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Aerocapture Technology Development Needs for Outer Planet Exploration

Paul Wercinski, Michelle Munk, Richard Powell, Jeff Hall, and Claude Graves

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**Aerocapture Technology Development Needs
For Outer Planet Exploration
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The purpose of this white paper is to identify aerocapture technology and system level development needs to enable NASA future mission planning to support Outer Planet Exploration. Aerocapture is a flight maneuver that takes place at very high speeds within a planet's atmosphere that provides a change in velocity using aerodynamic forces (in contrast to propulsive thrust) for orbit insertion. Aerocapture is very much a system level technology where individual disciplines such as system analysis and integrated vehicle design, aerodynamics, aerothermal environments, thermal protection systems (TPS), guidance, navigation and control (GN&C), instrumentation need to be integrated and optimized to meet mission specific requirements. The aerocapture technology roadmap herein identified uses as a basis, missions specific to Saturn's moon Titan, and at Neptune. This paper identifies on-going activities, their relevance and potential benefit to outer planet aerocapture that include; New Millennium ST7 Aerocapture concept definition study, Mars Exploration Program aeroassist project level support, and FY01 Aeroassist In-Space Guideline tasks (UPN 713-xx-xxx). Included are details of aerocapture technology disciplines and their interdependencies for use in the Appendix A: Outer Planet Aerocapture Technology Roadmap. This white paper will identify critical technology gaps (with emphasis on aeroshell concepts) and strategies for advancement.

Definition of Aeroassist Terms

Aeroassist is the broadest term that describes the maneuver of a flight vehicle within a planet's atmosphere using aerodynamic forces. Subsets of aeroassist are terms such as aerocapture, direct entry aeroentry, aerobraking and aerogravity assist.

Aerocapture involves the integrated use of technologies to apply aerodynamic forces to fly a trajectory through a planet's atmosphere to sufficiently decelerate an entry vehicle and place the payload (e.g. communications orbiter) into planetary orbit. Aerocapture has never been performed.

Direct Entry involves the passage of an entry probe from a hyperbolic orbit through a planet's atmosphere for the purpose of taking measurements within the atmosphere (Galileo probe) or landing on the surface (Pioneer-Venus, Mars Pathfinder). To date, only ballistic (unguided) direct entries have been performed.

Aeroentry involves those missions that enter the planet's atmosphere from orbit (i.e. Viking). The only substantial difference from a direct entry is the lower entry velocity; furthermore, an aeroentry is usually thought of as guided, terminating in a precision landing (such as the Space Shuttle).

Aerobraking involves initially propulsively capturing into a high-energy orbit and then performing multiple high-altitude, passages through the atmosphere to enter into a final working orbit. This process can take several months to perform, as with the Mars Global Surveyor.

Aerogravity Assist involves using propulsion in conjunction with flight through a planetary atmosphere to achieve a greater turning angle during a planetary fly-by. This maneuver requires a high lift-to-drag ratio vehicle, and could significantly shorten trip times to the Outer Planets (such as Pluto).

Aerocapture Challenges and Benefits

Recent interest in developing aerocapture technology stems from the changing character of NASA's solar system exploration program^{1,2}. Fly-by missions are giving way to orbiter, in-situ, and sample return missions, and many of those require spacecraft to enter and maneuver in a planet's atmosphere in order to meet their mission objectives.

The tradeoff of using an aerocapture maneuver is the mass penalty of the propulsion system including fuel mass versus the additional spacecraft mass required for the aeroshell structure including payload integration to meet the required delta-v requirement. To date, the planetary mission requirements for orbit insertion delta-v on the order of 1 km/s have only marginal benefits from aerocapture technology. The combination of mission requirements and technology integration difficulties has been sufficient to slow the development of aerocapture technology and prevent any prototype flights to date. Table 1 below identifies mass benefits of aerocapture versus propulsive insertion for possible future planetary exploration missions.

Table 1. Aerocapture Mass Saving Estimates for Planetary Missions

Mission Name	Description	Delivered Spacecraft Mass (kg)	All-propulsive Arrival Mass (kg)	Aerocapture Arrival Mass (kg)	Propulsive: Aerocapture Mass Penalty Factor	Delta-V Required for Capture (km/s)
Mars Sample Return	CNES-NASA baseline Mars Orbiter	900	2000	1100	1.8 : 1	2.5
Titan Explorer	8 yr SEP + VGA to Saturn, 1400 km circular orbit: 5.2 km/s entry speed	1100	2989	1375	2.9: 1	4
Neptune Orbiter	10,000 x 500,000 km orbit, 28.9 km/s entry velocity	500	4743	833	5.6:1	7
Venus Surface Sample Return	Sample return vehicle in a 300 km circular orbit, 11.6 km/s entry speed	2600	12716	3714	3.4:1	5
Saturn Ring Observer	56,000 km circular orbit, 26.1 km/s entry speed	500	12295	3125	4.0: 1	8
Mars Micro-orbiter	Piggyback payload to 600 km circular orbit, 6.4 km/s entry speed	100	261	125	2.1: 1	3

Another benefit of aerocapture that is not shown in the above table is that it enables shorter interplanetary cruise times. Figure 1 shows trades in mass reduction in useful inserted mass (payload) as a function of trip times to Neptune, i.e. the shorter the trip time, the faster the arrival speed at the planet and the greater the delta-v needed for insertion into orbit. Past studies have identified advanced interplanetary propulsion systems such as solar electric that can enable significant trip time reductions³. Hence, many Outer Planet mission scenarios would require the coupling of advanced propulsion with aerocapture.

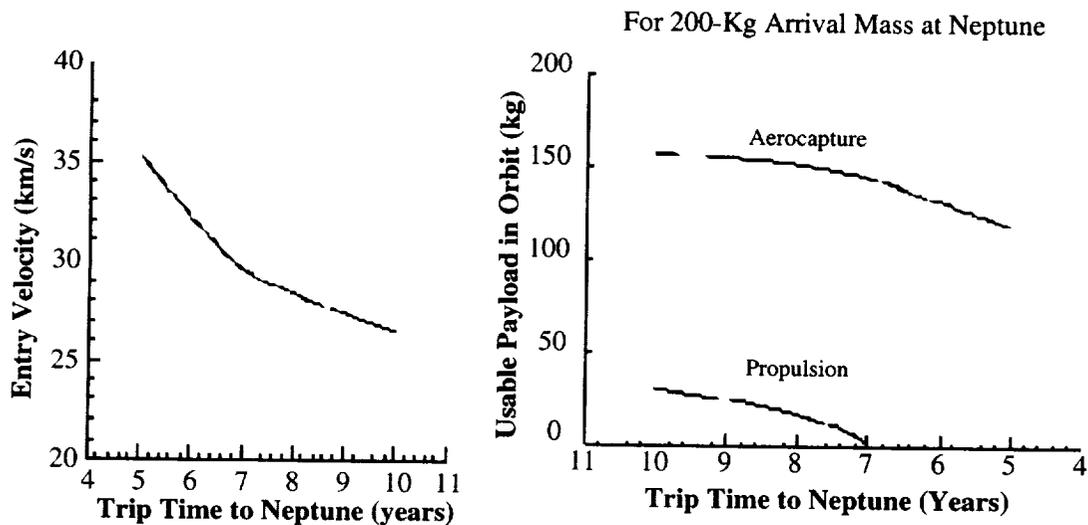


Figure 1. Mass Savings for Neptune Aerocapture Mission

Aerocapture Technology Gaps for Outer Planet Exploration – Introduction

The challenges of performing aerocapture for outer planet missions such as Titan Explorer or Neptune Orbiter require investments to advance the technology readiness of the aerocapture technology disciplines for the unique application of outer planet aerocapture. Immediate investments in aerocapture technology disciplines are needed in order to meet near end of decade authority to proceed (ATP) for outer planet missions. These advancements would need to accommodate the unique H₂/He gas composition of Jupiter/Saturn/Uranus/Neptune planetary atmospheres and to a lesser degree, the N₂/CH₄ atmosphere of Titan. Disciplines that are uniquely coupled to outer planet missions and requiring focused investments include TPS, Aerothermal Environments, H₂/He focused ground based facilities, Aerodynamics, Structures and Systems Analysis Studies. Investments in GN&C and Instrumentation are needed to a lesser degree, especially if NM ST7 Aerocapture is successfully implemented. Also, mission requirements will likely require development of entry vehicle shapes that extend beyond the current low L/D knowledge base. The demands of flight certification of critical technologies and expected flight conditions will require advancements in TPS and its ground based testing. The following sections on specific Aerocapture technology disciplines provide more details on the technology gaps and recommendations for technology advancement.

Aerocapture is very much a system level technology where individual disciplines and the resulting aerocapture vehicle design must work together:

Integrated Vehicle Design and System Analysis Discipline: must provide overall shape, subsystem integration such as TPS and structure, as well as interface with payload and other mission systems. Performs end-to-end simulation and analysis of all technologies and evaluates technology alternatives.

Aerodynamic Discipline: must provide required aerodynamic performance for trajectory control.

Aerothermal Heating Discipline: must provide predictions of aerothermal heating conditions surrounding the entire entry vehicle that includes time-integrated heat loads.

Thermal Protection System (TPS) Discipline: must protect the spacecraft from intense aerothermal heating due to hypersonic atmospheric flight.

Guidance, Navigation, & Control (GN&C) Discipline: must 'fly' autonomously to sense the vehicle's flight trajectory, provide control, and overcome dispersions due to uncertainties in navigation, atmospheric knowledge, and vehicle performance.

Instrumentation Discipline: must provide flight data for determination of critical aerocapture system performance.

Aerocapture Technology Gaps for Outer Planet Exploration – Discussion

1. Systems Analysis and Integrated Vehicle Design Capability

Integrated vehicle design capabilities will support trades studies for evaluation of aerocapture vehicle preliminary design that meet a wide variety of application planets and address requirements such as delivered payload mass, operational orbit conditions and interplanetary trajectories. In some technology disciplines, tools will need further development to enable rapid evaluation of system-level impact, risk, and payload accommodation. This capability will span a broad spectrum of aerocapture mission applications.

The range of design activities available in a multidisciplinary environment depends on the manner in which the various disciplinary software tools are linked together. Designers are often interested in the response of a system to changing circumstances, so the design environment should provide the flexibility to permit convenient modification of parameter values, variables and objectives. The system should also be extensible; so that analysis modules can be easily replaced as increasing fidelity is required in the later stages of development.

Therefore, technology advancement in the Systems Analysis and Integrated Vehicle Capability Discipline involves:

- 1) integration of design tools to establish capabilities for system analysis for outer planet aerocapture

- 2) performing preliminary design studies with focus on aeroshell shape trades and end-to-end systems analysis
- 3) performing technology assessments at various stages of technology development and mission design development.

2. Aerodynamics

In order to determine the feasibility of high-speed aerocapture at the outer planets, an accurate trajectory simulation of the flight vehicle is the critical. The shapes to be considered for OP aerocapture missions are likely to be different than current low L/D concepts. For some missions, mid lift-to-drag ratios may be required to meet requirements for payload packaging, entry corridor requirements, and aerothermal and load environment constraints. A multi-conic geometry is a preferred geometry for such mid lift-to-drag missions. On the other hand, if the mission design required high drag ballutes, then the expected trajectory and the resulting low-density flow regime will require a different emphasis on aerodynamic prediction methods.

Technology development is needed to determine the aerodynamic characteristics, i.e., static lift, drag, and moment coefficients and various dynamic coefficients of an aeroshell geometry. In order to reduce the extent of entry dispersion to the minimum, it is highly desirable that these aerodynamic coefficients be known to a high degree of precision. As an example, trim angle should be known at least within two degrees and hopefully to within one degree. All other parameters should be desirably known to a comparable degree of precision.

There are three parameters that must be correctly accounted for in the determination of those aerodynamic parameters: 1) gas chemistry, 2) Reynolds number effects, and 3) sensitivity to shape change. The atmospheres of the outer planets contain mostly hydrogen and helium. Non-equilibrium behavior in these gas mixtures could affect the aerodynamics and if so, it should be accounted for. The Reynolds number effects including transition to turbulence must be predicted correctly. The effects of ablation on vehicle outer mold line (OML) shape change and resulting pressure distribution variations must also be accommodated in prediction methods.

Therefore, technology advancement in the Aerodynamic Discipline involves:

- 1) The near term investment in validating CFD methods for generating aerodynamic data base for OP missions involving low to mid- L/D shapes and ballutes. The database would include determination of the static and dynamic stability characteristics of candidate aeroshell shapes.
- 2) Validation will require a) identification of phenomenon that affect aerodynamics, constructing and conducting appropriate experiments to quantify levels of uncertainties in aerodynamic predictions in CFD. Combination of wind-tunnel, ballistic range and shock tunnel tests will provide the data as needed to meet uncertainty requirements. Unique flight environments experienced by ballutes, i.e. low-density flows and aero-elastic effects must be accommodated.

3. Aerothermal Environments

The severity of the heating environments of the outer planet entries will be between those for the Pioneer-Venus, which produced a peak heating rate of about 5 kW/cm², and the Galileo entry, which produced a peak radiative heating rate of about 20 kW/cm². Aerocapture missions to Titan may experience lower heating rates. It is highly desirable that the predictions be accurate to within about 30% to match current forebody aerothermal environment uncertainties for Mars entry vehicle heatshields such as MER. Systems analysis trades will further define the required aerothermal uncertainty goals. In contrast for afterbody flows, even for Mars vehicles, the aerothermal environment uncertainty could be up to 300%. Technology development is needed to reduce the uncertainties.

In defining the heating environment, again the above mentioned three phenomena (gas chemistry, turbulence, and gas-surface interaction - ablation) must be correctly determined. Existing ground based facilities cannot accurately simulate the heating environment. The recent advances in Computational Fluid Dynamic (CFD) modeling has lead to the recognition that validated CFD codes can be used to provide aeroheating predictions if the CFD codes utilize validated model representation for each of the phenomenon that contributes to the heating. These phenomena include shock layer dissociation, radiation, and viscous boundary layer heating under laminar and turbulent conditions, diffusion, gas-surface interaction including catalytic effects, gas-injection, material ablation, and recession. For example, in the earlier method of heating environment definition, which was used for Pioneer-Venus and Galileo, gas-

surface equilibrium was invoked. For a more precise description of the heating environment, it is necessary that the nonequilibrium nature of the gas-surface interaction be correctly accounted for. In the past radiative and convective heating phenomena have been treated more or less independently. In order to be more precise, the interaction between the two phenomena should be correctly accounted for as well. Nonequilibrium radiation and shock layer radiation absorption by ablation products, if it occurs, should also be correctly predicted.

The aerothermal predictive tools and analysis will be affected by the material response and hence various levels of coupling between the aerothermal environment and the TPS material interaction will be required especially where high heating requires the use of ablative TPS materials.

Therefore, technology advancement in the Aerothermal Discipline involves:

- 1) Development of high-fidelity CFD tools that are tailored for hydrogen-helium atmospheres, nonequilibrium environments, coupled with TPS interaction such as pyrolysis-gas injection and surface ablation. This capability also must account for turbulent transition, nonequilibrium gas-surface interaction, interaction between convective and radiative phenomena, and radiation emission or absorption by the ablation products.
- 2) Validated CFD methods to predict afterbody heating under a wide range of conditions and this will require evaluating and applying turbulence models, shear-layer and base recirculation interaction and local low density effects.
- 3) The developed CFD tools must then be tested against the ground test data and flight data results from Apollo, Pioneer-Venus, and Galileo missions. In addition, additional data sets from wind tunnel and ballistic range facilities would be used to improve knowledge of transition/turbulence and afterbody wake effects.
- 4) The developed CFD tools must then be tested against heritage data and new laboratory data, if needed. For example, shock tubes simulating extremely high speed, non-equilibrium H₂/He radiation phenomena were utilized for the Galileo project.

4. Thermal Protection System (TPS)

For the outer planet aerocapture missions, the extremely high heat loads, (the time integration of the heat flux) will require advancements in low thermal conductivity materials that can still sustain relatively high heat fluxes. Modifying current TPS materials or developing new materials to meet the relatively high heat fluxes expected for mid L/D aerocapture vehicle will be necessary. All approaches for TPS development will require ground based testing and flight certification in the appropriate gas composition, i.e. H₂/He for Neptune aerocapture. Alternatively, ballute strategies for aerocapture will require application of thin film, deployable, flexible materials.

Carbon-phenolic was used for both Pioneer-Venus and Galileo missions. For ballistic, entry probe high heat flux missions in the atmospheres of Saturn, Jupiter, Uranus, and Neptune, this class of materials, i.e. highly dense TPS for high heating and high pressures, seems to be adequate. However, it should be understood that the requirements for TPS for a direct entry atmosphere probe (Galileo) are significantly different than the requirements for an aerocapture vehicle. The heat load for aerocapture trajectories is factors greater than direct entry trajectories, thus driving the TPS design to withstand significant heat conduction. Early systems level trades could provide insight in the suitability of choices of TPS materials, especially for aerocapture applications. Development and flight certification involving the technologies of heating environment, TPS materials, and instrumentation need testing of the TPS materials in an arcjet.

Currently, no flight-qualified TPS materials exist for outer planet aerocapture missions. Even re-certifying carbon phenolic is problematic since there are no current manufacturers of this TPS. An H₂/He arcjet testing facility is a critical capability required for TPS flight certification. This H₂/He arcjet was fundamental for the success of the Galileo mission. At present, the H₂/He arcjet (also known as the Giant Planet Facility for use in the Galileo project) is no longer in operation but could be brought back on line. The GPF facility produced a combination of radiative heating and convective heating with a hydrogen-helium mixture, which bounds the expected heating rates for the outer planet missions. In the least, the GPF facility will have to be refurbished, but at a cost significantly lower than building a facility from the ground. The facility may have to be modified depending on the particular mission chosen to simulate, including the run duration.

Therefore, technology advancement in the TPS Discipline involves:

- 1) Developing and modifying suitable TPS materials for outer planet aerocapture missions; for example manufacturing light weight ablators, carbon-phenolic, or possibly advanced lightweight, hybrid designs.
- 2) Refurbishment of an arcjet of the power-input level of 60 MW or higher, operating with hydrogen-helium mixture as the test gas
- 3) Characterizing thermochemical and mechanical properties of these materials in the appropriate environment to support material downselect processes
- 4) Developing a computational tool that describes the behavior of the materials accurately, and demonstrating its accuracy by comparing with experimental data.

5. Instrumentation

The environments that an entry vehicle experiences in flight cannot be replicated in totality by any ground based facility. There is a strong need for measuring the performance and response of critical aerocapture technologies in flight to quantify risk and performance of the design. Design of entry capsules depends on our ability to model and the fidelity of the math models. High-fidelity numerical simulations of the aerothermal environment, the TPS material response, and the atmospheric flight dynamics are the primary tools for planetary aeroshell design. Mars Pathfinder, Stardust, Genesis, Mars Microprobe, and MER are examples of recent missions that have employed these simulations.

Uncertainties associated with these design tools increase the aeroshell mass, technology selection, and the mission risk. Conversely, with an adequate set of flight data combined with ground test data, post-flight validation of the fluid and the thermal design models can lead to a reduced aeroshell mass on future missions and the ability to design with confidence advanced aeroshell configurations. Further, for missions requiring advanced entry technology such as a high L/D shape for precision landing, or revolutionary concepts such as ballute, flight measurement may enable new missions not possible today.

Obtaining flight data has been a challenge primarily because the benefit of flight data has been perceived as not mission relevant for that specific mission. Also, sensors add weight, cost, and in some cases risk. The success of the flight data is achieved only when useful information extracted from the flight data leading to improved understanding and thus, resulting in validation to the design tools/models and designs. The benefit of sensors cannot be derived without the commitment from the program and without requirements at the project level. The FIRE-II, initial unmanned Apollo flights, and the first five Space Shuttle Orbiter flights are some of the examples where the commitment to obtain flight data was very successful and the flight data allowed a better understanding of the performance of design tools and technology. As a result, risk was reduced and the Apollo and Shuttle Programs were successful.

The TPS is a mission critical hardware since it is a single point of failure and hence instrumentation needs to focus primarily on TPS and the aerothermal environments that drive its performance. The Pioneer-Venus vehicles carried thermocouples imbedded in the heatshield, while thermocouples and recession gages were used for the Galileo Probe. There were questions as to the accuracy of the thermocouples for the Pioneer-Venus vehicles. The gages on Galileo Probe seemed to have functioned correctly. Future atmospheric probe missions to Jupiter (and to a degree, the other gas giant planets) will directly benefit from the heatshield flight data from Galileo.

Instrumentation techniques have improved significantly in recent years, and one can also hope for greater allowance for data bits. New light weight sensors capable of measuring surface heat-flux, temperature, recession, and wall catalysis are currently being developed and demonstrated in laboratory settings. Continued funding to mature these sensors and test them at realistic entry conditions of relevance to outer planet missions will directly impact both the quality and quantity of future flight data. The need for lightweight, low-power sensors reaches beyond outer planet missions and an investment in sensor development will benefit not only all the planetary missions but also ground based testing.

Therefore, technology advancement in the Instrumentation Discipline involves:

- 1) Continued development of smaller and more accurate instruments for measuring temperature both surface and in-depth, onset and end of pyrolysis, and surface recession; direct measurement of heating rate including the catalytic and the non-catalytic components would be highly valued, if it could be made; and
- 2) Testing and calibration of these instruments in an arcjet under correctly simulated conditions to verify their functions including integration of sensors with TPS materials.

6. Aerocapture GN&C

An autonomous aerocapture capability in the Earth's atmosphere was developed and human rated for the Apollo program to provide flexibility in selecting earth landing sites after returning from the moon, and to provide a capability to maneuver after entry into the earth's atmosphere to avoid late developing weather conditions at the chosen landing sites. The need to use this capability never occurred during the Apollo missions, so this capability was not flight demonstrated during the Apollo program. In addition, aerocapture guidance and control has been analyzed extensively for the Earth and Mars environments using several different classes of guidance algorithms, including analytical predictor corrector, numerical predictor corrector, and a terminal point controller based on stored reference trajectories and with different independent variables. Several algorithms have been developed in detail and evaluated extensively for earth and Mars aerocapture. Several algorithms have performed well in these evaluations and are candidates for aerocapture applications. Presently, the CNES Mars '07 Orbiter mission, part of a joint United States and French Mars set of missions to return Mars atmosphere and soil samples to the earth, includes aerocapture for efficient insertion into Mars orbit. Four candidate aerocapture guidance algorithms and candidate control concepts that were well established during the U. S. Gemini, Apollo, and Space Shuttle programs and the French Atmospheric Re-entry Demonstrator program are being considered for this mission. Multiple guidance algorithms have been shown to perform acceptably, using proven aerocapture simulation capabilities, for the Mars '07 mission and the issue is which guidance algorithm is best, rather than if any guidance algorithm is acceptable. A joint U. S., France Aerocapture Working group has been established, with three NASA Centers and CNES participating, to best use the combined CNES and NASA expertise, capabilities, and resources to successfully demonstrate Mars aerocapture on this mission.

While there are similarities in the aerocapture flight mechanics for different planets, there are differences that present challenges for the aerocapture GN&C, compared to aerocapture at Mars or Earth. These potential differences include the arrival state vector accuracy (both the deviation from nominal and the uncertainty in the state vector), knowledge of the atmosphere and the atmosphere variation along the flight path, aerodynamic heating limitations on the aerocapture flight path, and uncertainty of the aerodynamics in the planetary atmospheres. The primary factors that drive the key aeroshell aerodynamic characteristics and the required in-flight control of these aerodynamic characteristics are the arrival state vector accuracy, atmosphere variability and uncertainty, limitations on the flight path from aerodynamic loads and aerodynamic heating, and the uncertainty in the aeroshell aerodynamic characteristics. While the flight aerocapture flight mechanics have been shown analytically to be similar for deceleration into earth, Mars, Venus, Neptune, and Titan low energy orbits, these factors need to be assessed, in more detail for the planets that have sufficient atmosphere, to determine these effects on the aerocapture GN&C. For example, the aerodynamic control parameters need to be assessed to determine if trajectory control should be achieved by direct aerodynamic lift, aerodynamic lift and drag, or aerodynamic drag modulation, and to determine how this modulation should be accomplished. The need for processing additional in-flight measurements to counter the effects of atmosphere uncertainty and variability needs to be determined. Use of either direct lift and drag modulation or drag control modulation would require a different aerocapture guidance and control concept from those presently being considered for aerocapture.

The requirements for the on-board navigation system need to be determined, but the performance requirements are expected to be within the present system capabilities. The variability and knowledge of the planet's atmosphere is a key factor in determining the feasibility of aerocapture at a planet and in the implementation and complexity of the GN&C system.

Therefore, technology advancements for the GN&C Discipline are needed in the following areas:

- 1) Improved knowledge of the planet's atmosphere structure and variability,
- 2) Development and demonstration of aerocapture guidance and control capability for the different planets. A goal is for the guidance and control concepts to be common for the different destinations.

NASA's Recent Support in Aeroassist

The next section of this report briefly discusses a subset of past and on-going NASA missions that have required aeroassist and aerocapture technology. This review is intended to better understand the unique and similar technology applications for Outer Planet aerocapture

Galileo Probe

The Galileo entry probe (GP) mission to Jupiter was originally proposed as early as the late 1960s. The focused entry vehicle design and technology development to support this mission spanned approximately a decade. The Galileo entry probe represents NASA's only outer planet direct entry probe mission to date and thus can serve to give perspective and contrast to current outer planet planning. Since GP was a direct entry mission, the mission design and technology requirements are significantly different from outer planet aerocapture. The GP encountered the most severe heating environments of any known entry mission. The GP required development of analysis tools to predict the aerothermal heating encountered, especially since these predictions determined the degree of ground based testing required to flight certify the thermal protection system and assess margin and risk to the overall design. Furthermore, GP was instrumented with sensors in the heatshield to enable proper trajectory reconstruction and to assess the performance of the TPS⁴. GP flew an uncontrolled ballistic trajectory at Jupiter that precluded the need for GN&C, and only basic understanding of a subset of the vehicle's aerodynamic performance.

The Galileo probe successfully entered in 1995 and performed its scientific mission. (Note that the GP was built in the early 1980s) The probe also carried instruments that measured the TPS ablation that resulted in significant mass loss (almost 30% of the entry mass) and shape change. Although this phenomenon was anticipated and factored into the design, even to the extent of roughly doubling the TPS mass, the returned flight data showed significant differences with pre-flight predictions. In fact, the ablation near the end of the cone frustum resulted in a near burn through of the TPS. It was only through this critical instrumentation of the flight vehicle that this performance data could be obtained and used to assess the performance of design tools and the TPS performance.

It needs to be noted that during the 1970s and 1980s during the Galileo development, the Galileo Project benefited from NASA's base research and technology program and investments. This base program supported highly trained and specialized experts, facility and testing capabilities could conservatively be estimated to be from 3-5\$M per annum (in then year dollars) in non-direct project specific costs. These investments directly supported the aeroassist technology disciplines described herein and thus fundamentally advanced the TRL of individual disciplines for GP. As a result, specific aeroassist mission applications, i.e. Viking, Space Shuttle, Pioneer Venus Probes and Galileo, could focus more on higher TRL advancement and mission specific integration of these disciplines. Significant capabilities that NASA once had during pre-Galileo development no longer exist, both in expertise and ground test facilities used for H₂/He flight certification.

Apollo

Apollo missions faced many challenges to meet the stringent requirements to safely transport astronauts. Highly successful Apollo missions proved the design and established the feasibility of the high-speed Earth entry using lift and closed-loop guidance. The high heating rates experienced by Apollo mission were a significant challenge considering the reliability requirements and these were met by a significantly over-designed heatshield, along with conservatism in all aspects of the entry capsule design. The GN&C algorithms developed during Apollo program have continued to be valuable, and advanced GN&C algorithms for the Mars Smart Lander mission has utilized the lessons learned from Apollo design. Though considerable challenges were faced in the design and development of the heatshield, the aerodynamic database as well as the aeroshell shape and integration, these are not directly applicable to the outer planet aerocapture missions. In the case of TPS, the material used for the Apollo heatshield is no longer available. Flight data from Apollo missions can be useful to a limited extent in demonstrating and validating some aspects of the design tools.

Aeroassist Flight Experiment (AFE)

In the 1980's, NASA undertook a technology demonstration of Earth aerocapture. The AFE was to be delivered to Low Earth Orbit with the Space Shuttle, then would use a solid rocket motor to fire into the Earth's atmosphere at Apollo return-like speeds. The vehicle would perform an aerocapture, then be picked up by the Shuttle and returned to Earth for inspection and analysis. The AFE shape was a blunt raked-cone with a lift-to-drag ratio of about 0.25. The vehicle was over 2 meters in diameter. It used a Shuttle tile-like TPS system, and was heavily instrumented. The guidance algorithm was adapted from previous missions. This experiment was well developed when it was cancelled due to budgetary problems;

if flown and successful, it would have provided a system demonstration of aerocapture, advancing the TRL significantly.

Aeroassist Workshop (1997)

A meeting of the nation's experts in the field of Aeroassist met in 1997 at JPL. The Workshop covered many topics including overviews of results of the Galileo entry and assessments of technology readiness of aeroassist disciplines for atmosphere entry probe missions to Saturn, Uranus, and Neptune and aerocapture missions to Neptune.

Tentative conclusions from Galileo:

- Forebody mass-loss approximately 30% greater than predicted
- Radiative heating/flowfield code requires revision
- Turbulent boundary layer heating models contain large uncertainties
- Modeling of boundary layer transition on ablating bodies needs improvement
- Use newer and better CFD codes
- Use better (empirical) transition models

Recommendations for Neptune Aerocapture:

- Computational Modeling for He/H₂ Atmospheres, 3D High Energy Flows
- Reactivate Necessary Arcjet Facilities for He/H₂ High Energy Testing
- Advanced Materials Certification (Lightweight, Insulation, Ablation Resistant)
- Vehicle Design (include: TPS, Aerodynamics, GN&C, Structures, Payload Integration)
- Develop Flow Prediction Codes and Verify Performance
- Perform TPS Materials Certification
- Design, Test, Demonstrate Viable Aerocapture Vehicle (if needed)

Furthermore, it was the overwhelming consensus of the workshop participants that flight data from all future aeroassist missions are critical to reduce risk and advance component technologies.

Recent Mars Missions using Aeroassist

Mission-focused projects have contributed only in a limited way to the technology maturation of Aeroassist. The challenges of the specific mission and the balancing of cost, risk and the design choices to make the mission successful have resulted in indirect benefits, especially the recent Mars missions. Details of specific Mars and other entry mission designs, entry-descent-landing descriptions, and overviews can be found in Ref 6.

Mars Pathfinder (MPF)

The challenge was to successfully use the blunt body shape from the Viking heritage and a TPS material (also Viking heritage) to withstand higher heat-flux and heat-loads than Viking. Significant resources were devoted to re-establishing proven technologies and developing tools such as trajectory simulation, aerodynamics and aerothermal environment predictions and TPS testing for qualifying materials. The mission was accomplished via an unguided ballistic entry trajectory and the mission flew successfully. Unfortunately, MPF flew with only limited TPS instrumentation measurements, which did not reduce design uncertainties.

Mars'98 / DS -II

Mars 98 lander entry vehicle design did not require any significant changes to the MPF design. DS-II was a very low-cost and high-risk mission that baselined a TPS material without any flight heritage for a heatshield. The probe was small and provided higher heat flux than MPF. The entry trajectory was again an unguided ballistic entry but unfortunately mission failure due to unknown cause did not advance technology.

Mars 01 (Aerocapture) Mission

Cancellation of the original Mars'01 mission, which included both an aerocapture orbiter and a separate lander, was indeed a setback to advancing NASA's expertise in aeroassist technology. Lack of a

demonstrated aerocapture flight demo was considered an excessive risk by project managers, leading to the cancellation of aerocapture and the baselining of propulsive orbit insertion.

Considerable design work performed up to a Phase A level led to an aerocapture mission based on the MPF blunt configuration. The required aerodynamic forces were to be achieved by maintaining the attitude of the entry body at a lift-generating orientation during the hypersonic entry. Either a ballast weight with the center of mass offset similar to that of Viking and Apollo design or a small trim tab as a appendage on the leeward side was envisioned to provide a passive way of maintaining the entry vehicle attitude. The predicted heating profile along the lifting trajectory was well within the MPF heating conditions. The characteristic higher heat loads for aerocapture though did require a redesign to the expected thickness of the TPS, i.e., approximately doubling the thickness of TPS used in MPF. The design was to incorporate not only instrumentation similar to that used in MPF but also state-of-the-art lightweight sensors imbedded to provide detailed aero/aerothermal data during the aerocapture maneuver. If the design had been completed and the mission been successful, Mars'01 mission would have clearly advanced the aerocapture technology to a higher technology readiness level.

Mars Exploration Rovers (MER)

The MER mission consists of two entry vehicles, built based on the MPF design ('build-to-print') with minimal changes. This in turn results in an unguided ballistic entry trajectory similar to that of MPF, with a lower heating compared to MPF due to lower entry velocities, and hence minimal changes to the TPS design. Due to cost considerations and lack of project requirements, no instrumentation is considered. The relatively benign entry environment and lack of instrumentation will not advance aeroassist technologies.

Mars Smart Lander (MSL)

MSL is baselined as a low L/D blunt body configuration with relatively low heating and TPS requirements. It is currently in phase A trade studies. Development of preliminary GN&C algorithms has been performed for MSL.

Mars Mission Summary for Aeroassist

Although the recent Mars missions that have flown successfully have not directly impacted Aeroassist technologies for Outer Planets in significant ways, they have contributed indirectly by identifying many of the challenges for missions utilizing Aeroassist technologies. For example, in the area of TPS design, the recent MPF mission had a constant thickness TPS on the forebody, while the limited knowledge and flight data required a considerable mass margin for the backshell TPS. This was an acceptable choice for relatively low heating conditions for the Mars missions; smaller size entry shells and the payload mass requirements were within permissible range. The future missions indeed will require considerable attention to these questions. Similarly, as a result of relatively lower heating, recession and turbulence were not factors that affected the aerodynamic performance of design during these missions. This will not be the case for majority of the OP aerocapture missions. GP experienced significant recession and the lessons learned from limited analysis of GP flight measurement was very useful in identifying the importance of understanding the interaction between turbulence and TPS material response and the resulting changes in aerodynamic performance. As stated earlier, Aeroassist technology should be viewed as an integrated system wherein interactions between varieties of disciplines need to be understood and the design needs to be optimized based on the interactions for the specific mission.

In Space Aeroassist Working Group Directed Tasks (FY01)

NASA's experts in Aeroassist once again convened in 1999, to put a comprehensive plan in place for supporting both robotic and human exploration needs. Participants from 5 centers have continued to meet at least annually to prioritize tasks to be funded by the In-Space Propulsion Technology Program. The following is a list of tasks funded in FY01, which were focused on Mars missions. For FY02, the tasks will be re-examined and re-prioritized in light of interest in OP missions and recent delays in the Mars Program.

- **CAD-Linked Aero/Aerothermal Tool Development:** Focuses on integrating software tools to perform aero/aerothermal modeling and aeroshell configuration trades. The intermediate software product was used extensively on Mars Smart Lander trade studies. Task scheduled for completion at the end of FY03.

- Non-Equilibrium Flow/Radiation Models: Focuses on improving aerothermal/radiation modeling capabilities for high speed Earth entry. Reexamination of Apollo flight data was a first priority. Task scheduled for completion at the end of FY03.
- Improved Mars-GRAM Using MOLA Data: Improves the Mars-GRAM atmospheric model to include Laser Altimeter data, reducing density errors near the Mars surface. Task scheduled for completion at the end of FY02.
- Aeroassist Flight Measurement Technology: A conservative approach at aeroassist vehicle instrumentation; to look at how to improve/repackage existing sensors (mainly pressure sensors) to minimize mass, volume, and power while withstanding the harsh flight environment. Silicon carbide sensor testing ready to begin at end of FY01. Task scheduled for completion at the end of FY03.
- TPS Aerothermal Sensors: Develops advanced, solid-state sensors (much smaller and lighter than traditional sensors) for use in instrumenting aeroassist vehicles. Prototype heat flux sensor developed in FY01. Task scheduled for completion at the end of FY03.
- Mars Deceleration Systems: Focuses on expanding the Viking parachute deployment envelope to enable larger payloads to land on Mars. Competitively-selected contract awarded October 2001. FY02 study phase will be followed by wind tunnel testing in FY03.
- Design, Analysis, and Testing of High-Temperature Composites: Focuses on new structures concepts that will reduce the TPS requirements by withstanding higher bondline temperatures during flight. Coupons ready to be tested at start of FY02. Task scheduled for completion at the end of FY03.

New Millennium ST7 Aerocapture Concept Definition Study

As of mid-September, 2001, the NM ST7 Aerocapture concept definition study had just concluded its midterm presentation. By end of CY01, the NM ST7 downselect will be performed to determine which concept study is approved for flight development. The reference aerocapture demonstration mission is to be a blunt body, low L/D (lift-to-drag) ratio vehicle entering Earth's atmosphere at approximately 10 km/s and performing a 2 km/s maneuver to demonstrate end-to-end performance of autonomous aerocapture.

If the NM Aerocapture demo is performed as proposed (in CY05), there will be advancements to the TRL (technology readiness level) of several Aerocapture disciplines. The primary advancement will be in the GN&C discipline that has the highest generality of application for aerocapture missions, i.e. lessons learned for Earth aerocapture can be readily applied to an Outer Planet aerocapture. Other aerocapture disciplines will advance to a much lesser degree but only if the aerocapture demonstration is properly instrumented to measure in-situ performance of critical aerocapture technologies and if flight environments are similar. The table below summarizes the relative TRL advancement of aeroassist disciplines with an Earth aerocapture demonstration with respect to outer planet aerocapture.

Discipline	Feed-Forward To OP	Comment
Aerodynamics	moderate	Earth atmosphere hypersonic aerodynamics is relatively advanced, rarefied flow aerodynamics will benefit. Will have more direct benefit to Titan (N2 atmosphere) than S/U/N (H2/He atmosphere)
Aerothermal	low	Simulations highly dependent on atmosphere composition. Understanding of afterbody flows improved if properly instrumented.
TPS	low	Outer planet aerocapture will require different class of TPS materials. Possible that low speed Titan aerocapture would have similar heating environments and TPS requirements.
GN&C	moderate	Controller algorithms will be applicable to outer planet aerocapture, especially if similar shape aeroshell is used.

Aeroshell	moderate	Integration of analysis and design tools will advance to support overall integrated system performance. No advanced structure is planned, so any needed for OP will not be advanced.
Systems Analysis/ Payload Integration	high	Much experience will be gained in packaging, vehicle configuration studies.
Instrumentation	moderate	Sensor development and integration with TPS will advance. Aerothermal measurements will advance if implemented.

The NM ST7 aerocapture demo is an important critical step in reducing real and perceived risks in using aerocapture for planetary orbit insertion. It will also advance the overall end-to-end mission capability, which is a logical and prudent approach in flight test, especially since ground based testing cannot meet this need. Furthermore, an alternative aeroassist technique using ballutes is currently at a relatively lower TRL than aeroshell (rigid body) techniques. NM ST7 would have no direct advancement on ballute technology for aerocapture. Near term system level trades are needed to assess the cost/benefit of alternative aerocapture techniques that would have to include additional flight demos of alternative techniques such as ballutes.

French CNES Mars '07 Orbiter Aerocapture Mission

The French CNES Mars '07 Orbiter mission is one of a series of joint United States (U. S.) and French missions to return samples of the Mars atmosphere and soil to the Earth. One of the objectives of the Mars '07 Orbiter mission is to demonstrate autonomous, efficient aerocapture into a low-energy Mars orbit in preparation for the later Mars sample return missions. This Mars '07 Orbiter mission will use a blunt body, low lift-to-drag ratio aeroshell similar to the aeroshell planned for NASA's Aeroassist Flight Experiment (AFE) that was scheduled, but later cancelled, to demonstrate earth aerocapture in the mid 1990's. This mission will advance the technology levels of several disciplines needed for aerocapture at other planets, with the primary aerocapture technology advancement being the GN&C discipline because of the high level of commonality of the aerocapture flight mechanics for different planetary destinations. This commonality has the potential to enable use of the Mars GN&C aerocapture demonstration as demonstration of aerocapture for other planetary destinations. The section on Aerocapture GN&C discusses this topic in more detail. The table in the New Millennium ST7 Aerocapture Concept Definition Study section that characterizes the technology advances for an Earth aerocapture is also applicable to the Mars '07 Orbiter aerocapture demonstration.

A joint U. S./France Aerocapture Working group has been established, with three NASA Centers and CNES participating. Specific details and inter-agency agreements on collaboration on how to best use the combined CNES and NASA expertise, capabilities, and resources to successfully demonstrate Mars aerocapture on this mission are still under negotiation. This U. S. and French cooperation for the Mars '07 Orbiter mission also makes the aerocapture technology demonstration data available to the U. S.

Aerogravity Assist

Aerogravity assist is an extension of the established technique of gravity assist with a planetary body to achieve increases in interplanetary transfer velocity through hyperbolic bending. This technique has been studied over the past decades and has significant potential to reduce interplanetary trip times. The technique though has significant technology development challenges in that it requires high L/D vehicle shapes, ultra-high performance TPS that enables sharp leading edges and minimal shape change, and efficient packaging of payloads within the aerogravity assist vehicle.

Aerocapture Ballute Technology Development

Since 1999, JPL has led a technology development effort in aerocapture ballutes in collaboration with NASA-Langley, the California Institute of Technology, the University of Queensland and various small companies. Ballutes are an alternative technology to aeroshells based on the use of large, inflatable drag structures towed behind the parent spacecraft. Large ballutes give very small ballistic coefficients ($M/(C_D A) < 1 \text{ kg/m}^2$) which results in much higher altitude trajectories than aeroshells, with attendant lower density flow and hence lower heat fluxes to the vehicle. Work has progressed in a broad multidisciplinary fashion including trajectory simulations, high temperature balloon materials development,

computational fluid dynamics simulations, shock and expansion tunnel testing, structural analysis, systems engineering and mission design. Much of this work is described in a series of papers cited and/or provided on the JPL ballute technology web site.^{7,8}

Aerocapture ballute technology is currently at a TRL level of 3, which means that it is not as mature as aeroshell technology. Nevertheless, the work to date indicates that it is a viable alternative to aeroshells that may provide superior performance for many future missions. The general programmatic intent is to continue to pursue development of both ballutes and aeroshells to a sufficient level of maturity that detailed comparisons can be made to identify which approach best serves which future missions. This strategy also helps mitigate delivery risk by having an alternative available in case one technology encounters insurmountable problems during development.

Summary

The challenges of performing aerocapture for outer planet missions such as Titan Explorer or Neptune Orbiter require immediate investments in aeroassist technology disciplines in order to meet NASA's Office of Space Science long term plans for solar system exploration. Aerocapture technology disciplines that are uniquely coupled to outer planet missions requiring focused investments include Systems Analysis and Integrated Vehicle Design, Aerodynamics, Aerothermal Environments, TPS, Instrumentation, and GN&C. Mission requirements and systems analysis will likely require development of entry vehicle shapes that extend beyond the current low L/D knowledge base. The demands of flight certification of critical technologies and expected flight conditions will require advancements in TPS and ground based testing. Approach navigation and atmosphere structure uncertainties will have to be quantified and factored into the system design, since they may be significantly higher than those for Mars or Earth.

There is no currently recognized need, among the NASA Aeroassist community, to perform additional flight demos of aerocapture for robotic planetary exploration if ST7 aerocapture is performed successfully and the Outer Planet aerocapture technology gaps described in this white paper are supported. If NM ST7 Aerocapture is successfully implemented, the GN&C technology discipline in particular will be applicable for OP applications.

Recent and on-going planetary entry missions, especially Mars missions, have helped sustain NASA's expertise in aeroassist. This capability, along with focused expertise in key technology disciplines, gives high confidence in NASA's ability to achieve the capability of performing aerocapture at the outer planets. However, this capability will need to be built upon and advanced beyond those currently under study for NM ST7 Earth Aerocapture demonstration or the Mars Exploration Program entry missions.

Technology gaps and a development roadmap have been identified in this white paper. The plan put forward represents inputs from experts throughout the agency in the field of aeroassist. It is anticipated that as OP aerocapture technology is developed and systems analysis is performed, that this white paper would be updated. Implementation of this plan and closure of the technology gaps will enable NASA's continued leadership in planetary exploration and establish an Agency capability to perform aerocapture at the Outer Planets.

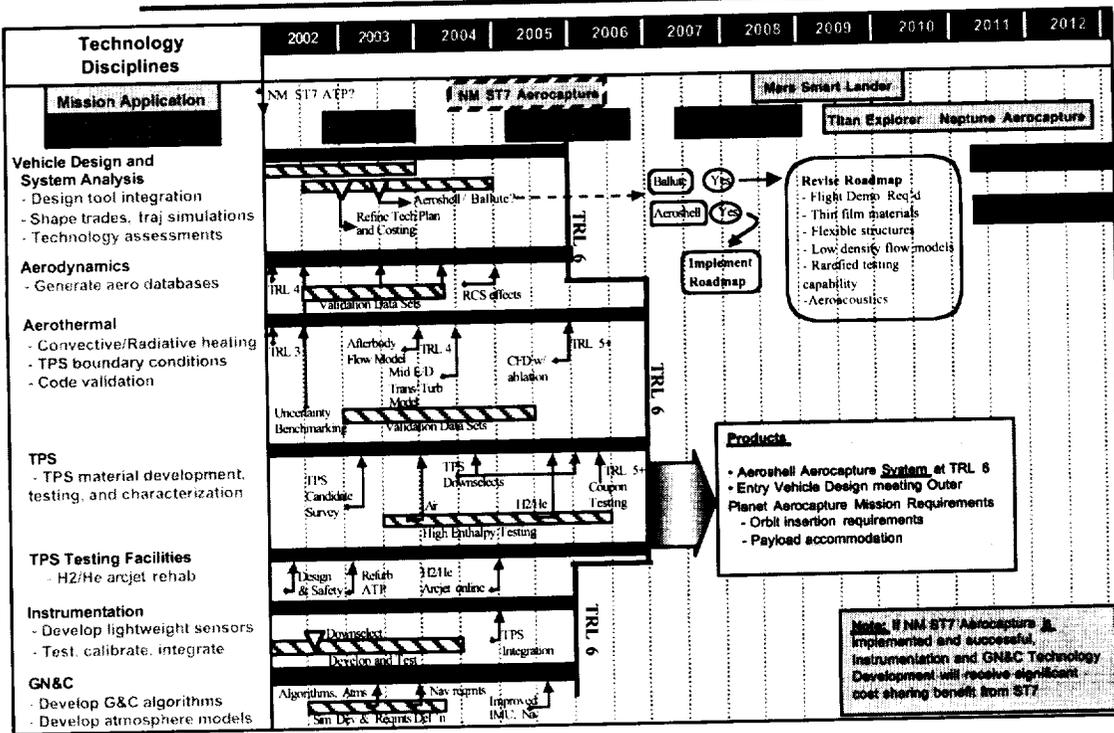
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Appendix A: Outer Planet Aerocapture Technology Roadmap



In-Space Propulsion: Aerocapture Development and Validation Plans



REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) The purpose of this white paper is to identify aerocapture technology and system level development needs to enable NASA future mission planning to support Outer Planet Exploration. Aerocapture is a flight maneuver that takes place at very high speeds within a planet's atmosphere that provides a change in velocity using aerodynamic forces (in contrast to propulsive thrust) for orbit insertion. Aerocapture is very much a system level technology where individual disciplines such as system analysis and integrated vehicle design, aerodynamics, aerothermal environments, thermal protection systems (TPS), guidance, navigation and control (GN&C) instrumentation need to be integrated and optimized to meet mission specific requirements. This paper identifies on-going activities, their relevance and potential benefit to outer planet aerocapture that include New Millennium ST7 Aerocapture concept definition study, Mars Exploration Program aeroassist project level support, and FY01 Aeroassist In-Space Guideline tasks. The challenges of performing aerocapture for outer planet missions such as Titan Explorer or Neptune Orbiter require investments to advance the technology readiness of the aerocapture technology disciplines for the unique application of outer planet aerocapture. This white paper will identify critical technology gaps (with emphasis on aeroshell concepts) and strategies for advancement.			
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