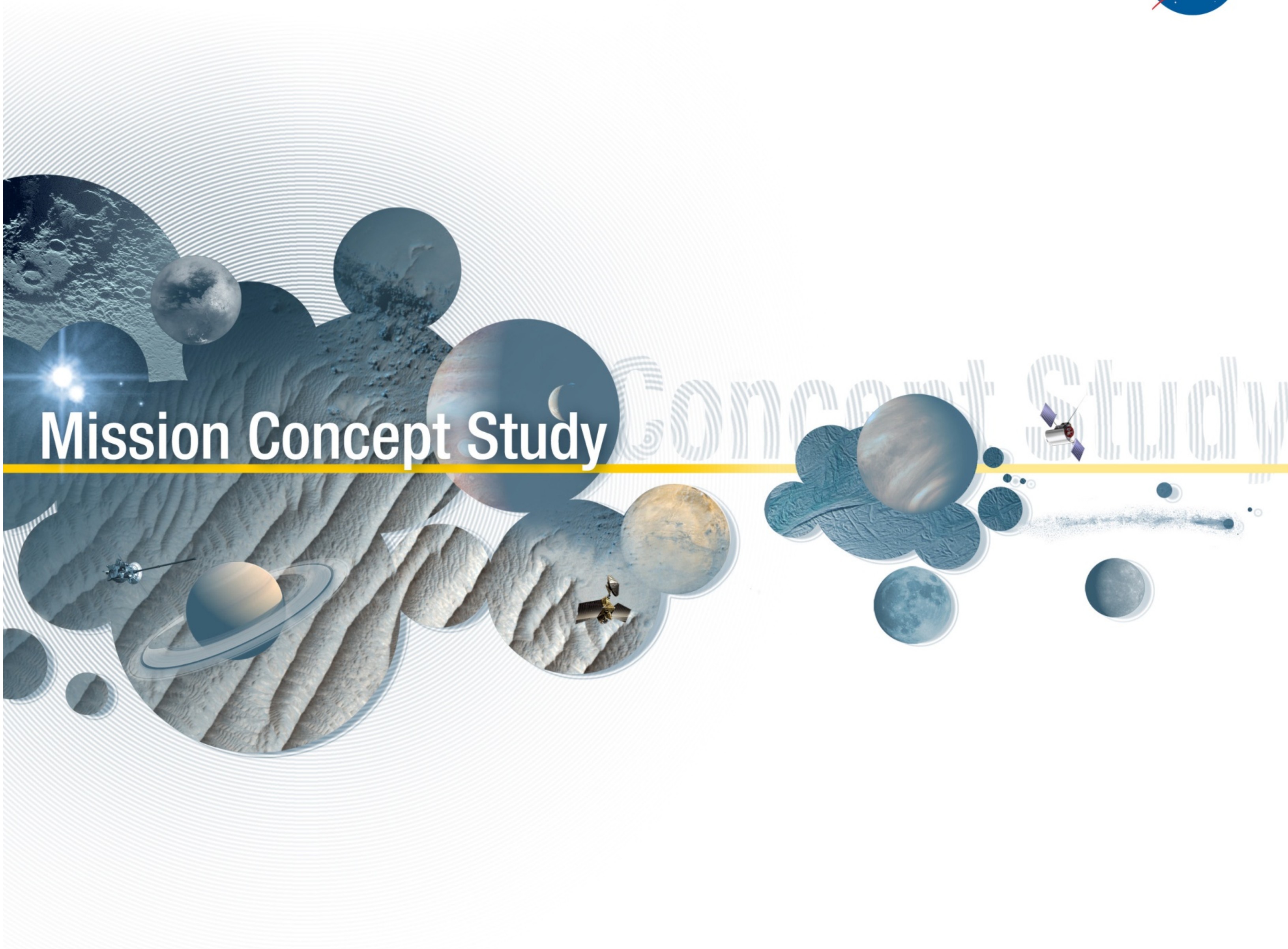
SDO-12367

National Aeronautics and Space Administration



Cryogenic Comet Nucleus Sample Return (CNSR) Mission Technology Study

Joe Veverka
veverka@astro.cornell.edu

Cryogenic Comet Nucleus Sample Return (CNSR) Mission Technology Study

Appendices

Executive Summary

This report documents the results of a study commissioned by the 2012 Decadal Report Primitive Bodies Panel to provide inputs to six key technological issues that need to be addressed to facilitate a Cryogenic Nucleus Sample Return (CNSR) mission and that will likely not be solved by other primitive bodies missions.

Our discussion is consistent with the panel's position that a detailed feasibility study for a CNSR mission should be conducted over the next decade (2011–2020) and should define a technological development program to enable a CNSR mission in the subsequent decade (2021–2030). This Technology Development Program will address technology needs for CNSR, mitigate mission development risks, and verify promising technologies and mission concepts via a test and evaluation program.

A number of key guidelines and assumed mission requirements have been established in close collaboration with panel members to frame the ensuing discussion and recommendations contained in this report. The primary guidelines for this study include the following:

- The primary interest for the CNSR mission is to obtain a sample at depth(s) from beneath the surface layer.
- It is assumed that by the time a CNSR mission is launched, a Comet Surface Sample Return (CSSR) mission will have been accomplished and will have demonstrated how to obtain a surface sample.
- Simpler, lower risk alternatives and approaches are preferable, given significant uncertainties in the sampling environment.
- The study objective is not to design an optimal CNSR system, but to respond to the six items provided by the panel.

The six specific items addressed in this report are listed below, along with the key findings or conclusions reached for each:

Item #1: *"What is the best way of obtaining a core at least 25 cm deep and 3 cm across? Does it require a 'real' landing as opposed to a 'touch and go'?"*

> Given the current state of uncertainty about cometary surface properties, a reasonably conservative engineering requirement for the core sampling system is that it be able to emplace a drive tube within a target as strong as lunar regolith. Working from the perspective that the lunar regolith provides a useful "worst-case" upper bound for comet sampling, a continuous, single-core sampling approach based on the techniques developed for the Apollo 14–17 missions is recommended for obtaining a single, stratified, subsurface core sample. The approach presented is compatible with a touch-and-go landing and does not require an actual landing on or anchoring to the comet surface.

Item #2: *"Might it be easier to obtain three samples from a specified depth (say 0 cm, 10 cm and 25 cm) each about 25 gm and from the specified depth within ± 5 cm?"*

> A core sampling system that would obtain separate samples at predetermined depths down to 25 cm is inherently more complex than a system designed to obtain a continuous core to that depth. Mechanisms are required to open a coring chamber, acquire a small core, and then close the chamber, together with a sensor system to measure accurately the depth of penetration and an autonomous control system. Obtaining a contiguous 25-cm core involves lower engineering risk and provides superior science.

Item #3: "What is the optimum way of verifying that the sample contains at least 20% ice (and presumably accompanying volatile organics)?"

The study team classified potential approaches to sample verification. The study did not focus on the issue of sample size verification, which implies measuring sample volume and/or mass, but concentrated on the question of measuring water ice content. Various potential measurement approaches were considered and classified according to the criteria provided in the study guidance. It is concluded that none of these is a mature technique already suitable for CNSR. Moreover, it is not clear that any of the techniques meets all of the desired criteria (simple, easy to implement, low cost, measurement applicable to the actual bulk sample, measurement specific to water ice). Further development is clearly needed in this area.

Item #4: "What prudent provisions for re-sampling are available if the sample does not meet the ice-content requirement?"

Science guidance was provided to the study to bound the discussion of a potential re-sampling strategy, to be applied in the event that a first sample collected did not meet the stipulated water ice content requirement. To satisfy the key requirements and assumptions, a CNSR mission should be equipped with, at a minimum, two redundant core sampling mechanisms, along with the capacity to store and return to Earth at least two independently sealed core samples at cryogenic temperatures, potentially collected from differing locations on the comet surface.

Items #5 and #6:"What is the most efficient way of encapsulating the sample?" "What methods can be used and what is their relative difficulty/cost to maintain the sample at: a) 90° K? b) 125° K? c) 200° K?"

The key requirements for the encapsulation and cryogenic return of a comet nucleus core sample are driven by the need to preserve scientific integrity of the sample from the point of collection through to final analysis in an Earth laboratory. Primary concerns involve minimizing sample contamination, avoiding alteration of its chemical or physical state, and preventing loss of ice and volatile organics, throughout the collection, return, and analysis phases of the mission timeline. An important secondary goal is preservation of the stratigraphy of a core sample. These key science requirements drive a number of technological considerations, primarily in the thermal and mechanical areas.

The study concludes that the thermal design of a cryogenic comet sample return is feasible, and the storage temperature required to preserve water ice after a long cruise phase is about 125 K. A two-stage refrigerated capsule design, including an intermediate stage cooled by using the resources of the spacecraft, provides a cold stage capable of surviving a long cruise phase and the return to Earth. During the final re-entry and recovery, the cold stage is supported by the combined cooling capability of a mechanical cooler and phase change material. Key design requirements for the mission are the sample volume, structural design loads during re-entry, and the recovery time period.

From a mechanical perspective, a mechanism is required to contain the sample and pack it sufficiently to remove any voids within the sample canister. This mechanism is not required to seal the sample, but it must be capable of compressing the sample contents within the canister such that they are not free to move about and mix appreciably as they are subjected to the shock and accelerations associated with re-entry and recovery. This mechanism must eliminate large voids in the core sample, and prevent expansion or disturbance during re-entry and the impact of the return capsule upon the ground.

The exclusion of terrestrial atmosphere from contact with the sample and the retention of evolved gases resulting from the sublimation of ices in the sample both require the sample canister to be hermetically sealed. The sample canister must retain its hermetic seal against a significant pressure difference. Therefore, the storage temperature needs to be chosen to minimize the structural requirements on both the container and the sealing process. An evolved gas capture system and provisions for an emergency over-pressure relief valve are also recommended.

On the basis of a number of factors noted in the discussion of thermal and mechanical technology issues for CNSR sample encapsulation and Earth return, the use of a parachute as part of the re-entry system is a key decision for future consideration. From a thermal perspective, it is noted that a parachute-supported landing would significantly reduce design acceleration loads and would be the preferred approach. From a mechanical perspective, a softer landing supported by a parachute-assisted landing would maximize the potential for preserving sample stratigraphy and maintaining hermetic sample seals that could be compromised by high-load impact damage. The eventual design of the CNSR sample containment and return systems, and the choice of utilizing a parachute-assisted re-entry over a ballistic one, will need to trade off the potential benefits identified above against the inherent complexities and associated risks of depending on a successful parachute deployment. It is likely that applicable planetary protection requirements would also factor significantly in this trade space.

On the basis of currently adopted sample mass and volume requirements, and the associated thermal analysis presented, the power requirements for active cooling of the samples during Earth-approach and re-entry/retrieval phases are likely to be significant. After the return capsule separates from its host spacecraft, the required power will need to be supplied entirely by batteries housed within the sample capsule. It is reasonable to conclude that batteries will probably drive the size of the CNSR return capsule and that the mass of those batteries is likely to be a significant driver in the overall design of the spacecraft, as well as the return capsule. The return capsule will need to be able to accommodate the combined mass and volume of the batteries, sample containers, and cooling system.

This report concludes with a roadmap of key technical capabilities, as derived from the discussion, that need to be developed to realize a successful CNSR mission. The top-level elements of that roadmap include:

- Reaching agreement as to the expected range of comet properties;
- Development of simulants that embody the range of comet properties;
- Development of cryogenic sampling mechanism(s) that can be proven to work with the comet simulants under realistic environmental conditions;
- Development of a sample verification system for the quantitative assessment of sample volume and/or mass, as well as the fraction of water ice in the sample;
- Development of a cryogenic, hermetically sealed sample encapsulation and containment system;
- Development of a cooling system for the return capsule for use after its release from the spacecraft, through re-entry, landing, and until recovery by a terrestrial laboratory; and
- Development of a sample return capsule that can accommodate the combined mass and volume of a sample holder, cooling system, and batteries.

All of the identified key capabilities and supporting technologies will need to be extensively tested under increasingly realistic conditions to both raise their Technology Readiness Levels (TRLs) to 5 or above by the end of the decade and be considered as ready for use on a CNSR mission in the subsequent decade. This testing has the potential to mitigate substantially the development risk of a CNSR mission.

1. Introduction and Background

1.1 Study Purpose and Objectives

The purpose of this study is to provide inputs to six key technological issues identified by the 2012 Decadal Report Primitive Bodies Panel that will need to be solved to facilitate a Cryogenic Nucleus Sample Return (CNSR) mission. The panel believes these issues will not be solved by other primitive bodies missions likely to precede a CNSR mission. Our discussion is consistent with the panel's position that a detailed feasibility study for a CNSR mission should be conducted over the next decade (2011–2020) and should define a technological development program to enable a CNSR mission in the subsequent decade (2021–2030). This Technology Development Program will address technology needs for CNSR, mitigate mission development risks, and verify promising technologies and mission concepts via a test and evaluation program.

The overriding objective is to provide assurance that the key CNSR-required technologies can all be raised to at least Technology Readiness Level 5 (TRL 5, full-scale prototype testing) in the coming decade.

1.2 Study Guidance and Assumed CNSR Science Goals

The following key guidelines for conducting this study have been established, in close collaboration with the sponsor:

- Simpler, lower risk alternatives are preferable, given significant uncertainties in the sampling environment.
- The study objective is not to design an optimal CNSR system, but to respond to the six items provided by the panel. The statements for these items are reproduced in the sections below. The responses to two of the items, #5 and #6, have been combined into a single response.
- It is assumed that by the time a CNSR mission is launched, a Comet Surface Sample Return (CSSR) mission will have been accomplished and will have demonstrated how to obtain a surface sample. The primary interest for the CNSR mission is to obtain a sample at depth(s) from beneath the surface layer and to maintain it cold enough to return material to the Earth in the ice phase.

The following set of top-level science goals is assumed for this study:

Floor:	Return one sample from a single site, with water ice and less volatile organics intact (i.e., no water ice melting or loss of "moderately volatile" species to vacuum).
Baseline:	Return one sample from a single site, with >20% water ice by mass, with water ice, most volatile organics preserved, and stratigraphy intact. (It is noted that the preservation of stratigraphy is highly desired, but it is recognized to be difficult to achieve).
Desired:	Return up to several kilograms of samples from multiple sites on the nucleus, with stratigraphy and all ices intact, and no cross-contamination of collected samples.

1.1.1 Document Organization and Format

As was noted above, the study objective is to provide individual responses to each of the six question items assigned by the panel but not to lay out a comprehensive CNSR mission concept. The responses to these six targeted questions are provided in the sections of the document that follow. The mapping of document sections to item numbers is as follows:

- Section 2: Study Item #1
- Section 3: Study Item #2
- Section 4: Study Item #3

- Section 5: Study Item #4
- Section 6: Study Items #5 and #6

Note that the responses to Items #5 and #6 have been consolidated into a single section because of the overlapping and highly coupled nature of those two topic areas.

The last section of the study report, Section 7, presents a proposed technology development roadmap for the key technologies discussed in the preceding sections of the document.

2. Item #1: Obtaining a Single, Stratified, Subsurface Core

"What is the best way of obtaining a core at least 25 cm deep and 3 cm across? Does it require a 'real' landing as opposed to a 'touch and go'?"

2.1 Background, Key Requirements, and Assumptions

We discuss here the requirements to obtain core samples of comet nucleus material, in which preservation of stratigraphy is a desired goal. Our assumption is that one or more missions prior to a CNSR mission will have determined surface geophysical properties to the extent needed to give confidence that core sampling at subsurface depths will be successful. These missions will include Rosetta, which will drill into the surface of its target (67P Churyumov-Gerasimenko), and a CSSR mission (by assumption, perhaps as a NASA New Frontiers mission).

The most important physical parameter to determine for core sampling is the *relative* density, which is a percentage describing how the bulk density relates to the minimum possible value, ρ_{min} (0% relative density, when particles are sprinkled gently into a container), versus the maximum possible value, ρ_{max} (100% relative density, as achieved under mechanical agitation but without crushing the grains):

$$Relative\ density = \frac{\rho_{max}}{\rho} \times \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}}$$

To acquire a core sample, an appropriate degree of compaction of the material sampled must be achieved. A loose (low relative density) soil requires a greater degree of compaction for core sampling than a high relative density soil. For example, lunar regolith within the uppermost 15 cm is typically dense, with relative density >65%, increasing with depth to values >90% below 30 cm. Hence the successful core samplers used on Apollo missions 14–17 (e.g., the "4-cm drive tube") were those that required lesser degrees of sample compaction. Specifically, the 4-cm drive tube had an external tapered bit and a thin-walled design, used on Apollo 16 and 17, versus the "inverted funnel" bit for the thick-walled 2-cm design used on Apollo 11.

It is currently thought, based on Deep Impact (DI) results, that cometary surface material is loose and fluffy, that is, of low relative density. If the DI results are generally relevant to the surfaces of all comets, then the experience with the Apollo core sampling drive tubes may not apply to comet sampling. Successful core sampling of a comet surface may require a drive tube design that significantly compacts the sample, in contrast to the Apollo 4-cm drive tube design. It may be prudent, given residual uncertainties of target surface geophysical properties that may remain even after prior landed missions have been completed, to accommodate more than one core tube design for use on a CNSR mission. In any case, given these uncertainties, simpler, more straightforward approaches to sample collection that can operate under the widest possible range of surface conditions are preferred.

We thus adopt the perspective that the lunar regolith provides a useful "worst-case" upper bound for comet sampling. Specifically, we assume that the penetration resistance and bearing strength of the comet surface will be bounded on the high side by the values for lunar regolith. We currently expect that future in situ comet missions will show the comet surface to be weaker than lunar regolith, but it seems reasonable to require that the core sampling system be able to emplace a drive tube into a target as strong as the lunar regolith. The penetration resistance, for example, is usually modeled as the sum of two terms, the first of which is proportional to the surface cohesion (in a Mohr-Coulomb model for shear strength) and the second of which is proportional to the acceleration of gravity. The cohesion of lunar regolith is typically ~1 kPa, whereas the estimated cometary value from DI is perhaps as much as an order of magnitude lower. The surface gravity of a comet is about 1000 times lower than lunar gravity. Hence the penetration resistance of the comet surface is expected to be much less than that for lunar regolith, possibly by more than an order of magnitude. A reasonably conservative engineering requirement for the core sampling system is that it be able to emplace a drive tube within a target as strong as lunar regolith.

2.2 Core Sampling of Extraterrestrial Body: State of the Art

Although there is considerable engineering and scientific experience with core sampling on Earth, core samples were last obtained on an extraterrestrial body by Apollo astronauts on the Moon. The astronauts used core tubes that were pounded into the lunar surface with a hammer, as shown in Figure 2-1. Design changes were implemented with successive missions, as illustrated in Figure 2-2, to improve the collection of well-packed core samples and to reduce the force required to drive the core tube into the regolith.

Figure 2-1. Astronaut Alan Bean driving a core sampler into the lunar surface with a hammer. (Image courtesy of the NASA JSC Imagery Services, http://science.ksc.nasa.gov /mirrors/images/html/as12.htm.)

We adopt, for the purpose of making quantitative estimates, the parameters of the later Apollo mission 4-cm drive tubes (the Apollo 15–17 Core Tube design as indicated in Figure 2-2) for core sampling. These were tubes with an inner diameter of 4.13 cm, an outer diameter of 4.39 cm, and an internal sample length of 34.9 cm. They were constructed of 6061-T6 Al with a 17-4 PH stainless steel cutting bit. The drive tube mass was ~190 g. The capacity of one of these tubes was 468 cc. The bit was externally tapered with a fitting for a screw-on cap at the end. There was a spring-loaded keeper pushed onto the top of the core by the astronauts to secure the sample.

The static force to push these tubes to depths of 30 cm or more was up to ~200 N, depending on terrain (less in looser regolith like that found on crater slopes and fresh rims and more in denser regolith of inter-crater areas). Apollo astronauts could not achieve such high static force, and they emplaced the tubes by hammering. The hammer used in later Apollo missions had a mass of 1.3 kg, and ***on the order of 50 hammer blows*** were required to emplace a drive tube. The reason for the large number of hammer blows is believed to be the rapidly increasing density and material strength of the lunar regolith (see Figure 2-3) [1].

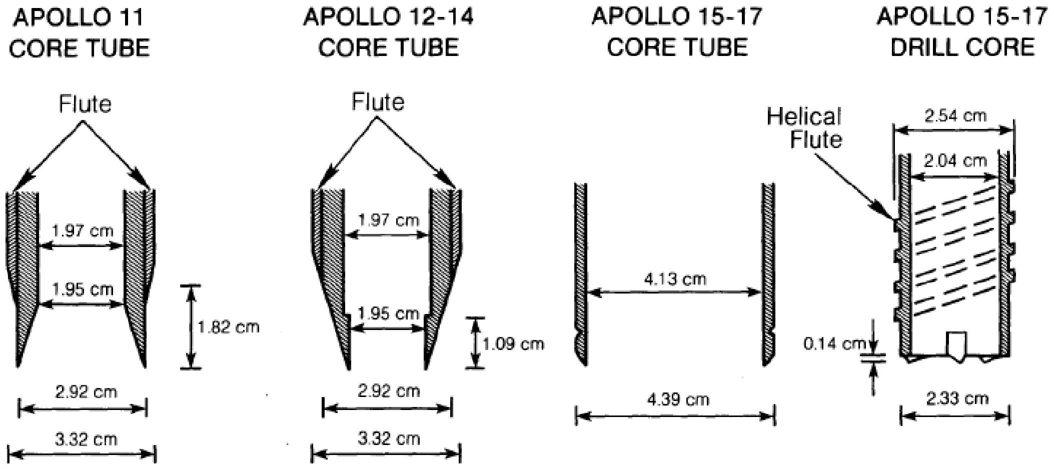


Figure 2-2. Cross-sections and dimensions of the lunar core samplers used on Apollo missions. (Image reproduced from ref. 1; © 1991Cambridge University Press.)

The ESA Triple-F study of a CNSR mission also reported a core sampling experiment that successfully extracted a core from a comet simulant material. This core, which had a diameter of 0.75 cm and a comparable length, was less than 0.5 cc in volume and was much less than the desired capacity for a CNSR sample. The simulant used was a highly porous dust agglomerate. The Triple-F study discussed the technical challenge of core sampling low-strength cometary materials without damaging or disrupting the physical structure. Consistent with study guidance, we will assume that a suitable comet simulant material will be defined for engineering testing and that coring of this material will be demonstrated in realistic environments (vacuum, low temperature, and low gravity).

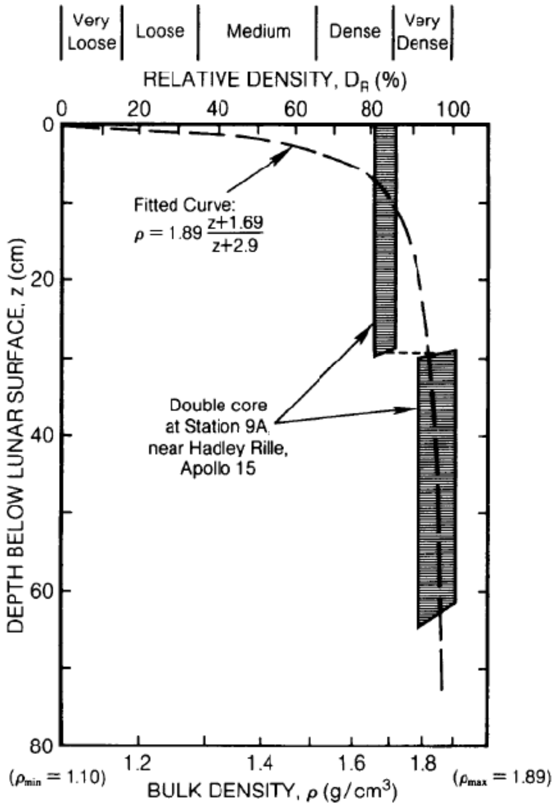


Figure 2-3. Bulk and relative density of lunar regolith vs. depth from Apollo 15. (Image reproduced from ref. 1; © 1991 Cambridge University Press.)

2.3 CNSR Core Sample Acquisition System: Key Characteristics

Taking into account the CNSR mission science goals and the Apollo lunar coring experience, a sample acquisition system to acquire core samples from a comet needs to be developed with the following characteristics:

1. Fast-acting penetration, <1 s.
2. Ability to sample dense (ρ = 1.7 g/cm^3) regolith to 25-cm depths.
3. Hard stop to limit penetration depths >>25 cm if the penetration forces are much less than required to penetrate lunar regolith.
4. Mechanisms to restrain and compress core samples so as to remove voids, prevent escape of sample, and preserve stratigraphy during re-entry and landing.
5. Double-wall drive tube construction, with an inner sleeve to hold and allow extraction of the sample, leaving the outer drive tube behind in the comet surface.
6. Design of sample canister (storage and sealing system) that allows for possible presence of material on the outside of the core or beyond the nominal core volume envelope.
7. Hermetic seal to maintain pressure and eliminate contamination.

The first four of these design elements will be discussed in subsections below. The elements involving sample encapsulation will be further addressed in the response to Item #5 (Section 6).

2.3.1 Fast-Acting Penetration and Ability to Sample Dense Regolith

Using the lunar example, the CNSR samplers should conservatively be designed to overcome a dense (ρ = 1.7 g/cm^3) regolith for cores up to 25 cm deep. Various approaches for inserting a core sampler into the cometary surface should be considered, including the following:

1. Apply static force from anchored spacecraft.
2. Apply static force from hovering spacecraft firing thrusters.
3. Apply dynamic force using spacecraft inertia to drive the core tube into the surface.
4. Apply dynamic force from hammering (percussive coring).
5. Apply dynamic force from impact coring (drive tube is a projectile fired into the surface).

All of the above emplacement approaches require precision guidance and control of the spacecraft in 6 degrees of freedom relative to the surface at very low altitudes.

We do not consider Approaches 1 and 2 to be viable CNSR methods of sample collection. Approach 1 requires anchoring and is thus likely difficult. Following the results of the Deep Impact mission, there are likely large risks involved with anchoring to the comet surface. Approach 2 requires large thruster firing before and/or during sampling. This approach thus entails potentially serious compromise of CNSR mission science because firing thrusters near the comet surface, especially just before and during sample acquisition, can lead to contamination of the sample or the sample system and/or to surface disturbance leading to dust generation.

Approaches 3 and 4 require control thruster firing before and/or during sampling. The percussive coring method (Approach 4) may require significant time (more than 1 s) to complete emplacement. Approach 5 may allow limits to thruster firing until after sampling for liftoff.

Approach 3, which relies on spacecraft momentum to insert a core sampler into the surface, has the advantages of avoiding requirements to perform a long-duration fixed landing or to anchor to the surface. However, the approach still has the disadvantage of needing to allow for or compensate for spacecraft lateral velocities of up to 5 cm/s. A fast sample acquisition time of ≤3 s is required to minimize the amount of displacement that must be accommodated while the core sampler is stuck in the comet surface to ≤25 cm.

Approach 4, an autonomously operated percussive coring system that is emplaced onto the target and that drives itself into the surface by repetitive hammering, has been demonstrated in terrestrial experiments. The performance requirements (power, total energy, and operating time) of such systems in the cometary environment of low gravity and low surface strength are unknown.

The harder or denser the surface layers are, the more difficult it becomes to obtain a large sample quickly (Figure 2-4). The CNSR core sampling apparatus could feature a hermetic, pyrotechnic device that would fire the core sampler into the surface of the comet (Approach 5), obviating the use of spacecraft momentum to drive the sampler tubes home. The core sampling insertion and retraction from the surface would still need to be completed in 1–2 s to minimize the amount of time that the spacecraft must operate in close proximity or contact with the body.

The ability to complete the core sampling operation quickly also minimizes the degree of sample alteration by heating (if the sample device is warmer than the target or if it dissipates considerable mechanical energy over time while sampling).

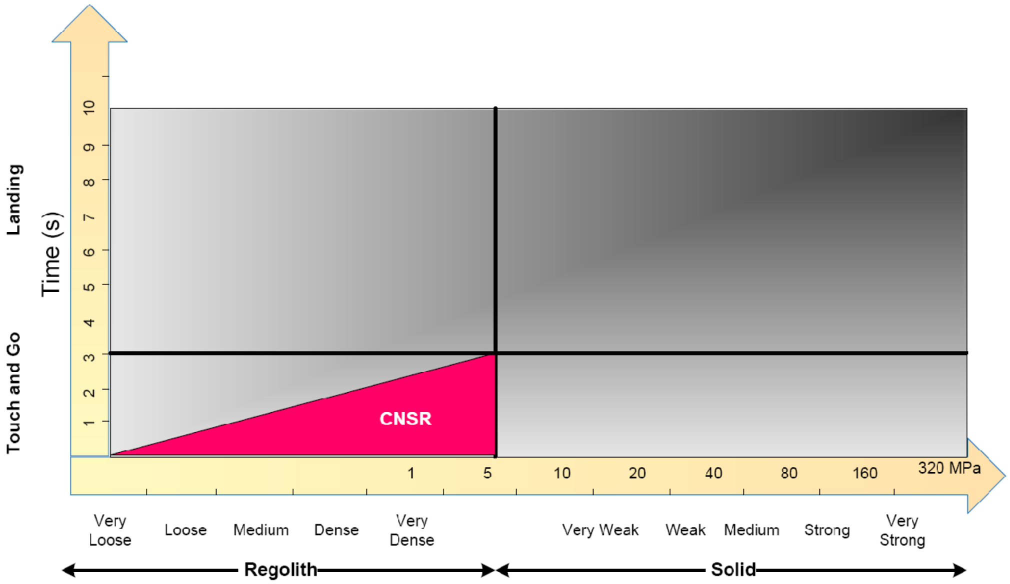


Figure 2-4. Touch-and-go comet surface sampling, depicting the trade space between landing and touch-and-go sampling across the entire spectrum of loosely packed regolith to strong solids.

Approach 5 for impact coring requires low-velocity drive tubes to sample the low-strength cometary surface. For a 200-g drive tube with the bit and cross-section of the Apollo 4-cm drive tube, a simple estimate gives a minimum kinetic energy of 68 J to overcome a nominal penetration resistance for dense lunar regolith of 1.5 MPa; the corresponding impact velocity is 26 m/s. This result is a lower bound to the required impact velocity. An upper bound is obtained from the results of laboratory impact experiments at low velocity [2] into perlite-plaster (a weak target simulant, with a static bearing strength of 1.5 MPa, versus lunar regolith with typical bearing strength of <100 kPa). These experiments suggest that penetration is momentum-controlled, and that 25-cm penetration into perlite-plaster requires a 600-g penetrator at 20 m/s (e.g., an Apollo-style 4-cm drive tube made entirely of steel instead of Al) or a 200-g penetrator at 60 m/s. Such projectile velocities are obtainable with standard space-qualified pyrotechnic devices.

2.3.2 Hard Stop, Sample Containment

Because of the wide range of soil property estimates for comets spanning several orders of magnitude, it is advised that the core penetrator have a mechanical hard stop to limit its depth of penetration. If the actual surface properties of the comet are at the low end of the estimates and the sampler is designed for lunar soil, the core could continue to penetrate far below the surface. If the core sampler were to penetrate several meters below the surface:

- A tether system may be required to retrieve the core. This would significantly complicate the core sampling system. Additionally, tether systems have a poor record of success in space.
- The core sampler could become grossly contaminated on the external surfaces, especially the rear surface, upon extraction. This contamination could significantly complicate the transport and storage of the core sampler.

Core samples are more easily obtained in higher relative density soils. If the comet’s surface properties are at the lower end of the predictions, the collected material may not be packed into the core sampler. A mechanism is required to contain the sample and pack it sufficiently to remove any voids within the sample canister. This mechanism is not required to seal the sample, but the sample cannot be allowed to remain loose within the canister as it is subjected to the shock and accelerations associated with re-entry and recovery.

2.3.3 Double-Wall Drive Tube, Canister Design, and Hermetic Sealing

It is envisioned that the drive tube coring systems would feature double-walled construction, with an inner sleeve to allow holding and extraction of the sample, leaving the outer drive tube behind in the comet surface. Beyond the potential for facilitating rapid extraction of the core, leaving the outer drive tube behind could afford the possibility of post-extraction analysis of the regolith surrounding the hole that results from the core being removed. The outer section of the drive tube left behind in the comet affords, in principle, an opportunity to emplace contact instrumentation or even active experiments. The latter may be as simple as heating the surface to artificially stimulate cometary activity.

Careful materials selection is required for surfaces of the sampling mechanism that will come into contact with the sample to resist damage from sampling and to minimize contamination of the sample.

CNSR science requires that the core samples be hermetically sealed in deep space and that they remain sealed throughout re-entry and recovery operations. The hermetic sealing of the sample canister must be accomplished even if the outside of the core sampler carries comet materials or if comet materials protrude outside the nominal volume envelope of the drive tubes.

2.4 Additional Implications for CNSR Mission/Spacecraft Design and Development

Consistent with the study guidance, we assume that a prior CSSR mission will have demonstrated successful proximity operations near a comet, including an autonomous landing on its surface such that sample acquisition is performed. The Rosetta mission is currently on its way to a rendezvous with comet 67P Churyumov-Gerasimenko. The Rosetta lander Philae will land on the comet, anchor there, and drill into the comet surface. These landed operations may also be demonstrated prior to CNSR.

2.4.1 Provisions for Extensive Evaluation and Test Program for Key Technologies

Although we have two likely approaches for CNSR sampling, these will need to be designed, implemented, and tested in near-zero gravity to raise their TRLs above 5.

2.4.2 Technology Development Roadmap

Refer to Section 7 of this report.

3. Item #2: Obtaining Multiple Samples at Varying Depths

> *"Might it be easier to obtain three samples from a specified depth (say 0 cm, 10 cm and 25 cm) each about 25 gm and from the specified depth within ± 5 cm?"*

Recent advances in scientific understanding of the physical nature of comet nuclei have changed our perception of engineering requirements for sampling a comet surface. Many lines of evidence show that comet surfaces are mechanically weak and are composed of highly porous, low-strength material. High-strength, brittle material is either absent or very unlikely to be encountered on a comet surface. Given this understanding, it is feasible to obtain contiguous, well-packed core samples of a comet to at least 25 cm. The ESA Triple-F study reached the same conclusion.

A core sampling system that would obtain separate samples at predetermined depths down to 25 cm is inherently more complex than a system designed to obtain a continuous core to that depth. Mechanisms would be required to open a coring chamber, acquire a small core, and then close, together with a sensor system to measure accurately the depth of penetration and an autonomous control system. Obtaining a contiguous 25-cm core involves lower engineering risk and provides superior science.

Alternate approaches for obtaining multiple samples at varying depths were considered for this study. One would provide multiple drive tubes of different sizes (wall thicknesses, lengths, and bit configurations) to accommodate better the uncertainty in mechanical properties of the comet surface. It may be prudent to provide for acquisition of more samples than the mission intends to return. Attempting to remove comet material from any sampler, so that it might be used again if an inadequate sample was obtained, is scientifically unacceptable, primarily because of cross-contamination concerns. Such a practice would also increase engineering and operational complexity, and, therefore, risk. It is scientifically preferable to use a different sampler, if possible, or otherwise add more sample to that already obtained. If multiple core samples are to be returned, they can be stored in a single sample canister that is hermetically sealed, but the different core samples do not need to be hermetically sealed from each other, assuming they are taken in close proximity to one another such that cross-contamination would not be a concern. Each sample would need to be separately packed and physically contained, in any case.

Although we assert that obtaining a contiguous 25-cm core (as described in the previous section) involves simpler sampling operations and lower engineering risk and provides superior science, it should be noted that one possible advantage of taking one or more much smaller samples at depth may be that fewer resources would be required for the hermetic sealing and cryogenic cooling of the much smaller volume samples over the return trip to Earth. The core sample shown in the Triple-F study, for example, is very small (listed as <0.5 cc) compared to the sample mass requirements assumed for this CNSR study. There are potential advantages of collecting and returning very small samples, starting with much lower heat lift and battery requirements. Individual core sampling may also be much easier for smaller samples than for the larger samples considered in this report, although the feasibility of being able to obtain a continuous core to a 25-cm depth, as required by CNSR, with a much smaller (<1-cm) diameter is questionable. If the individual sample mass requirement were lowered, this could lead to the use of some alternative mechanism to collect multiple, small cores at depth. As discussed above, however, such a collection apparatus becomes increasingly complex (e.g., having a means to open a port at an accurately known depth, get a core, and then close again). Although an acknowledged challenge, it could become a trade worth considering if, say, hundreds of kilograms of batteries would be required on the return capsule to keep higher-mass samples cooled through re-entry and recovery.

As for the science implications of potentially returning multiple, but smaller, samples, the situation is unclear. It is likely that a total sample of <1 g would not satisfy science requirements. However, if instead there is up to 1 g taken at depth, combined with hundreds of grams taken as a “grab” sample from near the surface, then the combination might be sufficient. In that case, one could argue that only the small sample from depth needs to be kept at cryogenic temperatures and hermetically sealed, whereas the much larger remainder of the sample could be allowed to freeze dry in vacuum and/or kept warmer.

4. Item #3: Verification of Acceptable Ice Content

"What is the optimum way of verifying that the sample contains at least 20% ice (and presumably accompanying volatile organics)?"

4.1 Key Requirements and Assumptions

Science guidance concerning sample verification was provided to the study. The science community wishes to ensure that an acquired sample is suitable for Earth return, or in other words, that it meets science requirements, prior to committing to return the sample. The form of the commitment may be inserting the sample into the sample canister and/or closing the hermetic seal of the canister, both of which may not be reversible.

The principal science requirement presented to the study, aside from overall sample size, was a sufficient abundance of water ice in the sample. Specifically, the following points were stipulated:

- Simpler approaches to detecting the water ice content of a collected sample are preferable.
- The sampling instrument is assumed to not be a major part of the CNSR mission payload, and so must be simple, low-cost, and easy to implement/operate. It only needs to detect the water ice fraction of the acquired sample.
- Methods that do not require alterations of the collected sample (e.g., physical contact, heating, separation of samples, etc.) are preferred.
- Methods that measure the actual sample to be returned are preferred over methods that measure different samples acquired nearby.
- The 20% water ice content requirement applies to the bulk sample and not to point measurements.

The study team classified potential approaches to sample verification. The study did not focus on the issue of sample size verification, which implies measuring sample volume and/or mass, but concentrated on the question of measuring water ice content. Various potential measurement approaches were considered and classified according to the criteria provided in the study guidance: Does the measurement apply to the bulk sample as opposed to, for example, a surface layer? Does the measurement apply to the actual sample to be returned, which implies that it must be nondestructive and cannot alter the sample? Does the measurement specifically measure water ice?

4.2 Discussion of Potential Sample Verification Approaches

Verification of the water ice content of the collected sample is required for mission assurance before return of the CNSR spacecraft to Earth is allowed. Various potential approaches to making this complicated determination are listed below. None of these is a mature technique already suitable for CNSR. Moreover, it is not clear that any of the techniques meet all of the desired criteria (simple, easy to implement, low cost, measurement applicable to the actual bulk sample, measurement specific to water ice). As already mentioned, the study team anticipates that a separate means will be provided by CNSR for verification of sample acquisition and sample size (e.g., high-resolution imaging and sample mass measurement).

The following potential sample verification techniques are considered:

- Near Infrared (IR) Spectral Mapping
- Differential Scanning Calorimetry/Evolved Gas Analysis (DSC/EGA)
- Neutron Spectroscopy

- Microwave Complex Permittivity

Table 4-1. Verification of water ice content in the sample.

	Bulk?	Nondestructive?	Specific to Water Ice?
Near IR Spectral Mapping	No	Yes	Yes
DSC/EGA	Yes	No	Yes
Neutron Spectroscopy	Yes	Yes	No
Microwave Complex Permittivity	Yes	Possible	Yes

Near IR Spectral Mapping. This technique involves spectral mapping of the sample, presumably down to submillimeter or microscopic scales, to search for and measure water ice spectral features. This measurement may not be feasible solely as a passive spectral reflectance measurement, but it may require active illumination. The technique characterizes only a surface layer of the sample (on the order of a micron) and not the bulk sample. The spectral mapping technique is familiar on planetary missions, and it is accommodated on the Rosetta mission.

DDSC/EGA. A portion of the collected sample is heated at constant volume starting from the ambient collector temperature (~125 K), until no volatile material is left (*T* ~ 450 K). The amount of applied heater power required to raise the temperature is recorded versus temperature and pressure. This DSC technique measures the heat capacity of the bulk sample and the latent heats of any volatile species released as the temperature is raised. It can be combined with chemical analyses of the evolved gases. These EGAs can use mass spectrometry, with or without gas chromatography. DSC/EGA experiments were flown to Mars on Phoenix, and EGA experiments are accommodated on Rosetta. Another EGA experiment was flown to Mars (but never operated) on the Deep Space 2 (DS-2) mission to search for water ice, but this experiment used a Tunable Laser Spectrometer instead of a mass spectrometer to measure evolved water vapor.

Although the DSC measurements alone can be specific for water ice, there can be complications with interpretations of these measurements in the case of complex materials with unknown admixtures of various icy phases. Detailed comparisons with a library of simulant materials in the laboratory can help with quantitative measurements of ice content, but it is not clear at present whether definitive determinations can be made in a timely manner, which will be required to support CNSR. Hence, it may be preferable to combine DSC with EGA, although the additional EGA requires a significant increase in payload cost and complexity. With EGA, definitive determinations of water ice content may be available rapidly.

Unfortunately, DSC and EGA are both destructive measurements that require heating of the sample. Hence this technique cannot be used to verify the actual sample to be returned for CNSR. The DSC/EGA techniques can be applied if the CNSR sample is subdivided, with a portion of the acquired sample put into a calorimetry/EGA chamber, or if a separate sample is acquired for DSC/EGA.

We note that the science risk of measuring not the actual sample, but a nearby sample, may be acceptable. The issue is essentially whether a subsample, or a nearby acquired sample, is representative of the actual to-be-returned sample. It is not fundamentally different from the risk of analyzing part of a laboratory sample and generalizing to the entire sample or even to the entire source body.

Neutron Spectroscopy. Measurement of the relative abundances of epithermal (medium-energy) versus thermal (low-energy) neutrons is an established technique for measuring the hydrogen abundance of planetary materials because soil containing hydrogen is more efficient at moderating neutrons. This technique has been applied to the Moon and Mars. This technique measures abundances of hydrogen (protons) as opposed to water, so it is not specific to water ice. It is a nondestructive technique that applies to a bulk sample, which is usually on the order of a meter in size. However, further analysis or experimentation is required to determine whether neutron spectroscopy using ambient excitation (by cosmic rays) can actually measure the relatively small, less than a liter, CNSR samples against the ambient background in a timely manner. More rapid, quantitative neutron measurements are possible if an artificial source (a neutron generator) is accommodated, but again with a significant increase in payload cost and complexity.

Microwave Complex Permittivity. Determination of microwave refractive index and absorption versus wavelength is a sensitive technique to sense water content of soils. The penetration depths for the radiation are millimeters to centimeters, which match well to the expected dimensions of the CNSR-collected sample (20–100 cm long by 5–10 cm wide). Measurement involves including the sample as the termination load in a microwave resonant circuit and measuring its resonant frequency, and it is highly sensitive because of its differential (before sample inclusion in the sample chamber vs. after sample capture and inclusion) nature. The amount of required microwave power is small, on the order of microwatts to milliwatts, and thus easily provided by the spacecraft batteries and a tunable Gunn diode source. The applied power needs to be kept low to ensure that there is no heating of the sample.

High specificity to water content can be obtained by tuning the microwave radiation to frequencies matching the dipole resonances of water molecules (0.5–10 GHz), and simple microwave sensing circuits have been described in the literature [3–5]. However, free water molecules in liquid or gaseous form will be ~100 times more absorptive due to microwave rotational transitions than water molecules in solid ice, so it may be necessary to produce free water in the sample to make the water content determination. This can be performed by letting the collected sample come to thermal equilibrium in the sample collection chamber, producing some water vapor above the comet sample, or by collecting a second sample in parallel. Unfortunately, any creation of liquid water in the sample would be at least partially destructive because it would lead to the possibility of aqueous alteration, as would any heating of the sample (if needed) to raise the water vapor pressure.

Another complication is that the sample will likely be acquired in metal tubes and placed into a metal sample canister. The microwave measurements may require insertion of probes into the sample or accommodation of vacuum waveguide feedthroughs.

4.2.1 In Situ Experiment

An alternative approach to sample verification was discussed by the study team to analyze material from the hole left in the comet. A possible active experiment was considered to make the penetrator itself into a heat source within the comet, assuming a double-walled penetrator such that after the inner portion with the core sample is extracted, the outer portion of the penetrator is left behind in the comet. It could subsequently heat the comet material (it should be cold initially to collect the comet sample). With sufficient heat generation to raise the temperature of local ice by at least 10 K, it would increase the local vapor source rate dramatically, by more than an order of magnitude. Such a local increase in activity can be measured locally by the spacecraft, by sitting in the plume with a mass spectrometer, by imaging (of entrained dust), or by spectroscopy (detection of water vapor).

This technique does not measure the actual sample to be returned, and moreover it is complicated by the uncertain thermal contact between the penetrator and borehole. Detailed modeling would be required to estimate the transport of heat and vapor migration through the local cometary material from the borehole, leading to uncertainty in the assessment of local water ice and other volatile content. However, such an in situ experiment may be of great scientific interest, independent of sample verification, especially if the emplaced penetrator(s) also accommodate in situ measurements of comet physical properties. Measurements of comet mechanical, seismic, thermal, and electrical properties were included on Rosetta.

5. Item #4: Provisions for Re-Sampling If a Core Is Unacceptable

"What prudent provisions for re-sampling are available if the sample does not meet the ice-content requirement?"

5.1 Key Requirements, Assumptions, and Constraints

Science guidance was provided to the study to bound the discussion of a potential re-sampling strategy, to be applied in the event that a first sample collected did not meet the stipulated water ice content requirement. Specifically, the following points were stipulated:

- Simpler, lower risk re-sampling strategies are preferable.
- The single, contiguous core sampling approach discussed in the response to Item #1 (Section 2 above) is baselined.
- A sampler used for the first coring operation must not be cleaned out and reused for a second attempt because of cross-contamination concerns.
- If the initial sample collected is deemed to be valid and is successfully stored for return, then subsequent collections should not be attempted.
- If the initial sample collected is deemed to be invalid, it should not be discarded in an attempt to acquire and analyze a second sample.
- It is assumed that if the first collected sample were deemed to be unacceptable on the basis of overall sample volume or mass, the same re-sampling strategy would be applied for the second sample as if it had failed the water ice content requirement.

5.2 Recommended Re-Sampling Strategy

To satisfy the above key requirements and assumptions, a CNSR mission should be equipped with, at a minimum, two redundant core sampling mechanisms, along with the capacity to store and return to Earth at least two independently sealed core samples at cryogenic temperatures, potentially collected from differing locations on the comet surface. Such redundancy would also benefit the mission from the perspective of mitigating sources of single-point failure. The recommended CNSR re-sampling strategy is illustrated in Figure 5-1 and described as follows.

Assuming that both sampling mechanisms are functional at the time of the comet encounter, one of them would be used in the initial attempt to collect a scientifically valid core sample, utilizing the techniques for collection and assessment discussed above in the responses to Items #1 and #3 (Sections 2 and 4), respectively.

Should the first sample collected be determined to satisfy the water ice content requirement (and presumably the stipulated minimum sample mass/volume requirement), it would then be conveyed into the return capsule and sealed for return. Under this scenario, we take the position that no further core sampling operations should be conducted, given the risks inherent in attempting additional close approaches to the comet surface. Note that the ability to verify the activation and quality of the hermetic containment seal may also be of value in further refinements of this strategy, but it is outside of the scope of the current study.

In the event that the first sample collected does not meet the 20% water ice requirement, it would still be prudent to store and seal it for return as a contingent sample. After that, given the touch-and-go core sampling approach baselined above, and the need to avoid contaminating sample sites with close-in thruster firings, the protocol should be to relocate to the next best targeted sampling site on the comet (as previously determined by remote sensing) for a second core sampling attempt.

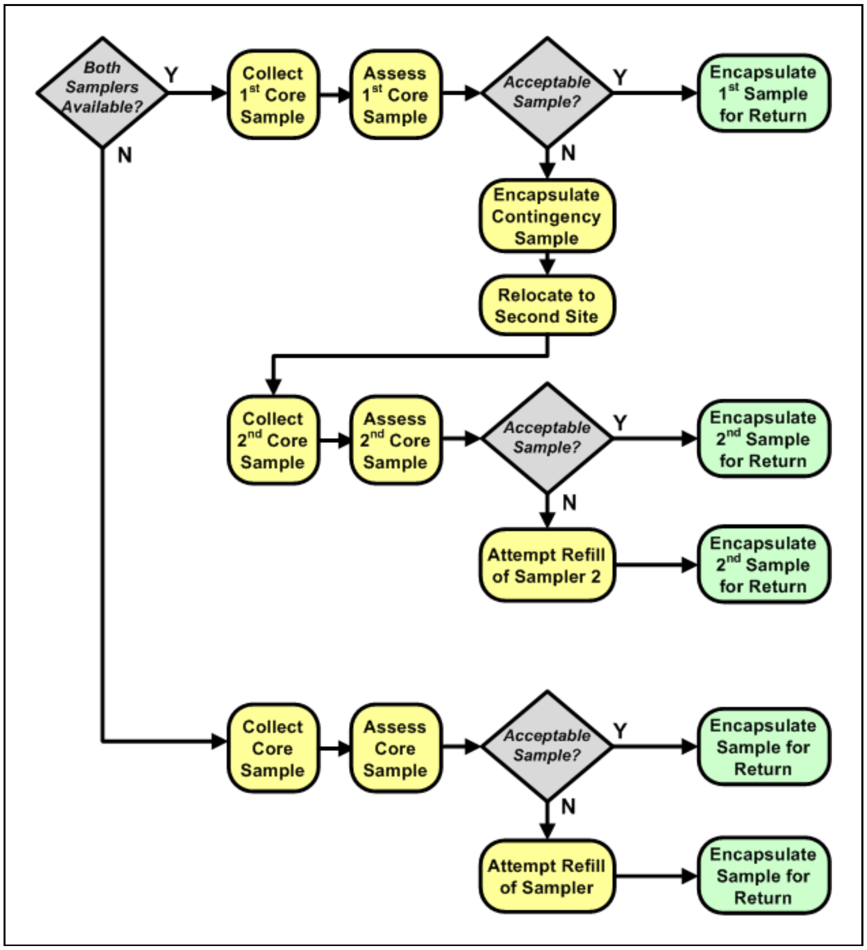


Figure 5-1. Recommended re-sampling strategy for CNSR mission.

If the second collected sample also fails to meet the minimum water ice content requirement, one additional effort should be made with the second sampler to pack in whatever additional material possible. Note that the possibility of attempting a second filling of the last available canister may not be possible, depending on the eventually adopted sampler design. Regardless, no attempt would be made to remove material already collected from the collector because this is considered to be technologically and operationally prohibitive.

If only one of the two samplers were operable at the start of the comet encounter, then the one operable sampler would be operated as if it were the second one in the two-sampler strategy above.

Given the above discussion, for maximum mission flexibility and assurance, we advise that the CNSR sample return capsule (SRC) be designed so that as many as two collected samples, depending on events, could be returned to Earth. We do not advocate building two separate SRCs because this would involve undue cost and complexity. Rather, a single SRC should be designed to be capable of containing and maintaining at least two sample cores in its interior for cryogenic return to a terrestrial laboratory.

Given that a second sampling attempt, if necessary, would be made from a different surface location than the first, two fully redundant sample collection and handling mechanisms should be baselined for a CNSR mission because of cross-contamination concerns. As was concluded in the above discussion on water ice detection methods, it is scientifically preferable to use a unique sampler for each collection, if possible.

5.3 CNSR Technology Development Implications

This issue does not require a technology development study because it is more a question of mission operational strategy and the potential use of redundant systems. Nonetheless, it is expected that there will be significant lessons learned between the writing of this report and the timeframe of an eventual CNSR mission that would further inform the subsequent development of the proposed re-sampling strategy. In particular, lessons learned are expected to come from the Rosetta and CSSR rendezvous missions. Although it is not yet known exactly what these lessons will be, it is possible at this point to anticipate some of the likely issues, including the following: (1) difficulties of sampling near an active site, known to be rich in volatiles but high in outflowing, optically thick gas; (2) the friability and strength of the upper few centimeters of cometary nuclei, overlaying a weak interior; and (3) the time involved in setting up a sequence for a touch-and-go approach, descent, sampling event, and departure.

In addition, we do expect the final adopted designs of the CNSR sample acquisition and cryogenic return systems to affect the eventual options available for a repeat sampling strategy. The strategies and options outlined above depend greatly on the ability to support redundant samplers and to have a containment system that can accommodate more than one continuous, full-length core sample. If resource constraints somehow make these accommodations prohibitive, alternative strategies will need to be considered.

6. Items #5 and #6: Encapsulation and Return of Sample Maintained at Cryogenic Temperatures

“What is the most efficient way of encapsulating the sample?”

“What methods can be used and what is their relative difficulty/cost to maintain the sample at: a) 90°K? b) 125°K? c) 200°K?”

6.1 Key Requirements, Assumptions, and Constraints

The key requirements for the encapsulation and cryogenic return of a comet nucleus core sample are driven by the need to preserve scientific integrity of the sample from the point of collection through to final analysis in an Earth laboratory. Primary concerns involve minimizing sample contamination, avoiding alteration of its chemical or physical state, and preventing loss of ice and volatile organics throughout the collection, return, and analysis phases of the mission timeline. An important secondary goal is preservation of the stratigraphy of a core sample. The sample depth requirement of 25 cm and the stratigraphy requirement are derived from the current understanding of the comet nucleus, which holds that the expected value of the diurnal thermal skin depth is nominally 10 cm. Material acquired from depths of <10 cm is expected to be depleted in volatiles.

These key science requirements drive a number of technological considerations, primarily in the thermal and mechanical areas. The sample must be kept sufficiently cold to prevent aqueous alteration, $T \leq 263$ K, throughout the entire mission. To prevent other forms of alteration, such as ice sublimation loss or transitions from amorphous to crystalline ice (occurring at ~135 K), preservation at cryogenic temperatures will be required as will be discussed below. Finally, the sample must be hermetically sealed before re-entry into Earth’s atmosphere, and the seal must be maintained through sample analysis in a terrestrial laboratory.

CNSR will be a Category V mission for planetary protection requirements. Current NASA policy considers comets to have uncertain biological potential based on a 1998 National Research Council report. It is currently unclear whether CNSR will be designated as an “unrestricted Earth return.” Planetary protection restrictions such as quarantine requirements for the sample and/or sterilization requirements for the spacecraft or its subsystems are potential mission cost drivers. (Mars samples, for instance, must go into a Biosafety Level-4 facility.) Planetary protection requirements for comet sampling need to be defined.

6.1.1 CNSR Mission Timeline

The CNSR mission timeline assumed for conducting the science and engineering analyses for this portion of the study comprises five distinct phases, as shown in Table 6-1.

Table 6-1. Assumed CNSR mission timeline.

	Pre-Encounter	Encounter	Return Cruise	Earth Approach	Earth Re-Entry and Landing
Duration	years	days	~2 years	days	1 day
Significant Activities/ **Events/ Features**	Bakeout and Cleanliness Control Preliminary Site Selection	Final Site Selection Sampler Cool Down Surface Approach Sample Collection In Situ Analysis & Re-Sampling (if needed) Cleanliness Control Encapsulation and Hermetic Sealing	Sample Cooling (Active or Passive) Pressure Management Maintain Hermetic Seals	Return Capsule Separation Active Sample Cooling Pressure Control Maintain Hermetic Seals	Re-Entry Parachute-Assisted Landing Maintain Sample Integrity Pressure Management Active Cooling Through Retrieval Maintain Seals

6.1.2 Characterization of Encapsulated Sample During Return: Sublimation Effects

To model the ice mass loss rate due to sublimation, the saturation vapor pressure *P* over bulk ice (or simply, vapor pressure) was calculated versus absolute temperature *T* by using the referenced databases and literature. The curve empirically fitted to experimental data by Murphy and Koop [6] was used for hexagonal water ice. The CO_2 vapor pressure was obtained from the Chemical Engineering Research Information Center (CHERIC) database [7]. The CO and HCN vapor pressures were obtained from the National Institute of Standards and Technology (NIST) database [8]. All of these were compared with the simpler approximation for vapor pressure used by Prialnik *et al.* [9]. There was reasonable agreement within 10% for H_2O, CO_2, and CO, but the HCN vapor pressure used by Prialnik *et al.* falls below the values given in the NIST database by more than an order of magnitude below 140 K. It is cautioned that experimental data do not appear to be available over the full temperature range of interest for all four ices, and extrapolations are required.

The vapor pressure *P* over bulk ice is related to the sublimation mass flux *q* in g cm^{-2} s^{-1} from the ice surface in vacuum by

$$q = P\sqrt{\frac{m}{2\pi kT}}$$

where *m* is molecular mass, *k* is the Boltzmann constant, and *T* is temperature. It is useful to define a surface recession speed v_s for bulk ice by

$$v_s = q/\rho_{\text{bulk}},$$

where ρ_{bulk} is the bulk density. This v_s is the speed at which the surface will recede because of sublimation mass loss. If we consider a sphere of solid ice at fixed T sublimating in vacuum, the radius and mass of the sphere decrease as follows:

$$\frac{R}{R_0} = \left(1 - \frac{v_s t}{R_0}\right)$$

$$\frac{M}{M_0} = \left(1 - \frac{v_s t}{R_0}\right)^3$$

where R_0 and M_0 indicate the initial radius and mass, respectively, at $t = 0$. In this simple model, the ice sphere exposed to vacuum will lose one-half of its initial volume (or mass) after time t such that

$$v_s t / R_0 = 0.2063. \tag{1}$$

Alternatively, at $v_s t / R_0 = 0.0345$ the ice ball would lose 10% of its initial mass.

Eq. 1 is a convenient criterion to evaluate the fraction of the mass lost to sublimation at temperature T.

Figure 6-1 shows the recession speed v_s in cm yr^{-1} for each of the four ices versus temperature T; symbols are plotted over the temperature range for which experimental data are available, and dashed lines are plotted where extrapolations are made. To apply this figure, we use Eq. 1 to find the value of v_s at which a solid ice sphere with an initial volume of 1000 cc (R_0 = 6.204 cm) would lose 50% of its original mass after 2 years. This recession speed is v_s = 0.64 cm yr^{-1}.

Hence Figure 6-1 shows that the temperature at which a 1-liter water ice ball would lose half its original mass to sublimation after 2 years is T = 162 K. Also from Figure 6-1, the corresponding temperatures for CO_2 and HCN ice are 97 K and 110 K, respectively (the latter is uncertain). Although not shown in Figure 6-1, the corresponding temperature for CO ice is 29 K.

A significant finding from Figure 6-1 is that for bulk ice exposed to vacuum over 2 years (that is, vapor pressures vented to vacuum), there is substantial loss to sublimation even at very low temperatures. At 200 K, for instance, even a 1-liter ball of water ice would be completely lost to sublimation, while the other three ices are more volatile and would be also be lost.

However, there is a complication arising from the expected granular nature of cometary material. The ice near a comet surface is not likely to exist in the form of solid boulders as considered so far, but it is expected to exist as a fine-grained, porous regolith. Such a material is believed to exhibit a much higher sublimation rate per unit volume (for a sample volume much larger than the grain size) than bulk solid because of a much larger surface-volume ratio (e.g., review by Prialnik *et al.* [9]).

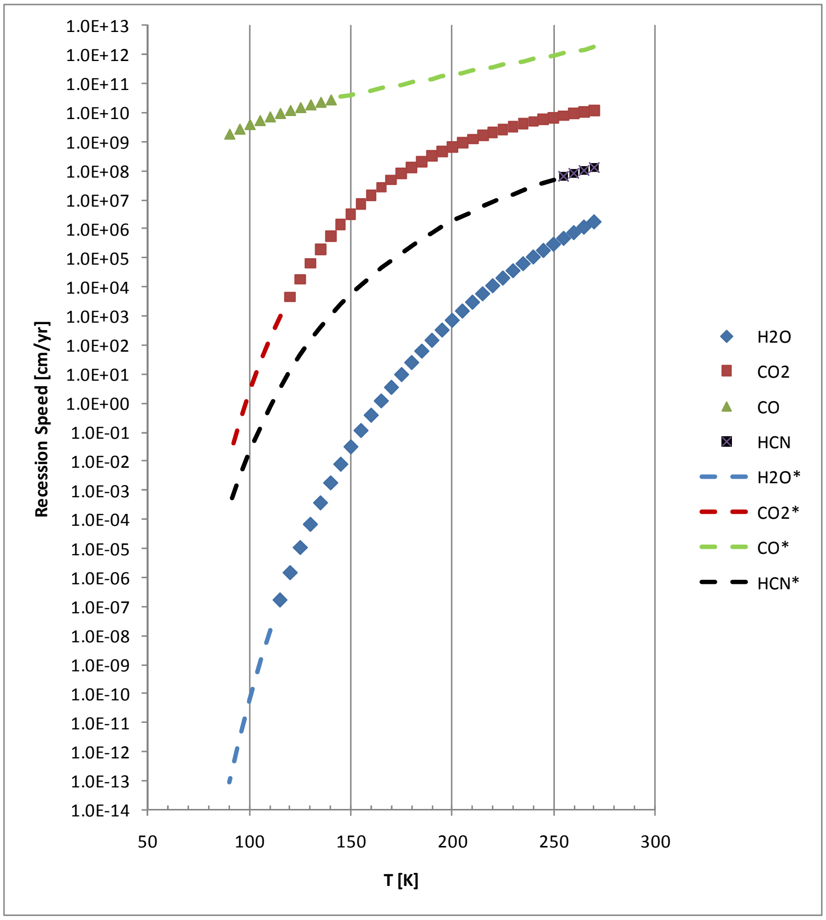


Figure 6-1. Bulk ice surface recession speed from sublimation into vacuum at temperature *T*.
***Plotted symbols indicate laboratory data, and dashed lines indicate extrapolations.**

Hence the ice sublimation mass loss when exposed to vacuum is even greater than has been estimated so far. However, the quantitative enhancement of the sublimation rate is uncertain because it depends on the unknown physical structure of cometary material. The importance of the granular medium effect can be understood heuristically by considering that the cometary ice exists in the form of small, probably <<1 mm, grains. Therefore, to apply Figure 6-1, the appropriate size scale is not the overall size of the sample (which is several centimeters for anticipated sample volumes) but a *much smaller* value determined by a microscopic grain size or a pore size. For instance, a widely used model (Mekler *et al.* [10]) considers that the sample is permeated and vented by a set of long capillary tubes. In such a picture it can be shown that fractional mass loss rate is

$$\frac{\dot{M}}{M} = v_s \frac{2}{r_p}\left(\frac{\rho_{bulk}}{\rho} - 1\right)$$

where r_p is the capillary tube radius and ρ and ρ_{bulk} are the densities of porous sample and bulk solid, respectively. Because these physical structure parameters for a comet surface are unknown, the result is again that the appropriate value of R_0 to use in Eq. 1 and Figure 6-1 is much smaller than the overall sample size.

To illustrate the calculation, Table 6-2 shows the mass fraction remaining after sublimation loss for 2 years into vacuum, assuming two cases. The first is the bulk ice case discussed above, ignoring the granular medium effect. The second is a granular medium case, (arbitrarily) assuming the value 1 mm for R_0 in Eq. 1.

Table 6-2. Remaining mass after 2 years of vacuum exposure, assuming bulk ice and granular medium cases.

Temp K	H2O (bulk)	CO2 (bulk)	CO (bulk)	HCN (bulk)	H2O granular	CO2 granular	CO granular	HCN granular
150	0.969	0.000	0.000	0.000	0.048	0.000	0.000	0.000
125	1.000	0.000	0.000	0.000	0.999	0.000	0.000	0.000
100	1.000	0.003	0.000	0.978	1.000	0.000	0.000	0.168
90	1.000	0.987	0.000	1.000	1.000	0.404	0.000	0.984

According to Table 6-2, preservation of an icy sample exposed to vacuum requires even lower temperatures for a granular medium model than for bulk ice. As already mentioned, at temperatures as high as 200 K, all four ices are completely lost in either model. At 150 K, water ice is largely preserved in a bulk ice model but not in a granular medium model. Cooling to 125 K provides assurance that water ice will be preserved, but the other three ices are still completely lost. Even at the lowest temperature considered, the CO ice is completely lost, and even CO_2 ice may be substantially lost depending on the granular medium structure.

The conclusion is that to preserve the cometary ice in a sample, a means to provide a hermetic seal is needed. The sample must not be exposed to vacuum pressure for 2 years, but it needs to equilibrate to its saturation (partial) pressures. A hermetic seal in any case is needed after entry into Earth's atmosphere. However, it will be technically difficult to design a seal that will withstand a pressure differential of much more than 1 bar (as it must open to accept the sample at the comet and then close and seal in deep space). Inclusion of a positive pressure relief valve will be necessary to keep the interior pressures at reasonable values to avoid mechanically damaging the sample return container. For reference Table 6-3 shows the saturation vapor pressures of the four ices at representative temperatures. Some values are extrapolated, as discussed above.

Table 6-3. Saturation vapor pressure in Pa for four ices.

Temp K	P H2O	P CO2	P CO	P HCN
200	1.63E-01	1.58E+05	4.04E+07	3.61E+02
150	6.11E-06	6.82E+02	7.09E+06	9.70E-01
125	1.87E-09	3.52E+00	2.41E+06	7.10E-03
90	1.40E-17	2.11E-06	2.39E+05	3.75E-08

If the sample contains significant CO ice, which may not be likely considering the high volatility, there is a possibility of generating high pressures within a sealed sample volume (from 2.39 bar at 90 K to >400 bar at 200 K). For the other three ices, the overpressure within the sample volume is moderate even at 200 K.

However, it is unlikely that there will be enough CO in the sample to put the pressure up to the saturation vapor pressure, but it is likely that there will be enough to generate a few bars of pressure. A simple estimate is made by assuming that the sample contains at least 20% ice and assuming a CO/H_2O ratio of 5%, which would not be unusual for a short period comet (there are much higher values in long period and new comets, but these are not likely to be the CNSR target). At 125 K, the saturation vapor pressure of CO is ~24 bar corresponding to ~2.3 mol/L of vapor, which is 65 g/L. If we have as much as 500 g of comet sample, containing at least 100 g of ice, we would likely have up to 5 g of CO. This would support roughly 2 bar of pressure in the sealed sample volume of about a liter. If the sample is richer in ice and/or CO, the vapor pressure could be higher. Alternatively, the CNSR target could be much poorer in CO relative to H_2O.

In closing, it should be noted that the sublimation discussion above assumes simple bulk mixing, which may not be realistic for the comet sample (although the discussion bounds the sublimation rate; that is, the sublimation loss will be more than that for the pure hexagonal water ice but less than those for the volatile ices). We do not expect that there will be any bulk volatile ice in the sample, but we can expect that volatiles will be trapped in amorphous water ice, which has slightly higher vapor pressure than hexagonal ice. Experiments show that trapped volatiles are released at ~120 K. Hence at temperatures (~125 K or ~135 K) that we are discussing, the volatile species are released from the water ice (which will not fully recrystallize at those temperatures). However, once the saturation vapor pressure is attained in the sealed sample canister, then the volatile species will recondense into bulk ice. This will be the result for CO_2 and also HCN unless the abundance is unexpectedly low (<0.19 g/L at 125 K). Methane has a complication in that it can form a clathrate hydrate. As we have mentioned, CO will not recondense. To prevent the loss of volatiles from amorphous ice and then recondensation, it is possible that the temperature should be kept safely below 120 K, as opposed to the 125 K level that was identified in the study request, and used as the basis for analysis in subsequent sections of this report. If further study were to show that the sample temperature should indeed be kept below 120 K, resulting implications for science and for engineering would need to be addressed. On the basis of current information, a change from 125 K to 120 K would not fundamentally change the thermal analysis presented below.

6.2 Thermal Analysis

The thermal requirements for a comet sample return have been reviewed in terms of the temperatures needed to preserve the sample during transit and the thermal control options available. During the long transit in space, the return capsule will need significant resources (power, attitude, and radiator area) from the host spacecraft. The driving design item for a cryogenic sample return mission is the re-entry and recovery of the capsule. While the overall approach appears to be feasible, there are specific areas that will require significant engineering development.

6.2.1 Mission Timeline—Thermal Implications

A version of the assumed CNSR mission timeline (Table 6-1 above), as viewed from the thermal engineering perspective, is shown below in Table 6-4. In the initial, pre-encounter stage, the sampling equipment and canister will require some type of contamination control to make sure they remain clean as the spacecraft undergoes residual bakeout in the early mission.

Prior to sampling, the sample collection mechanism and storage system will need to be cooled to their normal operating temperature. Depending on the specific design, this period will probably take several days. As the sampling system gets cold, it will tend to accumulate contamination from the local spacecraft outgassing. During this time, some care should be taken at the spacecraft level to control outgassing and vent it away from the sampler area. The duration of the actual sampling period is assumed to be relatively short and will not affect its temperature control. Spacecraft position and sun angle will be critical to the local sample temperatures during this part of the mission.

Table 6-4. CNSR mission thermal timeline.

	Pre-Encounter	Pre-Sample Cooldown	Cruise Duration	Pre-Entry Attitude	Re-Entry
Duration	years	days	years	10 days	1 day
CNSR					
Activity	Bakeout	Active or passive cooling	Active or passive cooling	Active cooling	Active cooling
Hot Parasites			0.5–1.5 W		
Cold Parasites			1.3–4.0 W		
Hot Environ.				2.4–6.6 W	5–9 W
Cold Environ.				1.4–5.5 W	
CSSR	3-cc sample		13 K		2 h
Cold			0.3 W heat leak		0.6 W
Hot			1.4 W		2.8 W

Once the sample has been collected, it must survive the voyage home and re-entry. The temperature limit requirements are discussed below, but cooling requirements for a cryogenic sample during the long cruise phase will be on the order of 10 W. Both active and passive cooling options are available. The preference of one approach over the other will be a function of the eventual spacecraft design.

Note that in the thermal timeline of Table 6-4, all listed power values refer to thermal heat leak needed to support the cryogenic section. The electrical power or passive means needed to provide that thermal heat leak are described below. Also note that, for purposes of this study, the size of the cryogenic vessel was taken to be 15 cm in diameter by 30 cm in length.

The active cooling option involves the use of a mechanical cooler with a significant heat lift capacity (5 W or 10 W at the operating temperature). The main impact for the spacecraft will be in terms of requirements for electrical power (on the order of 100 W). Passive cooling could be used to save power, but this approach would place other requirements on the system. A passive radiator could provide the cooling needed, but it would also place stringent attitude control requirements upon the spacecraft to keep the radiator facing away from the Sun. The radiator size would depend on its own parasitic heat inputs but would need to be at least a few tenths of a square meter. It would need a thermal link to the cryo storage area that was either breakable or one-way.

During the majority of the nominal 2-year return cruise to Earth, it is assumed that the spacecraft can maintain a thermally favorable attitude for the passive radiator or the mechanical cooler hot sink. As the spacecraft approaches the Earth in preparation for capsule jettison and re-entry, however, the maintenance of such a thermally favorable attitude is by no means guaranteed. As many as several days before capsule separation, the spacecraft may need to assume attitudes that are optimal for mission design considerations but may not thermally support the radiator pointing requirements imposed by a passively cooled cryo storage system. Depending on the details of an eventual mission, it may not be possible to reconcile these conflicting requirements during this phase, and so it is prudent to baseline the need to switch to active cooling at the point where the radiator pointing requirements can no longer be supported. Therefore, for the remainder of the time connected to the spacecraft, the return capsule would need to be on active cooling, supported either by spacecraft bus power or by batteries, depending on spacecraft ability to support active cooling power requirements during the pre-entry phase. However, if the spacecraft were to be designed such that active cooling is used throughout the cruise phase, then this pre-entry phase would simply be an extension of the cruise period, with no need to switch over or make unique accommodation provisions.

The final phase covers the separation from the returning spacecraft, the capsule re-entry and landing, as well as the recovery of the capsule from the landing site. After separation from the spacecraft, the power required to support active cooling of the sample would need to be supplied by batteries housed in the return capsule. It is assumed for this study that primary batteries would produce the largest power/volume ratio and are the best option for the final phase. On the basis of the discussion presented in Section 6.4, below, lithium thionyl chloride primary batteries provide a specific energy density of about 600 W-hr/kg and are available in size D cells that provide about 1.4 W-day/cell. Power and volume options for the return capsule are based on that value.

The details of the capsule return are a key part of the capsule thermal design. It is assumed for this study that the return is to the Earth. Other options, such as a return to the International Space Station, could also be considered. However, the thermal impacts of alternative return scenarios are not expected to change the basic approach presented here. The time period and power needed for the active cooling would remain the system drivers.

6.2.2 Temperature Limits

The above discussion on sublimation effects (Section 6.1.2) establishes the basic temperature limits for a comet sample return within the parameters of this study. It is assumed that the sample would include volatile ices along with dust. The volatility of H_2O, CO_2, CO, and HCN were examined in terms of their sublimation over a 2-year cruise phase at a variety of temperatures. The results indicate that above 150 K, none of the original ice would exist after 2 years. Below 125 K, water would exist in both amorphous and crystalline forms, but no other ices in their pure form would survive as solids; however, the possibility remains that the minority volatile species would remain mostly in the ice phase, if they are contained in cometary nuclei as clathrates or dilute solid solutions in a water ice matrix. At 90 K, the water, HCN, and the bulk CO_2 would mostly survive.

Requirements to return all evolved gases during transit would require the sample return capsule to be hermetically sealed. However, then the issue becomes the internal pressure in the capsule. The storage temperature needs to be chosen to minimize the structural requirements on both the container and the sealing process. As a result, a viable storage temperature for a sealed sample would need to be less than ~125 K.

Alternatively, if it were the case that the retention of evolved gases was not required, a higher-temperature option could include a vented sample containment system. In that case, water and other volatile ices would be lost in transit. The remaining sample would be freeze dried, so the desire would then be to prevent the loss of labile organics in the dust after return. The temperature necessary to accomplish this is ill-defined. A Comet Surface Sample Mission Study tasked by NASA and performed at The Johns Hopkins University Applied Physics Laboratory in 2007 recommended that, to prevent the loss of labile organics, the sample should never be allowed to warm above 300 K. The sample would still have to be sealed before re-entry to both support the thermal control and prevent contamination.

For the present study, two cases were defined as optional storage temperatures. The first is 125 K, which is needed to maintain water ice, whether the container is sealed or unsealed. The second is 300 K, which would be used when ice preservation is not required but preservation of labile organics in the sample is required.

Other specific temperatures listed in the present study request were 90 K and 200 K. As noted above, a 90 K sample temperature would preserve more of the solid ices. However, a cold sample temperature of 90 K, as opposed to 125 K, would have a significant impact on the overall design. Cooler heat lift is a function of the power applied and the cold tip temperature. The heat lift would increase by about 1 W. In the final recovery stage, low-power coolers provide about a 1-W heat lift capability, so the effect of the temperature reduction from 125 K to 90 K would basically double the combined cooler and battery mass. Therefore, in light of the above discussion, it can be seen that designing to a 125 K temperature limit presents a reasonable compromise in meeting the established science requirements as feasibly as possible.

On the higher side of the range of temperatures requested for consideration, a temperature of 200 K would not change the overall design approach but would make implementation considerably easier from a thermal deign perspective. Heat lift would be reduced along with the electrical power needed to support it. However, as noted above, the result would be the evaporation of the volatile ices. Therefore, the design would create a larger needed for evolved gas collection and/or control.

It also should be noted that the ESA Triple-F comet nucleus sample return mission proposal has apparently assumed less demanding temperature requirements than what is being considered for the study presented in this report. The Triple-F document states the need for a sample return temperature of 135 K to preserve the ice in solid form over the mission timeline. It also allowed that temperature to rise to 170 K for 2 h during atmospheric re-entry.

6.2.3 CNSR Study Thermal Design Approach

The basic design approach defined for the study is shown in Figure 6-2. The cold area is surrounded by a cryogenic phase change material. Beyond that is a vacuum insulation space, which provides the thermal radiator barrier. The structure is mechanically supported, but thermally isolated from the outer capsule, which is assumed to run near room temperature. The cold space is linked to either the mechanical cooler or passive radiator through a thermal link.

The details of the mechanical attachment and thermal isolation are the key items in determining the heat leak into the system and the protection of the sample from the external environment. The heat leak defines the cooling required, which in turn defines the battery size needed for the final phase. In Figure 6-2, the cold space is connected to an external cooling source, which could be either a mechanical cooler or a passive thermal radiator. As a supplemental cooling source, the addition of a phase-change material would provide an additional cooling capability for transient or failure cases. As noted earlier, for purposes of this analysis, the size of the cryogenic volume is assumed to be 15 cm in diameter by 30 cm in length, to allow for the possibility that cold section could contain several individually collected core samples of the dimensions called for in the study requirements.

As in all cryogenic systems, the design details are a tradeoff between the thermal isolation and mechanical support. For a proposed mission, the requirements and design of the sample return canister would need to be an early priority. For this study, low and high thermal resistances have been estimated. The high values indicate what should be achievable with a standard design approach: titanium flexure mount with multi-layer insulation (MLI). The low values represent what may be obtained through a special system, such as Kevlar cord supports and a gold-plated dewar type of insulation. The conclusion of this study is that the special system is needed. Therefore, the early design of the canister system and the use of a parachute-based re-entry are important risk-mitigation

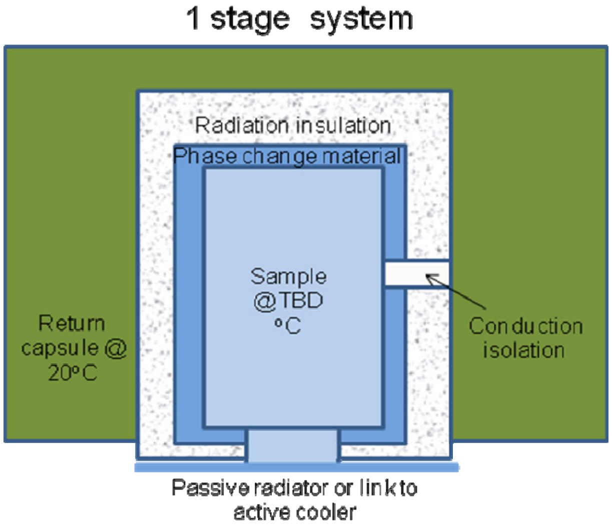


Figure 6-2. CNSR sample return concept.

activities. The extreme shock loads from a crash landing would certainly drive the structural requirements for the cryo-section support in a way that would increase the parasitic heat inputs.

The heat leaks into the cold area can be broadly defined in terms of a radiative and a conductive leak. As with any cryogenic system, there are a variety of heat paths through the insulation, including mechanical mounts, electrical harness, and local variations in the insulation. For this study all the conductive leaks were estimated as a single thermal resistance having a value between 50 and 150 C/W. As noted above, the lower value represents an insulation that could be achieved through a standard mechanical mount, and the higher value represents something that requires a more developmental approach. Similarly, the radiation heat leak includes all the area-based heat leaks across the insulation space. In Figure 6-2, the radiation insulation is the space between the cold and warm areas. The radiative isolation is defined in terms of an e* factor. For this study e* values were assumed between 0.01 and 0.03. As with the conductive resistance, the higher number represents a value that could be achieved with a standard design approach, and the lower value represents one needing more effort.

A preliminary look at the heat leaks into a cryogenic sample container is shown in Figure 6-3. The analysis uses the thermal resistances defined above for the conductive heat leak. The radiative leak uses the e* values defined and the surface area of the sample container. The analysis assumed a 30-cm-long by 15-cm-diameter refrigerated volume. The high and low heat leaks are shown along with their conductive and radiative components. The heavy lines show the cumulative minimum and maximum leaks. The results show the smallest expected heat leak between the return capsule and the sample area is between 1 and 2 W, at 125 K, while the largest would be between 5 and 6 W. The peak load during re-entry is expected to be about twice the cruise value for an hour.

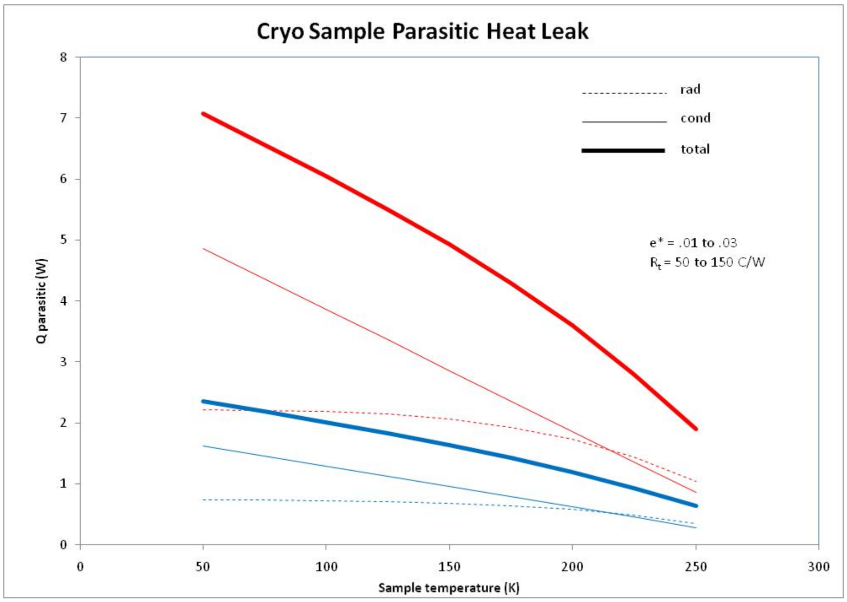


Figure 6-3. Cold stage heat leaks.

A slight modification to the thermal design approach that may produce better results is shown in Figure 6-4. The main difference is the addition of another stage of insulation. The cold area is mechanically mounted to the intermediate stage, which is in turn mounted to the warm structure. Thermal resistances of 50 to 150 C/W were used between the cold and intermediate stages, and resistances of 20 to 30 C/W were used between the intermediate and warm stages. A radiative isolation, e*, between 0.01 and 0.03 was used across the two isolation spaces. The intermediate stage also includes a connection to an external cooling source, either active or passive. This cooling of the intermediate stage allows the heat leak into the cold area to be significantly reduced.

This two-stage system, while more complex, affords significant benefit to a cryogenic sample return mission. The additional stage reduces the temperature and heat leak into the cold area at the expense of a higher heat leak into the intermediate stage. For a cryogenic sample return mission, the higher intermediate stage leak could be supported using resources from the supporting spacecraft. The lower heat leak into the cold area could be supported through a smaller cooler during the cruise phase, and the cooler coupled with a phase-change material would support the sample during the short period of the descent and recovery. Multiple stage systems are typically used in small cryogenic dewar coolers, both in the laboratory and in space, including for example, the Spatial Infrared Imaging Telescope III (SPIRIT III), Suzaku, and Infrared Laboratories dewar designs.

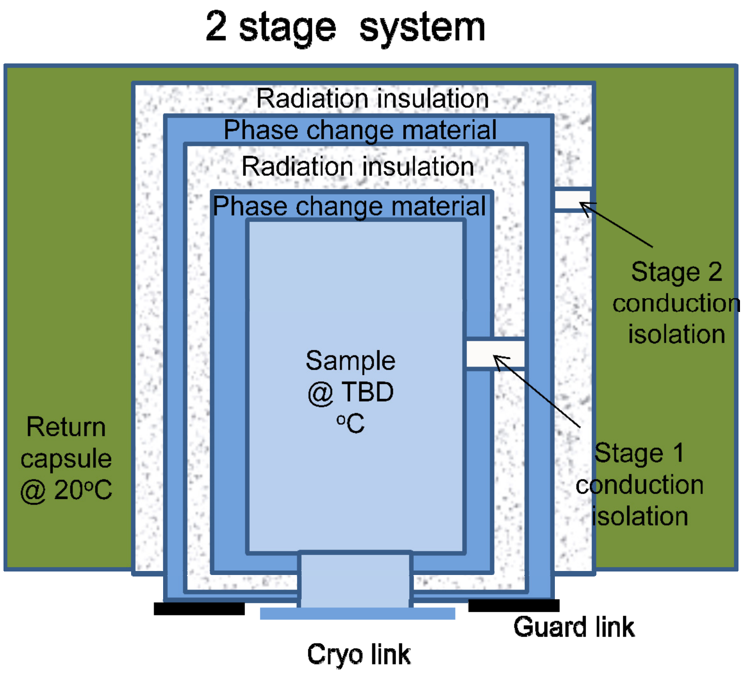


Figure 6-4. A two-stage sample return canister design approach.

Both passive and active cooling options were examined for the cruise phase. A mechanical cooler would provide a simple design approach but would require more electrical power. The passive radiator would use less power but would require a more complex mechanical configuration. In a two-stage system, with the intermediate stage at ~180 K, a passive design would include an external radiator tied through a thermal link to the intermediate stage. At 125 K, the cold stage most likely would require active cooling. During cruise, the externally mounted radiator would impose attitude constraints on the spacecraft to keep the radiator from viewing the Sun. In preparation for re-entry, the spacecraft would take up an attitude that may not be compatible with passive thermal control. Therefore, both stages would be switched over to active control. At that point, the thermal link to the passive radiator would have to be broken.

The heat leak during re-entry and recovery is a function of the local ambient temperature. It is important that the vacuum seal around the refrigerated section be maintained during this period. Using the same conductive and radiative resistances as defined above, heat leaks into the cold area are shown in Figure 6-5. The results show that the heat leak is in the range of 1–2 W for the best case but up to 3 W in a colder environment. During recovery, this leak would increase to about 9 W.

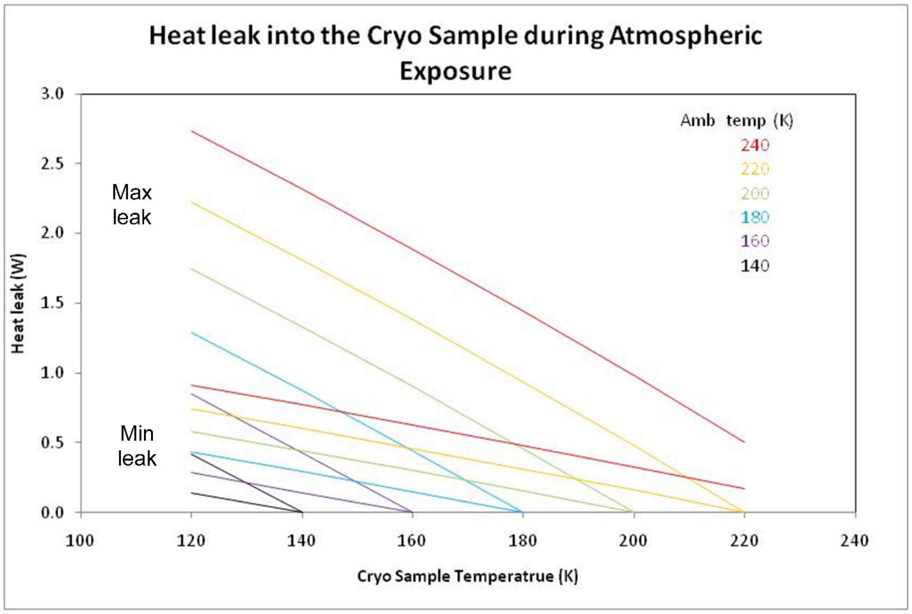


Figure 6-5. Cold stage heat leaks during re-entry and recovery.

The details of the re-entry present a variety of design options. The baseline design has the largest thermal load to the capsule coming during the soak back from the heat shield shortly after re-entry. One option to mitigate this heat pulse would be to jettison the heat shield as part of a parachute deployment sequence.

Once separated from the host-spacecraft, the cooling needed to support the cold area must come from batteries and the phase-change material. A preliminary sizing study was undertaken to determine the general options for the different items. The total cooling needed for a given heat leak over a given time period is shown in Figure 6-6.

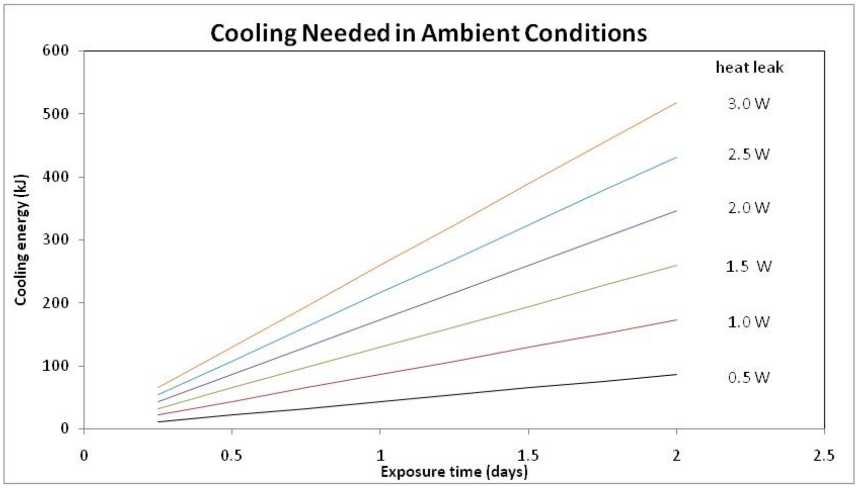


Figure 6-6. Cold stage heat leaks during re-entry and recovery.

Active cooling requires a mechanical cooler. There are a variety of cooler options available, including long-life and tactical. Generally, the lifetime of the tactical coolers is about 6 months whereas the long-life coolers last up to 10 years. Generally, tactical coolers are more efficient than the long-life ones. Electrical power is also a function of the heat lift required and the cold side temperature. A graph of the heat lift, cold end temperature, and electrical power used is shown in Figure 6-7. Smaller coolers lifting up to 1 W at 77 K require about 20 electrical W. From a battery sizing perspective, it is not practical to run a large cooler off a battery during re-entry and recovery. A small cooler with about a 1-W lift capability would require about 20 D cells per day. From the volume limitations of the return capsule, 40 cells is taken as a practical limit, limiting the allowable cooling to 2 W.

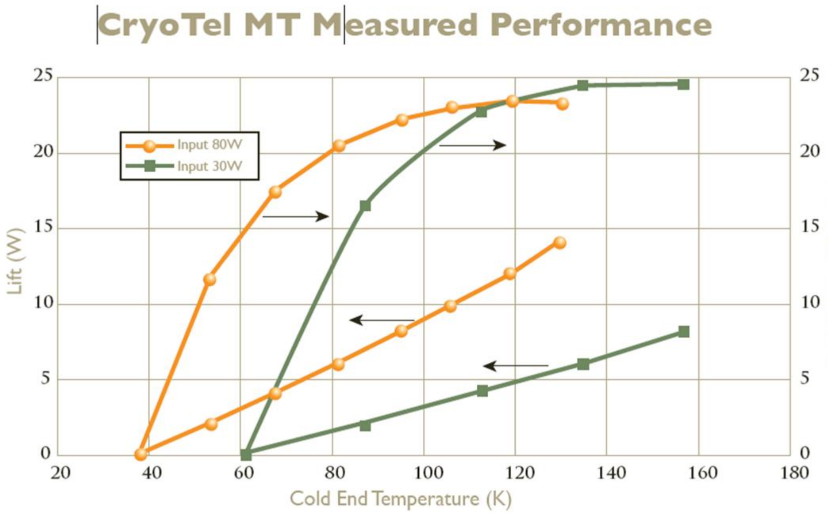


Figure 6-7. Sun power mechanical cooler performance.

One point of concern regarding the use of a mechanical cooler would be its ability to continue operating after a high-G impact. From a thermal perspective, a parachute-supported landing approach would be preferred.

The remainder of the ambient operation cooling required must come from the phase-change material. Phase-change materials tend to use the latent heat from the solid-liquid phase change to provide cooling to the system at a specific temperature. Gas phase transition substances may be used at cryogenic temperatures, but the reservoir volume needed to contain the gas at ambient temperatures limits the use in a volume constrained design. Other design issues with phase change materials are its latent heat at temperature, material toxicity, thermal conductivity, and coefficient of thermal expansion.

At cold, but not cryogenic, temperatures a variety of material are available. For example, n-hexane (C_6H_{14}) has a melting point of 178 K, a latent heat of 152 J/g, and a density of 655 kg/m^3. Assuming a design factor of safety of 2, 11 kg of phase-change would support a 10-W heat leak for 24 h, or a 5-W heat leak for 48 h. These materials would be used to cool the intermediate stage.

At much hotter temperature, substantially higher latent heats are available. A one-time use, vaporizing heat sink can provide as much as 10 times the cooling capability of conventional heat sinks. At 100°C, water can be used with a capability of 2500 J/g. At 30°C, available heat sink capability is closer to 1000 J/g. These materials could be used to maintain the capsule temperature during re-entry and landing to lower the peak load into the cryo storage area.

Although not commonly used, some work has been performed in the area of cryogenic phase-change materials. An example is the 60 K Cryogenic Thermal Storage Unit that flew onboard Space Shuttle mission STS-78. The system used nitrogen as a phase-change material and demonstrated operation at 60 K. The experiment was supported by the Air Force Research Laboratory and Goddard Space Flight Center. The system was integrated by Swales Aerospace. As noted above, the negative issue for a gas system is the reservoir volume needed to support the ambient operation. Also the mass of the packaging of these designs can be much larger than the phase-change material contained. Another example, which did not fly, was developed by

Energy Science Laboratories, Inc., and used 2-methyl-pentane and a solid-solid phase change. The design operated at ~100 K and provided a latent heat of ~100 J/g. The design of the device included filling such that the operating pressure inside the unit did not change dramatically over temperature. This feature allows a smaller package/material ratio.

Using a latent heat of 100 J/g, estimates for the amount of phase-change material needed as a function of the cooling provded are shown in Figure 6-8. The phase-change material is shown in terms of the increased capsule radius (starting size: 15 cm in diameter by 30 cm long) in Figure 6-9. Again, using a safety factor of 2, a 6-W load requries about 5 kg of material for 12 h. Five kilograms of material also will support a 3-W load for 24 h. The same 5 kg of phase-change material would add about 4 cm to the outside diameter of the capsule. The heat sink capability of the phase-change material coupled with the mechanical cooler could support a heat leak of about 5 W for 1 day.

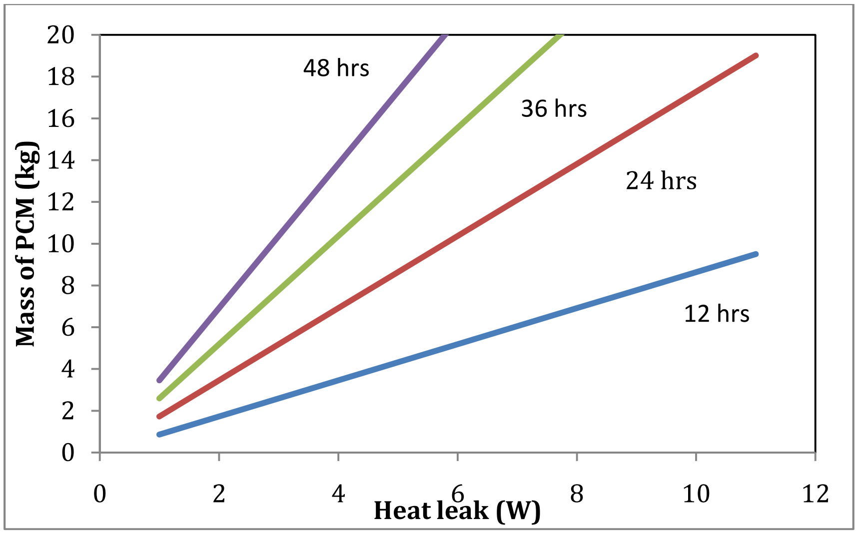


Figure 6-8. Phase-change material (PCM) as a function of heat load.

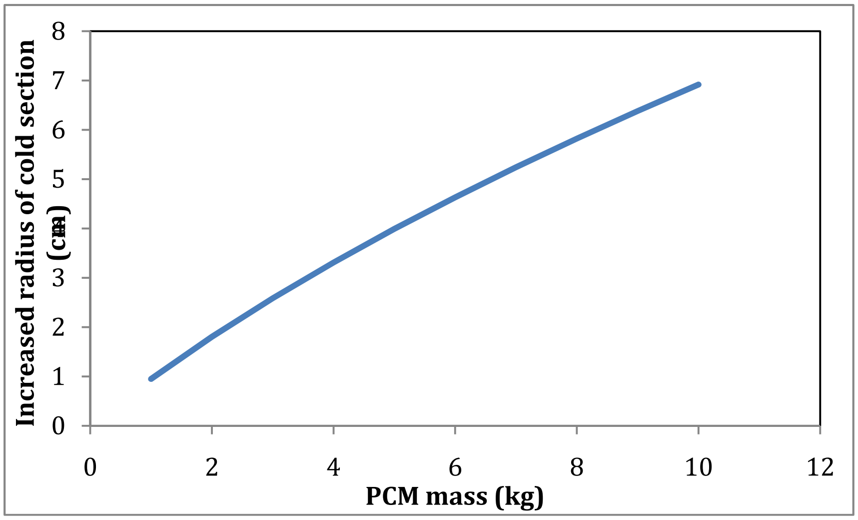


Figure 6-9. Increase cold section radius.

6.2.4 CNSR Sample Encapsulation and Return—Thermal Engineering Conclusions

The thermal design of a cryogenic comet sample return is feasible. The storage temperature required to preserve water ice after a long cruise phase is ~125 K. A two-stage refrigerated capsule design, including an intermediate stage cooled by using the resources of the spacecraft, provides a cold stage capable of surviving a long cruise phase and the return to Earth. During the final re-entry and recovery, the cold stage is supported by the combined cooling capability of a mechanical cooler and phase-change material. Key design requirements for the mission are the sample volume, structural design loads during re-entry, and recovery time period.

6.3 Mechanical Considerations

6.3.1 Core Sample Compression for Transit

As mentioned previously in the discussion of the core sampling approach in Section 2.3.2, a mechanism is required to contain the sample and pack it sufficiently to remove any voids within the sample canister. This mechanism is not required to seal the sample, but it must be capable of compressing the sample contents within the canister such that they are not free to move about and mix appreciably as they are subjected to the shock and accelerations associated with re-entry and recovery.

It has been shown that core sample stratigraphy can be extracted in both ice and regolith simulants (See Figures 6-10 [11], 6-11 [12], and 6-12 [13]). Lees and Chabot have shown that a core sample with asteroid regolith simulant will maintain stratigraphy even when subjected to random vibration of 14.1 g_{rms} (Figure 6-13) [13], and a 2871 *g* impact shock (Figure 6-14) [13], in a re-entry simulation test with a lightly compressed core sample in a core sampler.

Figure 6-10. Ice core sample showing stratigraphy from a comet core sampler. (Image reproduced from ref. 11.)

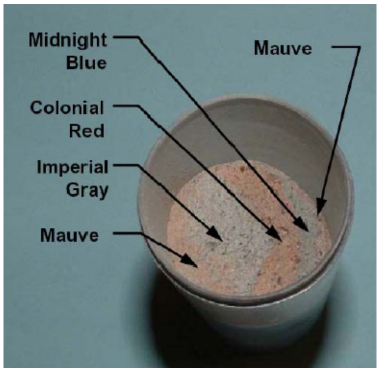


Figure 6-11. Diagonal slice of an asteroid regolith simulant core during core extraction. (Image reproduced from ref. 12.)

Figure 6-12. Regolith core sample, as poured from the sample in Figure 6-11, showing that stratigraphy was maintained following a re-entry simulation. (Image reproduced from ref. 13.)

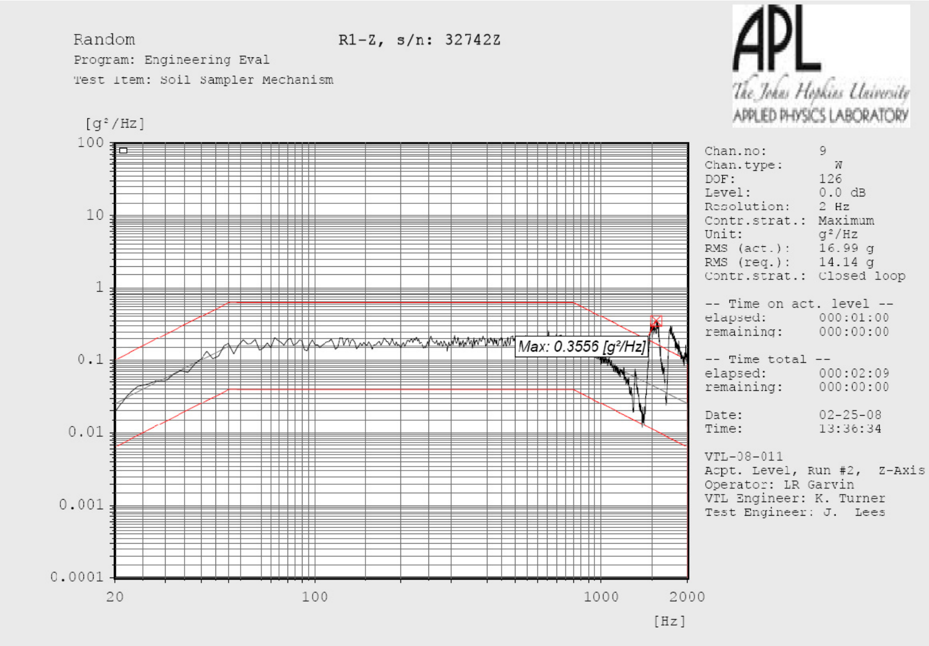


Figure 6-13. Core sample was subjected to 14.1 g_{rms} in two axes simulating possible vibration of a re-entry return capsule. (Image reproduced from ref. 13.)

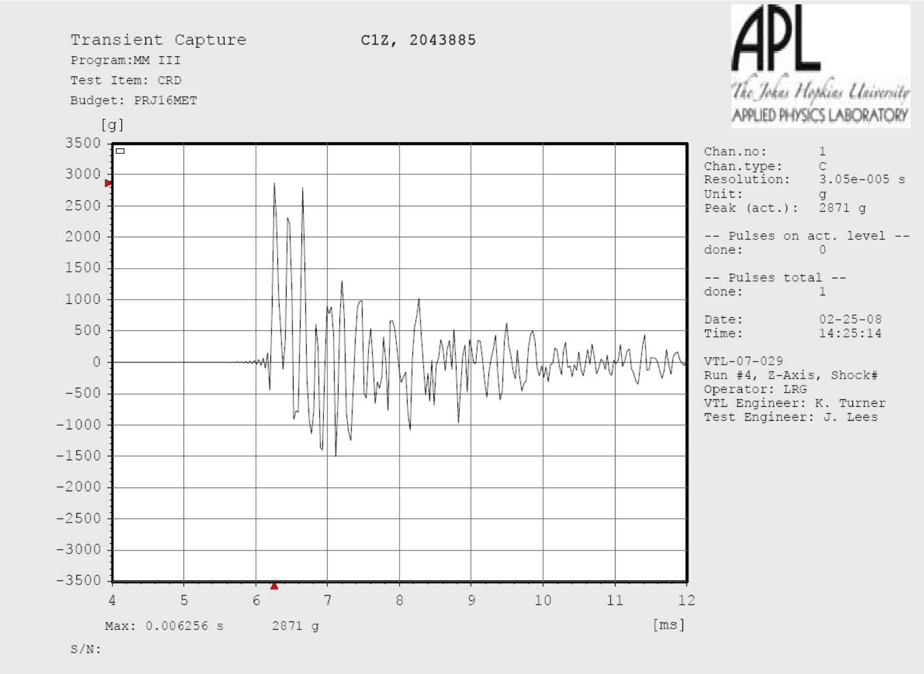


Figure 6-14. Shock test performed on core sample simulating a nominal shock of an SRC impacting the Utah Test Range. (Image reproduced from ref. 13.)

To accomplish the above, however, the core must not contain large void spaces. For low-relative-density samples, the core needs to be compacted to eliminate large voids in the core sample. A core compactor mechanism needs to be developed to compact the core either before or after sample storage. The compactor needs to be designed such that the core does not expand during the impact of the sample return capsule on the ground after re-entry.

6.3.2 Hermetic Sample Seals

The exclusion of terrestrial atmosphere from contact with the sample upon re-entry and the retention of evolved gases resulting from the sublimation of ices in the sample throughout the return both require the capsule to be hermetically sealed. However, the issue then becomes the internal pressure in the capsule. If the sample contains CO ice, its saturation pressure at 125 K is ~350 psi. The other ices are less problematic, but the storage temperature needs to be chosen to minimize the structural requirements on both the container and the sealing process. The sample canister will need to retain its hermetic seal against a significant pressure difference.

Hermetic seals need to be developed to seal each individual sample to:

- Prevent sample-to-sample cross-contamination in cases where more than one sample to be returned would be collected from differing surface locations;
- Maintain pressure to minimize sublimation of ices;
- Prevent escape of evolved gases from the sublimation that does occur; and
- Prevent Earth's atmosphere from entering and contaminating the returned samples on re-entry.

Soft metal seals are often found in vacuum systems, and are the most viable candidate for cryogenic sealing applications. Typical soft metals include aluminum, copper, gold, and indium. A seal may consist of a soft base metal and a sharp edge, similar to a conflat vacuum seal, as illustrated in Figure 6-15 [14].

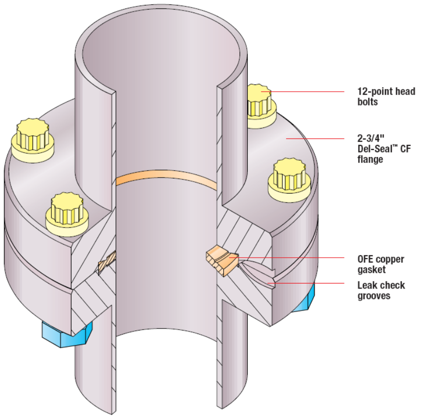


Figure 6-15. Conflat compressed metal gasket hermetic vacuum seal. (Image reproduced from ref. 14.)

These soft metal seals can take the form of gaskets or O-rings, or they can be directly plated onto a surface. At first glance, direct plating would appear to be the most reliable. For example, one would not have to worry about ensuring a metal gasket or seal would remain in place throughout the launch and cruise phases of the mission. However, commercial off the shelf (COTS) metal seals (see www.tfc.eu.com), such as those illustrated in Figure 6-16 which are similar to O-rings, are readily available with the following characteristics:

- Diameters: 5 mm to 7 m
- Temperature range: cryogenic to +750°C
- Pressure range: vacuum to 500 MPa
- Hermeticity: 10^{-9} mbar l/s
- Resistance: corrosion, radiation

Figure 6-16. Example COTS soft metal seals.

The seals will need to be capable of being autonomously activated for use on a cryogenic comet sample return mission. This would most likely be accomplished by using electric actuators and/or spring capture and release mechanisms that would be able to provide and maintain sufficient force to accomplish the seal, as illustrated in Figure 6-17 [15]. It is recommended that a sample storage capture and seal mechanism/system be developed and tested under temperature and vacuum conditions. Typically, seals are activated under ambient pressure and temperature conditions. For the CNSR mission, they would be activated under space pressures and sample temperatures.

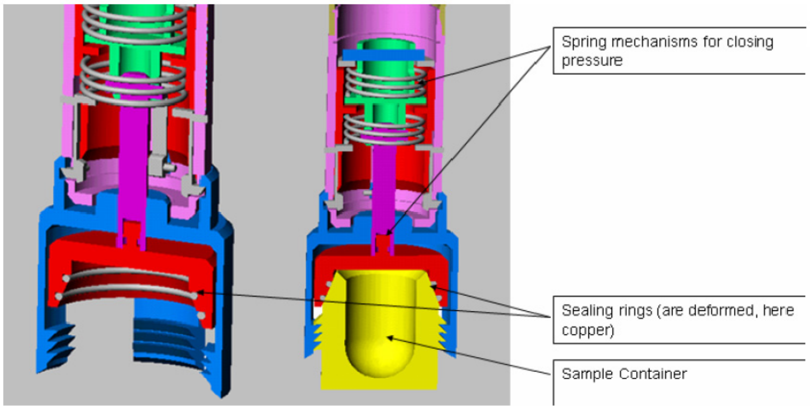


Figure 6-17. Triple-F capture and seal concept for a comet sample return mission. (Image reproduced from ref. 15.)

Development also needs to be directed to assess the contamination compliance of these types of seals, including surface cleanliness and chemical contamination requirements to be maintained throughout the sample acquisition process up through the time of encapsulation. Before the encounter, the sampling equipment and canister require some type of contamination control to make sure they remain clean in the early mission.

The ultimate selection of a hermetic sealing approach for a CNSR mission will also depend on the further development of mission science requirements, as well as an increased understanding of comet surface composition from precursor missions. Issues include the maximum design pressure for the seal to hold against vacuum; the maximum seal leak rates that can be tolerated; seal cleanliness requirements; and constraints on seal material selection (effects from corrosive or chemically reactive species in the comet sample). In addition, a key question is whether a one-time-use sealing technology is acceptable or whether the capability to seal and re-seal is preferable.

6.3.3 Volatile Capture and Pressure Relief System

The CNSR sample storage system will have two new and unique requirements for a sample return mission:

1. Maintain the sample returned to Earth at cryogenic temperatures.
2. Capture and maintain evolved gases sublimated from water ice and associated volatiles.

The ices will sublimate and increase the pressure of the sample captured. Thus, the sample will be at a higher pressure than the vacuum of space. Ideally, this pressure should reach equilibrium. However, if the pressure gets beyond a "safe" limit, the gas should be able to vent and be captured in another container that is not at cryogenic temperatures so that the gases can still be studied when returned to Earth (Figure 6-18). Such a system for capturing the evolved gases should store them in a way that will prevent, or at least minimize, chemical changes.

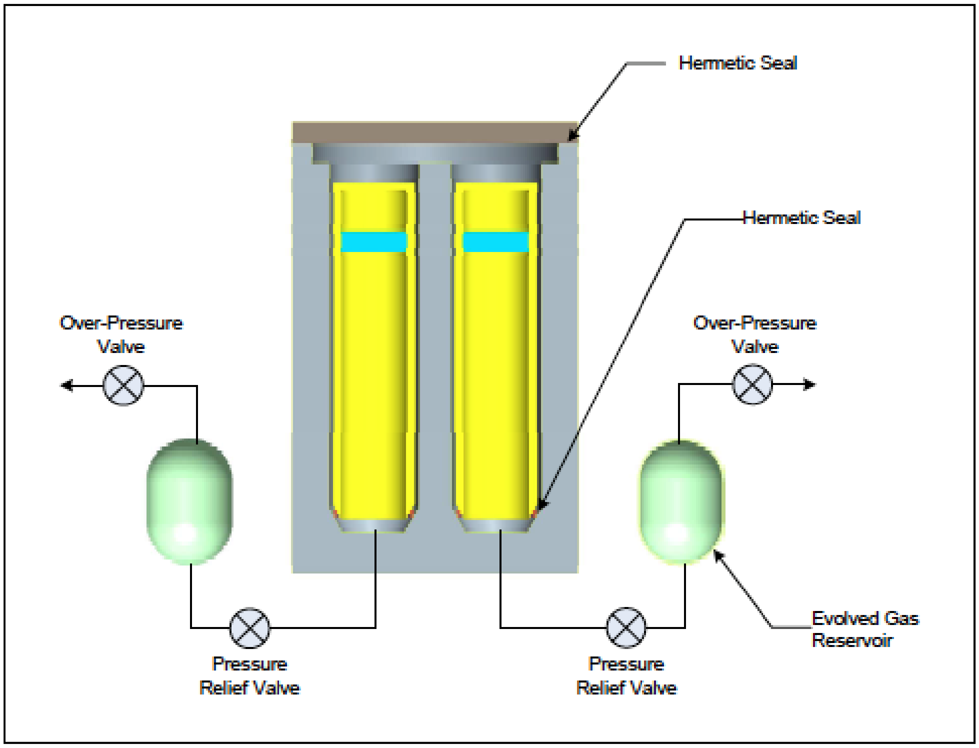


Figure 6-18. Gas relief and capture system concept.

In addition, for purposes of mission safety and reliability, an emergency high-pressure relief valve should be included in the design to protect the system from a catastrophic over-pressure by venting the system externally. The lines for carrying the gases out of the cryogenic area to either the evolved gas collection volume or the over-pressure relief vent should be designed to have the smallest possible diameter to minimize the heat leak to the cold area.

6.3.4 SRC Seal(s)

A sample return capsule (SRC) main door seal may also need to be developed. The first step would be to analyze the applicability of the SRC seals developed for the Genesis or Stardust missions (Figure 6-19) [16]. On the basis of currently defined CNSR core sample dimensions, it would appear that a much smaller door would be needed for CNSR, and perhaps the Genesis door seal could be easily scaled down. However, it is recommend that a development be initiated to verify that the design can be utilized for CNSR and that it would seal sufficiently well to maintain the vacuum seals required to maintain the sample at cryogenic temperatures through the re-entry and landing.

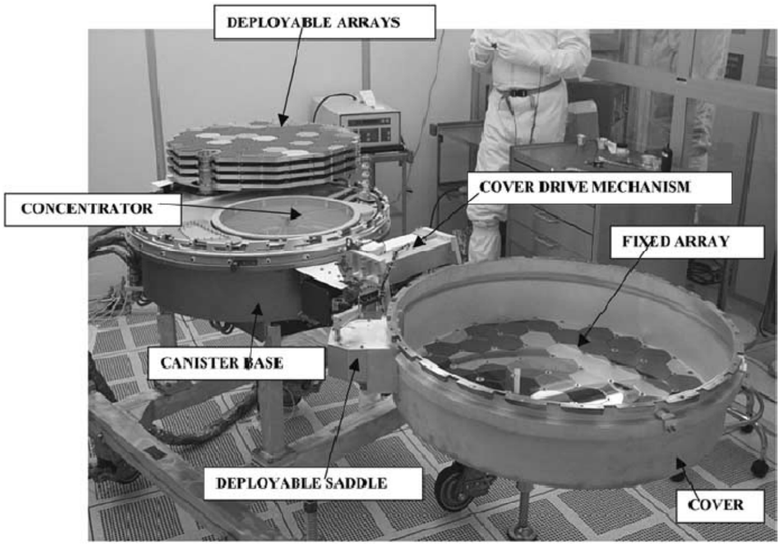


Figure 6-19. Conflat compressed metal gasket hermetic vacuum seal. (Image reproduced from ref. 16.)

6.4 Other Engineering Considerations

6.4.1 Parachute-Supported Landing

On the basis of a number of factors noted in the above discussion of thermal and mechanical technology issues for CNSR sample encapsulation and Earth return, the use of a parachute as part of the re-entry system is a key decision for future consideration. From a thermal perspective, it was noted above that a parachute-supported landing would significantly reduce design acceleration loads and would be the preferred approach. The extreme shock loads resulting from a ballistic impact landing would certainly drive the structural requirements for the cryo-section supports and internal construction in a way that would increase the parasitic heat inputs. Also of concern would be the ability of the mechanical cooler to continue operating after a high-G impact. Moreover, a parachute-assisted landing would allow for the ejection of the heat shield as soon as subsonic speeds were realized. As was discussed above, the baseline design has the largest thermal load to the capsule coming during the soak back from the heat shield shortly after re-entry. One option to mitigate this heat pulse would be to jettison the heat shield as part of a parachute deployment sequence.

From a mechanical perspective, a softer landing supported by a parachute-assisted landing would maximize the potential for preserving sample stratigraphy and maintaining hermetic sample seals that could be compromised by high-load impact damage.

The eventual design of the CNSR sample containment and return systems, and the choice of utilizing a parachute-assisted re-entry over a ballistic one, will need to trade off the potential benefits identified above against the inherent complexities and associated risks of depending on a successful parachute deployment. It is likely that applicable planetary protection requirements would also factor significantly in this trade space.

6.4.2 Sample Return Capsule Power, Mass, and Volume Accommodation

On the basis of currently adopted sample mass and volume requirements, and the associated thermal analysis presented above, the power requirements for active cooling of the samples during the Earth-approach and re-entry/retrieval phases are likely to be significant. After the return capsule separates from its host spacecraft, the required power will need to be supplied entirely by batteries housed within the sample capsule.

The current best primary batteries are lithium thionyl chloride or similar chemistries. They have a specific energy density of ~300 W-h/kg and ~700 W-h/L. To bound the discussion, the following is assumed:

1. The sample capsule will need to be cooled by battery power from 50 to 100 h from the release from the main spacecraft until it is in a controlled environment on the ground.
2. The required heat lift is between 2 and 10 W thermal.

Depending on the cooler technology and hot and cold end temperatures, current coolers need between 20 and 100 W of input electrical power per watt of heat lift. Thus the required battery energy on the return capsule would be between 2000 and 100,000 W-h. This means that the battery mass would be between 7 and 300 kg, and the battery volume would be between 3 and 140 liters.

From the above, it is reasonable to conclude that batteries will probably drive the size of the CNSR return capsule, and the mass of those batteries is likely to be a significant driver in the overall design of the spacecraft as well as the return capsule. The return capsule will need to be able to accommodate the combined mass and volume of the batteries, sample containers, and cooling system.

Given these implications, an eventual CNSR mission would benefit from opportunities to reduce the need for battery-supplied active cooling where possible. Such possibilities could include reducing sample mass/volume requirements (and thereby decreasing the required heat lift), providing for the detachment of the heat shield (to reduce the soak back to the sample containers), and reducing the amount of time on battery power (e.g., releasing the capsule from the spacecraft as late as possible and recovering the capsule on the ground as rapidly as possible). Advancements in phase-change material applications or other passive cooling technologies could also lessen the extent of active cooling required, but they would not eliminate it.

7. Proposed Technology Plan

There are a number of technical capabilities that need to be developed to make the CNSR a practical mission, and they are listed below. Each of these capabilities is key to eventual mission success. Several of these items must be dealt with serially because capabilities that follow depend strongly on the availability of precursors. The relevant sections of the study report in which each of these items has been discussed are listed within parentheses.

1. Agree on the expected range of comet properties (2, 3, 6).
2. Develop simulants that embody the range of comet properties (2, 6).
3. Develop cryogenic sample mechanism(s) that will work with the comet simulants (1, 2).
    a. Test sample mechanism with simulants (1, 2).
    b. Test in increasingly realistic environments (temperature, gravity, …) (1, 6).
4. Develop sample verification system (3).
    a. Quantitative assessment of sample volume and/or mass (3).
    b. Quantitative measurement of the fraction of water ice in the sample (3).
5. Develop cryogenic sample encapsulation and containment system (6).
    a. Mechanical containment (6.3).
    b. Thermal insulation (6.2).
    c. Hermetic sealing of sample holder (6.3.2).
    d. Thermal control while attached to spacecraft (6).
    e. Trapping and containment of evolved gasses (6.3.3).
    f. Overpressure relief (6.3.3).
    g. Passive and/or active cooling of the sample container during spacecraft cruise (6.2).
6. Cooling system for the return capsule after release from the spacecraft (6.2).
    a. Cooling technology that can operate through re-entry deceleration (6.2.3, 6.4.1).
    b. Battery power system for 50–100 h of operation (6.4.2).
    c. Possible phase-change thermal buffer material (6.2).
7. Return capsule that can accommodate sample holder, cooling system, and batteries (6.4.2).
    a. Choose parachute or parachute-less return capsule (6.4.1).
    b. Separate the heat shield after re-entry (6.4.1, 6.4.2).

All of these key capabilities and supporting technologies will need to be extensively tested under increasingly realistic conditions to raise their TRL levels to 5 or above by the end of the decade; testing is also needed before they can be considered as ready for use on a CNSR mission in the following decade. This testing has the potential to mitigate substantially the development risk of a CNSR mission.

Appendix A. References

1. Heiken, G. H., D. Vaniman, and B. M. French, eds., *Lunar Sourcebook: A User's Guide to the Moon*, Cambridge University Press, New York, NY (1991).
2. Anderson, W., T. Ahrens, A. Gibson, R. Scott, and K. Suzuki, Emplacement of penetrators into planetary surfaces, *J. Geophys. Res.*, 101(E9), 21137–21149 (1996).
3. Schmugge, T., "Soil Moisture Sensing with Microwave Radiometers," in Proceedings of the Sixth Annual Symposium on Machine Processing of Remotely Sensed Data and Soil Information Systems and Remote Sensing and Soil Survey, Institute of Electrical and Electronics Engineers (IEEE) (1980).
4. Barkeshli, K., *A C-Band Microwave Dielectric Probe for In-Situ Detection of Soil Moisture*, Technical Report, University of Michigan, Ann Arbor, MI (1985). Available at http://hdl.handle.net/2027.42/21004.
5. Denoth, A., Snow dielectric measurements, *Adv. Space Res.* 9, 233–243 (1989).
6. Murphy, D. M., and T. Koop, Review of the vapour pressures of ice and supercooled water for atmospheric applications, *Q. J. R. Meteorol. Soc.* 131, 1539–1565 (2005).
7. Chemical Engineering Research Information Center (CHERIC) database, http://www.cheric.org/research/kdb/hcprop/cmpsrch.php.
8. National Institute of Standards and Technology (NIST) database, http://webbook.nist.gov/chemistry/.
9. Prialnik, D., J. Benkhoff, and M. Podolak, Modeling the structure and activity of comet nuclei, in *Comets II*, M. Festou, H. Keller, and H. Weaver, eds., University of Arizona Press, Tucson, AZ, pp. 359–387 (2005).
10. Mekler, Y., D. Prialnik, and M. Podolak, Evaporation from a porous cometary nucleus, *Astrophys. J.* 356, 682–686 (1990).
11. Lorenz, R. D., W. V., Boynton, and C. Turner, Demonstration of comet sample collection by penetrator, in Selected Proceedings of the Fifth IAA International Conference on Low Cost Planetary Missions, *Acta Astronaut.* 59(8–11), 1000–1007 (October–December 2006).
12. Lees, J., and N. Chabot, "Small Body Sampling Techniques Being Developed at JHU/APL," Paper IAC-08-A3.5.4, in Proceedings of the 59th International Astronautical Congress, Glasgow, Scotland (2008).
13. Lees, J., and N. Chabot, "Small Body Sampling Techniques Being Developed at JHU/APL," Presentation at the 59th International Astronautical Congress, Glasgow, Scotland (29 September–3 October 2008).
14. MDC Vacuum Products Corporation, Product Catalog, Section 1, p. 25, www.mdcvacuum.com.

15. Küppers, M., et al. *Fresh From the Fridge, Comet Nucleus Sample Return Mission*, a proposal in response to ESA's Cosmic Vision Call in joint collaboration with Roscosmos.
16. Burnett, D. S., et al., The Genesis Discovery Mission: Return of solar matter to Earth**,** *Space Sci. Rev.* **105,** 509–534 (2003).

Additional References for Further Reading

A'Hearn, M. F., et al., Deep Impact and sample return, *Earth Planets Space* 60, 61–66 (2008).

Allton, J. *Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers*, JSC-23454 (1989).

Carrier, D., G. Olhoeft, and W. Mendell, "Physical Properties of the Lunar Surface," in *Lunar Sourcebook: A User's Guide to the Moon*, G. H. Heiken, D. Vaniman, and B. M. French, eds., Cambridge University Press, New York, NY, pp. 475–567 (1991).

Finzi, A., et al., SD2—How to sample a comet, *Space Sci. Rev.* 128, 281–299 (2007).

Gromov, V., Physical and mechanical properties of lunar and planetary soils, *Earth Moon, and Planets* 80, 51–72 (1998).

Appendix B. Acronyms

CHERIC	Chemical Engineering Research Information Center
CNSR	Cryogenic Nucleus Sample Return
COTS	Commercial Off the Shelf
CSSR	Comet Surface Sample Return
DI	Deep Impact
DSC	Differential Scanning Calorimetry
DS-2	Deep Space 2
EGA	Evolved Gas Analysis
ESA	European Space Agency
IR	Infrared
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
PCM	Phase-Change Material
SPIRIT III	Spatial Infrared Imaging Telescope III
SRC	Sample Return Capsule
TRL	Technology Readiness Level