CAPTEM

Curation and Analysis Planning Team for Extraterrestrial Materials

"Dedicated to Maximizing Planetary Sample Science While Protecting the Integrity of NASA Collected Extraterrestrial Materials"

CAPTEM ANALYSIS DOCUMENT

Analysis of Investments in Sample Return Capability to Reduce Risks and Costs of Sample Return Missions.

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This report was prepared by the Sample Return Technology Investment Working Group organized by CAPTEM.

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1. Executive Summary

The Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) was requested by the NASA Director of Planetary Science, Science Mission Directorate to organize an analysis of potential linkages between simple and complex sample return missions and to identify those critical investments that would best reduce risk and cost for increasingly complex sample return missions over the next 20 years. To this end, the CAPTEM analysis has identified the following findings:

Finding 1. Sample return from a wide range of planetary bodies provides valuable insights into the origin and evolution of the solar system. It is a valuable exploration tool, as it increases the value of both orbital and surface observations. It should be an important component in NASA's overall solar system exploration strategy.

Finding 2. Higher risk and cost is commonly associated with sample return missions relative to other types of solar system exploration missions. This is a result of a sample return mission commonly being more complex and the necessity for the spacecraft to return to its point of origin. However, sample return has many important attributes. First, it is the closest approximation to a human exploration mission. Second, samples provide a unique perspective of a planetary body that cannot be obtained by any other mission approach. The mitigation of cost and risk with a mission puts an even higher priority on early technology development for sample return missions than for more conventional mission types.

Finding 3. There are technology linkages among different types of planetary missions that provide feed forward to increasingly complex sample return missions. Investing in developing and flying these technologies will increase the rate of success of sample return missions and lower the overall cost.

Finding 4. There are several types of technology/capability linkages that either are appropriate for several missions with minor modifications or feed forward to more complex missions: (1) Linkages between sample return and non-sample return missions such as precision landing and hazard avoidance. (2) Linkages among different styles of missions (flyby, touch-and-go, surface landing) such as hard-landing on Earth and preserving environmentally sensitive samples. (3) Linkages with a single style of mission to a variety of planetary bodies such as sample collection, manipulation, and storage on a planetary surface or sample collection and verification of success during a touch-and-go mission, or inert collection material on a flyby mission. (4) Linkages between sample return and human exploration such as rendezvous around a distant planetary body and return to Earth.

Finding 5. Several priority investments were identified. These priorities are placed within the groupings noted in Findings 4.

Between non-sample return and sample return missions:

Precision landing and hazard avoidance
Robotic arm
Autonomous robotic capabilities

Among all sample return mission types:

Hard-landing and sample preservation during such a landing
Environment control of sample containment for future generations of sample return missions
Curation of environmentally sensitive samples and biologic-organic samples

Among Flyby missions:

Inert sample collection material
Gas collection and storage capability

Among Touch-and-go missions:

Sample collection and verification
Robotic manipulation of sample for collection and transfer to container

Among surface landing missions:

Variety of sample collection tools (drill, rake)
Robotic manipulation of sample for collection, transfer to container, and final selection or discard.
Adaptable sample containment

Feed forward from sample return to human exploration:

Mars Ascent Vehicle
Rendezvous around distant planetary body

Finding 6. There are many technologies that are specific to a single planetary body (i.e. Mars Ascent Vehicle, Mars rendezvous). Investment in these technologies will substantially reduce risk to a single sample return mission and perhaps will provide feed forward technology to more complex missions to the sample planetary body (i.e. human missions) to reduce both cost and risk.

Finding 7. A Sample Return Technology Program (SRTP) would reduce the cost to individual missions, provide the technology in a more timely and cost effective way than could be provided if one had to depend solely upon mission-specific development, enable missions possibly otherwise unachievable within cost and schedule constraints, and provide an evolutionary path from simpler to more ambitious sample return missions. As shown, investments in technologies with commonalities across numerous missions would be beneficial to sampling of a variety of planetary settings. The success of such a program would be aided by (1) developing clear, prioritized goals with demanding yet achievable schedules, (2) Coordinate the Sample Return Technology Program (SRTP) with on-going mission-specific technology development programs and with prospective mission acquisitions, (3) Develop a clear, precise understanding of the current and desired end-point TRL of the selected technologies, (4) Provide a dedicated budget sized to the goals and schedule, (5) Use competitive procurements for technology developments, (6) Require a full technology development plan , and (7) Annual program/project assessment.

2. Introduction

Sample return missions provide a unique perspective not offered by either orbital or surface missions – the opportunity to study the returned material in well equipped Earth laboratories. Compared to most analyses done on a planetary surface, this unique perspective is based on scale (down to angstroms), precision, sample manipulation capability, and the ability to modify analytical experiments as logic and technology evolves. Sample return provides fundamental chronological and geochemical ground truth that enhances the value of both orbital and surface observations far beyond their stand-alone importance. Further, sample return is a vital necessity for the human exploration program for resource identification as well as human health and safety issues. The price paid for this unique and valuable information is increased cost and risk relative to other types of missions. To conduct sample return missions from a wide range of planetary bodies (asteroids, comets, small moons, Moon, Mars, Venus) on a regular basis these two factors must be minimized. Rather than looking at sample return as single point missions, each requiring their individual technology development, it would be much more advantageous to examine sample return technologies as threads linking simple missions (both sample return and non-sample return missions) to more complex missions and include them at the onset or early in the development of an exploration strategy. This approach, which is not planetary body specific, would result in an evolving technological heritage and thereby reduce cost and risk in each subsequent sample return mission.

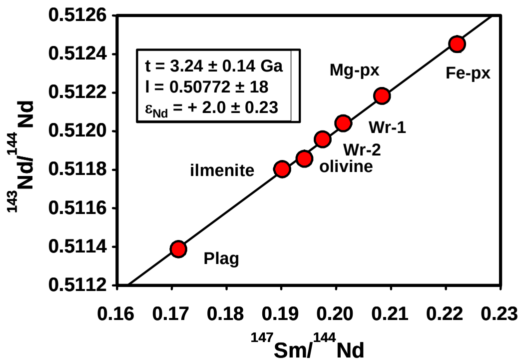
This analysis was requested by the NASA Director of Planetary Science, SMD. The mandate of this action committee was to define technological linkages between simple missions and complex sample return missions and to identify those critical technological capability investments that would best reduce cost and risk for increasingly complex sample return missions over the next 20 years.

This action committee is a temporary CAPTEM (Curation and Analysis Planning Team for Extraterrestrial Materials) committee. CAPTEM reports to the director of solar system science. The action committee is chaired by the CAPTEM chair. The committee consists of several permanent members of CAPTEM and outside members that bring expertise required to carry out the mandate of this endeavor. Membership of this committee include Ben Clark (Lockheed Martin), Noel Hinners (University of Colorado), Brad Jolliff (CAPTEM, NAC), Laurie Leshin (NASA Goddard), Steve Mackwell (Lunar and Planetary Institute), Clive Neal (CAPTEM; LEAG chair), Charles Shearer (CAPTEM Chair), Eileen Stansbury (NASA JSC ARES), Vladimir Lumelsky, (NASA Goddard), Mark Adler (JPL), and Jeff Taylor (University of Hawaii). As additional expertise was needed, technical contributions from other individuals, NASA Centers, and NASA analysis groups were requested.

The mandate of this action committee is to (1) identify technology components fundamental to carrying out sample return missions, (2) define how potential technology pathways feed forward through different classes of sample return missions, and (3) analyze what investments in sample return technology would reduce risk and cost of future sample return.

3. Importance of Sample Return to the Exploration of the Solar System

The unique planetary perspectives based on samples returned to Earth have a strong symbiotic relationship to orbital and surface observations/measurements. This unique perspective is closely tied to the use of terrestrial laboratories that have capabilities exceeding those of instrumentation currently associated with spacecraft surface (i.e., in situ) measurements. The terrestrial labs provide higher analytical accuracy and precision, afford a higher degree of spatial resolution (to angstroms), offer a high degree of sample manipulation, and facilitate multiple analytical approaches. Examples of these analytical attributes and the essential information that they yield are shown in Figure 1. These analytical



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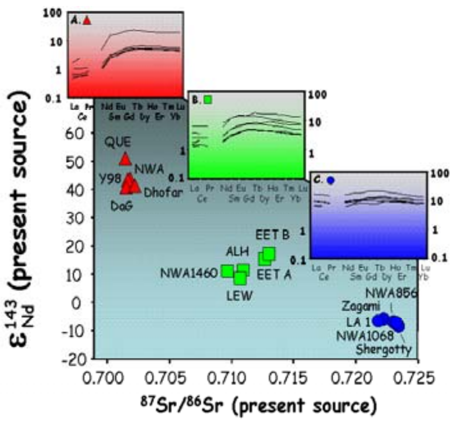

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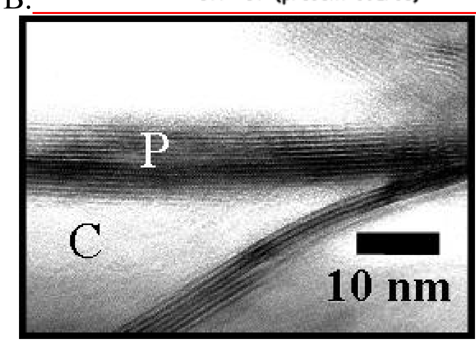

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Figure 1. Three examples that illustrate the multifaceted value of da derived from samples for understanding the origin and evolution of planetary body. (A). Sm-Nd isotopic data derived from an Apollo 17 mare basalt. In addition to illustrating the high precision required to produce a crystallization age for the basalt, it also illustrated that a high degree of sample manipulation is required to produce mineral separates and that the isotopic systematics also provide insights into the nature of the lunar interior (ε_{Nd}) and the impact history of the inner solar system as recorded on the Moon. (from L. Borg). (B) Sm-Nd, Rb-Sr, and Rare Earth Element data derived from martian basalts. This illustrates the precision required for the analysis and th usefulness of both multiple analytical approaches and the ability to modify experiments as logic and technology dictate over an extende period of time (from L. Borg). (C) TEM image illustrating H_2O-bearing sheet silicates within carbonates from martian meteorite ALH84001 (from A. Brearley).

attributes result in copious contrasts between sample return missions and other types of missions: (1) The best instruments can be used to analyze returned samples, not the best available at the end of mission design reviews. (2) Instrumentation is not limited by mass, power, reliability, data rate, the requirement to work autonomously, etc. This results in much lower cost to do an analysis**.** (3) Analyses are iterative and not limited by preconceived ideas at the time of the mission. (4) Unexpected or ambiguous result can be tested with additional measurements or modified experiments. <u>A new mission is not required to retest results.</u> (5) The diagnosis of analytical instrument technical problems and instrument repair can be better facilitated in a terrestrial lab, (6) The ability to modify experiments as logic and technology dictate over an extend period of time. (7) "Samples are the gift that keep giving" to future generations of planetary scientists. (8) Large numbers of scientists can *usefully* participate. This includes not only scientists involved in sample measurements, but also scientists who will place these data into a planetary context using orbital and surface measurements, and conversely the sample data will add value to the orbital and surface in situ measurements by providing a greater measure of groundtruth. The end result of all of these positive attributes of sample analysis and sample return missions is in a large science return and the establishment of a firm foundation to base other sample return and non-sample return missions upon. For example, the Moon is the best understood extra-terrestrial object because of the samples returned by the Apollo program and the planetary-scale context in which these samples could be placed through both orbital and surface observations**.** Numerous examples of the usefulness of samples in studying a planetary body and the importance of placing the samples with a planetary context are contained in "New Views of the Moon" (Jolliff et al., 2006).

The symbiotic relationships between sample return, orbital, surface, and exploration science enriches the data collected by any single approach and affirms that the integration of these approaches provides a logical and balanced scientific attack to exploring a planetary body (Figure 2). Examples illustrating the symbiosis between sample science-orbital science, sample science-surface science, and sample science-exploration science are shown in Figure 2. Samples from a planetary surface provide ground truth for orbital data, while orbital data allow samples from a local area to be placed into a regional and even planetary context. Surface material derived from a planetary interior (through volcanism or impact processes) can be inverted to interpret surface geophysical measurements, whereas surface measurements made by geophysical networks place the sample data within a context of planetary structure and dynamics. Finally, samples provide an initial foundation for understanding the in situ resource utilization potential and health hazards for human exploration of a planetary surface, while in situ measurements of mechanical properties of materials in a planet's environment will provide insights into their behavior during exploration and utilization.

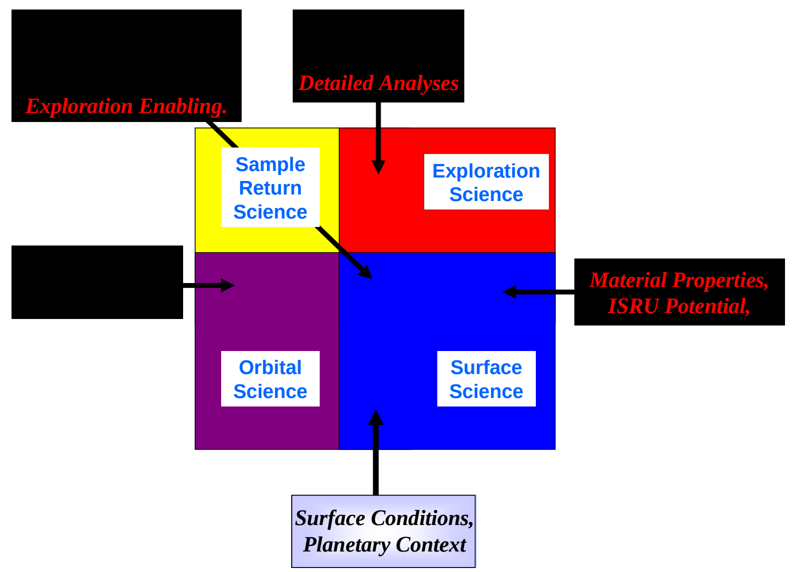

Figure 2. Overlapping relationships among sample return science, exploration science, orbital science, and surface science.

Using this balanced strategy for solar system exploration, with a robust sample return technology program, a variety of planetary bodies could be sampled over the next several decades. These include the Earth's Moon (specific terranes and environments unsampled by Apollo), Mercury, Venus, Mars, asteroids, comets, moons of the outer planets, and rings of outer planets. Many of these missions require some mission-specific technology development, but many sample return missions share similar technologies at the major system or subsystem level.

4. Historical Background

Returning samples of soils, dust, and atmosphere from planets, comets and asteroids to Earth for analysis was not recognized as important during the initial stages of space exploration. Yet, the dozens of United States and Soviet Union exploratory flyby and impact missions to the Moon and Mars in the early- and mid-1960s provided an initial stepping stone to sample return. Initial sample returns from the Moon by NASA were secondary to the overall goals of the Apollo Program. Robotic sample return missions that followed were few in number. They did, however, exhibit both the scientific promise and risk of sample return missions.

In the late-1960s and the 1970s, the United States and the Soviet Union pursued two different technological approaches to planetary sample return. NASA pursued a sample return strategy with its Apollo program, focusing on putting humans on the Moon. Sample return became the program's important second goal. Between July 1969 and December 1972, six manned Apollo missions landed on the Moon, emplaced science instruments and brought back a wealth of scientific data and about 380 kg of samples. Meanwhile, the Soviet Union sample return effort focused on an alternative to human missions. Beginning in July 1969 and ending in August 1976, the Soviet Union attempted 6 robotic sample return missions, all featuring automatic remote-control landing probes. Three of these missions accomplished their goal of returning lunar samples. The first success came in September 1970, with the Luna 16 mission bringing back to Earth 105 grams of lunar soil. This was followed by successes of Luna 20 and 24, bringing back 55 and 170 grams of samples, respectively.

Dramatic and successful as sample return was within the context of the Apollo manned program to land and explore the Moon, it resulted in a delay in the development of robotic sample return systems in the U.S. An automatic probe is controlled via a combination of remote commands by ground operators and its own autonomous decision-making means. It is cheaper and more universal than a manned flight; it can go where humans cannot.

Whereas there have been numerous orbital and surface missions initiated to a wide range of planetary bodies since the Apollo and Luna exploration of the Moon, there has been only three acknowledged sample return missions. The NASA's first automatic sample return mission (Stardust, a flyby to the comet Wild 2) launched only in 1999 and returned to Earth a sample material capsule in January 2006. Genesis followed (flyby mission, NASA, US) with a launch in 2001. It collected solar wind samples and successfully returned them to Earth in 2004, albeit with some damage to the sample collection plates. The Hayabusa mission was launched by the Japan Space Agency in 2003 to the asteroid Itokawa, to attempt collecting pebbles on its surface and returning the sample to Earth. The probe did land in 2005 on Itokawa, but experienced various problems, including the loss of its sample-collecting robot. It is expected to return back to Earth by 2010.

To date, no U.S. robotic sample return missions to a planetary surface have been attempted. As such a mission must include a sequence of challenging automation and control sub-tasks, its overall chance of success is the product of probabilities of success of individual sub-tasks. This puts a high premium on reliability of each sub-task. We are now approaching the required level. As an example, one likely component of many sample return missions is automated docking of two vehicles in space: the probe carrying the collected sample back from the planet has to dock with the orbiting Earth-return vehicle. Until recently only Russia and Japan have demonstrated limited automatic space docking. A major step in this area has been the recent Defense Advanced Research Projects Agency (DARPA) $300M Orbital Express experiment (March-June 2007): it has demonstrated a variety of successful docking operations - with exchange of fluids, exchange of hardware, etc.

5. Approaches to the Analysis

The organizational teleconference was held on April 13, 2007. Teleconferences were held approximately every two weeks until mid-June. The work product of each teleconference was clearly spelled out prior to each meeting. The committee met for two days at the Lunar and Planetary Institute for two full days on June 28 and 29, 2007. Members of the committee submitted contributions to this white paper during the month of August 2007.

This analysis was conducted in the following stages:

(1) Identifying technology components fundamental to carrying out sample return missions.
(2) Defining how potential technology pathways feed forward through different classes of sample return missions (i.e., sample containment).
(3) Defining the uniqueness of capabilities to a particular style of mission or planetary body (e.g., leaving the surface of Venus using balloons).
(4) Analyzing what investments would reduce risk and cost of sample return.
(5) Ranking sample return technologies and capabilities using the following criteria: (a) Commonality of technology among missions, (b) Criticality to mission success, (c) How much is overall risk of sample return missions reduced, (d) Reduce cost of future sample return missions, (e) Maturity of

technology/ capability, (f) Cost of development, (g) Relevance to high priority missions, and (h) Feed-forward thread from other missions (e.g., previous non-sample return missions demonstrate technologies that reduce risk/cost).

6. Styles of Sample Return Missions

6.1 Introduction

Returning samples from other planetary bodies to Earth is a complex endeavor requiring careful planning and execution. This begins with the mission objective(s) and the type of planetary body under investigation. Broadly speaking, planetary bodies can be subdivided into those with atmospheres and those without, with each type requiring a different sampling strategy. At the next level is the type of sample that will be collected and returned to address the science mission objectives. Such samples are broadly defined as solid, liquid, or gas. Each sample type requires specific technologies for sampling, caching, storage, and, once on Earth, curation to maintain them in a pristine state (i.e., unaltered from the condition the samples were in at the time of sampling). Each of the three broad sample types can be further subdivided. For example, solid samples include coherent rocks, dust, and ices, as well as unconsolidated regoliths; liquid samples could include water, methane, ammonia, etc.; and gas samples include different planetary atmospheres as well as volcanic gases. While this perceived complexity may lead one to conclude that each sample return mission requires an individualized technological approach to be successful, this white paper demonstrates that there are common technologies that link different sample return targets and strategies.

6.2 Sample Return Missions Styles

The term "mission style" refers to different ways of implementing the sample acquisition. As with planetary bodies and sample types, sample return styles can be defined by general categories – flyby, touch-and-go, and surface collection. While these three differ widely in the equipment required to prepare and to execute the sample collection phase, the following (equally important) phases - sample preservation and curation – are in principle identical in all.

6.2.1 Flyby missions. Here samples of material from the planet (or comet, or asteroid) are collected without touching its surface. The spacecraft flies over the planet, a single time or repeatedly, at an orbit sufficiently low so that the material sought crosses its trajectory. Such a mission was proposed, but not selected, to collect dust from the martian atmosphere. In fly-by missions a special collection device opens to collect dust/atmosphere particles. The sample collection unit proper can be essentially two-dimensional, something equivalent to a sticky paper that captures the particles, or a more complex three-dimensional collector. This type of mission is perfect for collecting samples of a planet's atmosphere or a comet's tail. A variant of this mission is one that creates a plume of material from an airless body that the spacecraft can fly through by impacting a probe into the surface.

As no landing is required, the only specialized technology needed is the sample collection unit, a relatively simple passive device. While being the simplest and therefore least expensive among the sample return mission styles, flyby missions are ranked noticeably lower than other styles in terms of scientific information they can yield. It may be a preferable style for a first exploratory mission, or if other sample return styles are not feasible. Table 1 illustrates several examples of flyby missions.

6.2.2 Touch-and-go missions In this type of mission the spacecraft briefly touches the surface of the space body, quickly collects the sample, and takes off, to move to another sample collection site or to return to Earth. This type of mission is ideal for asteroids or small moons, where the gravity force is negligible, obviating the need for elaborate expensive descent and ascent systems.

The virtual absence of gravity on asteroids brings about a problem opposite to that faced by a spacecraft landing on a planet: forces produced during the sample collection push the touch-and-go craft away from the asteroid, necessitating a special means to hold the craft in place – say, an anchor run into the ground or a thruster generating a balancing force.

The touch-and-go sample collection can be achieved with a relatively small and light craft. The Japanese sample return craft Hayabusa (spacecraft mass = 510 Kg) is an example of a touch-and-go mission: on November 19, 2005 it made a touch-and-go stop on the asteroid Itokawa. Hyabusa also illustrates an important technology development needed for this and all styles of sample return, namely verification of sample acquisition; while the spacecraft did make contact with Itokawa, there is no assurance that a sample was collected. Table 1 illustrates several examples of touch-and-go missions.

Table 1. Examples of flyby, touch and go, surface collection missions.

Mission Type	Planetary Body or Process	Sample type
Flyby		
	Mars, Venus	Atmospheric sample (dust, gas)
	Impact or volcanic plumes	plume (dust, gas)
	Comet	cometary dust
	Planetary Rings	dust
	Solar Wind	high-energy particles
Touch-and-go		
	Moons	regolith
	Asteroids	regolith, organics
	Comets	regolith, ices, organics
Surface Sampling		
	Comets	regolith, ices, organics
	Asteroids	regolith, rocks
	Moon/Mercury	regolith, rocks
	Mars, Phobos, Deimos	regolith, rocks, ices, organics
	Venus	regolith, rocks, atmosphere
	moons of the outer planets	regolith, rocks, atmosphere, organics

6.2.3 Surface Collection Obtaining soil samples from moons and planets (our Moon, Mars, Venus, etc.) requires the safely landing on the surface and spending sufficient time on it. This is the most complex of sample return mission styles, since the operation requires sufficient technical means to descend to the surface, reliably collect and preserve the sample, and then ascend from the planet in order to rendezvous with the waiting orbiter vehicle or to head directly toward Earth. Soft landing is critical to guarantee the right conditions for the sample collecting equipment. Besides the need for sufficient fuel for safe landing, the landing vehicle needs to carry an ascent stage. This increases the craft's mass considerably: typical mass estimates of the sample collection lander for Moon and Mars are in the range of 1,000-1,500 Kg. For comparison, the on orbit dry mass of the Luna 16 spacecraft was 5600 kg.

The sample collection equipment can appear in a great variety of designs, from a simple shovel or scoop to a torpedo device shot, during the descent, into the ground and used to acquire samples from under the surface, to producing an artificial explosion and then collecting the resulting debris. Other devices include a robotic manipulator arm to "grab" rock samples to coring devices that can return cores of uniform size from more substantial outcrops. The particular choice depends on many considerations, including the mission's science goal, budget, the desire to minimize complexity and maximize reliability, etc. The reduction in system complexity must be balanced by the need to provide sufficient sensing information to the device itself and to the ground operator (e.g., for teleoperation control of the task). Adding various sensors and cameras, or placing the sample collection tool in the hand a robot arm manipulator quickly adds to complexity and cost. Placing the sample collection device on a mobile robot rover adds much flexibility in the choice of specific sites of sample collection. This, again, adds to system complexity – and may, in turn, require additional complex hardware for transferring the sample from the rover back to the ascent vehicle. Table 1 illustrates several examples of surface sampling missions.

7. Technologies and Capabilities Required for Sample Return

7.1 Introduction

Sample return missions are generally more complex than other robotic planetary exploration missions because they need to return safely to their body of origin (Earth) with a "payload" of collected planetary materials. Perhaps, relative to other robotic missions, they are the closest approximation to human flight in overall goals. Further, in many cases a sample return has to perform a series of interrelated, complex tasks. Each stage of a sample return mission must accomplish its task and be integrated with follow on stages of the mission to be successful. The stages required to accomplish a generic sample return mission (regardless whether flyby, touch and go, or surface collection) and their relationship to one another during a mission is illustrated in the flow diagram in Figure 3. This diagram not only illustrates some of the similarities among all sample return missions, but also illustrates differences among flyby, touch and go, and surface collection with regards to the complexity in technology and coordination among technologies. Using this flow diagram, we identified required technologies within each sample return mission stage, identified potential technology linkages (and distinct uniqueness) among and within flyby, touch and go, and surface collection style missions, and ranked the technologies with regards to their potential for investment for lowering overall cost and risk of sample return missions.

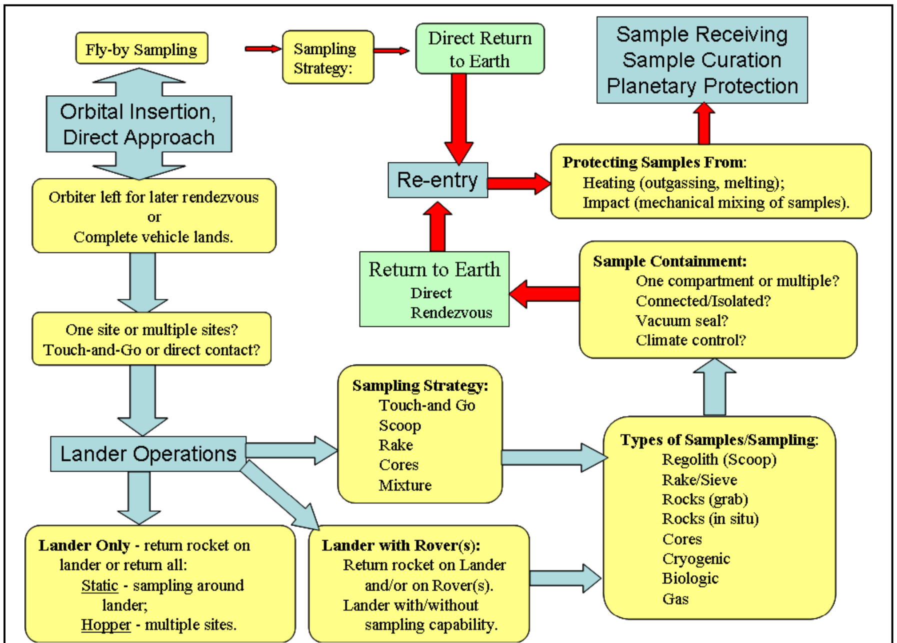

Figure 3. Flow diagram illustrating technologies and capabilities required to fulfill the objectives of a sample return mission.

7.2 Pre-launch: Sterilization protocols & verification procedures. For most missions, sterilization protocols and verification procedures are adequately developed. These technologies are deficient and costly for planetary bodies with demanding planetary protection requirements (e.g. Mars, Europa). Exploring analytical methods to quickly identify and fingerprint organisms on a spacecraft are worthwhile investments in lowering the cost of the pre-launch mission stage and increase mission success, especially if the mission has astrobiology-centered objectives. Developing these techniques will also lower the cost of pre-launch procedures for missions with less rigorous planetary protection requirements.

7.3 Orbit Insertion and Direct Approach

Orbit insertion and direct approach to landing are now relatively common events in solar system exploration. We have orbited an asteroid, the Moon, Venus, Mars, Jupiter and Saturn and have landed on an asteroid, the Moon, Venus (USSR), Mars, and Titan (ESA with significant NASA participation). The main issues to be worked will be targeting of specific sites on objects and then precision landing at those sites. This will be especially important if samples are cached ahead of the return vehicle landing or if a targeted geologic feature (e.g., terrane boundary) is required for science goals, in which case pinpoint landing may be required. With the possible exception of pinpoint landing, orbit insertion and direct approach activities should not be considered technological drivers on future sample return missions.

7.4 Target Body Lander Capabilities

7.4.1 Environments. Surface landers are designed uniquely for the target body's gravity, atmosphere or lack thereof, and surface characteristics, and for the payload mass, volume, and landing loads limitations. This results in few common aspects of these systems across targets. However, they all require that some bounds be placed on the possible environments that they might encounter during landing.

The key recommendation for bodies to be considered for sample return, as well as in situ surface investigations, is to consider the characterization of the surface and atmosphere (as applicable) of the target body by precursor orbiter missions. Often the science objectives of the orbiter significantly overlap lander environmental characterization for engineering purposes. This synergy should be explicitly studied and data requirements to benefit future landers be established during the science definition phase of these missions. For example, knowledge of atmospheric characteristics is needed for precision landing on Mars. This should be conducted even in those cases where possible landed missions (sample return or not), are considered to be in the far future.

7.4.2 Unique Challenges. Landing challenges for sample returns are the most significant at Mars. This is a result of considering and dismissing landed surface sample returns from Venus and the outer planet moons as infeasible with current launch vehicle and propulsion technologies ("Brute force" solutions are cost-prohibitive). This leaves Mars as the most difficult remaining target. Due to the mass requirements for a Mars sample return mission, the landing systems will either need to deliver masses significantly higher than our largest system currently in development, the Mars Science Laboratory entry, descent and landing system, or it will require a significant advancement to that system to enable a surface rendezvous (e.g., pinpoint landing of separate landers for sample collection and ascent from the surface). In either case, significant capability development will be required in advance of the first Mars sample return project start to mitigate those development risks.

7.4.3 Common Capabilities. One capability stands out as deserving of investment. That is terminal descent surface sensing with radio and optical sensors. This has consistently represented a significant development risk in recent Mars landed missions. The development and field testing of RADARs, LIDARs, and camera-based systems for surface-relative range and velocity measurements, map-relative location determination, and surface hazard assessment, in advance of those missions that will require them would greatly reduce the risks those projects will face.

This capability is common to landers over a wide range of possible targets. Only Venus and Titan may not require such sensors, due to their high atmospheric density and very low terminal velocity on descent drag devices. The remaining small and large bodies all require some form of terminal descent sensing, including touch-and-go targets. The LIDAR and camera-based developments would also reduce the development risk for orbital terminal rendezvous and sample transfer and acquisition verification systems.

The final key investment that would significantly benefit sample return landers is the characterization of previous landing systems, especially where aspects of those systems are difficult or impossible to test on Earth. The first sample return mission to a given target will often be preceded by in situ landed missions to that same target. The sample return lander will then develop the heritage of the previous landed mission to achieve its more ambitious objectives. In those cases the precursor missions should be equipped to characterize landing system performance for those key aspects. Examples of such difficult-to-test landing system aspects are the entry, hypersonic guidance, and parachute systems for Venus, Mars, and Titan.

7.5 Surface Mobility and Articulation

7.5.1 Environments. Surface mobility and articulation systems will be needed to access the desired samples, to place and operate the sample acquisition equipment, and to transfer the samples between surface elements. These systems will be highly optimized to their expected environments and their range, speed, and accuracy requirements. However, they all require that those environments be adequately characterized for design and for verification and validation activities.

The characterization of small (≤ 1 m) surface features of the target body by precursor missions is the key consideration for the design of surface mobility mobility systems for sample return (and in situ analyses). This includes the characterization of the materials from which the samples will be acquired. Often the science objectives of the precursor missions significantly overlap with environmental characterization for engineering design. This synergy should be explicitly emphasized and observation requirements be established during the science definition phase of these missions. This should be done even in those cases where possible sample return missions are considered to be in the far future. However, a balance must be made between enforcing the making of such observations with a negative impact on the precursor mission objectives.

7.5.2 Unique Challenges. Low gravity bodies pose unique challenges to reliable mobility and surface operations. As an example, in 2005 the Hayabusa spacecraft had attempted to drop its hopper robot onto the surface of asteroid Ikotawa, from the 200m height – when falling, the robot missed the asteroid and disappeared in space. Nothing of the kind would have happened on the Moon or Mars. If multiple samples from distinct locations are required for low gravity bodies, a trade study of multiple touch-and-go's vs. a hopper or crawler system would need to be performed. If a hopper/crawler system appears to be the optimal approach, then a technology development would be required in advance of the project to mitigate the development risk of that system. In particular, the issues of anchoring and providing a normal force for sample collection devices would need to be developed and tested. If a hopper is the desired approach due to range and speed requirements, then a technology development that includes a test program for multiple, safe hopper landings would be needed. In all cases, an alternative approach using touch-and-go should be maintained in the design space both for comparison with the technology developments and as a fallback design option.

For Mars, range and speed considerations may dominate the ability to collect a scientifically desirable sample, either by the sample collection rover if it arrives with the ascent vehicle, or by the sample fetch rover if it has to conduct the final leg of the surface rendezvous to collect a previously cached sample. Improved systems for the mechanical, sensing, and software aspects of high speed traverses, relative to the current MER/MSL technology, would be a valuable investment to mitigate other mission risks, such as adequate time for sample collection or risks to the accuracy of pinpoint landing for surface rendezvous.

7.5.3 Common Capabilities A significant challenge for sample collection on any surface will be the timeline in which the samples must be collected. This must weigh against the available communication sessions with Earth used to control the sample collection operations. (The one exception to this is Earth's moon, due to the very short light time and high availability of communications.) An investment in autonomous robotic capabilities in advance of a sample return project would pay significant dividends in the ability to collect samples and assure the quality of those samples. The higher the level of autonomous operations, and the more capable those operations are at compensating for uncertainties in the surface environment, the better the sample collection operations will be in speed and effectiveness. This investment in software capability would apply across a wide range of mobility, articulation systems, and sample return targets. An example of a high-level command would be the identification of a target location on an object some distance away by the operator on Earth, resulting in a single autonomous activity by the robot rover involving a number of operations - approach the target, select a specific site on the target, acquire a sample from that site, characterize the sample, and store the sample, all without operator intervention. Keeping the control for those operations with the operator would increase the required operational time by a factor of 100 or more compared to an autonomous operation. While such a slow pace was deemed acceptable in recent experiments with the Mars rovers, it may not be so in sample return missions.

The successful transfer of samples between mission elements and within those stages will require autonomy developments as noted above, as well as the development of reliable mechanical transfer (including verification) schemes and interfaces. So far no nation has demonstrated the ability for reliable transfer of sample material from one device to another (say, from rover to lander), either under autonomous or remote ground operator control. While the detailed designs will be largely unique to each mission (and readily tested on the Earth), they will share the key components that provide the robot's ability to operate autonomously in the planet's highly unstructured environment, resulting in high reliability and cost savings across the sample return missions. Modest investments in the exploration of different approaches to the reliable sample transfer problem will greatly facilitate sample return project formulation and implementation. In particular, highly reliable attachment, release, sensing, verification, and fault protection systems for sample transfers should be investigated. The development should allow for the acquisition of a sample container from a non-operating mission element. This work should take into account the maintenance of sample integrity and contamination control. For bodies with planetary protection sample return requirements (such as Mars), the prevention of inadvertent sample transfer and breaking the chain of contact for sample containment would need to be addressed as part of the sample transfer process.

7.6 Types of Samples/Sampling

As noted above, there are a variety of sampling missions styles range from simple flyby to a more complex "touch-and-go" sampling that does not involve direct landing on the surface to very complex landed sample return missions (with or without rovers; at one locality or several). Within these different mission styles are numerous sample types (Tables 1 and 2), some of which need specialized collection tools and caching capabilities. The commonalities of sampling technologies are highly dependent upon science goals and materials needed to fulfill those goals. An analysis of linkages between sampling technologies and missions is illustrated in Table 3.

Flyby missions are appropriate for collecting either material discharged from a planetary body through natural (cometary dust, impact or volcanic plume) or induced (impactor from the spacecraft producing plume from surface, such as demonstrated by Hayabusa) processes or skimming the upper atmosphere for gas and dust samples (Mars, Venus). The collection approaches used by Genesis and Stardust missions provide a firm foundation for subsequent missions of this type. Some of the inherent cost and risk associated with these missions are tied to drag, heating, and the alteration of the impacted particles during collection. Although the sampling of various planetary bodies does have significant differences, there are collection approaches that have commonality. These include (1) development of a collector material that is more inert than the aerogel used in the Stardust mission, (2) developing approaches for collecting atmospheric samples during flyby that reduce collection-induced alteration, (3) strengthening of collection mechanisms for different planetary bodies (Venus versus Mars) and (4) approaches for producing artificial plumes from the surface of a planetary body.

Touch-and-go missions appear to be a cost effective way for the collection of regolith samples from low-g, airless planetary bodies such as asteroids, moons and comets. There are several sample collection approaches that could be used on these missions such as a scoop attached to a tether/arm or firing projectiles at the surface and collecting resulting material (i.e., Hayabusa). There are numerous cost and risk concerns about collection of samples in this way, but collection technologies for these types of missions have significant commonality. While NASA does not have flight experience with this type of sampling, there has been some development associated with Discovery missions (e.g., Deep Impact, NEAR). However, further development is needed. For example, although this type of sample collection was tried on the Hayabusa mission, no nation has yet successfully demonstrated the touch-and-go sampling. Further, sample collection, verification of successful collection results during missions, transfer, and storage mechanisms are not well developed. Sample mass is relatively low and could be compromised by engine plume impingement. As the failure to land the Hayabusa's robot onto Itokawa illustrated, on this type of missions the ground operator control is overly sensitive to the command latency due to Earth-to-target distances: given the lack of gravity, even a small difference between the actual and the assumed spacecraft-to-target distance can be crucial.

Many of these problems associated with touch-and-go missions can be remedied to make them more competitive for Discovery-class missions. This includes the development of high-speed sampling mechanisms, as well as transfer and storage mechanisms, more reliance on autonomous operation, and the capability of verifying a successful sample collection event. Scooping samples from a surface seems to be more promising than projectile-style collection for collecting both a larger sample mass and larger rocks. However, sample mass requirements are dependent upon the science goals of the mission. Enabling more than one descent and collection (multiple sampling of the surface) would enable collection of a larger sample mass with potentially more sample diversity.

Sample return missions from a planetary surface have a much higher variety of potential sampling tools than either flyby or touch-and-go missions. These are designed for the collection of a variety of different sample types that are closely linked mission science and sampling philosophy (Table 2 and 3). These sampling tools include scoop to sample bulk regolith, rake or sieve to select course-fines in the regolith, coring devices to sample outcrop or large rocks, robotic hand to select large rock samples, as well as potentially cryogenic, biological, and gas sample acquisition.

Of the different sampling approaches, the scoop is the best developed. NASA has experience in this type of sampling and robotic arms are well developed. This approach could be done from a simple lander or in conjunction with a rover. It also has significant commonality through most types of surface sampling missions and is the least risky. Development of sampling, transfer, storage, and verification mechanisms, including an integrated system would be important in reducing risk and cost for numerous types of sample return missions. To extend this sampling tool's use to more hostile environments such a Venus, reengineering would be required to withstand higher temperatures and pressures.

One disadvantage of collecting samples with a scoop is that the planetary regolith cannot be high-graded for individual rock fragments. Sieving the regolith with either a sieve or a rake provides a lower technology method of separating coarse-fines from the regolith. Coarse-fines collected by a rake by Apollo astronauts were of great scientific value because of their chemical diversity. NASA has experience in this type of sampling, but not robotically. Robotic arms will have to be developed to either transfer regolith to a sieve or operate a rake. Mechanisms to transfer samples to storage and to manipulate samples (to discard) are highly desirable for this type of sample collection as well as all of the following sampling technologies.

Having the ability to collect rocks larger than coarse-fines or cores has significance for the analysis of coarse-grained lithologies, for better understanding the petrogenetic relationships among lithologies, and for sample distribution to a large number of labs for a large diversity of analyses on the same sample. Although robotic arms are well developed, this method of sampling requires a "robotic hand" to grab the sample and then cache the sample on the rover until collection is complete. The ability to discard samples from the cache is important in order to allow the return of samples that most impact the science objectives.

For sampling outcrops and large rocks, coring provides access to samples unavailable by any other techniques. Coring provides greater access to sample diversity in a given location; gets below weathered rock surfaces, allows collection of oriented samples, and enables examination of regolith stratigraphy. Coring allows the collect of samples of know dimensions that enables efficient storage. NASA begun the development of this technology, but it has not been proven in flight-like environments. Key to the development of coring is operations in vacuum or near vacuum (Mars) environments, the robotic deployment of drill stems, and understanding sample contamination during coring. As with other sampling technologies, developing the ability to discard, transfer, and store cores is important.

Sampling environmentally sensitive samples is very relevant to a wide range of planetary problems associated with Mars, the Moon, comets, asteroids, and Venus. Cryogenic and biologic sampling is important for many of these planetary bodies and their level of complexity is substantially greater than sampling methods thus far discussed. Both methods require developing environmental controlled sampling, sample manipulation, and caching that involves limited changes in temperature and limitations in the degree of contamination. Sampling methods with these criteria must feed into sample containment that provides the same conditions. The first steps in developing these sampling methods require investments in more simple robotic sampling technologies and containment.

In addressing the technologies needed for routine sample return, we examined several different approaches. The first was concerned with the types of sample that may be collected, the investment needed, and whether the investment was in developing the technology, or whether the technology was already available but engineering was required to develop it for application to planetary exploration (Table 1). The assumption made was that investing in development and/or engineering advancement would automatically reduce risk associated with sample return.

Table 2.

Sample Type	Investment	Development	Engineering
Atmospheric Dust	Inert Collector Material	X	
	Strengthening Collection Mechanism		X
	Optimal speed/height of insertion & collection		X
Gas	Sample collection & verification mechanisms, containers, and seals	X	
	High speed sample collection (e.g., flyby) mechanisms	X	X
Regolith (Scoop)	Sampling, transfer, storage, & verification mechanisms	X	X
	Multiple descent/ascent		X
	Robotic arm		X
Coarse-fines (Rake)	Sampling, transfer, storage, & verification mechanisms	X	X
	Multiple descent/ascent		X
	Coupling this sampling technology with rovers	X	X
Cores	Sampling, transfer, storage, & verification mechanisms	X	X
	Environmental control on sampling, transfer, and storage mechanisms	X	
	Multiple descent/ascent		X
	Robotic deployment of drill stems	X	X
Rocks	Sampling, transfer, storage, & verification mechanisms	X	X
	Multiple descent/ascent		X
	Development of robotic "hand" for grab samples	X	X
	Integration of imaging system, including microscopic/hand lens, with sampling system	X	X
	Development of systems to sample in-situ outcrops	X	
Cryogenic	Sampling, transfer, storage, & verification mechanisms	X	X
	Environmental control on sampling, transfer, and storage mechanisms	X	
	Monitoring of samples during return to Earth	X	
	Design of Curation Facility	X	
Biological	Sampling, transfer, storage, & verification mechanisms	X	X
	Environmental control on sampling, transfer, and storage mechanisms	X	
	Design of Curation Facility	X	
	Monitoring of samples during return to Earth	X	
	Sterilization procedures (forward and backward)	X	X

Table 3. Simple, Intermediate, Complex Mission Concepts.

Flyby Sampling			
	Simple	***Intermediate***	***Complex***
Spacecraft			
Sample type	Dust	Dust	Atmospheric/volcanic gases and dust
Mode	Fly through upper atmosphere. Fly through volcanic plume	Fly through plume produced by projectile fired from spacecraft	Fly through plume/atmosphere
Sampling mechanism	Aerogel (or equivalent) capture	Aerogel (or equivalent) capture	Canister + aerogel (or equivalent) capture
Touch-and-Go Sampling			
Spacecraft			
Sample type	Regolith	Regolith	Regolith + Rock
Mode	One descent and grab	More than one descent at the same site	More than one descent at different sites
Sampling mechanism	Tether and scoop	Tether and scoop	Tether, scoop, mechanical "hand"
Landed Sampling			
Spacecraft	Lander (no rovers)	Fetch rover	Sampling rover or hopper
Sample Type	Regolith	Regolith + rocks	Regolith, rocks, ices, gases
Mode	Sampling from lander - one site	Sampling from Lander - multiple sites	Sampling from Lander - multiple sites
Sampling mechanism	Scoop, rake or sieve	Sampling cache	Scoop, "mechanical hand", corer, rake or sieve

7.7 Launch from Surface

7.7.1 Ascent vehicle The method of returning samples to Earth must be tailored to the object of interest. For example, samples collected at a comet, asteroid, or very small moon can be transported back to Earth by the spacecraft that accomplishes the outbound leg of the mission. Low-gravity bodies, with escape velocities measured in cm/s, can be accessed with simple thruster-class engines, which all 3-axis stabilized spacecraft include. Many credible missions of this type have been proposed based upon proven engineering capabilities.

On the other hand, launching from the surface of Venus, for example, is extraordinarily challenging not only because the surface gravity and escape velocity are equivalent to that for a launch from the surface of Earth, but also because the atmospheric drag is one hundred times higher. Balloon-borne rocketry is in principle a solution, but the engineering challenges are so great that sample return from Venus is not currently or foreseeably credible within the cost/benefit constraints of the planetary exploration program. Likewise, for the giant planets and many of their satellites the energetics are highly unfavorable to such missions.

Earth's moon, with its modest gravity and an escape velocity of 2380 m/s, does require a significant rocket capability but with the absence of an atmosphere, the engineering designs are so straightforward that several different missions have been proposed to be feasible without new technological advances. An example is Moonrise, a New Frontiers class mission, which was successful in being down-selected for a detailed Phase A Concept Study. Several U.S. institutions have claimed to have this capability without the need for a special advanced technology development program. For another large moon of similar size, Titan, ascent would be extremely challenging because of the cryogenic surface environment, its extended dense atmosphere, and the gravitational well of Saturn. But development of sampling technology for the Moon's permanently shadowed craters to sample the putative hydrogen deposits would also be applicable for use on, for example, Titan, as well as for comets.

Mars is an intermediate case. For this planet, the engineering challenges are neither simple nor insurmountable --- this is the conclusion of NASA in-house studies as well as private and government-funded studies by at least three major industrial firms. Furthermore, return of documented martian samples is the highest priority sample return mission in the solar system according to numerous NASA advisory groups and is very high in future Mars science objectives.

Mars surface gravity is 38% of Earth, and its escape velocity is 5027 m/s. Various studies have considered liquid, solid, gel, and hybrid propellant systems. NASA-funded and directed consortium studies considered all options. This funding was terminated in 2001. Although no new technological breakthroughs are required to develop a Mars Ascent Vehicle (MAV), there are many uncertainties surrounding its actual implementation. These uncertainties are critical to development of the entire Mars Sample Return (MSR) scenario because the size, configuration, and thermal capabilities of the landed system for MSR are totally dependent upon the design details of the MAV. Thus, the MAV is the critical link in the chain of a MSR mission scenario, which takes advantage of staging the sample into Mars orbit. This architectural approach is desirable for two independent but very important reasons: (1) it minimizes the mass of the system and hence lowers the cost of the Earth launch vehicle, and (2) it "breaks the chain of contact" between Mars and Earth to relieve planetary protection concerns. In this scenario, the martian samples would be packaged in a container, sometimes called an Orbiting Sphere (OS), which would be left in Mars orbit for pickup by an independent Mars orbiter / Earth transit vehicle.

From a cost and implementation risk standpoint, the MAV is currently the most critical link in the chain for a successful MSR mission. If NASA would sponsor the development of the MAV now, significant risk to the program and a far more competitive, lower risk MSR program could be constructed. It is therefore recommended that NASA re-institute MAV development. In contrast to the previous approach, however, when budgetary support was greater than now realistic, it is recommended that a fully independent competitive development be sponsored, rather than a large consortium approach. The basic requirements for a MAV should be developed in sufficient detail to enable an effective competition. Previous specifications were for multiple samples with an aggregate mass of 0.5 kg to be segregated and containerized into an OS of nominal 19-cm diameter and a total mass of 5 kg. The OS would constitute the payload of the MAV, and the MAV would have various performance requirements such as launch platform instability limits, final orbit parameters and their uncertainties, capability to operate in a cold martian environment, etc. NASA should develop the MAV to include at least one demonstration test flight, notionally from a highly altitude balloon in Earth's atmosphere to simulate the martian atmospheric drag conditions. Once a MAV development is finalized, the MSR program can be placed on a much firmer footing with respect to cost, cost risk, development time, and reliability.

7.7.2 In Situ Resource Utilization (ISRU). The capability of producing propellants on Mars to power the return of samples could have significant benefits to a Mars sample return mission. The concept of ISRU, reviewed recently by Landis et al. (2007), is simple: use the atmosphere and perhaps regolith of Mars to manufacture fuel. This reduces the amount of propellant that must be transported to Mars, which may translate into lower cost and/or a larger mass of sample returned. One argument against ISRU is that the technology is unproven, hence adding risk to the mission. However, one might argue that there is reduced risk from adding margin to the ΔV needed for sample return. In addition, human space exploration would benefit greatly from development of this capability.

In spite of its importance and useful previous research, considerable technology development is needed. The systems must be of low mass, otherwise there would be little benefit. Research is needed into the most practical approach (e.g., solid oxide electrolysis, Sabatier reaction, etc.), which involves both laboratory studies of methods and integration of new knowledge of the Martian surface into our planning. All candidate systems need to be tested rigorously to determine propellant yields, operational lifetimes, losses, and other important factors. This requires a specific research program and needs to begin soon to know if in-situ propellant production can be developed in a timely fashion to enhance Mars sample return missions. It is noted that successful demonstration of ISRU capabilities will also reduce risk for exploration activities beyond sample return, such as for human exploration and commercial development of the Moon, as well as human exploration of Mars.

7.8 Sample Containment and Preservation

Obviously any sample container or cache should be constructed from materials that will not contaminate the collected samples. A review of such materials can be found in Neal (2000). Different levels of sample containment and preservation have been desired, depending upon the type of target body and the ambitiousness of the science objectives. For example, for a so-called “cryogenic sample return” for cometary sample return (CSR) containing the original volatiles (ices), a temperature of 150 K or lower is needed to preserve H_2O-ice in its presumable pristine crystalline phase, and even lower temperatures would be required to preserve suspected higher volatility components such as CO, N_2, or other ices. This temperature requirement is extremely difficult to meet: the sample could not be allowed to exceed this temperature from the time it is collected to the time it is interred in the sample curation facility in hot Houston, TX. This would include the energetic sample collection process itself, the spacecraft carrier, the entry heating, and an exposure of hours to perhaps days in the desert recovery site (e.g., Utah or Australia). Obviously, this could be a major engineering challenge. However, it is also possible to construct CSR mission scenario’s for which this is not necessary by providing means to analyze volatile compositions at the comet or to preserve samples as gases, and then concentrate mission resources on successful return of the highly important non-volatile mineral phases and amorphous components. Similar considerations would be needed for sample return from the polar regions of the Moon, Mars, Mercury, as well as from outer planet moons and comets.

At the other extreme are lunar surface samples (excluding permanently shadowed regions), which intrinsically are devoid of significant volatiles and are periodically baked at higher temperatures (380 K or higher) by the lunar diurnal cycle. Some lunar samples do not need compartmentalization – for example, grab samples of surface rocks, bulk samples of regolith, or high-graded lithic fragments. Asteroidal samples are typically in a similar category, for which sampling is relatively straightforward and stratigraphic sampling is of lesser or no concern.

On Mars, for example, the situation is much different because samples of bedrock are of extreme importance and many rocks of interest may be much too large to return to Earth. To collect sub-samples of these materials, small coring drills have been suggested and prototypes built. Deep drilling (few meters, or more) is also of interest on Mars and comets, and sub-samples of these cores could be accomplished with a mini-corer. For this important reason, NASA should consider further future funding support of minimum-energy, mini-coring drills that can operate in vacuum or near-vacuum conditions.

An additional concern for Mars sample containment is planetary protection back contamination. These stringent requirements call for an assured sealing system with verification of the seal before samples can be permitted to be returned to Earth. Technical issues with this containment include fail-safe sealing in a dusty, intrinsically electrostatic environment. These are areas that should be considered for technological development, although many promising approaches are available and it is possible that such capabilities could be developed with acceptable risk and on a timely basis by an authorized MSR Project.

An additional architectural option for sampling includes caching of samples by earlier missions. The Mars Science Laboratory (MSL) has now been directed to provide such caching capability. Although sample cores would be ideal, MSL will need to rely on storage of grindings and small-particle samples. Issues of importance include sample handling, segregation, standardization of a handover interface, and perhaps containerization. However, the MSL implementation will be a demonstration that even late in a development project, the project can accommodate a sample return cache because of knowledge gained from previous sample return missions (an indirect sample return technology program of sorts). If dedicated technology-development funds were available, it might be useful to investigate options for achieving these goals in the most efficient means possible.

The most challenging of these is comet cryogenic preservation. A container that has higher thermal preservation properties (using thermal isolation and possibly phase-change buffers or active coolers) could be an enabling step, although careful systems engineering and recovery operations would have to be invoked to provide the end-to-end thermal preservation.

7.9 Return to Earth

7.9.1 Direct Sample Return. We have significant experience with returning spacecraft safely to the surface of the Earth, from both robotic and human missions. In particular, the Mercury, Gemini, Apollo and Soyuz return capsules have repeatedly tested heat-shielding insulation sufficient to maintain modest temperatures inside the capsules and parachute systems capable of providing a moderately soft landing. Robotic reentry is also reasonably mature, and has generally less rigid requirements than human reentry systems, due to the normally more robust and smaller payloads. The trades between minimization of mission cost and capsule mass for robotic missions generally favor smaller capsules with less robust heat shielding and harder landings. The recent success of the Stardust and Genesis missions in returning extraterrestrial samples to Earth safely (despite problems with parachute deployment with the latter mission) illustrate that no major technological challenges stand in the way of Earth reentry for robotic spacecraft containing extraterrestrial samples.

There are, however, special considerations for certain types of samples. Cryogenic samples, where high temperatures may result in melting or loss of volatiles, can be transported relatively safely through the interplanetary medium, but will likely require effective containment and active cooling systems during reentry. Such systems add mass and complexity to sample return missions. In some instances passive-cooling systems, such as phase-change materials, may suffice but would require more robust reentry capsules and rapid recovery at Earth's surface. In addition planetary protection issues involving minimization of sample release probabilities may require multiply degenerate containment systems, as well as new technology to verify effective containment before and during reentry. Such systems will add mass and complexity, and increase mission risk.

7.9.2 Orbital Rendezvous. Given the major fuel requirements to lift mass from the surface of the larger planetary bodies (Mars, icy moons, etc.), the additional requirements of lifting active cooling systems, hardware associated with planetary protection needs, and heat-shielding for Earth reentry will have a significant impact on mission cost. Alterative models would involve fully autonomous rendezvous with a return spacecraft in orbit around the planetary body being sampled or in Earth orbit. The savings in mission cost through reduction in landed mass and vehicle size must be traded against mission risk associated with autonomous rendezvous and sample capsule transfer above a distant planet and/or, perhaps, human assisted or autonomous rendezvous in Earth orbit. Such risk has been partially mitigated through the recent DART mission. However, additional testing of capsule transfer, capsule security, and connection to required cooling or security systems for reentry may require additional testing, especially for samples with planetary protection concerns. Transfer of containment systems between spacecraft systems in Earth orbit may provide additional capability for sterilization of return component exteriors in order to "break the chain" of potential forward contamination before reentry.

7.10 Re-entry and Landing

Genesis and Stardust missions demonstrated two methodologies for re-entry and landing of sample return vehicles: “soft landing” landing via parachute and survivable “hard landing”, although the latter was inadvertent and the sample return container was breached. With the potential for the return of Mars samples, planetary protection concerns will probably dictate that such a mission must be able to survive a “hard landing”. Based on the conclusion that most sample returns will involve “survivable hard landing”, what are important technologies that will preserve sample integrity?

The Stardust mission showed that the technologies are available to protect and preserve samples collected in a flyby mode. Further development of this technology for flyby missions is probably much more mission dependent. The preservation of samples collected from touch and go and surface landing missions are probably more dependent on the nature of the material collected than the planetary body. For example, suites of delicate martian sulfates are more susceptible to damage than martian basalts during a landing on Earth. To insure sample integrity during re-entry and landing, it seems that investments could be made in (1) defining overall philosophy of sample loading/isolation on a planetary surface prior to launch, (2) designing sample containment (see above) that insures sample integrity during landing, and (3) testing of designs using geological materials that have mechanical and chemical properties that mimic expected returned samples.

7.11 Sample Receiving, Handling, and Curation

7.11.1 Introduction. Sample curation is the critical interface between the collection of samples and subsequent laboratory research of those samples. The primary purpose of curation is to maintain the scientific integrity of the samples and includes documentation, secure storage, preparation and distribution of samples for research, education, and public outreach. With careful curation the value of samples are preserved for new analyses to answer future questions for decades beyond mission completion.

Robotic and human explorers can be expected to collect rock, soil, dust, core, organic or biological, ice, fluid and/or gas samples in the course of future planetary exploration from a diversity of planetary bodies. These samples can be used not only to increase our understanding of the origin and evolution of our solar system but also to evaluate the engineering aspects of planetary characteristics such as environment effects on humans and spacecraft or using resources to aid future exploration.

A track record exists for successful curation and processing of “traditional samples” (rocks, soil, cores, dust) under normal laboratory conditions. Receiving, handling, storing, and preserving the scientific integrity of returned samples is critical to sample return missions. In addition to needing to refine technologies and techniques to be able to handle requirements associated with new analytical capabilities (improvements associated with contamination, micro-sample handling, etc.), certain types of sample return missions will not be viable unless and until proper curation techniques are developed. In particular the requirements and technologies associated with atmospheric gases, environmentally sensitive samples (including cold curation), and a biological containment environment must be developed to enable several high priority sample return missions.

7.11.2 Environmentally sensitive samples. The scientific community has shown increasing interest in returning samples that are susceptible to phase changes or chemical alteration to Earth for detailed analyses. Although planetary surface in situ analysis is likely to remain the primary method of measuring volatile-rich materials, the ability to return samples that retain entrained volatiles provides the necessary localized, extremely high resolution ground-truth to complement the broader range of in situ analysis and provide a richer, more detailed and complete understanding of the planetary body.

Understanding the extent and properties of volatile-rich material within permanently shadowed lunar polar regions is a near-term high priority exploration objective for both scientific and engineering / resource availability reasons. In addition, the ability to handle volatile-rich materials returned from Mars and asteroids are a high priority. In general terms, the ability to handle and preserve samples subject to phase changes or chemical alteration is applicable to the Moon, Mars, Venus, asteroids, comets, and outer planet moons even though the specific character of those changes and the methods of preserving them vary by planetary body. The Mars scientific community has previously recommended that “fresh igneous rocks be preserved at < 260 K and that samples containing clay-like minerals be preserved at < 230 K” (Gooding, 1990; Carr, 1999). The concern is that any liquid or labile H_2O will enhance alteration and isotopic exchange if temperatures are much above Mars ambient. Thus, soils or weathered rock samples may need to be collected and curated at or below 230 K. In addition, it is necessary to have minimum “head space pressure” to prevent volatile loss by sublimation/evaporation. Obviously, temperature ‘cycling’ past any phase change, such as in freeze/thawing, must also be avoided. Placing comets as primitive bodies in the framework of the planetesimals that formed the planets within our solar system requires understanding their relationship to asteroids and meteorites. As a result the Solar System Exploration Roadmap highlights a sample return from a comet nucleus as high priority. To obtain sufficient understanding of how comets relate to early solar system formation and evolution requires preserving and analyzing the delicate ices and organics present in cometary nuclei. Such samples could contain clues to the primitive precursors of life from organic molecules resident in ices that have been preserved far from the Sun for much of the age of the solar system. Technologies for cold/cryogenic and organic-contamination-free curation are necessary to enable these important mission types in addition to the pressure and temperature management to necessary to maintain sample integrity and minimize sample phase changes. The specific temperatures necessary for cold/cryogenic curation depends on the specific scientific objectives and specific planetary body and is relevant to lunar polar deposits, Mars, and icy bodies.

Technologies for cold/cryogenic storage and monitoring temperature variations during storage are mature and reasonably well understood. The techniques and technologies for efficient, reliable and economic cold/cryogenic transport with appropriate monitoring from curation facilities to the research scientists is less mature than long-term storage technology but should not present any significant difficulties. However, the techniques and technologies necessary for cold/cryogenic processing without compromising the integrity of the samples are much less mature. Investing in studies of sample handling protocols and requirements for environmentally sensitive samples will focus the time phased technology priorities by defining a feed forward path from the Moon to asteroids to Mars and Venus. An important part of sample processing is subdividing samples without contaminating or otherwise compromising scientific value including monitoring and documenting changes to the sample caused by processing. Significant advances are necessary in subdividing techniques and technologies, especially in dealing with rock/regolith ice mixtures. Even though primarily necessary for research, cold mineralogy and understanding ice/rock impact physics also require development to aid in assessing changes to the sample made during processing and the acceptable limits and constraints to processing techniques.

7.11.3 Receiving, curation and processing in a biological containment environment. Several planetary bodies of interest for sample return missions are classified "Restricted Earth Return" and must meet strict planetary protection requirements necessitating the development of capabilities for evaluating and containing possible biological hazards in the returned samples. In particular this has direct application to Mars and icy moons of outer planets (Titan, Europa). Initial operations associated with receiving "Restricted Earth Return" samples will need to be carried out under biocontainment for hazard assessment and life detection. Research on the worst known biohazards is currently done in laboratories that satisfy requirements for BioSafety Level 4 (BSL-4), issued by the Centers for Disease Control and Prevention and the National Institutes of Health ("Biosafety in Microbiological and Biomedical Laboratories", U.S. Dept. of Health & Human Services. 4^{th} edition, 1999) and/or similar standards from the World Health Organization. BSL-4 requirements are sufficient to define the biocontainment requirements for any "Restricted Earth Return" samples. There are several such labs worldwide, and they have excellent safety records: no cases of worker illness or environmental contamination have been reported. Existing biocontainment technology is mature and works. Although these biocontainment facilities are extremely successful at protecting the environment from biohazards associated with samples they do not begin to satisfy the stringent requirements necessary for protecting the integrity of samples from the environment.

Technology for extremely clean conditions is also mature and has been led by advances in the semiconductor industry. Very efficient systems to filter particles out of the air has been followed by substantial progress in limiting Airborne Molecular Contamination (AMC), which is primarily composed of semi-volatile organic compounds. There are no requirements for sterility or biocontainment in the semiconductor industry. The Food and Drug Administration (FDA) has stringent sterilization requirements for avoiding contamination of products, and also requires strict containment of highly potent pharmaceuticals. This is a highly competitive, strictly regulated business, with industry focusing on satisfying FDA requirements so that they may proceed with the production of their varied products. However, the pharmaceutical industry does not need to address the extremely low levels of contamination from trace-levels of inorganic contaminants, life-like organic compounds, and dead organisms that are of concern in preserving the scientific integrity of returned samples.

The technologies and techniques to meet requirements for biological containment while maintaining the scientific integrity of the returned samples does not currently exist. The present requirements to maintain biocontainment in an environment that is non-contaminating in order to protect the samples are unique to NASA. Fortunately, certain aspects can be borrowed from existing biomedical and industrial technology and practices but integrating these aspects into the necessary functions will take considerable effort.

Building a biologically clean sample receiving/handling facility and developing safe and secure sample handling protocols may be costly, based on previous studies. Investments in studies of unique "out of the box" concepts for implementing a biologically clean sample handling facility will be important in not only determining viable approaches to meeting planetary protection requirements but also in focusing and prioritizing future investments. Specifically, early work refining the necessary planetary protection requirements will reduce the cost associated with over-design. In addition, a thorough review of existing BSL-4 facilities, their capabilities, and the suitability and availability of using an existing (or modified) facility will provide important information.

Increasingly, use is made of isolated mini-environments when clean containment is required. Technology advancement needed of existing containment / isolation cabinets is necessary but doable to provide the necessary double wall construction to prevent leakage either from the cabinet contents into the environment (escape of sample biohazard) or the environment into the sample containing cabinet (sample contamination). Transfer ports and transfer containers for moving samples between isolation cabinets are mature but assessing changes necessary for material restrictions required for maintaining sample integrity will involve technology development. Current curation sample handling and processing techniques rely on handling samples using Teflon covered gloves and simple tools. Gloves applicable to double-walled systems do not exist with adequate reliability, performance, and low-offgassing self-healing properties. Remote manipulation and simple robotic systems integrated into isolation cabinets may be able to replace the current human-gloved handling of samples. There remain issues of material compatibility with sample contamination requirements and the variety of sample handling and processing motions that must be accommodated. These systems must be low-offgassing, provide no or easily identifiable wear and abrasion products, no contaminating lubricants, and either external or sealed motors. Technology development is also needed to modify existing capabilities to address the different sample processing tasks at both macro- and micro-scale (such as sample splitting, rock drilling, subdividing, etc.) for the different sample types (rocks, ice, dust, etc.) but has promise for providing the means for clean and precise sample processing.

Although addressed in the landed vehicle and reentry contingency requirements sections, sterilization is also important for curation. Investments for a better understanding of the degradation of science associated with different sterilization techniques will be necessary to build on work in developing proper contingency plans for any receiving facility (e.g., Allen et al, 1999; Neal, 2001). In addition, techniques for cleaning and sterilizing the equipment and tools that come in contact with samples must be developed that are non-contaminating. Many techniques for sterilization already exist and are dependent on the characteristics of the item to be sterilized and may only require modest modifications for compatibility with remote manipulation systems and end effectors, isolation gloves, and packaging that come in contact with samples.

8. Technologies/Capabilities Relevant to Different Planetary Bodies

Any sample return mission will comprise a set of key capabilities as discussed above: A method for retrieving and containing the sample(s), returning to earth, etc. Some of these capabilities will be common between different missions, allowing technology development investments to be leveraged across multiple missions. However, the diversity of scientific goals, which can lead to different sampling strategies, and the diversity of environmental conditions at each sampled target (e.g., gravity, atmosphere or lack thereof, and physical characteristics of the material to be sampled) leads to the conclusion that each mission will contain some unique elements. The collectors on Genesis, for example, were precisely and specifically designed for the sample collection environment of the solar wind, and would not have worked for other sample return missions.

Our assessment of capabilities needed for sample return missions considered the uniqueness of each required capability across a multitude of envisioned missions. We conclude that there are three main areas where mission-specific capabilities should be considered: (1) entry/descent/landing, (2) sampling, and (3) launching from the surface. As discussed above, EDL will always be challenging, but it is a challenge we have met previously and successfully on many objects in the solar system. For intensive sampling of small bodies, there is the unique need for anchoring to the surface. In order to design an anchoring device, we will need to mine the information from recent missions such as Hyabusa and Deep Impact, and may well need more information from upcoming missions such as Dawn and Rosetta to assess the details and diversity of surface properties of small bodies. The very properties that may make these objects easy to sample (namely, relatively unconsolidated materials at their surfaces), may well make them difficult to anchor to. In addition, the atmosphere of Venus is not nearly as well studied and understood as the Mars atmosphere. Both for possible sampling strategies, EDL, as well as ascent, a better understanding of the venusian atmosphere, including improved predicative models, is needed.

Sampling tends to be an object-specific and science-specific task, although some common capabilities may be used. For example, regolith sampling and rock coring on the Moon, Mars and Venus (and possibly some other moons) may be achieved using very similar systems. Although these sampling systems will have similar functionality, each must operate in a very different environment, which will likely lead to unique designs. For comets and the martian, lunar, and mercurian polar regions, cryogenic sampling devices are needed, and preservation of cryogenic samples also presents unique technology development challenges that feed forward into the design of the sample return capsule.

Launching from the surface of sampled objects also presents critical and unique challenges, depending on the size of the object, and the presence of an atmosphere. Launching solutions will likely look very unique from object to object. Specifically, capability is needed to launch from the martian surface, which will likely entail a small solid-rocket booster. The higher gravity and thick atmosphere of Venus present unique challenges for returning samples. Balloon technology and airborne launching platforms need to be considered. Finally, the US has never returned samples launched robotically from an airless body like the Moon. So even this relatively straightforward low-g, airless return will require some development of capability.

9 Technology/Capability Linkages among Different Planetary Bodies

9.1 Introduction.

It was the intent of this analysis to investigate technology linkages among planetary sample return missions for the purpose of identify systems or subsystems that could be used for several different types of missions. This in itself would lower the cost and risk of SR missions by developing and evolving similar technologies thru numerous missions rather than invest and utilize a new sampling approach for each mission. The commonality identified .in this analysis occurs in several manners:

(1) Commonality between sample return missions and non-sample return missions.
(2) Commonality within each mission type.
(3) Commonality across all mission types (flyby, Touch-and-go, landing on a planetary surface).
(4) Feed-forward commonality.

9.2 Commonality between sample return missions and non-sample return missions.

There is substantial commonality between systems necessary for successful sample return missions and missions whose goals lie elsewhere and do not include sample return. These linkages are mostly among planetary surface missions, although some are appropriate for touch-and-go missions. These technology commonalities include precision landing on a planetary surface and hazard avoidance (for both touch-and-go, planetary surface), autonomous operation of rovers (planetary surface), and a flexible robotic arm with the capability to accommodate multiple tools (in situ analytical instruments, as well as sample collection tools).

9.3 Commonality within each mission type.

Each planetary environment provides unique challenges for sample return missions. Yet, there are linkages among mission types. In some cases, the technology is nearly identical among potential missions. In other cases, the technology designed for a relatively simple sample return mission feeds-forward with modifications to more complex missions that either sample more hostile environments or sample more environmentally sensitive samples.

9.3.1 flyby missions. Linkages among flyby missions are illustrated in Table 4. Some of the important commonalities among flyby mission technologies include inert collection material, capabilities for collecting gas, a system that verifies samples have been collected and adequately sealed, and a return vehicle capable of surviving hard-landing on Earth and maintenance of sample integrity (i.e., issues of container security and alteration of samples during reentry and landing). Sterilization protocols and verification procedures are very similar on all such missions. Another series of linkages that are appropriate for both more complex flyby missions and other types of sample return missions are tied to requirement to collect, return, and curate environmentally sensitive samples that are composed of either organic or non-organic materials. These include environmental control during sampling, sample container that is climate controlled, monitoring environmental conditions of sample container, and cold/cryogenic (ice) – organic material curation and storage protocols. Applications of these technologies are science goal dependent and would be components that would be applicable to later landed sample return missions to several of these bodies.

9.3.2 Touch-and-go missions. Technology linkages among touch-and-go missions are illustrated in Table 5. Some of the important commonalities among touch-and-go mission technologies include a collection system that allows collection of samples from multiple surface sites, the ability to store and isolate samples collected from each site, and the ability to collect the largest sample mass possible. Other linkages include the capability of collecting gas, a system that verifies samples have been collected and return vehicle capable of surviving hard-landing on Earth and maintenance of sample integrity (i.e., issues of container security and alteration of samples during reentry and landing). Sterilization protocols and verification procedures are very similar on all such missions. Another series of linkages that are appropriate for both more complex, touch-and-go missions are tied to the mission requirement to collect, return, and curate environmentally sensitive samples and are the same as for fly-by missions. Applications of these technologies are science goal dependent and would be components that would be applicable to second-generation sample returns missions to several of these bodies.

9.3.3 Missions requiring landing on a planetary surface. Technology linkages among missions that land on planetary surfaces are illustrated in Table 6. Sterilization protocols and verification procedures, autonomous positioning/hazard avoidance and pinpoint landing capabilities are technologies that exhibit linkages among all of the sample surface return missions. However, the qualifications for each of these technologies are dependent upon planetary protection requirements for a planetary body, mission science, and mobility capabilities/requirements. Perhaps, the linkages among these technologies should be viewed as evolutionary from missions requiring limited sterilization and pin-pint landing (e.g., early lunar missions) to those with more rigorous requirements (e.g., Mars). Another important commonality among surface landing-sampling mission technologies includes a collection system that allows collection of multiple types of samples (e.g., tools that collect cores, rake samples, regolith, and rocklets), collection from multiple surface sites, the ability to store and isolate samples collected from each site, and the ability to collect the largest sample mass possible. Other linkages include the

Table 4: Technologies and capabilities with significant linkages for flyby missions

MISSION STAGE	PLANETARY BODY				
	Comet	**Mars**	**Venus**	**Plumes***	**Planetary Rings**
PRE-LAUNCH:					
Sterilization protocols & verification procedures	X	X	X	X	X
SAMPLING:					
Collection of "dust" with inert collection material	X	X	X	X	X
Collection of gas	X	X	X	X	X
Sample acquisition verification procedures	X	X	X	X	X
Environmental control on sampling and storage	X	X	X	X	X
SAMPLE CONTAINMENT:					
Unreactive, strong sample containers	X	X	X	X	X
Environmental monitoring (and control if appropriate)	X	X	X	X	X
Sealing/resealing of sample container - verification of seal	X	X	X	X	X
Gas containment at pressures different to 1 bar	X	X	X	X	X
SAMPLE RETURN:					
Return vehical capable of surviving hard-landing	X	X	X	X	X
Environmental monitoring (and control if appropriate)	X	X	X	X	X
CURATION:					
Development of cold/cryogenic (ice) curation and storage protocols	X	X	X	X	X
Development of gas sample curation and storage protocols	X	X	X	X	X
Development of biological/organic sample curation and storage protocols	X	X	X	X	X

*Plumes produced by natural impacts, human induced impacts, or volcanism.

Table 5: Technologies and capabilities with significant linkages for touch-and-go missions

MISSION STAGE	MISSION TYPE			
	Moons	**Asteroids**	**Comets**	
PRE-LAUNCH:				
Sterilization protocols & verification procedures	X	X	X	
SAMPLING:				
Autonomous Positioning/ Hazard Avoidance	X	X	X	
Multiple Sample Acquisition	X	X	X	
Multiple sites sampled	X	X	X	
Sample acquisition & transfer mechanisms	X	X	X	
Sample acquisition verification procedures	X	X	X	
Environmental control on sampling and storage	X	X	X	
SAMPLE CONTAINMENT:				
Separation/isolation of separate samples to prevent cross contamination	X	X	X	
Unreactive, strong sample containers	X	X	X	
Environmental monitoring (and control if appropriate)			X	
Abrasion between samples and the container needs to be minimized	X	X	X	
Sealing/resealing of sample container - verification of seal	X	X	X	
Gas containment at pressures different to 1 bar	X	X	X	
SAMPLE RETURN:				
Environmental monitoring (and control if appropriate)	(X)		X	
CURATION:				
Development of cold/cryogenic (ice) curation and storage protocols	(X)			X
Development of gas sample curation and storage protocols	(X)		X	
Development of organic/biological sample curation and storage protocols	(X)		X	

(X) = only certain samples will require such technologies capability of collecting gas, a system that verifies samples have been collected and return vehicle capable of surviving hard-landing on Earth and adequately sealed, and a return vehicle capable of surviving hard-landing on Earth without affecting sample integrity. Sterilization protocols and verification procedures are very similar on all such missions. Another series of linkages that are appropriate for more complex, surface landing missions are tied to the mission requirement to collect, return, and curate environmentally sensitive samples that are composed of either organic or non-organic materials (i.e., ices). These include environmental control during sampling, sample container that is climate controlled, monitoring environmental conditions of sample container, and cold/cryogenic (ice) – organic material curation and storage protocols. Applications of these technologies are science goal dependent and would be components that would be applicable to second-generation sample returns missions to several of these bodies.

9.4 Commonality across all mission types (flyby, touch-and-go, landing on a planetary surface).

There are several feed-forward technologies that have commonality across many of these sample return mission types. Sterilization protocols and verification procedures are needed for all of these missions, although the extent is highly variable. For example, these protocols and procedures are very different for the Moon compared to Mars. Other technologies that cut across these three types of missions include systems that verify samples have been collected, containment systems that maintain sample integrity during reentry, and a return vehicle capable of surviving hard-landing on Earth. Another series of linkages that are appropriate for more complex sample return missions are tied to requirement to collect, return, and curate environmentally sensitive samples that are composed of either organic or non-organic materials. These include environmental control during sampling, sample container that is climate controlled, monitoring environmental conditions of sample container, and cold/cryogenic (ice) – organic material curation and storage protocols. Applications of these advanced technologies are science goal dependent and are components that would be applicable to subsequent surface sample returns missions to several of these bodies.

By integrating Tables 4-7, we propose the enabling technologies shown in Table 8 as being the important ones to focus on regarding investment for reducing risk. The three categories of enabling technologies proposed represent, respectively, 1) technologies with greatest impact on all types of sample types and mission scenarios, 2) technologies with the impact on the majority of sample types and mission scenarios, and 3) technologies that will be needed for special sample types (e.g., gas, ices, etc.) and/or sampling targets. We recommend that for maximum impact, development of the technologies that impact the acquisition of all sample types/mission scenarios be undertaken immediately. This would be followed by the second category, leaving the third category to be developed on a mission-by-mission basis. It must be stated that not all sample return missions will necessarily provide major feed-forward capabilities for future missions. Such missions should not be unduly penalized relative to mission proposals with significant feed-forward capabilities, but should be judged on their scientific merit.

10. Ranking of Technologies/Capabilities to Reduce Risk and Cost of Sample Return

Using the ranking scheme illustrated in section 5 and the breakdown in commonality used in section 9.1, sample return technologies have been ranked. The ordering of categories or technologies within each category is not an attempt at ranking.

10.1 Linkages between non-sample return and sample return missions:

10.1.1 Precision landing and hazard avoidance. The development and field testing of RADARs, LIDARs, and camera-based systems for surface-relative range and velocity measurements, map-relative

Table 6: Technologies and capabilities with significant linkages for surface missions

MISSION STAGE	MISSION TYPE					
	Comets	**Asteroids**	**Moon/Mercury**	**Mars**	**Venus**	**Moons**
PRE-LAUNCH:						
Sterilization protocols & verification procedures	X	X	X	X*	X	X*
SAMPLING:						
Autonomous Positioning/ Hazard Avoidance	X	X	X	X	X	X
Pin-point landing capability	X	X	X	X	X	X
Multiple Sample Acquisition	X	X	X	X	X	X
Multiple sites sampled	X	X	X	X	X	X
Sample acquisition & transfer mechanisms	X	X	X	X	X	X
Sample acquisition verification procedures	X	X	X	X	X	X
Environmental control on sampling and storage	X			X	X	
SAMPLE CONTAINMENT:						
Separation/isolation of separate samples to prevent cross contamination	X	X	X	X	X	X
Unreactive, strong sample containers	X	X	X	X	X	X
Environmental monitoring (and control if appropriate)	X	X	X	X	X	X
Abrasion between samples and the container needs to be minimized	X	X	X	X	X	X
Sealing/resealing of sample container - verification of seal	X	X	X	X	X	X
Encapsulation: regular cores vs. irregular rocks vs. loose regolith samples vs. ice samples vs. biological samples vs. gas/atmospheric sample	X		X	X	X	X
Gas containment at pressures different to 1 bar	X			X	X	
SAMPLE RETURN:						
Low mass lander/ascent vehicle infrastructure	X	X	X	X	X	X
Autonomous vertical alignment of ascent vehicle for return	X	X	X	X	X	X
Environmental monitoring (and control if appropriate)	X			X	X	
CURATION:						
Development of cold/cryogenic (ice) curation and storage protocols	X			X	X	
Development of gas sample curation and storage protocols	X	(X)	(X)	(X)	(X)	X
Development of biological sample curation and storage protocols	(X)			X		

* = significantly higher requirement due to planetary protection for Mars and Europa
() = sample dependent.

Table 7: Technologies and capabilities with significant linkages across Mission Types

MISSION STAGE	MISSION TYPE			
	Flyby	**Touch-&-Go**	**Surface (Static)**	**Surface (Mobile*)**
PRE-LAUNCH:				
Sterilization protocols & verification procedures	X	X	X	X
SAMPLING:				
Autonomous Positioning/ Hazard Avoidance		X	X	X
Pin-point landing capability			X	X
Multiple Sample Acquisition		X	X	X
Multiple sites sampled		X	X	X
Sample acquisition & transfer mechanisms		X	X	X
Sample acquisition verification procedures	X	X	X	X
Environmental control on sampling and storage	(X)	(X)	(X)	(X)
SAMPLE CONTAINMENT:				
Separation/isolation of separate samples to prevent cross contamination	(X)	X	X	X
Unreactive, strong sample containers	X	X	X	X
Environmental monitoring (and control if appropriate)	(X)	(X)	(X)	(X)
Abrasion between samples and the container needs to be minimized		X	X	X
Sealing/resealing of sample container - verification of seal		X	X	X
Encapsulation: regular cores vs. irregular rocks vs. loose regolith samples vs. ice samples vs. biological samples vs. gas/atmospheric samples			X	X
Development of non-silicate aerogel	X			
Gas containment at pressures different to 1 bar	(X)	(X)	(X)	(X)
SAMPLE RETURN:				
Low mass lander/ascent vehicle infrastructure			X	X
Autonomous vertical alignment of ascent vehicle for return			X	X
Environmental monitoring and control	(X)	(X)	(X)	(X)
Hard-landing vehicle & sample preservation	X	X	X	X
CURATION:				
Development of cold/cryogenic (ice) curation and storage protocols	(X)	(X)	(X)	(X)
Development of gas sample curation and storage protocols	X	(X)	(X)	(X)
Development of biological sample curation and storage protocols	(X)	(X)	(X)	(X)

(X) = sample dependent

Table 8: Enabling Technologies for Sample Return.

1. Technologies that impact all sample acquisition types and all sample return mission scenarios	
Pre-Launch	Sterilization protocols and verification procedures.
Sampling	Autonomous Positioning/Hazard Avoidance Multiple Sample Acquisition. Sample acquisition and transfer mechanisms. Sample acquisition verification procedures.
Sample Container	Separation/isolation of separate samples to prevent cross contamination.
	Unreactive, strong sample containers.
	Sealing/resealing mechanisms for sample container.
	Seal verification procedures.
Sample Return	Low mass lander/ascent vehicle infrastructure.
2. Technologies that impact the majority of sample types and majority of mission scenarios	
Sampling	Pin-point landing capability
Sample Container	Environmental monitoring (and control if appropriate).
	Abrasion between samples and the container needs to be minimized.
	Gas containment at different pressures to 1 bar.
	Environmental monitoring (and control if appropriate) during time on surface and during return.
Sample Return	Low mass lander/ascent vehicle infrastructure.
Curation	Development of cold/cryogenic curation and storage protocols.
	Development of gas curation and storage protocols.
3. Technologies required for specialized sampling/sample targets	
Sampling	Ability to sample multiple sites
Sample Container	Encapsulation: regular cores vs. irregular rocks vs. loose regolith samples vs. ice samples vs. astrobio samples vs. gas/atmospheric samples.
	Development of non-silicate aerogel for dust sampling.
Sample Return	Autonomous vertical alignment of ascent vehicle for return.

location determination, and surface hazard assessment will be important at reducing risk and cost to most missions and increasing science yield.

10.1.2 Robotic arm. Robotic arms have been used during many non-sample return missions for the manipulation of instruments. Further investment to improve dexterity and autonomy would greatly aid sampling of different types and reduce risk of sampling, sample manipulation, and sample storage. In addition, it would reduce overall cost by having an adaptable technology and reducing time spent collecting samples on the surface. This investment will also benefit non-sample return missions that require manipulation of planetary materials or instruments.

10.1.3 Autonomous robotic capabilities. An investment in autonomous robotic capabilities in advance of a sample return project would pay significant dividends in the ability to collect samples and the quality of those samples. The higher the level of the available autonomous operations, and the more capable those operations at compensating for uncertainties in the environment, the better the sample collection operations will be in speed and effectiveness. This investment will also benefit non-sample return surface missions, especially those where the ground operator control becomes inadequate due to command latency (at large Earth-target distances, such as with Mars and Venus).

10.1.4 Sterilization protocols and verification procedures. These protocols and procedures are very mission dependent. They are more rigorous for Mars than the Moon. Also, they are potentially more rigorous for Mars sample return than for a mission not returning from the martian surface. However, developing protocols and procedures for missions with rigorous requirements will provide cheaper alternatives to less rigorous missions. For example, developing quick and comprehensive genetic fingerprinting of spacecraft organisms for Mars sample return will have feed back to missions with less meticulous requirements.

10.2 Linkages among all sample return mission types:

10.2.1 Hard-landing and sample preservation during such a landing. Genesis and Stardust missions illustrated the potential successes and dangers of hard-landing. This technology is fairly advanced, yet destruction to serious damage of fragile samples during this stage of a mission adds risk to the mission's success. Studies testing the relationships among sample fragility, sample container construction, sample packing procedures, and hard-landing procedures should continue (see Neal, 2001, for initial studies).

10.2.2 Curation of environmentally sensitive samples and biologic-organic samples. First generation sample return missions to Mars and second generation missions to other planetary bodies will collect samples that require curation in terrestrial labs significantly different than traditional geological samples. Mars samples will require a curation that combines biological containment within a clean lab environment. Temperature sensitive samples (i.e., ices) will require curation under cold, clean lab environments. Initial studies of these curatorial approaches would be valuable to mission success.

10.2.3 Environment control and monitoring of sample containment. Second and third generation sample returns from planetary bodies such as comets, moons, asteroids, Mars, and Venus will require environmental control of sample containers to preserve sample integrity. These approaches will add substantial cost to a mission. Investigating approaches to lowering cost of such technologies is not too premature.

10.2.4 Sample acquisition verification. Verification that a sample has been acquired is needed across all types of sample return missions. This need has been emphasized by the Hyabusa mission.

10.3 Linkages among Flyby missions:

10.3.1 Inert sample collection material. Stardust was a great success in collecting cometary samples. However, there was a noticeable interaction between the collection material and samples. Developing more inert collection material will decrease the overall risk to the science goals of flyby missions.

10.3.2 Gas collection and storage capability. Sampling gases making up planetary atmospheres and discharged from planetary bodies provides a rich source of solar system information for a wide range of planetary bodies. Such collection, storage, and preservation of gases have not been achieved by any previous mission. Although the collection techniques will be different for flyby missions than other sample return missions, storage and preservation approaches may feed forward.

10.4 Among Touch-and-go missions:

10.4.1 Sample collection and verification. A variety of techniques have been used or proposed to collect samples in a touch-and-go mode. Approaches should be investigated to maximize sample quantity, to increase the number of potential samples collected, to isolate individual samples, to increase the possibility of success and to verify that success. Tools developed for touch-and-go missions may feed forward to later landed missions.

10.4.2 Robotic manipulation of sample for collection and transfer to container. A touch-and-go sample return mission may require a sampling robot. As the Hayabusa mission illustrated, the typical low-gravity environment imposes unique requirements on such robots (low weight, high precision, low accelerations in order not to "fly away").

10.5 Among surface landing missions:

10.5.1 Variety of sample collection tools (drill, core, rake). Various tools could be used for collection of samples on a planetary surface. Each has advantages for collecting specific types of surface or near-surface materials. There is a need for investment in tools that can work in a near autonomous mode with a robotic arm, lander, or rover. This would increase scientific value of sample and decrease risk and cost of operations on the planetary surface. Second and third generations of these tools could be "hardened" to work in more inhospitable environments such as lunar shadowed regions and Venus. However, materials used in the construction of these tools should be chosen so as to minimize the contamination/alteration of the samples during acquisition.

10.5.2 Robotic manipulation of sample for collection, transfer to container, and final selection or discard. The effective transfer of samples between mission elements and within those elements will require autonomy developments as noted above, as well as the development of reliable mechanical transfer schemes and interfaces. While these designs will be unique to each mission and readily tested on the Earth, modest investments in the exploration of different approaches to the reliable transfer problem will greatly facility sample return project formulation and implementation, as well as reducing risk. In particular, highly reliable attachment, release, sensing, verification, and fault protection systems for sample transfers should be investigated.

10.5.3 Adaptable sample containment. The ultimate sample containment vessel should be constructed from materials that do not contaminate the samples, allow samples to be isolated from one another, manipulated or even removed and discarded, be adaptable for a variety of missions and sample types, have the capability of being sealed without contaminating samples, and have the capability of protecting the samples during launch from the planetary surface and return to Earth. Second and third generations of sample containment may require environmental control and monitoring.

10.6 Feed forward from sample return to human exploration:

10.6.1 Ascent Vehicle. Technology requirements for ascent from a planetary surface are unique to each planetary body. Many technologies are in place to fulfill the goals of launching from the surfaces of airless bodies the size of the Moon and smaller. The problem lies with bodies larger than the Moon that have atmospheres (i.e., Venus, Mars). In the case of Mars, investment in a Mars Ascent Vehicle is critical. The combination of 1-g gravity and dense atmosphere make ascent from Venus particularly challenging. However, technology defined and demonstrated for the Moon and Mars, may retire substantial risk for Venus surface sample return.

10.6.2 Rendezvous around distant planetary body. Establishing the capability of orbital rendezvous with a sample container launched from a planetary surface is particularly important for return of samples from Mars. For Mars, it provides a less costly method of returning samples to Earth than direct return and it is an important approach in fulfilling planetary protection requirements. Such technologies and procedures are perhaps important in sampling of other planetary bodies such as Venus and moons of the outer planets where there are concerns either with direct return from the surface or planetary protection. Return of humans from the martian surface would also involve a similar, although much more scaled-up approach.

11. Program Implementation

The intent of the Sample Return Technology Program (SRTP) is to reduce the cost to individual missions, provide the technology sooner than could be provided if one had to depend solely upon mission-specific development, enable missions possibly otherwise unachievable within cost and schedule constraints and provide an evolutionary path from simpler to more ambitious sample return missions.

To help guide its activity, the study team developed a set of guidelines that it believes would help assure a productive SRTP. These guides are based primarily upon the experience of the team members; they are not the result of an in-depth assessment of past technology programs.

1. Develop clear, prioritized goals with demanding yet achievable schedules

It was recognized at the outset that the SRTP would of necessity be complementary to technology developments unique to certain targets (e.g., Mars). This arises from the fact that the technology needs of the different sample mission types vary tremendously and that there is a limited set of mission opportunities within the timeframe of the program. This requires, then, that the enabling technologies be prioritized according to their potential to serve multiple missions over the next one to two decades.

Given that there is often a five to seven year process for the development of a specific mission (proposal to flight), the SRTP needs to be structured to produce a useful product within a timeframe of about five years. Shorter is likely to result in unachievable schedules. Longer defeats the purpose of enabling missions within a reasonable time frame.

2. Coordinate the SRTP with on-going mission-specific technology development programs and with prospective mission acquisitions.

Sample return missions involve a number of technologies and subsystems that make up the larger sample return system. As such, the product developments in the generic SRTP must be rigorously and frequently coordinated with existing or planned mission-specific technology programs. Given that one goal of the SRTP is to provide critical technologies to potential PIs for Discovery, Scout and New Frontier missions, those investigators must be aware of the detailed goals and schedules of the developments and/or RFIs developed and implemented in order to give the SRTP more impact on current mission programs.

3. Develop a clear, precise understanding of the current and desired end-point TRL of the selected technologies.

Historically technology developments have suffered from the existence of the TRL-gap. There have generally been a large number of technologies in the TRL 1 – 3 bin and relatively few in the 4 – 6 bin. This occurs for two reasons: one, insufficient funding to go from 3 to 6 and two, insufficient mission pull.

The general requirement for insertion of technology into a mission proposal is that the technology be at TRL 6 by PDR. This allows, under ideal circumstances (adequate budget and thorough understanding of requirements), for a technology at TRL 5 to be taken to TRL 6 between selection and PDR. For insertion into PI-led mission proposals, we recommend that the SMRT take the technology to TRL 6.

4. Provide a dedicated budget sized to the goals and schedule

The historical impediments to successful technology development programs include inadequate and/or unstable budgets. This is not a trivial challenge. Technology developments are by nature difficult to budget given the unknowns in the development process. Thus, it is the important to prioritize technology investments. It is likely that one will need to start the process and assess the real needs of any given technology after Program initiation. For starters, however, one must and should rely upon the proposers to have sufficient knowledge of the technology and its challenges to develop a good first cut. Then, should the ensemble of developments require more funding than is available, the prioritization should be used as a major criterion to cull the portfolio. Obviously this must be augmented by science goals and mission impact considerations.

What constitutes a “reasonable” technology budget? There are no steadfast guidelines. One must make a judgment based on the ultimate value of sample return missions and the cost of the mission implementations being considered. It is likely that there could be some half dozen or so sample return missions over the next two decades. These could range in cost from $500M for Discovery class to $1B for New Frontiers class to $3-4B for Flagship class. In aggregate one is looking at some $6B in mission costs. It seems reasonable to devote 1% of that prospective cost to the development of enabling technology, independent of mission-specific technology. That equates to roughly $10M per year over a five-year period. Such amount roughly equates to what has been planned for Mars Sample Return specific technology development. Until one sees the specific proposals, this is at best an educated guess. However, to allocate less guarantees less. If less is warranted, there is no problem in reallocating funding to other science needs. To help bound the budget, we recommend that SMD convene a panel of technology experts to help structure it in response to a set of prioritized goals.

5. Use competitive procurements for technology developments.

Much as competitive proposals have become the standard for acquisition of science investigations, we believe that similar processes should be used to procure technology. There are pockets of expertise in government, industry and academia. An open solicitation with heavy emphasis on an understanding of the requirements and a demonstrated history of meeting equivalent challenges should be the norm.

6. Require a full technology development plan

A frequent problem with technology developments is meeting a schedule. We realize that there are significant unknowns in any technology development plan. However, without a plan including accomplishment milestones and budgets there is no way to judge progress. Technology development plans should include off-ramps and criteria for proceeding along any given path.

7. Annual program/project assessment.

A goal-directed technology program needs to be critically evaluated for progress against the goals. The frequency should be such as to not overburden the developers with bureaucratic reporting yet often enough to allow the program to assess progress towards the goals and to up-date the program considering science goals, budget availability and changing technologies. We suggest that annual reviews are appropriate and that such reviews be used as one forum to bring together the technology developers (including those working on mission-specific technologies), mission planners, and the sample science community.

12. Findings

During this analysis we have identified several findings that will reduce the long range cost of sample return missions, as well as the risk associated with sample return for increasingly complex missions.

Finding 1. Sample return from a wide range of planetary bodies provides valuable insights into the origin and evolution of the solar system. It is a valuable exploration tool, as it increases the value of both orbital and surface observations. It should be an important component in NASA's overall solar system exploration strategy.

Finding 2. Higher risk and cost is commonly associated with sample return missions relative to other types of solar system exploration missions. This is a result of a sample return mission commonly being more complex and the necessity for the spacecraft to return to its point of origin. However, sample return has many important attributes. First, it is the closest approximation to a human exploration mission. Second, samples provide a unique perspective of a planetary body that cannot be obtained by any other mission approach. The mitigation of cost and risk of the mission and its development puts an even higher priority on early technology development for sample return missions than for more conventional mission types.

Finding 3. There are technology linkages among different types of planetary missions that provide feed forward to increasingly complex sample return missions. Investing in developing and flying these technologies will increase the rate of success of sample return missions and lower the overall cost.

Finding 4. There are several types of technology/capability linkages that either are appropriate for several missions with minor modifications or feed forward to more complex missions: (1) Linkages between sample return and non-sample return missions such as precision landing and hazard avoidance. (2) Linkages among different styles of missions (flyby, touch-and-go, surface landing) such as reentry and hard-landing on Earth and preserving environmentally sensitive samples. (3) Linkages with a single style of mission to a variety of planetary bodies such as sample collection, manipulation, and storage on a planetary surface or sample collection and verification of success during a touch-and-go mission, or inert collection material on a flyby mission. (4) Linkages between sample return and human exploration such as rendezvous around a distant planetary body and return to Earth.

Finding 5. Several priority investments were identified. These priorities are placed within the groupings noted in Findings 4.

Between non-sample return and sample return missions:

Precision landing and hazard avoidance
Robotic arm
Autonomous robotic capabilities

Among all sample return mission types:

Hard-landing and sample preservation during reentry and landing on Earth
Environment control of sample containment for future generations of sample return missions
Curation and, if appropriate, distribution of environmentally sensitive samples and biologic-organic samples

Among Flyby missions:

Inert sample collection material
Gas collection and storage capability

Among Touch-and-go missions:

Sample collection and verification
Robotic manipulation of sample for collection and transfer to container

Among surface landing missions:

Variety of sample collection tools (drill, rake)
Robotic manipulation of sample for collection, transfer to container, and final selection or discard.
Adaptable sample containment

Feed forward from sample return to human exploration:

Mars Ascent Vehicle
Rendezvous around distant planetary body

Finding 6. There are many technologies that are specific to a single planetary body (i.e. Mars Ascent Vehicle, Mars rendezvous). Investment in these technologies will substantially reduce risk to a single sample return mission and perhaps will provide feed forward technology to more complex missions to the sample planetary body (i.e. human missions) and to sample return missions to other solar systems destinations to reduce both cost and risk.

Finding 7. A Sample Return Technology Program (SRTP) would reduce the cost to individual missions, provide the technology in a more timely and cost effective way than could be provided if one had to depend solely upon mission-specific development, enable missions possibly otherwise unachievable within cost and schedule constraints and provide an evolutionary path from simpler to more ambitious sample return missions. As shown, investments in technologies with commonalities across numerous missions would be beneficial to sampling of a variety of planetary settings. The success of such a program would be aided by (1) developing clear, prioritized goals with demanding yet achievable schedules, (2) Coordinate the SRTP with on-going mission-specific technology development programs and with prospective mission acquisitions, (3) Develop a clear, precise understanding of the current and desired end-point TRL of the selected technologies, (4) Provide a dedicated budget sized to the goals and schedule, (5) Use competitive procurements for technology developments, (6) Require a full technology development plan , and (7) Annual program/project assessment.
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