Extracted Venus Related Information from

NASA's 2006 Solar System Exploration Roadmap

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Note: the word "Venus" appeared 205 times in the roadmap.

Executive Summary

A Balanced Program of Solar System Exploration

Large (Flagship Class) Missions

…The program outlined here includes a set of five Flagship missions over 25 years to a variety of destinations in the inner and outer Solar System; namely to Europa, Titan/Enceladus, **Venus**, and Neptune/Triton. Among these, Europa should be the next target for a Flagship mission.

Furthermore, international collaboration provides cost reduction, risk sharing, and a broader public base for each of the partners. It also ensures continuation of the positive image of the United States gained from collaboration in missions like Cassini–Huygens. Existing collaborative models for future Jupiter–Europa exploration should be extended to collaborations on missions to the Saturn system and to **Venus**.

Section 1. Overview

This document lays out both a scientific rationale and a long–term plan for the exploration of the Solar System. The quest for answers to fundamental questions about the origin and evolution of the Solar System and of life within it is used to motivate missions to the remarkable planets and satellites in the outer Solar System, to the searing surface of Earth's estranged sister planet **Venus** and to the primitive remnants of planetary formation that orbit in the depths of space as asteroids and comets. This plan does not include Mars and the Moon for which NASA is developing other strategic roadmaps.

Section 2. Science Objectives

2.1 Habitability – A Guiding Theme

… While the concept of habitability can be articulated crisply, we recognize that the conditions for habitability remain poorly understood. The narrowest definition — that a habitable environment requires liquid water in order to sustain life as we know it — is a motivation for making Europa (which has subsurface liquid water) and **Venus** (which may have lost oceans of water sometime in its history) high–priority targets. Enceladus, where liquid water might yet exist near–surface, also then becomes an important target. But life might occur where other liquids substitute for water, and in planetary environments where organic molecules are briefly exposed to liquid water and then preserved. Thus, at these places the organic chemical steps leading to life might be available for analysis. For these last two reasons, Titan is considered a high–priority target for further exploration. …

2.2 Investigative Framework

2.2.1 Question One: How did the Sun's family of planets and minor bodies originate?

… Study the processes that determined the original characteristics of the bodies in the Solar System. Of particular importance is the way that the earliest formative processes, active during the first billion years or so, manifested themselves in the inner Solar System. These processes have left their imprint on the terrestrial planets and on asteroids. Unfortunately, the very early geological history of Earth has been nearly completely obliterated by the actions of tectonics, weathering, and biology; on our home planet the earliest rock records date back about 4.0 billion years, but no further. Nevertheless, petrologic, chemical and isotopic investigations of the most ancient rocks on the Earth — and on **Venus** — can help us to understand the earliest evolution of the terrestrial planets. Unlike the Earth, the Moon still retains some of the earliest records of the formation of the Earth–Moon system. Leading models suggest a very early origin of the Moon as a result of the collision of a Mars–sized body with the newly formed Earth. Samples from the Apollo and Luna Programs elucidated some of this history, but the nature of these samples, limited to equatorial regions of the lunar near side, leaves many key questions unanswered. The Moon's South Pole–Aitken Basin, one of the largest impact structures known within the Solar System, exposes material from deep within the crust and possibly even the upper mantle that was excavated by the impact, and may preserve melt rocks from the impact itself. …

Table 2.2. Question Two: How did the Solar System evolve to its current diverse state?

Objectives	*Investigations and Measurements*
Determine how the processes that shape planetary bodies operate and interact	* Multidisciplinary comparative studies of atmospheres, surfaces, interiors, and satellites. * Comparative studies of the climate evolution of Earth, Mars, and **Venus**. * Comparative studies of the current state and inferred evolution of Moon and Mercury. * Determine how the impactor flux decayed in the early Solar System.
Understand why the terrestrial planets are so different from one another	* Study **Venus**' atmospheric chemistry and surface / atmosphere interactions. * Study Mars meteorology and geophysics.
Learn what our Solar System can tell us about extrasolar planetary systems	* Conduct detailed studies of the gas giants and ring systems. * Determine the structure of the Kuiper Belt.

Understand why the terrestrial planets are so different from one another. The terrestrial planets formed at about the same time, in the same general region of space, and experienced similar forces and processes during their development. Yet today they are different in very fundamental ways, for a complex set of reasons that we are only beginning to understand. The atmospheres of Mars, **Venus**, and Earth reflect differences in initial volatile content and subsequent atmospheric evolution, with comparison of Mars and **Venus** providing particularly compelling evidence for completely different developmental pathways. The causes of such climate change are complex and their interactions not fully understood, but they are clearly of tremendous importance to our home planet. Comprehensive comparative studies of the atmospheric chemistry, dynamics, and surface–atmosphere interactions on both Mars and **Venus** will allow us to better understand their evolutionary pathways and the implications for habitability, both within our Solar System and in other solar systems. Of particular interest at **Venus** are the elemental, mineralogical, and geochemical nature of surface materials, combined with detailed investigation of noble and trace gases in the atmosphere.

2.2.3 Question Three: What are the characteristics of the Solar System that led to the origin of life?

Table 2.3 Question Three: What are the characteristics of the Solar System that led to the origin of life?

Objectives	*Investigations and Measurements*
Determine the nature, history, and distribution of volatile and organic compounds in the Solar System	* Analyze the chemical and isotopic composition of comets. * Determine Jupiter's water abundance and deep atmospheric composition. * Determine the chemical and isotopic composition of **Venus**' surface and atmosphere. * Determine the distribution of organic material on Titan and Enceladus.
Determine the evidence for and age of an ocean on the surface of **Venus**	* Search for granitic and sedimentary rocks. * Analyze the mineral composition of hydrated silicates and oxidized iron. * Investigate the interplay of volcanic activity and climate change.
Identify the habitable zones in the outer Solar System	* Characterize the geothermal zones on Enceladus. * Search for volcanically–generated and impact–generated hydrothermal systems on Titan. * Confirm the presence and study the characteristics of Europa's subsurface ocean. * Conduct comparative studies of the Galilean satellites.

… Once delivered to the planets, volatiles may be sequestered in surface and interior reservoirs, partitioned into the atmosphere, or lost to space. The volatile evolution of the three large terrestrial planets — Earth, **Venus**, and Mars — apparently took radically different paths with fundamentally different outcomes. These differences hold vital clues to understanding both the history and future of Earth and the potential that other planets may have been habitats for life at some point in their histories. One key means of understanding these differences is to trace the volatile history of **Venus**, and in particular the processes that led to the loss of the water that should originally have been present. **Pioneer Venus** and Venera provided some insight into the composition of the atmosphere and surface, but more detailed measurement of the chemical and isotopic composition of **Venus**' surface and atmosphere is required if we are to fully understand its evolutionary history.

We know that carbon dioxide on Mars is cycled between the atmosphere and the winter polar caps. At the poles there is evidence of a long history of frozen volatiles, which may preserve evidence of different climatic regimes and possibly of life–supporting environments. Current missions such as Mars Global Surveyor and Mars Odyssey are revealing striking evidence of past and present reservoirs of water on Mars — frozen at the poles and beneath the surface today, but possibly pooled in large ponds, lakes, or oceans in the past. Determination of the evolutionary processes, sources, and reservoirs of key volatiles on Mars will allow comparison with Earth and **Venus** and complete the picture of the original distribution of volatiles in the Solar System. …

Determine the evidence for and age of an ocean on the surface of Venus

Measurements by **Pioneer Venus** of condensed H_2SO_4 in the **Venus** atmosphere revealed an extremely elevated abundance of deuterium relative to hydrogen, and this in turn suggested that large amounts of water were lost through the atmosphere from the surface of **Venus** sometime in its history. Estimates of the total water loss vary, but it is generally agreed that at least the equivalent of Earth's oceans was lost by escape to space. However, no information on the timing of the loss is available. Model results have indicated that the loss was early, when ultraviolet fluxes from the Sun were high, but the overall luminosity of the Sun was 30% lower than today. This leads to the paradox that **Venus** may have lost its water via a runaway process, when the ambient solar flux at **Venus** was no more than 10% greater than what Earth receives today. The global geologic context revealed by Venera 15 and 16 and Magellan radar images is not constraining in this regard, showing a planet that has been almost completely resurfaced in the last billion years.

It is extremely crucial to understand how much water was lost from the surface and crust of **Venus** and when this loss occurred, because this bears directly on the long–term habitability of our own planet and the width of the so–called "continuously habitable zone" around solar–type stars. A **Venus** that remained habitable for billions of years implies a much wider continuously habitable zone than one that lost its water within a few hundred million years after formation; two billion years of biological evolution might have led to complex macroscopic life forms for which physical evidence might remain. To better constrain when **Venus** lost its water will require more precise atmospheric measurements as well as geochemical measurements on surface rock samples in carefully selected locales. For example, while hydrogen from the vaporized ocean could escape without a problem, the oxygen could not. Unless some other processes enabled all the oxygen to escape to space over time (such as photochemistry and/or solar wind scavenging) or the crust was overturned in an early episode of plate recycling, the crust must be oxidized to some unknown depth. Therefore, understanding the depth to which the surface is oxidized is a critical measurement to understand the history of water on **Venus**, and whether or not atmospheric escape was much more effective at getting rid of oxygen in the past.

If water persisted beyond the earliest part of **Venus'** history, there may have been an extensive period of plate tectonics, production of granites, and a hydrological cycle that led to the formation of extensive sedimentary deposits on continental platforms. Evidently much if not all of this putative Earth–like geology has been covered by the subsequent global onslaught of massive basaltic volcanism, but a few features seen in

Magellan data hint at the possibility that accessible granites and sedimentary structures might remain. A primary goal of **Venusian** surface exploration would be to locate and analyze granites and sedimentary structures — and in the case of the former, to use robotic isotopic dating techniques now under development to determine age.

A search for granites is a search for geology like that of our own Earth. But our experience in the exploration of Solar System shows that we consistently underestimate the diversity of expression of physical and chemical processes in planetary bodies. Even with water present in the crust for prolonged periods, it is possible that **Venusian** tectonics was never like that of Earth, or plate tectonics did not operate long enough or extensively enough to produce granites despite the persistence of liquid water. Therefore, a search for hydrated silicates and oxidized iron, against the possibility that a non–cycling crust was suffused with water for some extended period of time, is an important exploration goal for **Venus** as well.

Finally, the recent widespread basaltic volcanism on **Venus** may have altered the atmospheric chemistry and climate from an unknown and different climate state, perhaps one more typical of **Venus'** history than that observed today — just as the present glacial–interglacial climate regime of Earth is not the typical climate state recorded in isotopic records at least for the last several hundred million years. To search for evidence of different **Venusian** climate states will again require surface access and sampling of crustal rocks in various terrains and possibly at shallow depths just below the surface. …

Like **Venus**, Earth, and to some extent Mars, Titan's present–day climate may not be typical of the bulk of its history. Like Earth, Titan's lower atmosphere and surface climate are driven by a moderate greenhouse effect modified by convection and driven by the cycling of active greenhouse gases through gaseous and liquid phases in the surface–atmosphere system. On Earth, water is the multiphase greenhouse gas in which the other primary greenhouse gases — carbon dioxide and methane — can dissolve and hence create a very complex set of feedbacks on the climate. On Titan, methane is the primary greenhouse gas and surface liquid, in which other greenhouse gases (molecular nitrogen and hydrogen) can dissolve and hence amplify feedbacks. The lack at present of large reservoirs of surface liquid methane combined with the existence of chemically–active atmospheric methane — an intrinsically transient situation on geologic timescales — implies occasional refreshment of methane into the surface–atmosphere system, which constitutes a large–scale perturbation on the climate. What is Titan's climate like when methane is depleted, and conversely after large–scale injection (from the interior, most likely) of fresh methane? Is the present climate condition the result of a recent injection of methane, ongoing geysering of methane from near–surface crustal reservoirs, or a more quiescent descent from an earlier methane–rich to a future methane–depleted state?

2.2.4 Question Four: How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?

Objectives	*Investigations and Measurements*
Identify the sources of simple chemicals important to prebiotic evolution and the emergence of life	* Determine the chemical composition of comets and Kuiper Belt objects. * Study surface organic deposits on Titan, and interaction of surface with atmosphere.
Search for evidence for life on Europa, Enceladus, and Titan	* Identify and study organic deposits from the subsurface ocean on Europa. * Study biomarker signatures in surface organics in active/recently active areas on Titan. * Sample subvent fluids for biological activity.
Search for evidence for past life on **Venus**	* Search **Venus** samples for chemical and structural signatures of life.
Study Earth's geologic and biologic record to determine the historical relationship between Earth and its biosphere	* Investigate biological processes on the early Earth through multidisciplinary studies. * Examine the records of the response of Earth's biosphere to extraterrestrial events.

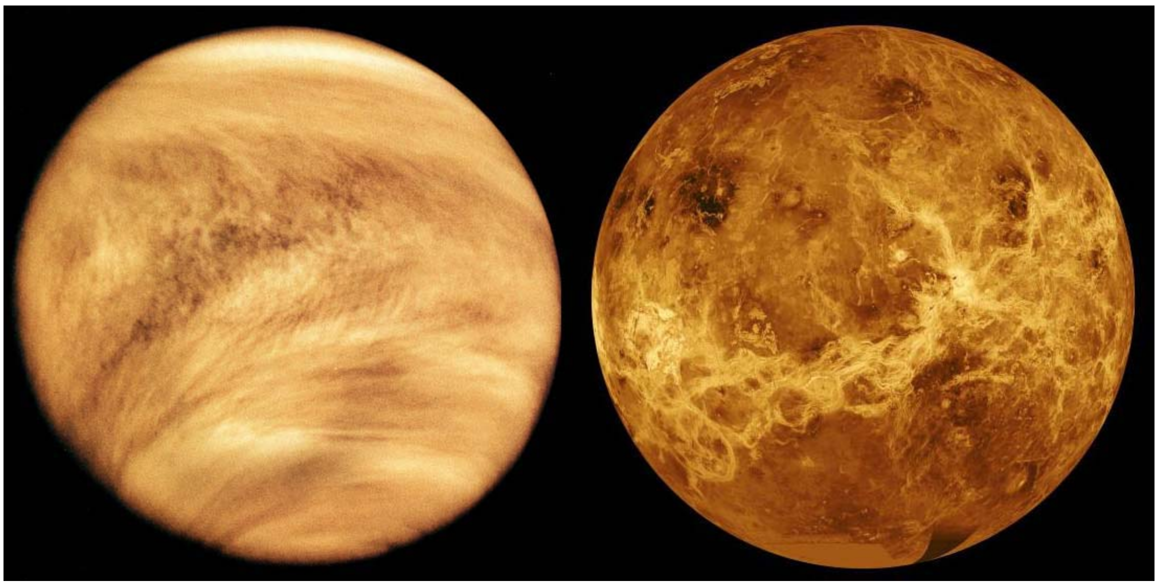
Search for evidence for past life on Venus

The putative persistence of liquid water for billions of years on the **Venusian** surface, which is of highest priority as a motivator for the investigation of **Venusian** surface geology, leads naturally to the question whether life ever originated or was transplanted to **Venus**, and the state to which it may have evolved on this nearest planetary neighbor of Earth. Extensive basaltic volcanism and the very high surface temperatures associated with the current extreme greenhouse regime militate against preservation of most types of biomarkers and biosignatures, but not all. Stable isotope biomarkers may have been preserved in ancient sediments. Some parts of the **Venusian** crust, particularly tectonically elevated terrains, have likely been spared erasure and burial by basaltic volcanism, and certain types of biomarkers such as hard shells or bones would remain stable even under the ambient conditions. Therefore, a search for remains of microscopic or even macroscopic organisms should be conducted on the surface of **Venus** in conjunction with the geological search for sedimentary deposits.

2.3.1 Venus — Key Member of the Inner Triad of Worlds

Venus, so similar in size to Earth and our closest planetary neighbor, is a nightmarish world of vast basaltic volcanic flows lying under a carbon dioxide atmosphere whose pressure is 90 times the pressure at sea level on Earth (Figure 2.7). The surface temperature of **Venus**, over 460 °C, is above the melting point of lead and well above the temperature beyond which water cannot exist as a liquid, no matter what the pressure. Even though **Venus** is 30% closer to the Sun than is Earth, such extreme conditions are surprising; its globe–circling sulfuric cloud layer reflects so much sunlight that the **Venusian** lower atmosphere actually receives less sunlight than does the surface of Earth. But the massive carbon dioxide atmosphere creates enormous greenhouse warming, and the resulting complete lack of water in the crust and on the surface not only rules out life as we know it, but also profoundly affects the geology of this otherwise near–twin of Earth. How long **Venus** has been in this state is unclear — its basaltic veneer formed within the last 1 billion years, erasing surficial signs of most earlier geologic history, and the isotopic enrichment of heavy hydrogen in the atmosphere's trace amount of water points to potentially large amounts of water earlier in **Venusian** history. The disorganized pattern of highlands and lowlands is a stark contrast to the Earth's granitic continents and basaltic ocean basins, suggesting that an organized system of global tectonics, analogous to terrestrial plate tectonics, failed on **Venus** eons ago, or never began. (See Figure 2.8.)

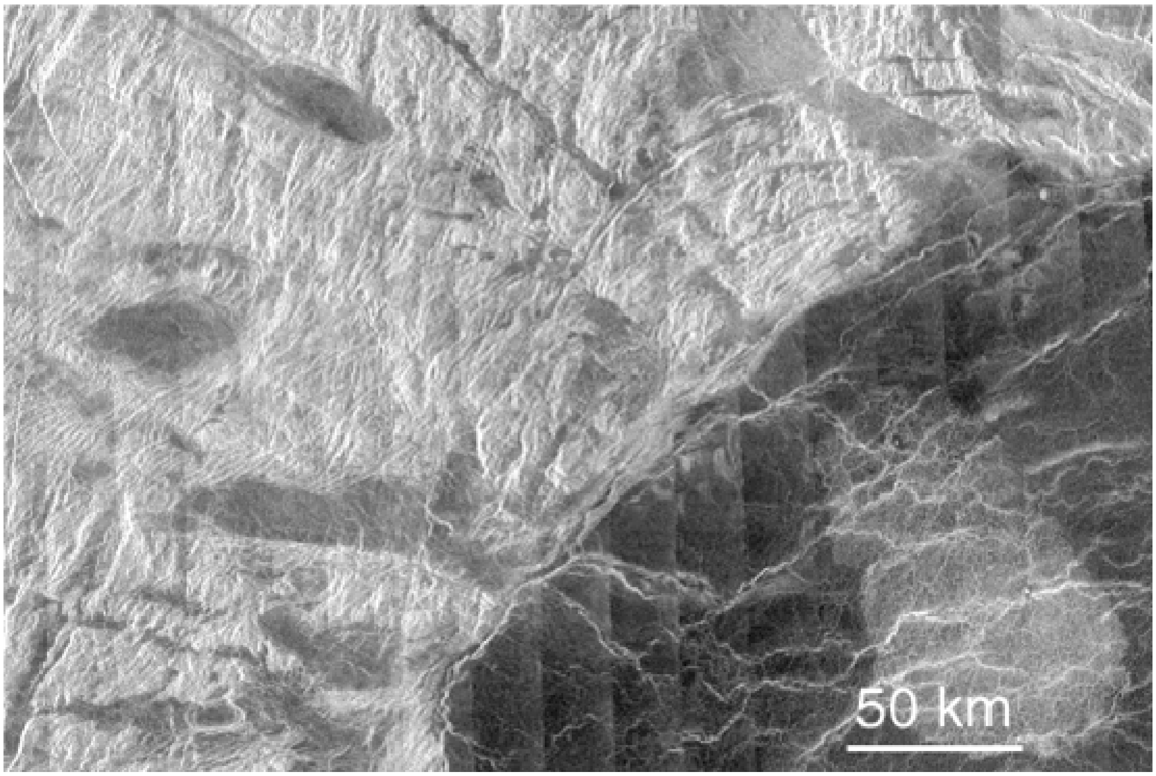
*Figure 2.7: Two views of **Venus**.*
*The view of Venus from NASA's **Pioneer Venus** (left) in 1978 is contrasted with the terrains of the planet as revealed by Magellan' radar mapping sensor which operated from Sept 1990 to Sep 1992. The **ESA Venus Express** is currently observing the atmosphere of **Venus** and a **JAXA Venus Climate Orbiter** is planned for launch in 2010, but no firm plans exist yet for follow on missions focused on high–priority science questions regarding the solid surface of **Venus**. The disorganized pattern of highlands and lowlands on **Venus** is a stark contrast to the Earth, suggesting that global plate tectonics failed on **Venus** eons ago or never began.*



But the ancient Sun of 4 billion years ago was 30% fainter than it is today, and early **Venus** might not have experienced much more solar heating than does Earth today. Did **Venus** lose its water and form a massive carbon dioxide atmosphere late in its history, or right at the start? There are few constraints on how long a warm ocean existed there. Theoretical studies of the early evolution of **Venus'** climate suggest that a lower bound for the longevity of an ocean is ~600 million years. However, that work admitted solutions for the longevity of an ocean on the order of the age of the Solar System.

It is conceivable that warm oceans persisted for billions of years on **Venus**, providing a crucible for life that may have been superior to that of Mars. The logical status of past life on **Venus** is in fact no different from that of past life on Mars or Europa. The difference is that telltale signatures of life itself may have disappeared or been severely modified as **Venus** evolved to the extraordinarily hot and dry planet we see today. On the other hand, the search for evidence of past surface water on Venus, and when it finally disappeared, must be a top priority for the astrobiological exploration of the Solar System.

*Figure 2.8: The tessera region of **Venus**.*
*Radar image of the **Venusian** highland tessera obtained from the Magellan spacecraft. Tessera are heavily deformed material of unknown origin and composition. Contractional and extensional structures occupy 8% of the planetary surface. One possibility is that these are ancient crustal structures that might retain the signature of a possible early **Venus** ocean. Determining the origin of these landforms will require measurements in situ and intensive mobile exploration by a vehicle able traverse substantial distances over these terrains performing close up imaging and sampling at diverse sites.*



As such, it is imperative to include a definitive assessment of the petrology and mineralogy of the **Venus** highlands, analysis of the crust for metastable hydrated silicates, measurements of the oxidation and mineralogical state of iron, and determinations of the C, O, S, and H isotopic abundances in the crust and lower atmosphere.

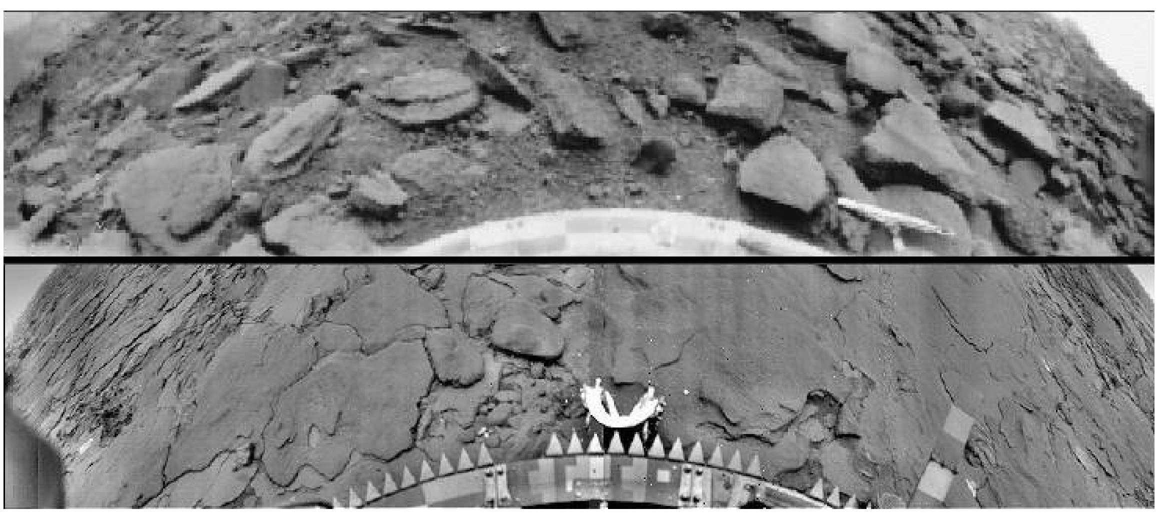
To know the answer to these questions is to understand whether the 0.7–AU region around a Sun–like star (Earth sits at 1 AU, or 150 million km, from the Sun) forms part of the long–term habitable zone or is just too close. Together with a fuller understanding of the evolution of the Martian climate, we can then address whether the habitable zone around a solar–type star is narrow, perhaps extending only 0.1 AU inward and outward of 1 AU, or occupies a significantly larger volume. **Venus** is the only planet within at least 4 light years, other than Earth, that has ongoing, active geochemical cycles, volcanism, and attendant climate feedbacks.

To study **Venus** as an integrated system is to look "outside the box" to understand how planetary processes shape a world that is so different from our own, but that had similar initial conditions. It is very likely that the terrestrial worlds that we will eventually find around other stars will be dominated by CO_2/N_2 atmospheres. Of the three terrestrial planets in our Solar System with substantial atmospheres, two are of this class. Understanding the radiative balance, circulation, geologic history, and internal structure of **Venus** through intensive spacecraft exploration will no doubt pave the way for an understanding of worlds yet to be discovered around other stars.

The **Venus** greenhouse is unique in the Solar System and utterly unlike that of Earth. Yet many details of Earth's climate are poorly understood. This is especially true of how climate is forced by changes in solar insolation [NAS03b]. The study of the **Venus** environment through measurements of its radiative balance, cloud microphysics, circulation, and atmospheric composition promises a far better understanding of the underlying principles of planetary atmospheres. An understanding of how planetary environments work is the key to better understanding how far in the future our own planet will yield up its life–giving oceans to a relentlessly brightening Sun and become a Dante–esque hell like **Venus**.

Venus' atmosphere will not tell us this story by itself. For answers, we must send mobile vehicles to the highlands of **Venus**, possibly with drills, to find ancient crust that has a granitic or andesitic signature — the signs of persistent plate tectonics and the action of liquid water on crustal formation. Should we find such a crust — an indication that Venus was at one time more like Earth — we might then plan a later and more ambitious effort to bring samples back to Earth to perform more detailed and delicate chemical and petrologic studies possible only in terrestrial laboratories. (See Figure 2.9.)

Figure 2.9: Surface images of Venus taken by the Russian Venera 9 & 14 landers.



The surface exploration of **Venus** represents a challenging undertaking that will require long–duration mobile operations in Earth–like gravity and potentially rough terrains, under atmospheric conditions 90 times terrestrial pressure at temperatures above the melting point of lead. Sample return missions, given the dense, hot atmosphere and strong gravity well, would be even more ambitious.

The exploration of **Venus** is a dual attack on the question of habitability from the point of view of planetary architecture (how wide is the long–term habitable zone?) and habitable worlds (by what processes did **Venus** lose its early habitability, and to what extent was this purely a question of proximity to the Sun versus small differences in intrinsic properties relative to Earth?). In conjunction with the study of Mars, the triad of atmosphere–endowed terrestrial planets will then be fully explored.

2.3.2 Europa, Titan, Triton ... and Enceladus

But a triad of a different kind awaits our robotic explorers in the outer Solar System: three moons with varying atmosphere and ocean environments that parallel in an odd way the differences among **Venus**, Earth, and Mars. Europa, Titan, and Triton orbit Jupiter, Saturn, and Neptune at distances of 5, 10 and 30 AU, respectively, from the Sun. Europa's icy surface is believed to hide a global subsurface ocean …

3. Missions

3.1 Formulating the Mission Set

3.1.2 The Mission Roadmap

… The Solar System Exploration mission roadmap advocates the continuation of small and medium class competed missions, represented by the Discovery and New Frontiers Programs. However, a key conclusion is that many of the most important questions comprising the guiding theme of habitability cannot be addressed with small and medium missions. This is because many of the required investigations demand journeys into the remote reaches of the Solar System, where propulsion, power, and communications drive operational costs; extreme environments of radiation and cold are encountered; and new types of observational platforms are needed to provide access. For the inner Solar System, many of the secrets can only be unlocked by extended mobile operations in the searing heat and intense pressures of the **Venus** surface, requiring new technologies and complex flight systems.

The priority goals for the Solar System Exploration Program are listed in Table 3.1, along with the specific investigations needed. In each case, the science objectives are cross–referenced against a specific mission and its mission class. It is evident that while much good science can still be done with a program based only on small and medium class missions, the goals that are central to habitability — understanding the conditions that give rise to life and evidence for life in the Solar System — would require a program of directed Flagship class missions. From these, the three highest priority missions are the Europa Explorer, the Titan–Enceladus Explorer, and the **Venus Mobile Explorer**. …

Table 3.1: Traceability Matrix: Scientific Questions, Objectives, and Missions.

Major Questions	R&A		Discovery				New Frontiers						Flagship (Small/Large)							
Objectives	Expt.‡	Theory	SB	Moon	Venus	Mercury	NH	Juno	SPABSR	VISE	CSSR	SP	C–H	EE	TE	VME	EAL	NTE	*CCSR**	*VSSR**
How did the Sun's family of planets and minor bodies originate?																				
Understand the initial stages of planetary and satellite formation	●	●	●	●	▲	▲	●	●	●		▲	●	▲	▲	▲	▲		●	●	●
Study the processes that determine the original characteristics of bodies in the Solar System	●	●	●	●		▲	▲	●	▲		●	●	▲	▲	▲			●	●	●
How did the Solar System evolve to its current diverse state?																				
Determine how the processes that shape planetary bodies operate and interact	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	●	●	●	●	●	●	●	●
Understand why the terrestrial planets are so different from one another	▲	▲			●	▲			▲	●						●				●
Learn what our Solar System can tell us about extrasolar planetary systems	▲	▲					▲	▲				▲	●	▲	▲	●		▲		●
What are the characteristics of the Solar System that led to the origin of life?																				
Determine the nature, history, and distribution of volatile and organic compounds in the Solar System	▲	▲	▲				●	●		▲	●	●	●	●	●	●	●	●	●	●
Determine evidence for a past ocean on the surface of Venus	▲	▲			▲					▲						●				●
Identify the habitable zones in the outer Solar System	▲	▲											●	●	●		●	●		
How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?																				
Identify the sources of simple chemicals important to prebiotic evolution and the emergence of life	●	▲	▲				▲						●	▲	●		●	▲	●	
Evidence for life on Europa, Enceladus, and Titan	▲	▲											▲	▲	●		●			
Evidence for past life on Venus	▲	▲														▲				●
Study Earth's geologic and biologic record to determine the historical relationship between Earth and its biosphere	●	▲																		
Identify environmental hazards and resources enabling human presence in space																				
Determine the inventory and dynamics of objects that may pose an impact hazard to Earth	●	▲	●				▲													
Inventory and characterize planetary resources that can sustain and protect human explorers	▲	▲	●						▲		●									

Convention: ● Major or Unique Contribution; ▲ Support Contribution

SB — small bodies; NH — New Horizons; SPABSR — South Pole–Aitken Basin Sample Return; VISE — Venus In Situ Explorer; CSSR — Comet Surface Sample Return; SP — Saturn Flyby with Shallow Probes; C–H — Cassini–Huygens; EE — Europa Explorer; TE — Titan / Enceladus Exp.; VME — Venus Mobile Exp.; EAL — Europa Astrobiology Lander; NTE — Neptune–Triton Explorer

*CCSR — Cryogenic Comet Surface Sample Return; VSSR — Venus Surface Sample Return * — beyond the 5 proposed Flagship missions*

‡ — "Expt" includes ground- and space-based observations with a range of NASA facilities including the Hubble and Spitzer Space Telescopes and, in the next decade, the proposed James Webb Space Telescope.

3.3 New Frontiers Program

3.3.1 New Frontiers Mission Overview

The New Frontiers Program comprises principal investigator–led medium class missions, addressing specific strategic scientific investigations that do not require Flagship class missions. The NRC's Solar System Exploration Decadal Survey [NRC03] recommended a prioritized list of five New Frontiers class missions for the decade 2003–2013. The first of these, the Pluto – Kuiper Belt Explorer (New Horizons) mission, was already in Phase A at selection and was launched successfully in January 2006. For the remaining four proposed missions, the NRC's order of priority was — South Pole–Aitken Basin; Jupiter Polar Orbiter with Probes; **Venus In Situ Explorer**; and Comet Surface Sample Return.

3.3.5 Venus In Situ Explorer (VISE)

The **Venus In Situ Explorer (VISE)** mission concept was envisaged by the NRC as a balloon mission that would study **Venus'** atmospheric composition in detail and descend briefly to the surface to acquire samples that could be then analyzed at a higher altitude where the temperature is less extreme. The VISE scientific measurements would help to constrain models of the **Venus** greenhouse history and stability as well as the geologic history of the planet, including its extensive resurfacing. VISE would also pave the way for a future Flagship class mission to the surface and low atmosphere of **Venus** and for a possible subsequent sample return from the extreme environment of Earth's neighboring sister planet. Although the VISE proposal was not selected in the New Frontiers 2 competition, it is expected that the concept could compete for the next New Frontiers opportunity.

3.4 Flagship Missions

In addition, the **Venus Mobile Explorer** mission was also identified as a Flagship class mission following missions to Europa and Titan. Its third place is due to technology considerations, which is perceived to be less mature than that for a Titan Explorer mission. The goal of this mission would be to conduct an extended mobile in situ investigation of the surface of **Venus**, a formidable challenge because of the extreme temperature and pressure reaching ~480°C and ~90 bars, respectively.

In the mid– and far–term, Flagship missions will be defined and selected to build on the results of earlier investigations. Examples of other high–priority missions that would represent major scientific advances include:

- An Enceladus Explorer that would build on the tantalizing Cassini discovery of ice plumes by performing comprehensive exploration of Enceladus.
- A Neptune–Triton Explorer (orbiter with probes) that would perform the first detailed exploration of this ice giant planet and its major moon Triton that is possibly a captured Kuiper Belt Object.

- A **Venus Sample Return** that would provide insight into the causes and effects of the apparent global climate change that **Venus** experienced in the distant past.

NASA will engage the broad science and engineering community in studies of these and other Flagship mission concepts to assess their feasibility and establish technology requirements for near–term investment. One characteristic common to all Flagship missions is that they depend upon continued investments in technology. The definition of these technology needs and the development of investment plans is one of the most important near–term activities that will enable these challenging, scientifically compelling future Flagship missions.

3.4.1 Europa Explorer

… The Europa Explorer (EE) spacecraft (Figure 3.9) would be launched on an indirect trajectory to Jupiter, exploiting gravity–assist flybys of both **Venus** and Earth. … As a result of the Earth and **Venus gravity–assist** maneuvers, the dry mass of the spacecraft would be expected to be three times that of the Europa Orbiter concept from 2001. …

3.4.3 Venus Mobile Explorer

A **Venus Mobile Explorer (VME)** is proposed for a new start in the second half of the second decade. This mission is sequenced after the Titan Explorer for several reasons. The later start date would permit an opportunity for the selection of a New Frontiers class **Venus In Situ Explorer (VISE)** as a precursor mission (currently in the New Frontiers AO mission set). It also provides additional time anticipated to develop high–temperature electronics and power technologies needed at the surface of **Venus** for long–lived missions. **VME** would take the next logical step in exploration of the Venus surface beyond the Magellan mission's epic radar reconnaissance and the presumed **VISE**. This mission would perform extensive measurements at the **Venus** surface, including a search for granitic and sedimentary rocks; analysis of the crust for metastable hydrated silicates, and measurements of the oxidation and mineralogical state of iron. Together, these landed experiments would enable the determination of how long ago an ocean disappeared from **Venus**, and therefore how long Venus may have had to potentially nurture life. Equipped with visual imaging and a targeted set of geochemical sensors, **VME** would use the methods of mobile scientific exploration.

Advantages of mobility were demonstrated by the Mars Exploration Rovers, although for **VME** an air mobility platform (see Figure 3.11) with long traversing would be preferred over a surface rover, which would have a limited range of hundreds of meters. The MER rovers have enabled extraordinary advances in the understanding of geochemistry and hence past climate conditions on Mars. A similar understanding for Venus would be enabled by **VME**, so that a more complete view of the interconnected cycles of chemistry, volcanism, and climate on **Venus** would be obtained. This understanding would be crucial for interpreting the spectral signatures and other data we would eventually obtain from terrestrial planets around other stars. The entire project, from new start to end–of–mission, could be accomplished in 6–7 years, including a surface stay time of days or weeks. The extreme temperature (~480°C), pressure (~90 bars) at the surface, and the highly corrosive atmosphere at about 10 km above the surface of **Venus** present challenges for materials, mechanisms, and electronics. The surface conditions may also be potentially hazardous due to extremely rough terrain, limiting surface access for sample collection. The technology challenges drive previous–decade technology investments and predicate this mission's new start upon a strategic technology decision point early in the decade.

Figure 3.11: Venus Mobile Explorer (artist's concept). Showing a metallic bellows, Stirling Radioisotope Generator with active cooling, and pressure vessel for in situ instruments and subsystems.

3.4.7 Venus Sample Return

A **Venus Sample Return** is a very difficult mission that would certainly follow a successful Mars Sample Return and an effective **Venus Mobile Explorer** mission. As for Mars, answers to detailed questions about the past suitability of **Venus** for the origin and sustenance of life can only be answered by bringing samples back to terrestrial laboratories. These include definitive interpretations of the petrology and mineralogy of crustal samples over scales from the regional to the microscopic and determinations of the C, O, S and H isotopic abundances in the crust and lower atmosphere. The implementation challenge lies not so much with **Venus** environmental issues (although they are not trivial) as it does with the mission energetics. There would need to be a buoyant ascent stage to collect the sample either from the surface or from another vehicle (deployed to the surface and back into the atmosphere) and then carried to an altitude from which atmospheric density is low enough for a launch to be feasible. At this point the propulsion needed is equivalent to an inner planet mission starting at Earth's surface. Needless to say, even with a very small sample return payload the buoyant stage would only be capable of reaching Venus orbit, where another Earth Return Vehicle would have to be waiting to rendezvous with the ascent stage, to transfer the sample for a return flight to Earth. Sample recovery at Earth would be similar to the proposed Mars sample return concept with a direct entry to a suitable recovery site (e.g., UTTR) expected. Advanced airborne systems and high–energy in–space propulsion are key capabilities needed for this mission.

4 Technology Development for Solar System Exploration

4.1 Overview

Table 4.1: Technology priorities for Solar System exploration.

Technology	Priority	Comments
SPACECRAFT SYSTEMS		
Transportation	●	▷ Aerocapture technologies could enable two proposed Flagship missions, and solar electric propulsion could be strongly enhancing for most missions. These technologies provide rapid access, or increased mass, to the outer Solar System.
Power	●	▷ Radioisotope power systems are needed for all five proposed Flagship missions, requiring a sufficient supply of plutonium. Advances in power conversion efficiencies would reduce the need for plutonium for a given power requirement, while the mass savings could be traded against payload, or increase mass margin on the spacecraft.
Communications	●	▷ The science return from every mission would benefit from improvements in direct–to–Earth communications infrastructure. In situ exploration with orbital assets would be strongly enhanced by improved proximity links.
Planetary protection	▲	▷ New planetary protection technologies will be needed to meet the anticipated requirements for in situ exploration to targets of interest for astrobiology.
Autonomy and software	▲	▷ Autonomous systems strongly enhance most missions by providing for more robust operations. New methodologies for software verification and validation and fault protection will substantially reduce the associated risks.
IN SITU EXPLORATION SYSTEMS		
Extreme environments	●	▷ The proposed Flagship mission set spans a number of diverse extreme environments, requiring technology advances in fields ranging from extremes in temperature and pressure, to high radiation and high heat flux during atmospheric entry. These technologies could also enhance the operational capabilities of the Discovery and New Frontiers missions facing temperature extremes or those with returned samples.
Entry, descent, and landing	▲	▷ New propulsive landing systems would enable operations on small bodies and satellites without atmospheres. Entry, descent, landing, and aerial operations on bodies with atmospheres (such as Titan and Venus) would be possible with the associated advances in technologies for extreme environments.
Planetary mobility	▲	▷ Access is critical to the in situ exploration central to the later Flagship mission concepts, making various types of mobility systems enabling for those missions. Advances in mobility technologies could also provide alternatives for various New Frontiers mission concepts.
SCIENCE INSTRUMENTS		
In situ sensing	●	▷ New technologies and instruments will be required for improved science return to targets of astrobiological interest, enabling several of the proposed Flagship missions. The instrument technologies will require associated development in sample acquisition and handling systems.
Components and miniaturization	●	▷ Every mission is either strongly enhanced or enabled by improvements in miniaturization and advanced component design. Missions with systems requiring isolation from the ambient environment will be particularly improved by lighter instrumentation.
Remote sensing	▲	▷ Flagship missions with orbital or extended aerial operations would be strongly enhanced by improved technologies for passive and active remote sensing, and smaller missions would benefit from these technologies, as well.
● Highest priority — new developments are required for all or most roadmap missions		
▲ High priority — either applications are more limited or can leverage existing work effectively		

4.3.2 Power

Power is a critical technology for the proposed missions in this Roadmap and the methods of generating, storing, and managing power are key to their success. Four of the planned Flagship missions are to destinations in the outer Solar System where due to extreme operating environments, RPS may be required for electrical power production and thermal management. In addition, little solar energy reaches the surface of **Venus**, to which the **Venus Mobile Explorer** mission would descend; furthermore, power conversion of the remaining solar energy would be infeasible at the ambient temperatures.

Radioisotope Power Systems

…

Dynamic Conversion Systems

NASA is also currently developing a Stirling Radioisotope Generator (SRG) with a dynamic power converter (Figure 4.7), which has comparable specific power to the MMRTG, but has a significantly higher thermodynamic efficiency. An advanced version of the SRG with an increased specific power is under consideration (Figure 4.8). In view of a shortage of plutonium–238 available to NASA, an SRG technology could be important to the Agency even though it has not reached the maturity level of the thermoelectric–based technology.

The higher thermodynamic efficiency of mechanical devices would be also important for the application of RPS power to the proposed **Venus Mobile Explorer** mission. Stored power is inadequate for the preliminary mission design of many months of operation near the **Venus** surface, and no other power generation technologies capable of tolerating the extreme temperature and pressure are likely available. A unique SRG for the **Venus Mobile Explorer** mission would not only generate electric power, but it would also enable a highly efficient heat pump that would cool the electronics and payload.

Current SRG development work does not include a requirement to operate in the 460°C **Venus** environment. *Future development work should include work on dynamic conversion systems for power generation and for active cooling to address the need for sustained power at or near the surface of **Venus***.

Figure 4.7: Illustration of a dynamic Stirling converter. Dynamic conversion provides significantly higher conversions efficiency than thermoelectric devices can achieve, but at the expense of moving parts and greater complexity. For long duration outer planet missions, lifetime issues of dynamic converters should be addressed. However, for power–generation in the Venus environment, where the mission lifetime is significantly shorter and the efficiency gain provides a critical advantage, dynamic systems will be required.

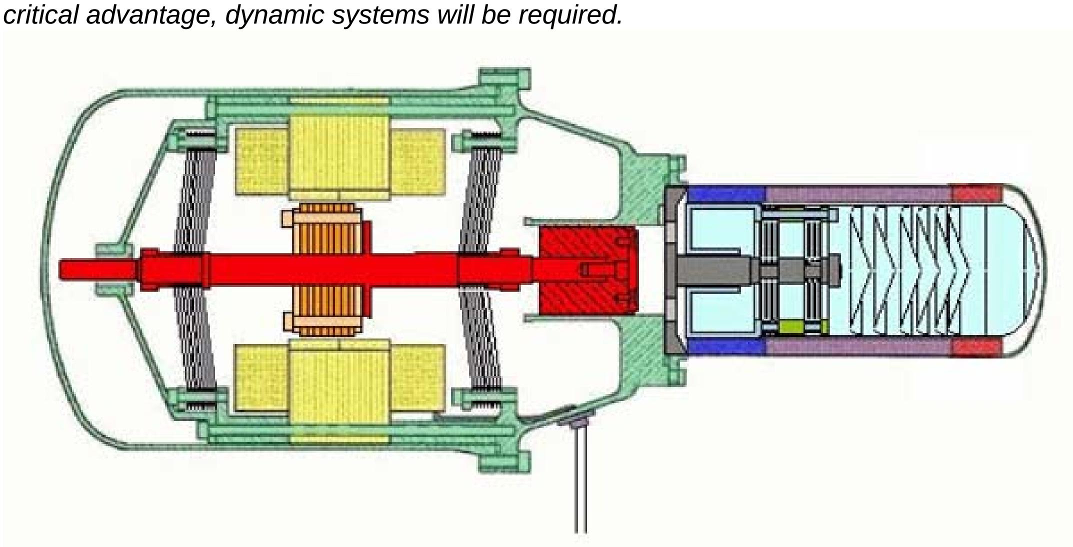


Figure 4.8: Illustration of a dynamic Stirling converter.
These devices utilize flexure bearings to minimize wear. The technology has been successfully used in space for cryogenic coolers, but not to date for power generation.

4.3.3 Communications

… Many of the proposed missions in this Roadmap could benefit directly from the development of proximity link technology for the Mars Exploration Program. This includes establishment of the protocols and various classes of software radios. Collaboration with ESA has resulted in interoperability of NASA and ESA Mars spacecraft for proximity relay purposes. The beneficiaries of this technology could include a small lander or impactor on the Europa Explorer, as well as relay communications for the potential Titan Explorer, **Venus Mobile Explorer**, and the Europa Astrobiology Lander.

4.3.5 Autonomous Operations

… However, Solar System exploration will require additional capabilities without a counterpart in the Mars Exploration Program. For example, the Solar System Exploration Roadmap includes mission concepts calling for proximity operations of sample return missions from small bodies, as well as aerial platforms monitoring and acquiring samples from the surfaces of Titan and **Venus**. Fortunately, frameworks now exist for autonomy implementation, particularly the Coupled Layer Architecture for Robotic Autonomy (CLARAty), a joint effort by NASA and major robotics universities; these efforts can ensure that investments in Mars technology are fully exploited.

4.4.1 Entry, Descent, and Landing

The term “entry, descent, and landing” has become so standard that we apply it here to the delivery of all types of in situ vehicles. The emplacement of aerial platforms generally occurs during the descent phase.

Entry
Many of the targets of interest in this Roadmap have dense atmospheres that can be used to decelerate the vehicle in order to reach its desired location. Entry systems for Titan and **Venus** could likely be accommodated with existing technology (Figure 4.13). On the other hand, requirements for the proposed New Frontiers Saturn mission and the Flagship Neptune–Triton Explorer mission would present greater challenges to entry technology, and missions entering Jupiter’s atmosphere will present the greatest challenges at entry. …

Descent
During the descent phase through a planetary atmosphere, the vehicle generally descends at a steady rate determined by the balance between gravitational and aerodynamic forces. With its thin atmosphere and strong near–surface winds, Mars presents a special challenge for atmospheric descent technology. On the other hand, descent in the thick atmospheres of **Venus** and Titan, with low surface winds, facilitates soft landings, as the successful landings of the Huygens probe and many **Venus probes** have demonstrated. It is therefore expected that the deployment and inflation of balloon systems for the proposed Titan Explorer and **Venus Mobile Explorer** missions would be straightforward, with the descent providing ample time for completing these operations.

Landing
Landing technologies are most challenging for planets and satellites without atmospheres. For landing on both Europa and Enceladus, a delta–V of several km/sec will be required. For a given entry mass, advanced chemical propulsion technology will lower the propellant mass, and consequently will increase the useful payload mass

fraction, as discussed in Section 4.3.1. However, guidance, navigation, and control technologies are also important. Although there is no single EDL system applicable to all of the widely diverse types of bodies of interest, the critical advanced technologies for precision landing and hazard avoidance can be utilized as a foundation for the capabilities needed by all missions.

Future potential Solar System exploration missions must land on airless objects of widely divergent gravitational fields, contend with extreme relief, and possibly descend and ascend under conditions of active plumes from the surface. In contrast, landing on bodies with dense atmospheres, such as **Venus** and Titan, represents comparatively straightforward engineering; for both bodies, descent vehicles designed primarily as atmospheric probes (i.e., **Pioneer–Venus** on **Venus** and Cassini–Huygens on Titan) have survived landings. …

4.4.2 Planetary Mobility

Two of the potential Flagship missions in this Roadmap, Titan Explorer and **Venus Mobile Explorer**, would require mobility in order to sample a relatively wide area of heterogeneous surfaces. While surface mobility is the method of choice on airless bodies and in the thin atmosphere of Mars, mobile aerial platforms represent a very attractive option for **Venus** and Titan.

Aerial

The thick atmospheres of Titan and **Venus** enable buoyant vehicles that are much less susceptible to being immobilized by surface obstacles or surfaces with low bearing strengths. Aerial vehicles can also travel over much greater distances with less energy consumption and would provide local imaging, as well as chemical and mineralogical sampling, at multiple sites for both the proposed **Venus Mobile Explorer (VME)** and Titan Explorer (TE) missions.

In the hot dense atmosphere of **Venus**, thin metal balloons could provide adequate buoyancy near the **Venus** surface and yet survive the **Venus** surface temperatures (Figure 3.11). For Titan, polymer–based films and fabrics that can retain their flexibility and resilience at low temperatures near 90K have been demonstrated (Figure 3.10). Long life, low temperature actuators will be required for altitude control of Titan Aerial vehicles (described further in Section 4.4.3, on technologies for extreme environments).

In order to pass the technology decision gates for both the proposed Titan Explorer and **Venus Mobile Explorer**, it would be necessary to invest in mobility systems. A sustained effort in both basic technology and advanced development is needed to prepare for these types of missions. Test facilities would be required for validating the performance of mobile vehicles in both extremely hot and extremely cold environments.

4.4.3 Extreme Environments

Future Solar System exploration missions will experience a wide range of possible conditions, from the comparatively benign environment of Mars, to the intense radiation environment around Europa, to the intense heat and crushing pressure within the atmospheres of **Venus** and Jupiter. These environments also include the extreme radiant and convective heating of planetary entry and the frigid temperatures near the surface of Titan. A table summarizing the targets and their extreme environments follows below (Table 4.2). The need for spacecraft to survive and make measurements in this wide variety of environments is a major challenge for the next generation of Solar System missions.

Technologies for extreme environments are categorized by the challenging environment conditions: High temperature and high pressure, low temperature, high radiation, and high heat flux (i.e., atmospheric entry). In general, technologies may be designed to fulfill one of three goals: to provide isolation from the extreme environment, such as an integrated thermal/pressure control vessel; to tolerate the extreme environment, such as radiation–hardened electronics; or to integrate isolation and tolerance in a system–wide hybrid design.

Table 4.2: Extreme Environments of Potential Target Bodies for Solar System Exploration.

	Mission Stage								
	Space	Entry		In situ					
Target	Radiation (krad/day)	Entry heat flux	Deceleration (g)	High pressure (bar)	Low temperature (°C)	High temperature (°C)	Day length (Earth day)	Chemical corrosion	Physical corrosion
High temperatures and high pressure									
Venus surface		30	400	92		500	400	H_2SO_4	
Jupiter (Gas giant)		42		100		450			
Low temperatures									
Lunar permanently shadowed regions					-230				
Comet nucleus		0.5*			-270				
Titan surface					-178			CH_4	
Enceladus					-199				
Low temperatures and high radiation									
Europa orbit	40								
Europa surface	30				-180				
Europa subsurface	0.3 at 10 cm								
Thermal cycling									
Moon					-180	120	27		Dust
Mars					-120	+20			Dust

* This heat flux is that at Earth and applies to any returned sample mission, such as the Comet Surface Sample Return.

High Temperatures and High Pressures

The surface of **Venus** presents a number of formidable challenges to in situ exploration, including temperatures of ~480°C and pressure of 90 bars in an atmosphere of carbon dioxide with corrosive components, such as sulfur dioxide. The New Frontiers class **Venus In Situ Explorer (VISE)** would have a limited lifetime comparable to those achieved by the Soviet **Venera** missions (several hours); however, the **Venus Mobile**

Explorer (VME) would operate for months and traverse significant distances to observe the surface at close range and sample from many sites. Probe missions to Saturn may also be targeted to reach a pressure of 10–20 bars, but the temperature there would be less than ~300°C at that pressure–depth. Accordingly, the primary driver for missions requiring extreme temperatures and pressures is Venus. (See Figures 4.14 and 4.15.)

For the proposed **VISE**, a short–duration mission, passive thermal control approaches may be adequate, while **VME**, a very long–duration mission, would require active cooling to “refrigerate” the thermally controlled avionics and instruments with minimum heat leaks. An aggressive early program of systems analysis is important to define the best approach and to determine realistic performance goals for this technology. In addition, pressure vessels used in the past may not be adequate for mission durations longer than a few hours and a new, lightweight, creep–resistant pressure vessel will need to be developed.

Use of an active thermal control system alone is not a practical solution because components dissipating a great deal of power would impose excessive demands on the thermal control system. However, components that can operate in the ambient environment, including high–temperature electronics, and energy storage, offer a solution. Hybrid systems combine communications and other high–power components hardened to operate without thermal control in the **Venus** environment with low power–dissipating, conventional digital electronics, thus operating at Earth–ambient temperatures in an actively controlled pressure vessel.

Both wide–bandgap semiconductor and vacuum tube approaches to high–temperature electronics have been demonstrated to operate at temperatures in excess of ~500°C, but there are no strong commercial drivers for this technology. Silicon–based electronics capable of operating at temperatures ~250°C are being developed for the oil drilling and automotive industries. Both the high–temperature electronics capable of operating at **Venus** surface ambient temperatures, as well as medium temperature (~250°C) electronics technology, are enabling for the proposed **Venus Mobile Explorer (VME)** Flagship mission. Medium temperature electronics would operate in *temperature controlled chambers, requiring significantly less active cooling than conventional electronics.* High–temperature electronics could benefit the **Venus In Situ Explorer (VISE)** mission and a technology validation experiment on that mission might also be appropriate.

Actuators that can operate at extremely high temperatures represent the main focus for technologies needed for sample acquisition mechanisms. These components require permanent magnets, gearboxes, and lubricants with the ability to perform at **Venus** surface temperatures. High–temperature actuators are needed by both the **VME** mission and the short–duration **VISE** mission.

*In general, missions to **Venus** would benefit from a number of technologies for high temperatures, including active thermal cooling, pressure vessels, high–temperature electronics, energy storage, and high–temperature mechanisms.*

Figure 4.14: Pressure vessel concept for exploration of extreme environments. For potential short–lived giant planet deep entry probes and for ***Venus*** *in situ missions, the high pressure and temperature must be withstood. The figure shows a pressure vessel concept with thermal insulation outside. The instruments and electronics are placed inside the pressure vessel, with a phase–change material (PCM) tray, which can absorb the heat generated by the instruments for a short period of time, measured in hours.*

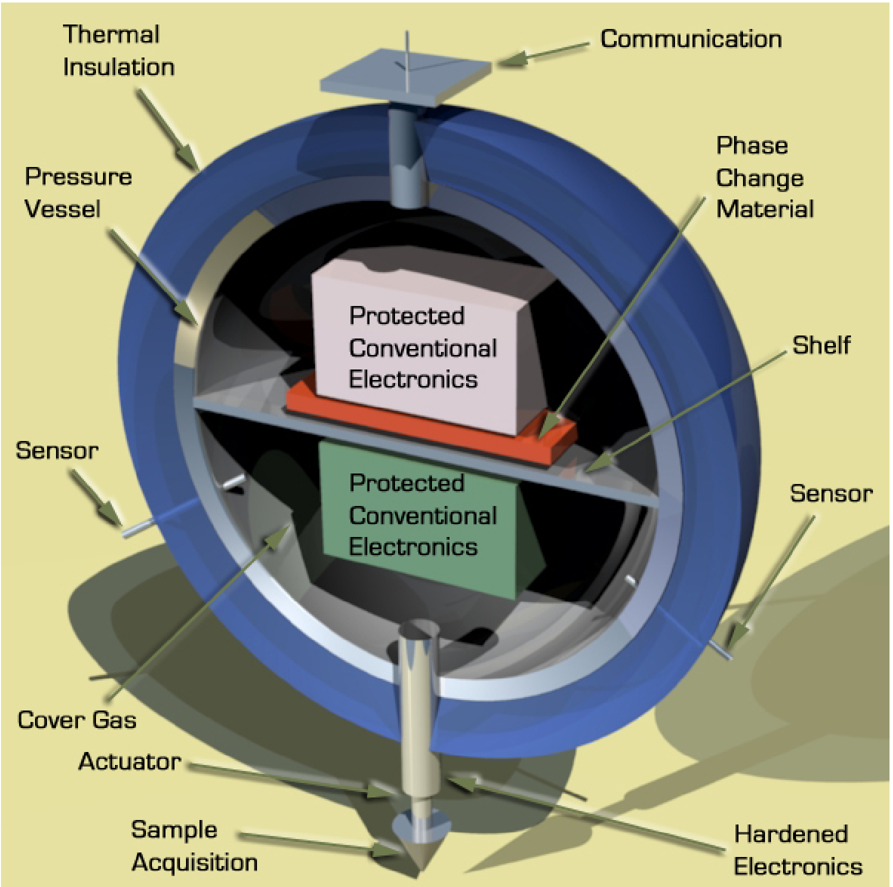
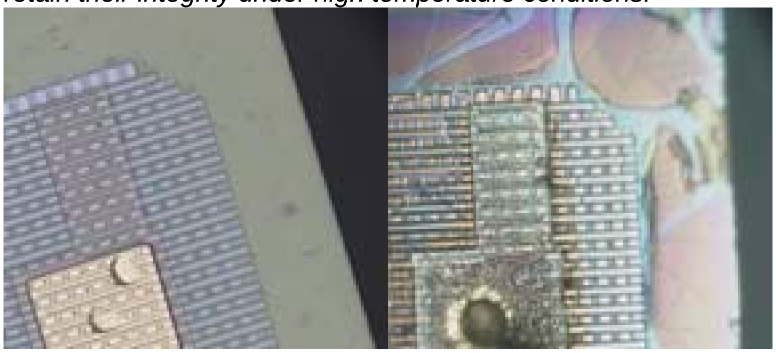


Figure 4.15: High–T electronics. Electric circuit at normal temperatures (left); and after ~24 hours exposed to 500°C (right). Useful high–temperature electronics requires not only electronic materials that retain their properties at high temperatures, but also packaging approaches that retain their integrity under high temperature conditions.

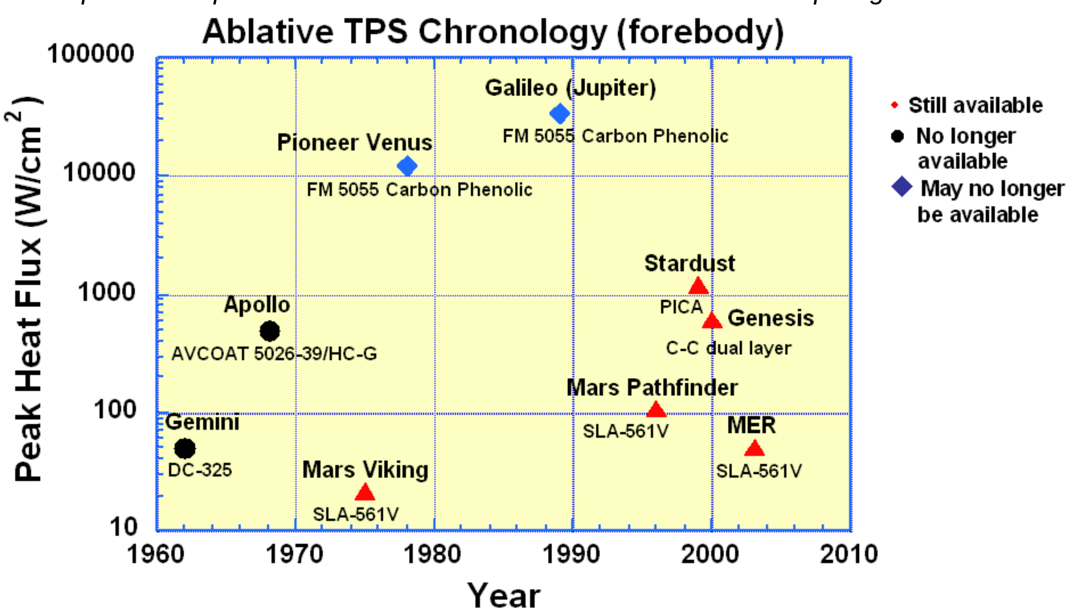


High Heat Flux

Entry into planetary environments exposes the aeroshell to severe thermal environments (Figure 4.16). Atmospheric drag is utilized to reduce the interplanetary hypervelocity entry to low speeds in the atmosphere, where the scientific measurements are performed or where the payload is delivered. This atmospheric entry results in the extreme aerothermal environment around the aeroshell. In conjunction with entry probe shape and velocity, the severity of the environment is driven by atmospheric properties, such as gas composition, density, temperature, and pressure.

At heat fluxes of 120 W/cm2, entry into the atmosphere of Mars and Titan is benign compared to conditions at Venus and much less severe than will be encountered by entry probes to the giant planets. …

Figure 4.17: Thermal Protection Systems — Materials. NASA entry probes have survived entry environments ranging from the very mild (Mars Viking ~25 W/cm2) to the extreme (Galileo ~30,000 W/cm2). The environment for the proposed Saturn and Neptune probes would be less severe than for the Galileo probe, but the most suitable materials may no longer be available. Aerocapture at Neptune would involve a different set of conditions requiring a tailored solution.



*… In summary, the investment in thermal protection technology would not only enable a Saturn probe mission but also a Neptune–Triton Explorer mission with probes and an aerocapture orbiter. Moreover, benefits also extend to **Venus** missions and to sample return missions.*

4.5 Science Instruments

4.5.1 Remote Sensing

Active Remote Sensing

… Active microwave systems play a key role in image the surfaces of objects with atmospheres that obscure the surface (**Venus** and Titan) and probing the subsurface of planets and satellites. The success of the Mars Advanced Radar for Subsurface and

Ionosphere Sounding (MARSIS) instrument (Figure 4.20) on Mars Express builds confidence in the potential use of this technology in the outer Solar System at Europa, Enceladus, and Titan. …

4.5.2 In Situ Instrumentation

In situ measurements would be needed for the three Flagship missions that would descend to the surface of Europa or operate at the surface and within the atmospheres of **Venus** and Titan. These instruments would be targeted at determining the characteristics of the Solar System that led to the origin of life (see Table 3.1). In this context, they would help answer questions about the nature, history, and distribution of volatile and organic compounds in the Solar System, determining the evidence of a past ocean on the surface of **Venus**, and identifying the habitable zones in the outer Solar System. They would also address the issue of how did life begin and whether it has evolved elsewhere in the Solar System. In this context, it is necessary to identify the source of simple chemicals important to prebiotic evolution; direct evidence for life on Europa, Titan, and Enceladus; and evidence for past life on **Venus**. Many of these questions would be much easier to answer if these materials could be returned to terrestrial laboratories. For these targets, this is impractical and hence in situ technologies must be brought to maturity.

In situ Analysis and Sensing

Answering questions related to habitability involves a vast range of measurement types far beyond the scope that can be discussed here. Mineral and isotopic analysis will be important to answer many of the questions related to **Venus** with instruments deployed on **VISE** and **VME**. For Europa, Titan, Enceladus, and comet samples, the focus would be on detecting and characterizing organic materials, possibly with biological significance. While the experience developing instruments for Mars is relevant, most of the target objectives are primarily composed of water ice and not silicates.

4.5.3 Component Development and Miniaturization

Component Development

New components and devices exploiting nanotechnology and microfluidics have potential for more sensitive and precise measurements for characterizing minerals and organic materials. A major focus of this work will be on the detection of evidence for extinct and extant lifeforms. In situ measurement capabilities applicable to extreme environments such as those of Venus, where conventional techniques applied at Mars may not be practical, are also needed.

As noted earlier, the NASA pipeline for these technologies has now been shut down. A slowdown in innovation will be the inevitable consequence.

Table 4.3: Impact of Advanced Technology Development on Roadmap Missions.

Major Questions	Discovery				New Frontiers						Flagship (Small/Large)							
Objectives	SB	Moon	Venus	Mercury	NH	Juno	SPABSR	VISE	CSSR	SP	C–H	EE	TE	VME	EAL	NTE	*CCSR**	*VSSR**
SPACECRAFT SYSTEMS TECHNOLOGIES																		
Transportation																		
▷ *Access to Space*					⊕	⊕					⊕				▲	▲		
▷ *Solar Electric Propulsion*	▲	▲	▲	▲	⊕	⊕			▲	▲	⊕		▲		▲	▲	▲	▲
▷ *Aerocapture / Aeroassist*			▲		⊕	⊕	▲				⊕		●	▲		●		▲
▷ *Advanced Chemical Propulsion*		▲		▲	⊕	⊕				▲	⊕	▲		▲	●			▲
Power																		
▷ *Radioisotope (RPS)*					⊕	⊕					⊕	▲	▲	●	●	▲		
▷ *Solar Power*	▲	▲	▲	▲	⊕	⊕			▲	▲	⊕		▲		▲	▲	▲	
▷ *Energy Storage*	▲	▲	▲	▲	⊕	⊕	▲	▲	▲	▲	⊕	▲	▲	▲	▲	▲	▲	▲
Communications																		
▷ *Direct–to–Earth Communications*	▲	▲	▲	▲	⊕	⊕	▲	▲	▲	▲	⊕	▲	▲	▲	▲	▲	▲	▲
▷ *Proximity Links*					⊕	⊕	▲			▲	⊕		▲		▲	▲		▲
Planetary Protection																		
▷ *Forward Planetary Protection*					⊕	⊕					⊕	▲	●		●			
▷ *Returned Sample Handling*					⊕	⊕			▲		⊕						▲	
Autonomy and Software																		
▷ *Autonomous systems*	▲	▲	▲	▲	⊕	⊕	▲	▲	▲		⊕		▲	▲	▲	▲	▲	▲
▷ *Software V&V*	▲				⊕	⊕			▲		⊕		▲	▲	▲	▲	▲	▲
IN SITU EXPLORATION TECHNOLOGIES																		
Entry, Descent, and Landing																		
▷ *Precision Navigation*	▲	▲			⊕	⊕			▲		⊕				●		▲	
▷ *Hazard Avoidance*	▲				⊕	⊕			▲		⊕		▲	▲	●		▲	
▷ *Small Body Anchoring*	▲				⊕	⊕			▲		⊕						●	
Planetary Mobility																		
▷ *Aerial*			▲		⊕	⊕		▲			⊕		●	●				
▷ *Surface*					⊕	⊕	▲	▲			⊕		▲	●				
▷ *Subsurface access*					⊕	⊕					⊕				●		●	▲
Extreme Environments Technologies																		
▷ *High Temperature/Pressure*			▲		⊕	⊕		●			⊕			●				●
▷ *Low Temperature*	▲	▲		▲	⊕	⊕	▲		▲		⊕		●		●		▲	
▷ *High Radiation*					⊕	⊕					⊕	▲			●			
▷ *High Heat Flux*			▲		⊕	⊕		▲	▲	●	⊕		▲	▲		●	▲	●
SCIENCE INSTRUMENTS																		
Remote–Sensing Instruments																		
▷ *Active Remote Sensing*	▲	▲	▲	▲	⊕	⊕					⊕	▲	▲	▲		▲		
▷ *Passive Remote Sensing*	▲	▲	▲	▲	⊕	⊕				▲	⊕	▲	▲	▲		▲		
In Situ Instruments																		
▷ *Analytical Instruments*	▲		▲		⊕	⊕	▲	●	▲		⊕		●	●	●		▲	▲
▷ *Sample Acquisition & Handling*					⊕	⊕	▲	●	●		⊕		●	●	●		●	●
Component Technology and Miniaturization																		
▷ *Component Technologies*	▲	▲	▲	▲	⊕	⊕	▲	▲	▲	▲	⊕	▲	▲	▲	●	▲	▲	▲
▷ *Miniaturization*	▲	▲	▲	▲	⊕	⊕	▲	▲	▲	▲	⊕	▲	▲	●	●	▲	▲	▲

Convention: ● Major or Unique Contribution; ▲ Support Contribution; ⊕ Ongoing Mission or Project

SB — small bodies; NH — New Horizons; SPABSR — South Pole–Aitken Basin Sample Return; VISE — Venus In Situ Explorer; CSSR — Comet Surface Sample Return; SP — Saturn Flyby with Shallow Probes; C–H — Cassini–Huygens; EE — Europa Explorer; TE — Titan / Enceladus Exp.; VME — Venus Mobile Exp.; EAL — Europa Astrobiology Lander; NTE — Neptune–Triton Explorer; *CCSR — Cryogenic Comet Surface Sample Return; VSSR — Venus Surface Sample Return * — beyond the 5 proposed Flagship missions*

4.6 Summary

4.6.2 In Situ Exploration

Access to extreme environments, both extremely hot near the surface of **Venus** and extremely cold at the moons of the outer planets, requires investments in a suite of technologies to enable probes and mobile platforms to survive and operate in these environments.

Recommendation: *NASA should initiate a technology development program in technologies for extreme environments. Many of the needed technologies are currently at a very low technology readiness level (TRL) and the gestation period of development is long. Accordingly, initiating this program as soon as practicable will have a major impact on the feasibility of future Flagship missions and will also benefit Discovery and New Frontier missions*.

7 Interdependencies

7.1 Interdependencies Among Missions and Mission Lines

7.1.2 Between the New Frontiers and Flagship Programs

New Frontiers (NF) missions are necessarily less ambitious technically than Flagship (FS) missions. In the cases considered here, the less ambitious New Frontiers missions are assumed to precede and feed forward capabilities into the FS missions. However, since the sequence of the New Frontiers missions is determined competitively, the coupling of the interdependencies will need to be less tight and more flexible than among the Flagship class missions. As Figure 7.1 illustrates, the next New Frontiers competition (NF3) is currently planned to occur in 2008. The NF3 selection will result in one of four New Frontiers candidates going forward. These selections may have impacts on the decision points for future FS missions:

- **Venus In Situ Explorer (New Frontiers) and Venus Mobile Explorer (FS)** — Both of these missions operate at or near the **Venus** surface. **VISE** is a fixed lander of limited duration (hours); **VME** would be a mobile mission of extended lifetime (months). The US has no experience in operating spacecraft on the surface of **Venus** even for limited periods and so **VISE** would be a valuable precursor to **VME**. It would still be an effective precursor if the selection of **VISE** was deferred to NF4 but no later if the **VME** schedule holds.

7.2 Technology Development and Infusion

7.2.1 Technology Development

... Flagship missions drive the development of enabling technologies that can and should be exploited by medium and small missions. Small and moderate missions may also validate new technologies and innovations, which can then be adopted in larger missions. Solar electric propulsion is an example in this Roadmap. The Mars Exploration Program, through its focused technology program, mitigates the risks of introducing many new technologies into science missions. In some cases, these technologies will also be applicable to outer planets, **Venus**, and other destinations. The New Millennium Program offers much more directed opportunities to validate flight technologies.

8 Roadmap Implementation

8.3 Impact of Mission Interdependencies on These Scenarios

The differences in flight rate among the various mission lines in Options A to D are likely to impact some of the interdependencies discussed in the previous chapter. These interdependencies are complex and the complete evaluation of them is beyond the scope of this Roadmap report. Some issues that need to be further evaluated include:

- The interdependency between NF **VISE** and the **Venus Mobile Explorer**. The VISE mission would have to be launched before FY17 to impact the technology decision point for the **Venus Mobile Explorer** stipulated here.
- The interdependency between the NF Saturn Probe and the Neptune Triton Explorer missions. The NF Saturn Probe mission would have to be launched before FY16 in order to acquire aeroentry data in the atmosphere of Saturn (an analog for Neptune) prior to the technology decision on date for NTE in FY22.
- Interdependencies with Mars Exploration Program missions and New Millennium missions are not adversely impacted by the options discussed here.

The impact of delays in implementing a Flagship program on cost–capped Discovery and New Frontiers missions also needs to be considered. As discussed in Section 7.1.3, new technologies developed for Flagship missions can benefit the smaller cost–capped programs.

8.4.1 Flagship Mission Implementation

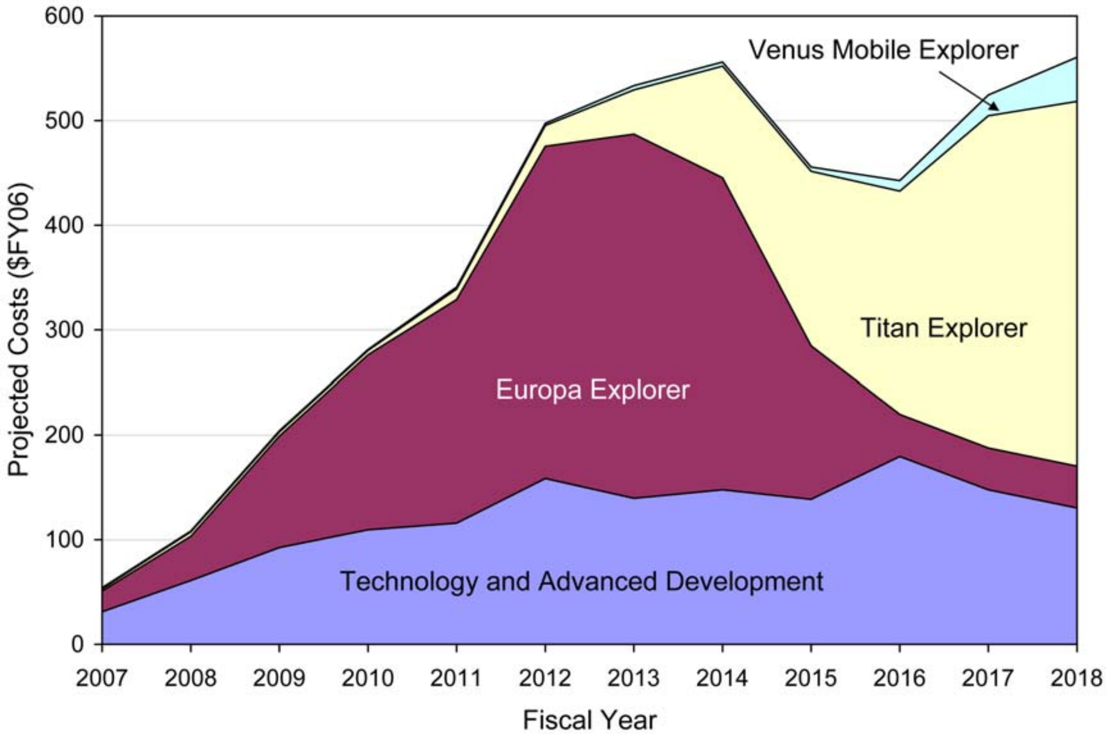
To understand some of the implications of funding profile issues associated with Flagship missions, three scenarios were analyzed for near–term budget impacts. A Cassini cost distribution model was assumed along with a *strictly pro forma projection*, based on a total mission cost of $2B ($FY05). The projected costs account for technology and advanced development, mission formulation, development and operations costs:

- **Baseline scenario**: Europa Explorer launches in FY15, Titan Explorer in FY20, and **Venus Mobile Explorer** in FY25 (see Figures 3.8 and 8.1)
- **One–Year Delay**: Europa Explorer launches in FY16, Titan Explorer in FY21, and **Venus Mobile Explorer** in FY26
- **Two–Year Delay**: Europa Explorer launches in FY17, Titan Explorer in FY22, and **Venus Mobile Explorer** in FY27

The projected technology and advanced development costs are based on assumptions described below in Section 8.4.2.

The $2B pro forma projection is in the mid range of Flagship missions. While the estimates are not strictly comparable to those appearing in Table 8.1, they do illuminate some key features of the mission funding profile of Flagship class missions at the mid–range of the cost of $2B in FY06 dollars. A 5–year separation between launch dates means that the peak spending cycles are well separated, while avoiding the prolonged hiatus caused by launching only one Flagship mission per decade.

Figure 8.1: Investment needs for Solar System Exploration Roadmap program of Flagship missions. This baseline scenario assumes that the first mission — Europa Explorer — is launched in FY15. The technology and advanced development investment is targeted primarily at the second and third missions, Titan Explorer and ***Venus Mobile Explorer****, which require investments prior to the decision points.*



8.4.2 Technology Development

The projections of technology and advanced development costs have been developed based on the following assumptions of technology needs for the first three Flagship missions:

…

- **Venus Mobile Explorer** has *major new technology requirements*. The technology for long duration operation in the high temperature/high pressure environment of **Venus** requires a long and sustained program of investment. An earlier investment will lead to earlier returns, particularly because early technology development would likely benefit the New Frontiers class **Venus** mission. The technology development may also point to the need for validation experiments that could be carried out on such a mission.

9 Conclusions and Recommendations

Strategy

The robotic exploration program that the Strategic Roadmap Team 3 was chartered to define requires a balanced program of research and analysis, a range of mission sizes with concomitant technology development, and a strong outreach program. The goals of searching for life across the Solar System and understanding the history of the Solar System require orbital and in situ investigations of the outer planets and their satellites and extended mobile exploration in the extreme environment of **Venus**. Such investigations are beyond the scope of the Discovery and New Frontiers class missions that constitute today's Solar System Exploration Program. These investigations will require development of technologies that will permit access to and operation within distant environments, environments with high radiation, and environments of extreme heat and cold.

Recommendation: NASA should initiate a program of Flagship missions to specifically address the search for past and present life in the Solar System and the origin and evolution of our planetary system.

Science

The goals of Solar System exploration can be addressed through seeking answers to five questions: How did the Sun's family of planets and minor bodies originate; how did the Solar System evolve to its current diverse state; what are the characteristics of the Solar System that led to the origin of life; how did life begin and evolve on Earth and has it evolved elsewhere in the Solar System; and what are the environmental hazards and resources that will affect the extension of human presence in space? Answering these questions will require intensive investigations of a variety of Solar System targets. Priorities in the near–term part of the Roadmap include Europa, Titan/Enceladus, and **Venus**.

Recommendation: A balanced program comprising small, medium, and large missions underpinned by a strong research and analysis program and technology program with supporting E/PO is needed to achieve the scientific goals of Solar System exploration.

Missions

A prioritized set of Flagship missions has been developed to address the scientific goals of the Roadmap. The priority order has been established using the three criteria of scientific merit, technological readiness, and opportunity established by the National Research Council in its Decadal Survey of 2003. The first Flagship mission in the sequence with highest priority is the Europa Explorer. With current technology it is practical to conduct intensive investigations from orbit, lasting for at least 90 days and potentially as long as a year.

Recommendation: NASA should initiate a Europa Explorer mission at the earliest possible opportunity beginning in 2015.

Recommendation: The Solar System Exploration program should be anchored by Flagship–class missions and supported by a set of competitive Discovery and New Frontiers missions. The Flagship missions in this program should be implemented as either small Flagship missions (<$1.4B or twice the cost of a New Frontiers mission) or a large Flagship mission (between $1.4B and $2.8B).

Recommendation: The recommended flight rate for Flagship missions is one mission every five years. New Frontiers missions should launch at the rate of 2–4 missions per decade and Discovery missions should fly at the rate of 4–7 missions per decade.

Recommendation: NASA can effectively reduce cost and risk by extending successful international collaboration models to missions to the Saturn system and to **Venus**.

Technology Development

All five Flagship missions described in this plan would be baselined to use radioisotope power systems (RPSs) for furnishing electrical power. Currently, there is an insufficient supply of plutonium–238 which would be used to fuel potential RPSs for these potential missions.

Recommendation: NASA must work with the relevant federal entities to ensure that adequate electrical power is provided for missions that require radioisotope power systems (RPSs).

Recommendation: NASA must also develop, at a pace consistent with planned missions, more efficient power conversion technologies to make the best use of the Pu–238 in the inventory. Not only will this provide more effective use of plutonium, but the gain in specific power is advantageous for a number of missions where mass is critical. Access to the outer Solar System is a vital part of the program described here and space transportation technologies are a key element of this access. Two of the missions — Titan (with or without Enceladus) Explorer and Neptune–Triton Explorer — would require the use of aerocapture to deliver payloads of the required mass into orbit with much shorter trip times than could be achieved with chemical propulsion.

Recommendation: NASA should continue to invest in aerocapture technology and conduct space flight validations of this technology in a time frame that is consistent with the decision points identified in this Roadmap.

Access to extreme environments, both extremely hot near the surface of **Venus** and extremely cold at the moons of the outer planets, requires investments in a suite of technologies to enable probes and mobile platforms to survive and operate in these environments.

Recommendation: NASA should initiate a technology development program in technologies for extreme environments. Many of the needed technologies are currently at a very low technology readiness level (TRL) and the gestation period of development is long. Accordingly, initiating this program as soon as practicable will have a major impact on the feasibility of future Flagship missions and will also benefit Discovery and New Frontier missions.

Integrated Program Plan

There are significant interdependencies among Flagship missions and between Flagship missions and the New Frontiers and Discovery Programs. These interdependencies can be exploited in order to reduce the cost and risk of Flagship missions. Equally important are the contributions of the Mars Exploration Program and the New Millennium Program, where the contributions are primarily technical. However, the goal of implementing the Flagship missions at the rate of one every five years may require reduction in the rate of existing Discovery and New Frontiers Program elements.

Recommendation: One small Flagship mission and one Large Flagship mission per decade may represent an appropriate balance with a small impact on Discovery and New Frontiers frequency. At present, NASA has no plans to initiate a Solar System exploration Flagship mission in the next five years. In view of the high priority attached to exploration of Europa by the National Academy and other studies, it should be the first Flagship priority. NASA should actively begin preparing for Europa Explorer as the first new Flagship mission. Titan is next in priority, as an object with an Earth–like balance of geological and atmospheric processes, and an active organic chemistry. Together with the exploration of Enceladus, it should further investigations by Cassini, to indicate the presence of accessible liquids on or under their surfaces. **Venus** is extremely high priority for its potential to tell us where the inner edge of the habitable zone lies for Sun–like stars; technologies for long–lived mobile surface operations will pace the readiness of a Flagship mission there. Following these, the next Flagship should be to Neptune/Triton or to access the Europan ocean depending on the results found by the earlier Flagships.

Recommendation: An investment of $100M annually in FY07 and FY08 can preserve the option for an FY15 launch of Europa Explorer and make a significant start in technology development needed for later missions. This would provide the Agency the opportunity to move out more aggressively on initiating the new series of Flagship missions if circumstances allow it.