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COMET NUCLEUS AND ASTEROID SAMPLE RETURN MISSIONS

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Abstract

During the 1991-92 academic year, the Pennsylvania State University has developed three sample return missions: one to the nucleus of comet Wild 2, one to the asteroid Eros, and one to three asteroids located in the Main Belt. The primary objective of the comet nucleus sample return mission is to rendezvous with a short period comet and acquire a 10 kg sample for return to Earth. Upon rendezvous with the comet, a tethered coring and sampler drill will contact the surface and extract a two-meter core sample from the target site. Before the spacecraft returns to Earth, a monitoring penetrator containing scientific instruments will be deployed for gathering long-term data about the comet. A single asteroid sample return mission to the asteroid 433 Eros (chosen for proximity and launch opportunities) will extract a sample from the asteroid surface for return to Earth. To limit overall mission cost, most of the mission design uses current technologies, except the sampler drill design. The multiple asteroid sample return mission could best be characterized through its use of future technology, including an optical communications system, a nuclear power reactor, and a low-thrust propulsion system. A low-thrust trajectory optimization code (QuickTop 2) obtained from the NASA Lewis Research Center helped in planning the size of major subsystem components, as well as the trajectory between targets.

Introduction

Three Advanced Design Program projects have been completed this academic year at Penn State. At the beginning of the fall semester the students were organized into eight groups and given their choice of either a comet nucleus or an asteroid sample return mission. Once a mission had been chosen, the students developed conceptual designs. These were evaluated at the end of the fall semester and combined into three separate mission plans, including a comet nucleus sample return (CNSR), a single asteroid sample return (SASR), and a multiple asteroid sample return (MASR). To facilitate the work required for each mission, the class was reorganized in the spring semester by combining groups to form three mission teams. An integration team consisting of two members from each group was formed for each mission so that communication and information exchange would be easier among the groups.

The types of projects designed by the students evolved from numerous discussions with Penn State faculty and mission planners at the Johnson Space Center Human/Robotic Spacecraft Office. Robotic sample return missions are widely considered valuable precursors to manned missions in that they can provide details about a site's environment and scientific value. For example, a sample return from an asteroid might reveal valuable resources that, once mined, could be utilized for propulsion.[1,2] These missions are also more adaptable when considering the risk to humans visiting unknown and potentially dangerous locations, such as a comet nucleus.

Comet Nucleus Sample Return Mission (CNSR)

Background

Presently, much of the scientific community's understanding of the universe has come from remote observation of the cosmos, but technological advances within the past thirty years have allowed for the study of retrieved cosmic materials on Earth. These Earth-returned samples have proved to be of immense scientific value, providing many answers and potential paths of inquiry.

Although comets have been observed for many centuries, a mystery still shrouds the composition of the comet nucleus. Comets are thought to have been formed simultaneously with the Sun and planets and therefore consist of the most chemically primitive solid matter known to have survived in the planetary system.[3] Thus, the examination of a sample from a comet nucleus would greatly add to knowledge of the solar system's origin.

Mission Objectives

A CNSR mission is proposed to return a comet nucleus sample in its own environment to Earth for study. The primary mission objective consists of three phases: rendezvous with a short period comet, acquisition of a 10 kg sample from the nucleus, and maintenance of the sample composition and crystalline structure for return to Earth. The secondary objective for the CNSR mission is to monitor comet activity through perihelion by using a penetrator equipped with scientific instrumentation.

The comet Wild 2 was determined to be the most suitable target because of its low inclination to the ecliptic plane, its short orbital period, and its recent change in perihelion distance. An encounter with Jupiter changed Wild 2's perihelion distance from 6.2 astronomical units (AU) to 1.6 AU. Consequently, the now short-period comet has the crystalline structure of a long-period comet.[4] A tethered coring unit will reach the comet nucleus and extract a sample that will be housed in a protective environment so that it may be returned to Earth in an unaltered state. Upon rendezvous with the comet, a sampling probe will extract a two-meter core sample from a target site where undisturbed material maintains a temperature less than 130° K.[3] The comet must have a relatively low mean temperature to retain its volatile material—any material above that temperature is believed to have experienced too much heating to be of great scientific value.

The last phase of the primary objective is to maintain, as best as possible, the sample's undisturbed state during the transit to Earth. This involves monitoring and controlling the sample's pressure and temperature, as well as keeping it physically stable. A chemically or physically altered comet sample would lead to false conclusions and a distorted picture of the origins of the solar system.

The secondary objective of the CNSR mission is to obtain as much information as possible on the activity of Wild 2. This ensures that the sample is representative of the comet and allows it to be placed in the proper context with respect to other comets investigated only by remote sensing. Sufficient characterization of the sampled comet also eliminates the need for multiple samples. To fully characterize the comet, a penetrator will be left behind to monitor the comet through perihelion. Characterization of the comet includes the determination of size, shape, density, and surface temperature distribution. The penetrator will monitor temperature and gas production changes of the comet until perihelion.

Mission Profile

The spacecraft will be launched on an Atlas IIA equipped with a Centaur IIA to inject the spacecraft into a low parking orbit and to provide the necessary Earth escape velocity (see Figure 1). The upper stage will then separate from the spacecraft, systems will be checked, and instrument booms and solar arrays deployed (see Figure 2 for spacecraft configuration). After Earth escape additional correction maneuvers during interplanetary cruise will insure accurate targeting for Wild 2.

At 100 to 200 km from Wild 2, the comet approach maneuvers reduce the relative velocity to 2 m/s. The comet's exact size and spin rate will then be determined and during the global characterization phase the surface will be mapped for candidate sampling sites. Candidate sites will be mapped in detail from an altitude of 50 km, and the coma gas and dust will be analyzed. While the spacecraft awaits final site selection it will return to an altitude of 100 km.

After a target site has been selected, the spacecraft will return to a low, *forced* synchronous orbit at 0.5 km above the selected site, reducing contamination of the surface by the thruster plumes. A sampling probe powered by liquid

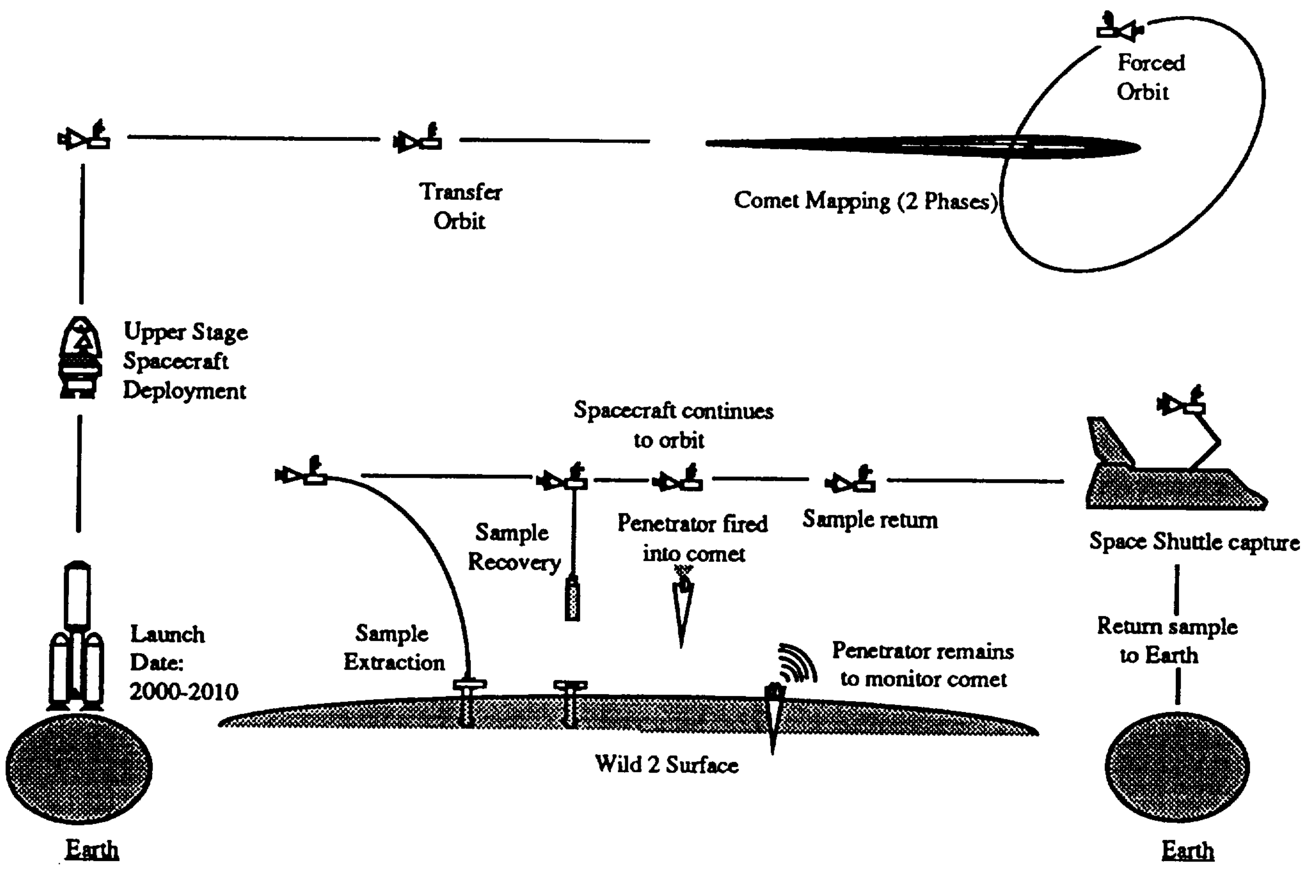


Fig. 1 CNSR mission profile

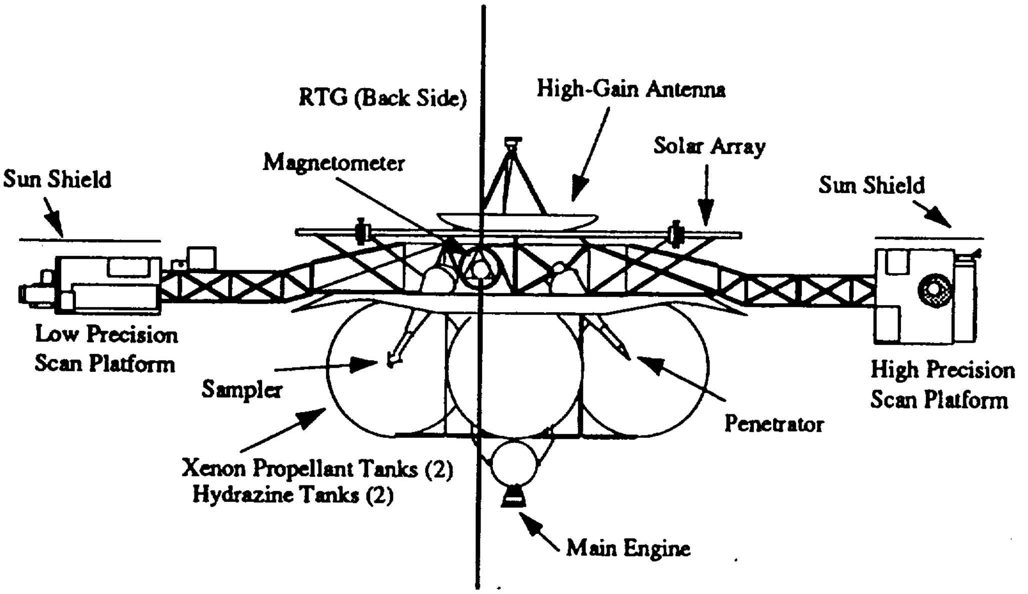


Fig. 2 CNSR spacecraft configuration

propellant rocket thrusters will then be jettisoned from the spacecraft to impact the target site. Because the spacecraft and the sampling penetrator are connected, a synchronous orbit must be maintained during extraction. Drilling commands will be sent from the spacecraft through cabling enclosed in the tether. After extraction, the tether will be used to retrieve the specimen from the sampling penetrator. Finally, a monitoring penetrator will be deployed and anchored into the comet to monitor Wild 2's activity. This penetrator will be equipped with scientific instrumentation to observe comet activity and return data. An optical communication system powered by a radioisotope thermoelectric generator (RTG) will relay the information to Earth. The RTG will also provide power for the scientific instrumentation.

After the sample has been safely retrieved, it will be returned to the spacecraft and hermetically sealed within multi-layer insulation. Once the sample has been secured in a thermally controlled environment, the spacecraft will depart from the comet leaving behind the monitoring probe. Heat pipes and phase change materials will be used to direct heat from the other spacecraft subsystems away from the sample.

The spacecraft will leave the comet and be placed on a direct Earth return trajectory. The Earth return trajectory will contain no additional maneuvers except those needed for navigational corrections. Upon arrival at Earth, the spacecraft's relative velocity will be reduced, and it will be placed in a circular Space Shuttle-accessible orbit and remain there no longer than approximately two weeks. The sample will then be retrieved by the Shuttle and returned to the surface in a thermally safe environment.

Table 1 Spacecraft mass budget

Element	Mass (kg)
Spacecraft structure	1309
Bus	801
Booms (truss structure)	102
Fasteners & joints (10%)	90
Deployment mech. (10%)	90
Contingency (25%)	225
Sampler	95
Penetrator	262
Power	93
Solar array	10
RTG	83
GN&C	83
Scientific instruments	134
Communication	7
Computer	12
Total	1990
10% electric wiring	199
10% mass margin	199
Thermal (8% dry mass)	159
Total dry mass	2547
Propulsion	2602
Propellant	2312
Tankage (10%)	231
Valves, tubing (25% of tank mass)	57
Total wet mass	5149

Overall Mass, Power, and Cost Budgets

The spacecraft will have a total mass of 5149 kg (see Table 1) and require a total operating power of 528 watts (see Table 2). A cost model[5] was applied to the mission estimating a total cost of $1.88 billion FY92 dollars (see Table 3).

Table 2 Power budget

Spacecraft component	Power (w)
GN&C	20
Mapping	150
Communications	122
Computer system	50
Structure	50
Thermal	40
Sample extraction	27
Avg. power	459
Margin (15%)	69
Total avg. power	528

Table 3 Cost estimation[5]

Mission Component	Cost ($M)
Computer	47.97
Communications	17.83
Power	135.31
Sampler	240.13
Penetrator	368.00
Thermal	123.04
Propulsion	0.51
GN&C	129.33
Scientific instruments	209.26
Structure	524.38
Launch system	85.00
Total	1880.76

Single Asteroid Sample Return Mission (SASR)

Mission Objectives

The primary objective of this mission is to extract a core sample from a target asteroid and return this sample to Earth for detailed compositional analysis. Secondary mission objectives entail performing a wide variety of scientific observations that will enable humankind to better understand the physical nature of asteroids, their possible origin, and their effect on the interplanetary environment.

Mission Profile

The mission designers selected 433 Eros as the target asteroid because of its accessibility, its relatively large size, and its well-known orbital parameters. In addition, at least three launch windows will exist for a mission to Eros between 1992 and 2010.[6]

Figure 3 illustrates the mission profile. The spacecraft will begin the mission with the landing struts, instrument booms, and high-gain antenna collapsed enabling them to fit in the launch vehicle shroud and withstand all launch forces. An Atlas IIA launch vehicle will propel the spacecraft into Low Earth Orbit (LEO). While in LEO, the spacecraft will perform checks of all systems. A Centaur will then inject the vehicle into the required transfer orbit after which the spacecraft will deploy the landing struts, booms, and high-gain antenna. Scientific measurements of the interplanetary environment will begin at this time. At a distance of one million km from Eros, the spacecraft will begin to photograph the asteroid and perform scientific observations. Once the spacecraft descends to an altitude of 2.5 km, it will maintain its position above a location on the surface. A passive/active sensing technique will utilize visual images and laser radar scans to identify a safe landing zone that is within the maneuvering range of the vehicle. The spacecraft will then land at this location and anchor into the surface with barbed spikes. Once secured on Eros, the scientific instruments will perform several observations and then cease operations to allow power to be concentrated on the drilling process. The drill will then proceed to extract a five-foot-long core sample. Once this sample is stored on the spacecraft, pyrotechnic charges will separate the vehicle's upper portion from the rest of the spacecraft and depart from the asteroid, leaving the drill and landing struts behind. If enough propellant remains, the spacecraft will perform the maneuvers required to complete a detailed map of Eros. Once the mapping is completed, or discovered to be beyond the capacity of the propulsion system, the spacecraft will begin the voyage back to Earth. On the return trip, the vehicle must again execute a mid-course correction. Upon arrival at Earth, the spacecraft will maneuver into LEO where it will remain until it can be retrieved by the Space Shuttle.

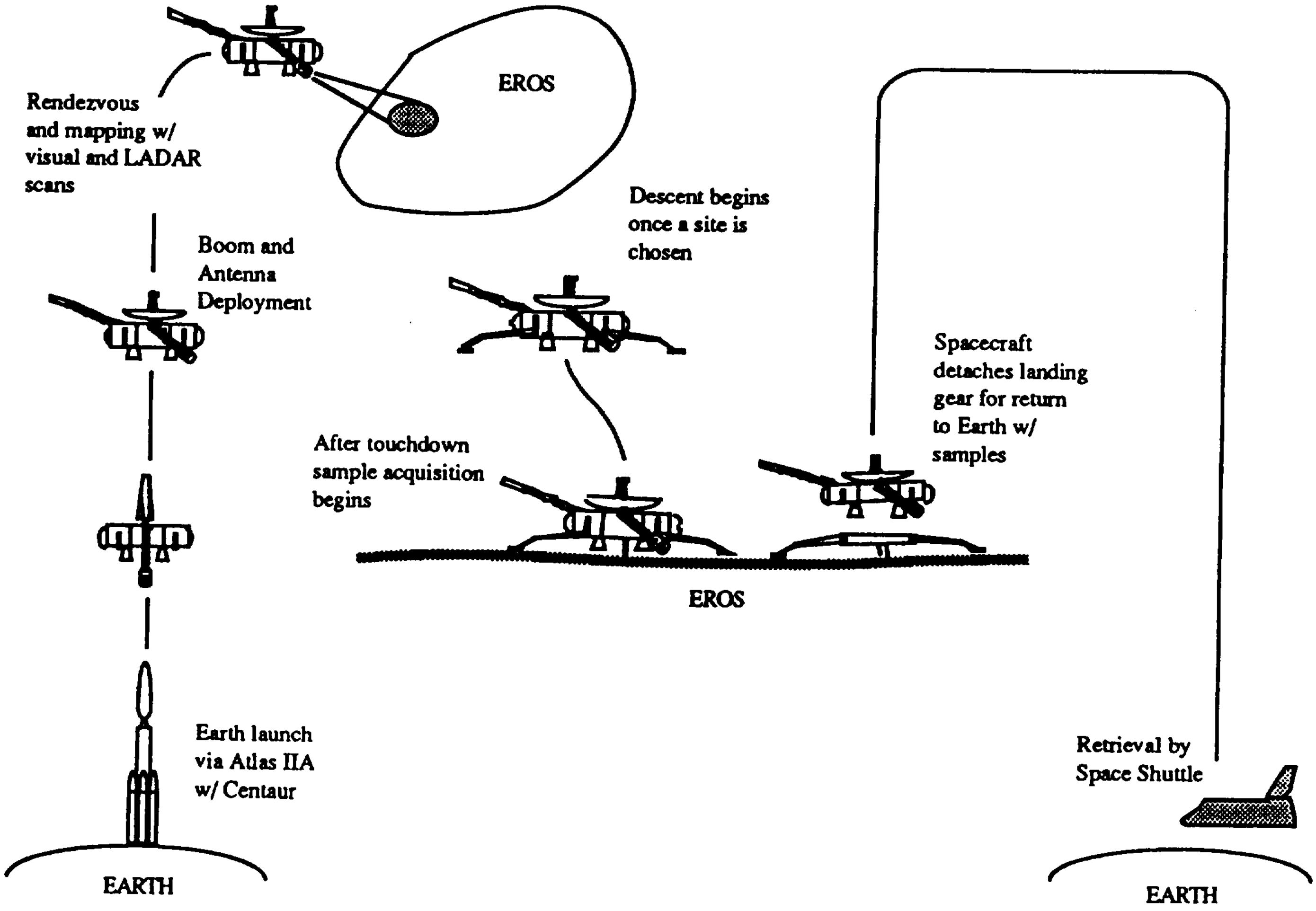
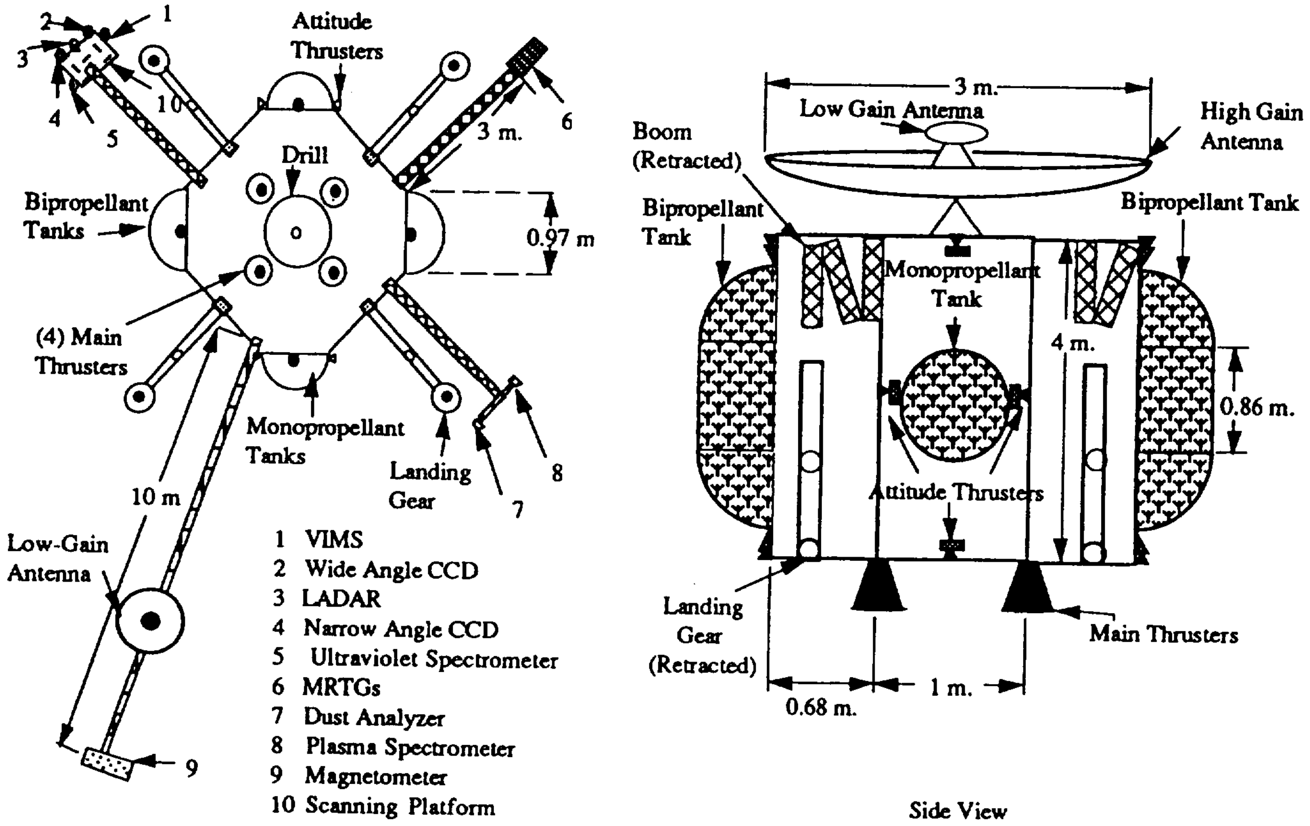


Fig. 3 SASR mission profile



Side View

Bottom View

Fig. 4 SASR spacecraft views

Spacecraft Description

Figure 4 illustrates the basic spacecraft configuration. The spacecraft structure will be a semimonocoque design constructed chiefly from beryllium. It will use three modular RTGs for general power consumption and will employ three batteries to provide the power required for drill operation. The vehicle will be propelled by four main thrusters that use a bipropellant consisting of monomethylhydrazine and nitrogen tetroxide. Twelve attitude thrusters will utilize hydrazine as a monopropellant. The control system will incorporate three-axis stabilization with momentum wheels. Spacecraft communications will be accomplished by one high-gain antenna and two low-gain antennas that operate in the Ka-band. The scientific payload will include: a visual and infrared mapping spectrometer, an ultraviolet spectrometer, a plasma spectrometer, a magnetometer, a dust analyzer, a laser radar system, and two charge-coupled device cameras. The thermal subsystem design consists of thermal blankets and heaters for the majority of the spacecraft. Thermal requirements for the drill necessitate the additional use of heat pipes and second-surface mirrors. The electronics will be mounted on cold rails from which heat will be transferred by heat pipes to the second-surface mirrors. In addition, the infrared-sensing instrument will require a radiative cryogenic coolant system. The command and data handling system must be highly autonomous, utilizing higher-order languages and hybrid architecture.

Overall Mass, Peak Power, and Cost Budgets

Table 4 shows the overall spacecraft mass budget and peak power budget. The peak power values are not totaled because all the subsystems will not be simultaneously operating at peak requirements during any particular time of the mission. Therefore, a total value for peak power would be of no significance. Table 5 summarizes the overall estimated cost budget for this mission in FY92$M.[5,7]

Table 4 Spacecraft mass and peak power budgets

Subsystem	Mass (kg)	Peak Power (w)
Propulsion	3633.11	150.0
C&DH	121.35	451.1
Drill	450.00	7500.0
Attachment	150.00	181.0
Structure	550.00	N/A
Scientific payload	116.2	114.2
Communications	32.00	80.0
Power	550.00	
GN&C	200.00	550.0
Thermal	50.00	60.0
Total	5852.66	N/A

Table 5 Overall mission cost budget[5,7]

Segment Description	Cost (FY92$M)
R & D testing	1141.16
First unit	57.09
Ground segment	1530.65
Launch segment	115.70
Total	2844.60

Multiple Asteroid Sample Return Mission (MASR)

Mission Objective

The goal of this mission is to return sample material from three asteroids to Earth for scientific analysis. Asteroids Euterpe, Psyche, and Themis will be sampled, covering three major classes of asteroids, S (stony iron), M (metallic), and C (carbonaceous), respectively. The MASR mission utilizes numerous state-of-the-art technologies including a nuclear reactor for the power system, a low-thrust propulsion system, a deployable truss structure, and an optical communications system.

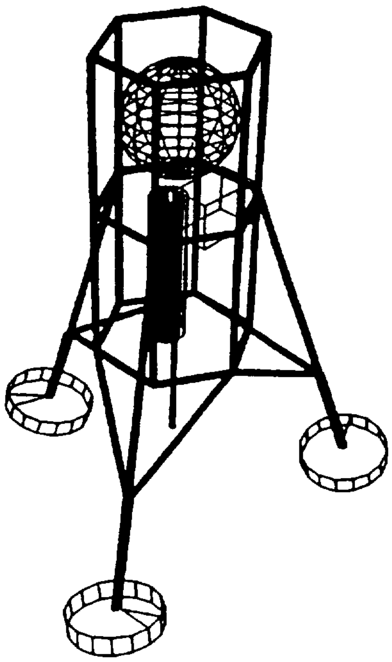


Fig. 5 Sampler/lander

Spacecraft Configuration

The spacecraft configuration consists of a tethered lander and a main spacecraft (see Figures 5 and 6). The tethered lander is stored inside the main spacecraft body and consists primarily of a drill and a small GN&C system. The spacecraft employs a reactor with shielding and radiator panels separated from the main spacecraft body by an expandable truss. This configuration keeps the harmful radiation from the reactor away from sensitive subsystems like the computer or scientific instruments. The main spacecraft body contains all required propellant, the lander, and all other subsystems.

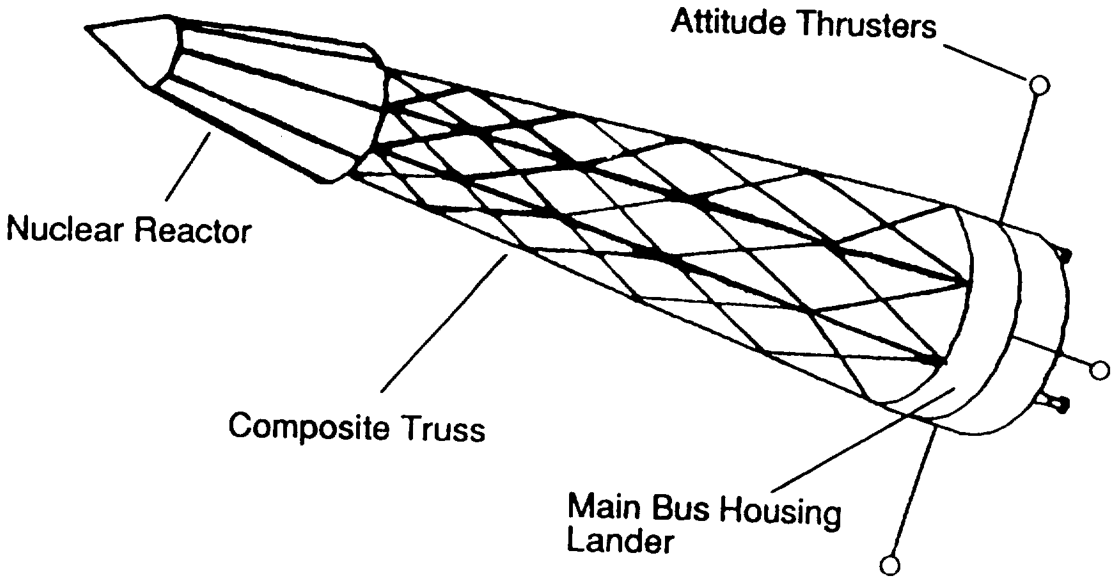


Fig. 6 MASR high technology spacecraft

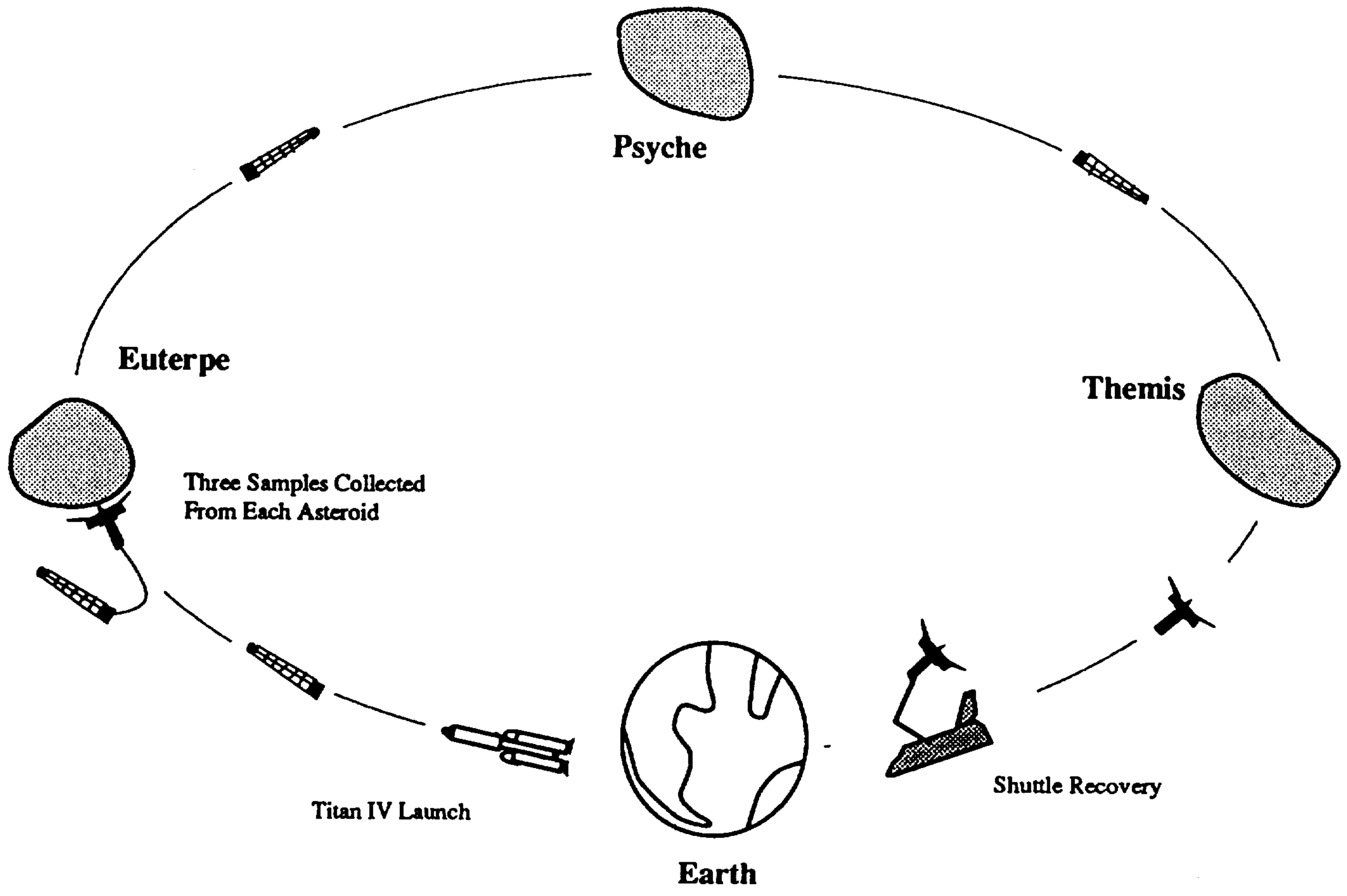


Fig. 7 MASR mission scenario

Mission Profile

The following description of the mission plan is summarized in Figure 7. The mission scenario begins by launching the spacecraft into LEO with a Titan IV on March 1, 2002. The Titan IV will be used because it is the only current launch system that can accommodate the spacecraft's mass, 15,800 kg, and size, 16 m long by 4.5 m diameter. During the launch phase, communication with the spacecraft will be through an omnidirectional antenna. Before the nuclear reactor is activated, power for the communication and housekeeping systems will be supplied by batteries. Once in LEO, the spacecraft will then deploy the partially collapsible truss structure and optical communications system, again by battery power. The omni antenna will then be switched off and the optical communication system used for the remainder of the mission. The reactor will be powered up and a functional check-out performed on all subsystems. The spacecraft will now rely on the nuclear reactor for power. A series of xenon thrusters will be activated, propelling the spacecraft toward the first target asteroid. The thrusters will cycle through thrust and coast stages to achieve the most efficient trajectory. This thrust profile has been calculated by NASA's QuickTop 2 (QT2) computer program.

Once the main spacecraft detects the asteroid with sensors, the rendezvous and docking (RVD) processor will take control and implement the necessary orbital maneuvers to orient the main spacecraft in the proper attitude. While the main spacecraft is approaching the asteroid, several scientific instruments will be collecting data to determine the best possible landing sites. A mass spectrometer, laser altimeter, and a radiometer will provide a complete map of the asteroid's surface. The main computer system will analyze this data and select the four best sites, three to sample and one as a backup. These landing sites may require additional maneuvering of the main spacecraft. The lander, while still attached to the main spacecraft through a tether, descends toward the asteroid and one of the landing sites. The lander's propulsion system will consist of 12 xenon thrusters powered by the reactor through a cable in the tether. The RVD processor on the main spacecraft will also control the lander during its rendezvous with the asteroid.

The lander attaches itself to the asteroid by drills in the landing pads. Three core samples, from three different locations on the asteroid, will be extracted from the asteroid along with other scientific data. While the lander is maneuvering to the next sampling site, the main spacecraft, while orbiting above, will follow it to the next site. This is necessary due to the limited length of the tether. Each sample will be encased in its coring barrel to prevent contamination. All samples and scientific information will be stored on the main spacecraft. Power and communications for the lander will be provided by the main spacecraft through the tether.

After the three samples are taken from the asteroid, the lander will then rendezvous with the main spacecraft. The RVD processor will also control these maneuvers and will dock the lander in the center of the main spacecraft. Once the lander is secure, the main spacecraft will then proceed to the next asteroid. Because of the large amount of data needed to be stored for these RVD maneuvers, data will be transmitted to Earth between asteroid encounters. When the next asteroid is located by the long-range sensors, the rendezvous and sampling scenario will then be repeated.

After the last sample is obtained, the lander will return and dock in its station in the center of the base of the main spacecraft. The main spacecraft will then begin its journey back to Earth. The return leg of the mission is similar to the first leg in that it will consist of a series of thrust and coast periods as calculated by QT2. Along with the thrust and coast periods the program provides the appropriate orbital paths for returning to Earth.

The ship will approach Earth to enter an orbit where it may release the lander, or the sample container alone, if feasible. This orbit will be designed such that the Space Shuttle, or its replacement in 2026, will be able to retrieve the samples.

After the sample container or lander is released, the main spacecraft will have completed its duties. The reactor will then be shut down using systems that are designed to function independently of the spacecraft. Two proposals have been suggested for dealing with the spacecraft after the mission is complete. The main goal is to eliminate possible contamination to the environment after the reactor is shut down. One proposed method is to have the main spacecraft thrust into a high nuclear-safe orbit that will not decay for approximately 1000 years. Another solution is to send the spacecraft on an Earth escape trajectory. If reentry were to occur after spending a long time in space, a majority of the radioactivity would have decayed. However, as an added safety feature, the nuclear system will be designed to safely accommodate accidental reentry. The SP-100 has been designed to remain inoperable, to survive the intense heat and aerodynamic forces of reentry, and to bury itself on impact in water, soil, or pavement.[8]

Overall Mass, Power, and Cost Budgets

Mass, power, and cost budgets[5] are shown in Table 6. A substantial safety margin is included in each of these categories to ensure a reliable design.

Table 6 Mass, power, and cost budgets

Subsystem	Mass (kg)	Power (w)	Cost[5]($M)
Communication	52	57	158
Computer	45	89	20
Drill	160	1200	329
GN&C	260	394	34
Landing gear	15	300	69
Launch vehicle	N/A	N/A	150
Power	6000	N/A	150
Propulsion	1800	86000	1423
Scientific inst.	120	250	180
Structure	220	N/A	373
Micromet. prot.	128	N/A	7
Thermal	125	N/A	16
Margin	400	1,000	50
Total	9325	89290	4227

Conclusion and Recommendations

Three design projects completed by the students have been discussed. There are still some unresolved issues in each of the missions which need to be addressed. First, a redesign of the monitor penetrator in the CNSR mission is required to place the RTG and optical communications package away from the rocket engine. Two members of the SASR team found that the hardness of the asteroid surface cannot be determined. A sampler drill to accommodate this variable should be examined. Using the QT2 trajectory code, the MASR mission length was calculated to be approximately 24 years. Missions of this length cause serious wear on systems. Reducing the length could be as simple as visiting the asteroids in a different order or visiting fewer asteroids.

Samples returned from the Moon by the Apollo astronauts have provided a wealth of information about its composition. Missions that return samples from comets and asteroids are important because they may reveal the intricate building blocks of the solar system. In addition, asteroids may contain mineral deposits that could be refined for use as propellants. Perhaps one day humans will visit the asteroids and comets, but until then these robotic missions can provide information of considerable significance to cosmologists and planetary geologists.

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