on Mars. More recently, with the dramatic changes in international politics, ambitious joint manned missions between the United States and the Soviet Union have been proposed to be launched in the early 21st century.

In light of these exciting developments, the Spacecraft Design course, which was newly established at UCLA under NASA/USRA sponsorship, has developed its curriculum around a design project: the synthesis of an unmanned martian landing probe. The students are required to conceive a preliminary design of a small spacecraft that is capable of landing at a designated site, collecting soil samples, and then returning the samples to orbit. The goal of the project is to demonstrate the feasibility of such a mission.

Mission Requirements

The detailed mission requirements are as follows:

Science objective. To collect 1.0 kg of surface material from the planet Mars for return to Earth for chemical and mineralogical analysis. The surface material is to come from the Hellas depression near Crater 29 at latitude -28.5°, longitude 283.0°.

Engineering objective. To design a Mars Surface Probe (MSP) that will descend from a Mars Orbiting Vehicle (MOV) to the surface of the planet, collect the surface material and return it to the MOV. The material can be in the form of granules obtained from drilling into the surface. The MOV with its attached MSP orbits about Mars in a circular path with the ascending node at 250° longitude, inclination angle +30°, altitude above the Mars mean surface of 600 km. As long as the MSP remains attached to the orbiting vehicle, all housekeeping functions such as electric power supply, command and telemetry, maintenance of constant temperature, etc., are provided to the MSP by the orbiting vehicle. The nominal temperature before the MSP is separated from the MOV is 20°C.

Project Organization

The project itself was divided into four areas of specialization: mechanical design, trajectory analysis, propulsion systems, and thermal control.

The main duty of the mechanical design specialist was to develop the general physical configuration of the spacecraft. Details such as the accessibility of the components, integration of subsystems, and mass property calculations had to be taken into account. In addition, the design of the soil collection mechanism, landing gears, and parachutes (if applicable) were also part of the mechanical designer's responsibility.

The trajectory specialist's first concern was to determine the optimum path necessary to allow the MSP to leave Mars orbit and land at the designated site. Detailed calculations were also performed by numerically solving the equations of motion of the vehicle at the vicinity of the planet surface, while taking into account atmospheric resistance. The ascending trajectory was also determined to allow the rendezvous of the landing vehicle and the orbiting mother ship.

The results from the trajectory analysis were then passed on to the propulsion specialist. Given this information, the propulsion specialist was required to determine the sizes of the rocket motors necessary for orbit maneuvering, deceleration, and ascent. The process of sizing of rocket motors includes propellant selection, estimation of propellant weight, nozzle sizing and design, and grain shape design (if solid propellant rockets are selected).

The thermal control engineer was responsible for the management of energy and for the thermal environment of the spacecraft. Aeroheating during atmospheric entry, internal temperature maintenance on the martian surface, and heat dissipation of electrical components were some of the major problems. The thermal specialist had to develop schemes of insulation, select appropriate batteries as power source, and analyze the heat transfer at various stages of the mission.

RESULTS OF ANALYSIS

Mechanical Design

General configuration. The general configuration of the MSP is developed to provide structural support of the propulsion system, the instrumentation required for the mission, and to withstand the landing impact. It also serves as the launch platform for the ascent rocket, which propels the payload into the rendezvous orbit (see Fig. 1).

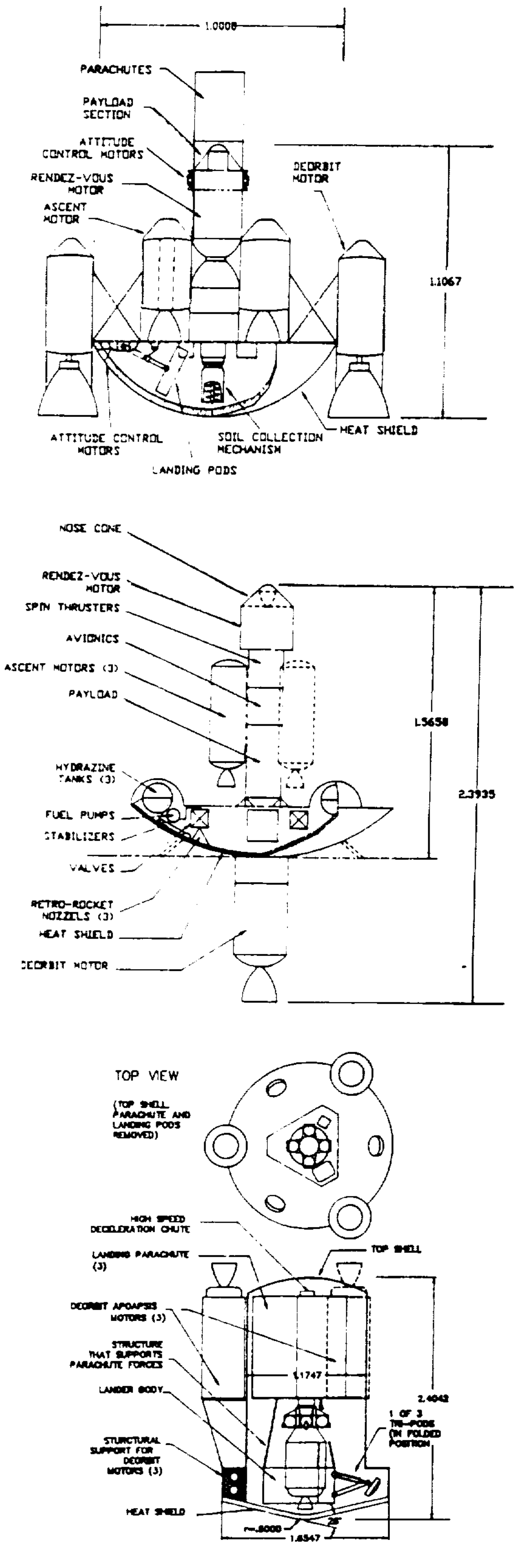

Fig. 1. Three Possible Configurations of the MSP

Vehicle deceleration system. For mechanical simplicity, parachutes are selected as the deceleration system. A high-speed deceleration chute, with a 4.52-m diameter cruciform canopy, is deployed at an altitude of 20 km. A second parachute, which has a flat circular canopy (39.4 m in diameter), is used for terminal descent. The combination of the two parachutes enables the MSP to land on the martian surface at a vertical speed of 10 m/sec.

Landing gear. Even though the MSP does not have any ultrasensitive instrumentation on board, it is still necessary to provide a reasonably soft landing to prevent possible damage to the subsystems. Collapsible aluminum honeycomb materials and oleo-pneumatic-type hydraulic shock absorbers are implemented in the landing gear/shock absorption system design for this purpose. Calculations show that this design is capable of withstanding about 8000 N, which is approximately equivalent to a load factor of 5 *g* (see Fig. 2).

Sample collection mechanism. The soil sample collection mechanism takes advantage of the atmosphere on Mars. The device consists of a drill, an aspirator, and a 200-W DC motor that drives both the drill and the aspirator. Dust particles generated by the drilling action are collected into the payload canister by suction, which is generated by the aspirator (see Fig. 3). The mechanism is expected to be operating for at most 15 min.

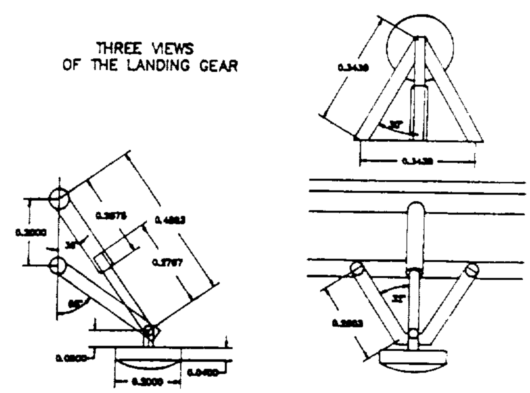

Fig. 2. Design of the Landing Pad

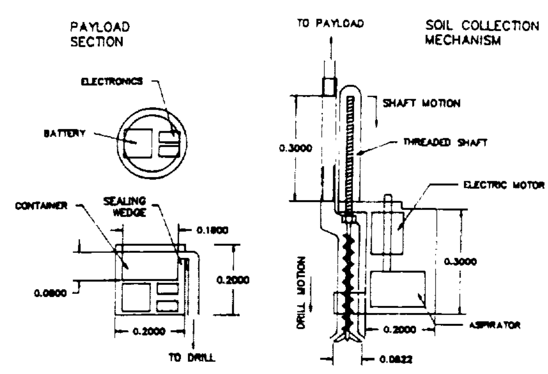

Fig. 3. The Soil Sample Collection Mechanism

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Table 1. Summary of Mass Properties of the MSP

No.	Item Name	Mass (kg)	Vertical Arm z	Vertical Inertia Mz^2	Horizontal Arm x	Horizontal Inertia Mx^2	Lateral Arm y	Lateral Inertia My^2
1	Payload	10	22	4,840	0	0	0	0
2	Power supply (upper stage)	5	5	125	0	0	0	0
3	Power supply (lower stage)	2×10	5	250	0	0	0	0
4	Parachute System	60	54	174,960	0	0	0	0
5	Structure	40	0	0	0	0	0	0
6	Heat shield	100	26	67,600	0	0	0	0
7	Sample acquisition system*	3.6	14	706	0	0	0	0
8	Deorbit motor and fuel	4×28	6	$4 \times 1{,}008$	16	$2 \times 7{,}168$	16	$2 \times 7{,}168$
9	Ascent motor and fuel	4×16	12	$4 \times 2{,}304$	18	$2 \times 5{,}184$	18	$2 \times 5{,}184$
10	Rendezvous motor and fuel	1×4	22	1,936	0	0	0	0
	Totals ($kg{\cdot}cm^2$)	403.6	—	263,665	—	24,704		24,704

*Sample acquisition system includes 1.36-kg Motov and 2.27-kg drill assembly.

MSP/MOV interface. A mechanism that allows the reattachment of the MSP and MOV at the final stage of the mission is also conceived. The design will permit a 7° angular misalignment and a 20-cm linear displacement during the rendezvous process (see Fig. 4).

Moments of inertia. The moments of inertia of each major components of the MSP are summarized in Table 1.

Trajectory Analysis

The trajectory analysis was broken down into several steps. First, an outline of the various stages of the mission was developed. Second, given the landing site, the minimum relative velocity change required and time of separation of the MSP were determined. With this information, more detailed calculations were performed, taking into account aerodynamic drag and the deceleration mechanism to determine more precisely the path for landing the spacecraft. Finally, the ascent trajectory and the ΔV required for rendezvous orbit injection were calculated in a similar fashion. The results are summarized in the following sections.

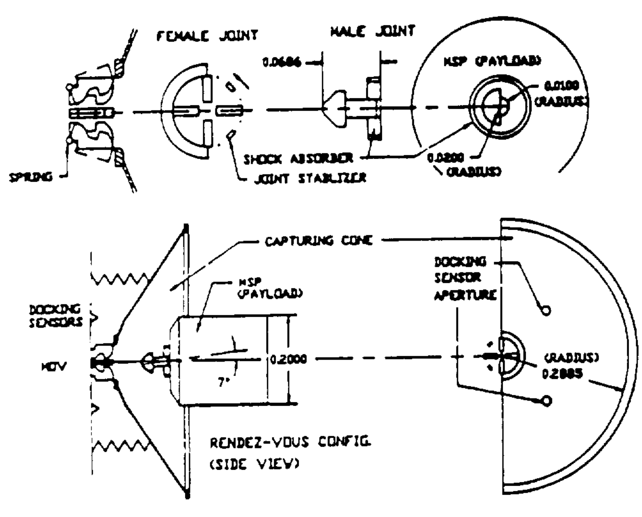

Fig. 4. MSP/MOV Interface Mechanism

Outline of the mission scenario. Prior to trajectory analysis, the major stages of the MSP mission were identified. These stages are listed in Table 2.

Table 2. Mission Scenario

0	MSP and MOV orbit Mars
1	MSP separates from MOV, injection into descent orbit
2	De-orbit rockets jettisoned
3	Deceleration parachutes deployed
4	Terminal decent parachutes deployed
5	MSP touch down on Mars
6	MSP collects soil sample
7	The ascent rocket motor is fired
8	The ascent rocket is jettisoned
9	Rendezvous rocket firing; injection into rendezvous orbit
10	MSP/MOV rendezvous

Delta-V determination. Since the MSP and MOV are originally in a circular orbit around Mars, the MSP must be injected into a new orbit that intersects the vicinity of the designated landing site with minimum fuel consumption. However, the MSP's angle of approach must be greater than 15° because of the geological features of the surface. Given this constraint and knowing the mass of Mars and the original orbit of the MSP/MOV, both the new orbit and the minimum change in velocity required to achieve the new orbit can be determined using the equations of orbital mechanics (see Fig. 5).

Similar analysis can be performed for the ascent trajectory. The minimum change in velocity required to boost the payload to the proper altitude and injection into the rendezvous orbit were determined.

Descent trajectory. As the MSP approaches the surface, the resistance of the martian atmosphere becomes more significant. Further, the deployment of the deceleration systems affects the final stages of the trajectory greatly. Thus, the results of the previous section provide the initial condition of a more detailed trajectory calculation, taking into account various perturbations, to the ideal solution (Fig. 6). The equation to be solved is Newton's second law of motion in two dimensions; in our case, this is a system of nonlinear, second-order differential equations. These equations were solved numerically by Euler's method (Table 3).

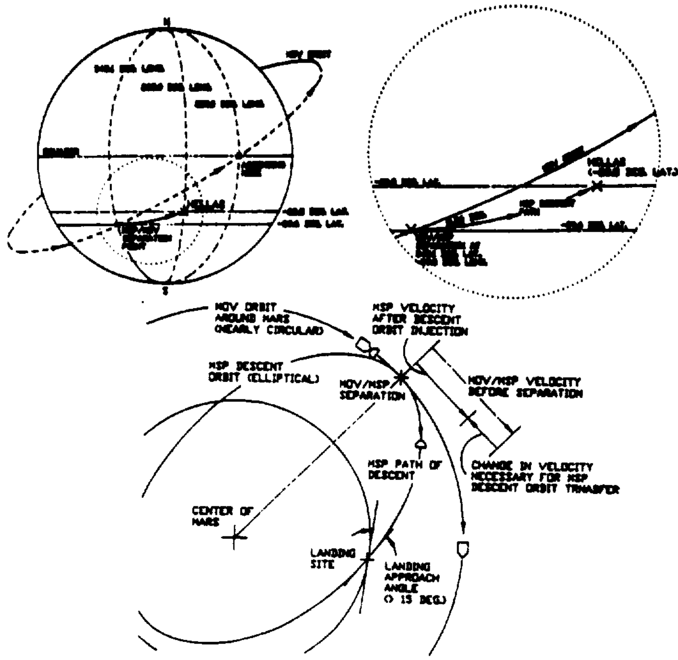

Fig. 5. Schematic Diagrams of the MSP Descent Path

Table 3. Summary of Trajectory Analysis

Separation occurs at:
-29.6° latitude, 341.1° longitude, 600.0 km altitude

Velocity after separation:
MOV: 3.281 km/sec
MSP: 2.790 km/sec
V: 795.0 m/sec

Descent elliptical orbit:
major axis length: 3134 km
eccentricity: 0.277

Descent Trajectory:
range: 3372.6 km
duration: 1524.5 sec

Time on Hellas: 57249 sec

Ascent Trajectory:
max. velocity achieved: 3407 m/sec
Range: 3420.1 km
duration: 1323.5 sec
circular orbit injection ΔV: 0.917 km/sec

Total mission time: 60096 sec = 16.69 hours

Propulsion

Based on the mission scenario and the required ΔV at various stages of the MSP mission, the types of propellant used for each of the rocket motors were selected. In addition, the size and shape of the exhaust nozzle and the requirements of the various subsystems were determined.

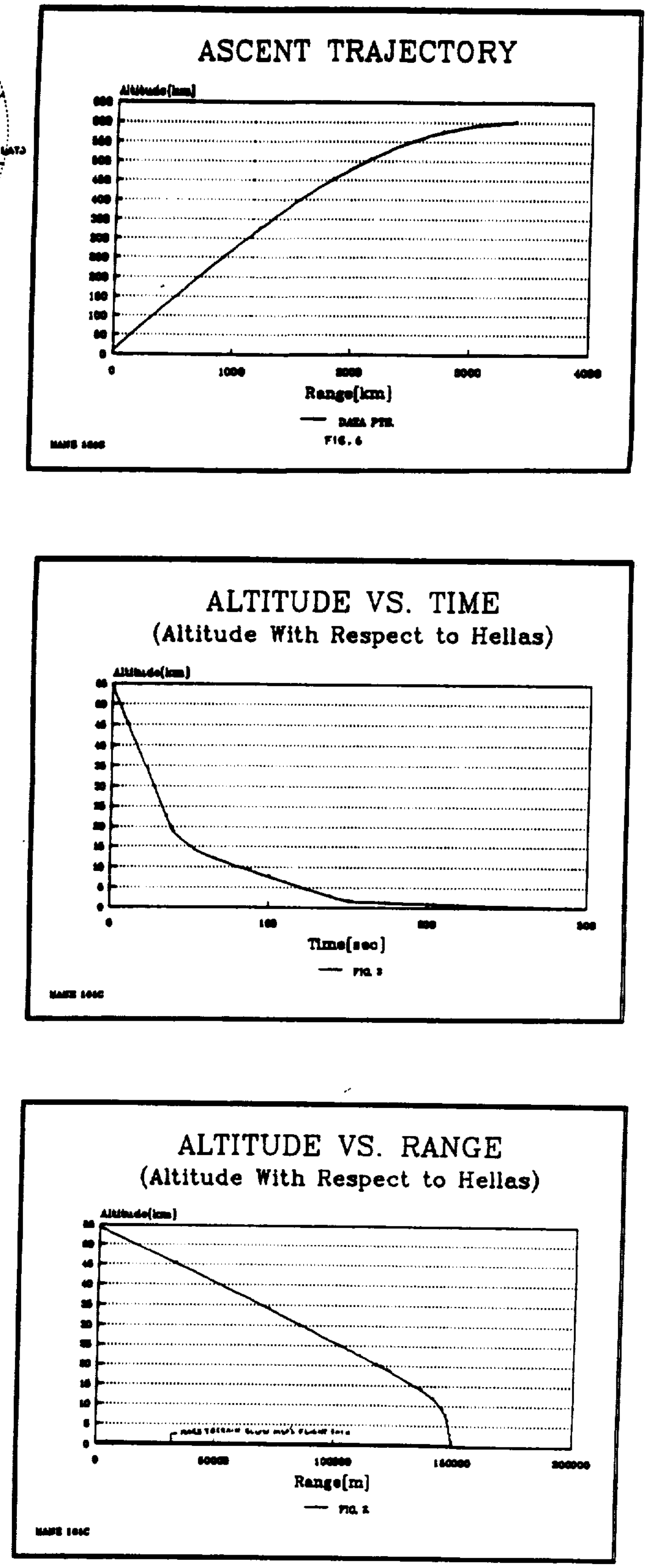

Fig. 6. Results of the Descent Trajectory Analysis

Propellant mass estimation. Given the change in velocity necessary at each stage of the mission and the estimation of total weight of the rest of the spacecraft by the mechanical designer, the propulsion specialist could estimate the mass of propellant needed. Given the mass and velocity prior to rocket firing and the final velocity, the mass expended to achieve the change can be calculated by conservation of momentum. A summary of a sample calculation is listed in Table 4.

Table 4. System Mass at Different Phases of the Mission

Event	Mass (kg)	Structure Dropped (kg)	Propellant Used (kg)
0	427.37		101.79
1	325.58	11.51	
2	230.07	60	
3	170.07		
4	170.07	93.63	
5	76.44		57.70
6	18.74	5.06	
7	13.69		3.69
8	10.00		

Rocket nozzle design. The exhaust nozzles must be carefully designed so that the performance (particularly the specific thrust) of each rocket engine can fulfill its function. For example, the ascent motor must have total thrust greater than its total weight in order to propel the payload into orbit. Ideal gas behavior is assumed throughout this analysis. The thrust force can be related to the nozzle throat area, exit area, and mass flow rate of the fuel/oxidizer mixture by 1-D compressible flow equations and thermodynamics laws. Since the exit area of the nozzle is essentially fixed by the physical size of the rocket itself, mass flow rate of the propellant and the throat area become the main variables. These variables are selected via iterative processes to yield the optimal thrust. Sample results are shown in Table 5.

Propulsion subsystems (gimbal, skin thickness, and grain design). A nozzle gimbaling scheme is also developed to maintain the stability of the ascent. For solid rocket applications, propellant grain shape is also determined to ensure an approximately constant generation of thrust in time (see Fig. 7).

Thermal Control

Thermal analysis for MSP during eclipse. When solar radiation to the MSP is blocked by the planet, the internal temperature of the spacecraft must be maintained so that temperature-sensitive instrumentation (battery, for example) will function properly. Steady-state energy conservation analysis shows that about 23 W of power is required to maintain a 20°C internal temperature.

Heat shield/aeroheating. During supersonic atmospheric entry, a large quantity of heat is generated by friction and the presence of a shock wave. Thermal analysis was performed on a graphite heat shield with thermal blankets (made of aluminized Mylar, separated by dacron mesh) on the inside of the shield. The calculation shows that the inside graphite shield will reach a temperature of 390 K. With the help of thermal blankets, the heat flux into the MSP itself will not cause any damage to the instruments.

MSP heat transfer characteristics at the martian surface. The major contributors of heat transfer during the MSP's stay on the martian surface are convective heat transfer due to winds, solar radiation, and the radiation of the martian surface (black body radiation). Analysis shows that, in order to maintain the 20°C internal temperature, 26 W is needed during daytime, and 48 W when solar radiation is absent.

Thermal environment maintenance scheme. The power requirement of the thermal control and the electrical components provides the basis for selecting a battery (Table 6). A zinc/silver battery, which is capable of an output of 28 V at 20 amp/hours, was chosen because of its superior energy density and weight among the available off-the-shelf selections.

Thermal control was achieved by an adaptive feedback-control system with heating coils and electrical grids. A block diagram of such a system is shown in Fig. 8.

Tolerable wind speed. An analysis was also performed on the maximum surface windspeed tolerated by the MSP before it tips over. Using simple but conservative assumptions about the drag coefficient of the MSP, it is shown that winds of up to 600 m/sec can be tolerated.

DISCUSSION AND CONCLUSION

Due to the time constraint of the course and shortage of test data of various components, many assumptions had to be made in the preceding analysis. Some of the more important ones are discussed in the following paragraphs.

Mechanical Design/Weight Estimate

Since a detailed structural analysis was not performed, the weights of the various structural members of the MSP were estimated based on comparison with other spacecraft with similar missions. However, conservative estimates are used throughout the process, and a large margin of safety was kept.

Trajectory Analysis

The actual atmospheric entry aerodynamics are quite complex, as chemical species are generated and dissociated under the intense heating of hypersonic flow speed. A more

Table 5. Specifications of the Rocket Motors

Rocket Motor	Propellant Type	I_{sp} (sec)	Max. Thrust (N)	Flow Rate (kg/sec)	Throat Diameter (m)	Exit Diameter (m)
Deorbit	Liquid	298.0	3558.4	1.2	0.028	0.254
Ascent	Solid	234.3	2902.7	1.22	0.0008	0.180
Rendezvous	Liquid	298.3	1170.1	0.40	0.0146	0.188

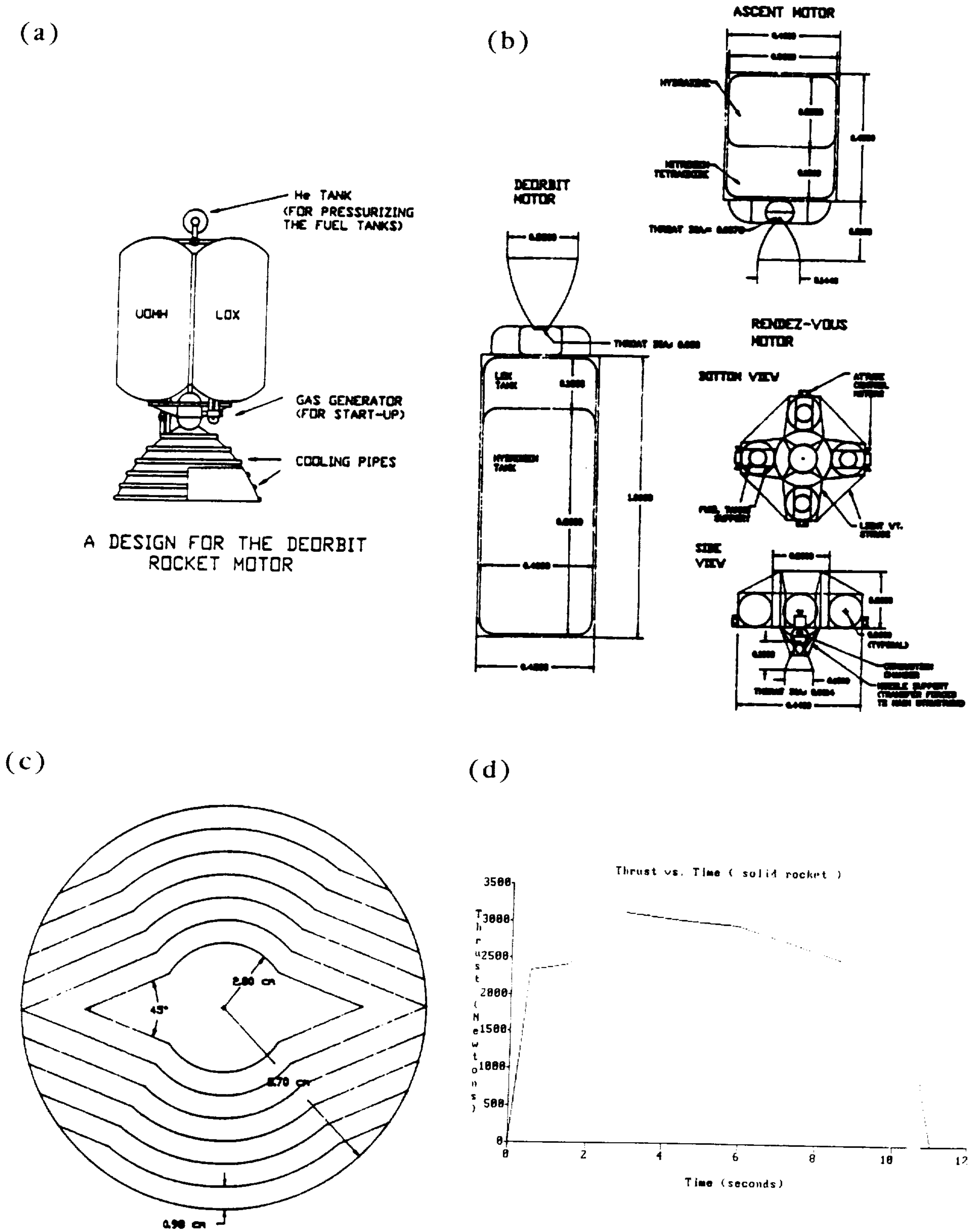

Fig. 7. (a) and (b) Dimensions of some of the rocket motors; (c) Proposed grain shape for a solid propellant rocket; (d) Thrust vs. time for the grain shape proposed in (c).

Table 6. Power Requirement and Battery Selection

Phase of Mission	Power Required to maintain at 293 K (W)	Control Power (W)	Time (min)	Energy Required (J)
Descent to 1	25.0	30	20.47	67,551
1 to 3	10.0	30	4.90	11,760
On the ground	Day: 25.76	30	490.00	1,639,340
	Night: 47.78	30	490.00	2,286,730
Drill	200.0	15		180,000
Ascent 5 to 8	12.6	30	22.00	56,236
Total Energy Required:				4,241,616
Battery Selected:	EPI 4445 with 20 amp/hr at 28 V			
	SZHR 7.0 with 7.0 amp/hr at 1.5 V/cell			
	Total Battery Weight: 20.75 kg			

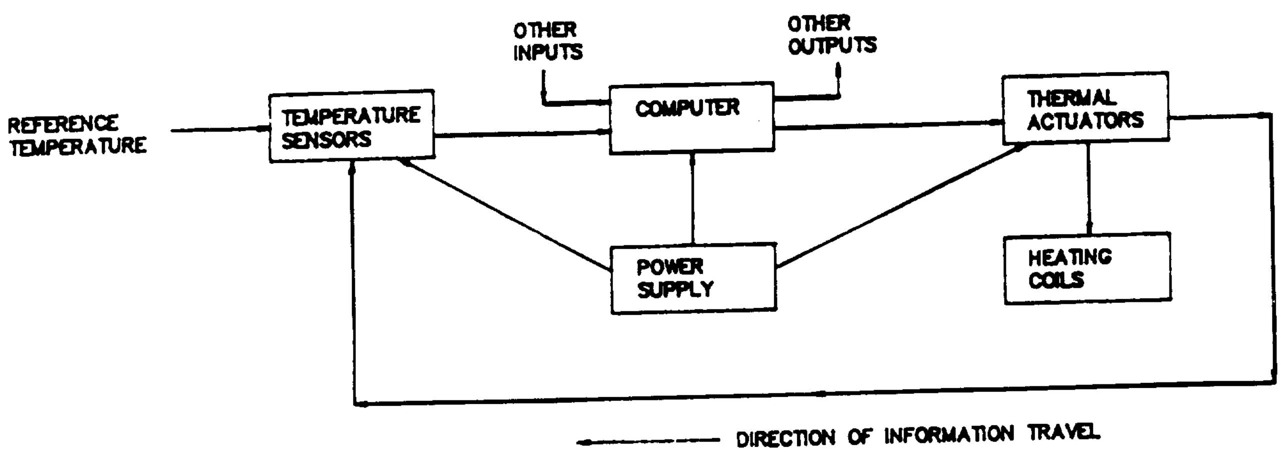

Fig. 8. A Block Diagram of the Thermal Control System

detailed computational fluid dynamics analysis could provide much better insight.

Propulsion Systems

As mentioned before, ideal gas assumptions are used throughout the analysis.

Thermal Control

In nearly all calculations performed on the MSP thermal environment, steady-state is assumed. Thus, thermal inertia and transient response of individual components of the MSP were neglected.

Conclusion

This preliminary study of an interplanetary exploration mission has shown the feasibility of such a mission. The students have learned valuable lessons about the complexity of spacecraft design, even though the mission is relatively simple.

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