A Comparative Study of Aerocapture Missions with a Mars Destination

Diane Vaughan*, Heather C. Miller†, Brand Griffin∞
Gray Research, Inc. 655 Discovery Drive Huntsville, AL 35806

Bonnie F. James‡
NASA, Marshall Space Flight Center, Huntsville, AL, 35812, USA
and

Michelle M. Munk§
NASA, Marshall Space Flight Center, Huntsville, AL, 35812, USA

Conventional interplanetary spacecraft use propulsive systems to decelerate into orbit. Aerocapture is an alternative approach for orbit capture, in which the spacecraft makes a single pass through a target destination's atmosphere. Although this technique has never been performed, studies show there are substantial benefits of using aerocapture for reduction of propellant mass, spacecraft size, and mission cost. The In-Space Propulsion (ISP) Program, part of NASA's Science Mission Directorate, has invested in aerocapture technology development since 2002. Aerocapture investments within ISP are largely driven by mission systems analysis studies. The purpose of this NASA-funded report is to identify and document the fundamental parameters of aerocapture within previous human and robotic Mars mission studies which will assist the community in identifying technology research gaps in human and robotic missions, and provide insight for future technology investments. Upon examination of the final data set, some key attributes within the aerocapture disciplines are identified.

Nomenclature

L/D	=	lift-to-drag ratio
MSFC	=	Marshall Space Flight Center
GN&C	=	Guidance, Navigation, & Control

I. Introduction

AEROCAPTURE is a method of establishing an orbit at a planetary destination by making a single pass through its atmosphere. Utilizing the natural resource of the planet reduces the necessary on-board propellant normally carried by conventional all-propulsive spacecraft, thus reducing cost, propellant mass fraction, and potentially shortening travel time. Aerocapture begins by a spacecraft entering a planetary body's atmosphere from a hyperbolic trajectory. Friction created by this maneuver generates high heating conditions on the vehicle, necessitating an advanced thermal protection system. The Guidance, Navigation, & Control (GN&C) system is autonomous so atmospheric and aerodynamic predictions are also critical to a successful maneuver. Additional key disciplines of aerocapture are: structures and materials, instrumentation, trajectory design, and systems engineering and integration. The significance of the key parameters within each discipline is explained in table 1. Most of the key parameters were identified and recorded, where they existed, to document previous mission study findings within the data set examined.

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* Systems Engineer, In-Space Propulsion, Gray Research Inc., Huntsville, AL
† Analyst, In-Space Propulsion, Gray Research Inc., Huntsville, AL
∞ Manager, Systems Analysis and Space Architecture, Gray Research Inc., Huntsville, AL, Senior Member AIAA
‡ Bonnie James, Aerocapture Technology Manager, In-Space Propulsion, MSFC/NP40
§ Lead Technologist for Aerocapture, In-Space Propulsion, MSFC/NP40, Senior Member AIAA

Parameter	Discipline	Why Significant
L/D	GN&C Aerodynamics	Drives shape and performance of the vehicle
Entry Velocity	GN&C Aerodynamics	Affects heating and corridor width; results from interplanetary trajectory
Heat Flux	Aerothermal TPS Atmospheric Modeling	Drives TPS material choice; results from atmospheric constituents and density, trajectory design, and vehicle shape. Predicted by aerothermal analysis
Heat Load	Aerothermal TPS	Drives TPS material thickness; results from trajectory and aerothermal predictions
Corridor Width	GN&C Atmospheric Modeling	Closely coupled with required vehicle performance and shape; results from atmospheric parameters, entry velocity, and delivery errors
Angle of Attack	GN&C Aerodynamics Structures Aerothermal	Affects lift, drag, and orientation of loads during atmospheric flight, affects flowfield around vehicle
Sensors	Instrumentation	Allows correlation of predictions to flight data; validates models and improves future designs
G-load	GN&C Aerodynamics	Affects structural design; is driven by L/D and guidance scheme. Important to human physiology.

Table 1 Significant Parameters within Aerocapture Disciplines

Aerocapture is a flight maneuver designed to aerodynamically decelerate a spacecraft from hyperbolic approach to a captured orbit during one pass through the atmosphere without the use of propulsion. Once the vehicle enters the atmosphere, bank angle modulation is used to remain safely within the flight corridor, preventing skip-out or planetary impact. Propulsion is used for attitude control and periapsis raise only. Figure 1 summarizes the maneuver.

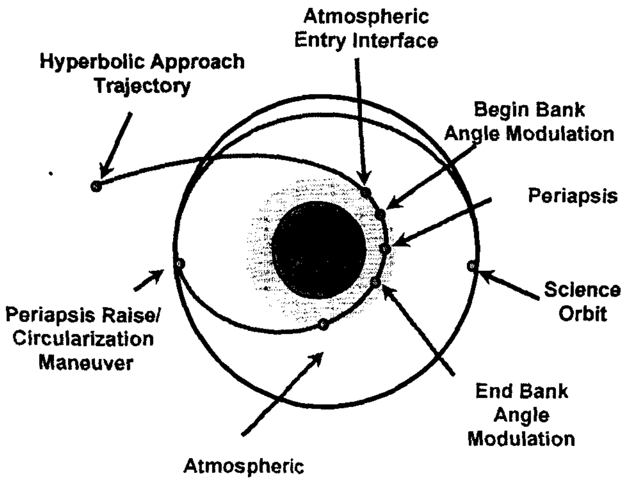

Figure 1 Aerocapture Maneuver Summary

II. Data Set Selection

A comprehensive search was conducted to identify reports, studies, and technical papers for robotic and human missions to Mars which used aerocapture in the mission design. Complete mission designs were selected for the data comparison since these reports provided more detailed information for desired aerodynamic parameters that described the aeroshell design and how the aerocapture would be performed.

Since there is no single storage area of documentation on this subject, a broad literature search began for relevant papers using the Internet and the NASA technical repository. The Redstone Scientific Information Center and Marshall Space Flight Center contractor libraries were also surveyed. In an effort to gather those published works that did not surface during these searches, individual NASA centers were solicited for contributions. The human Mars study references gathered during the writing of "A Comparison of Transportation Systems for Human Missions to Mars" (ref 1) were also utilized in this work. In all, 93 sources were identified, dating from 1979 to 2003.

III. Traceability of Data

Of the 93 Mars mission publications surveyed (Fig 2), 16 human aerocapture mission studies and 8 robotic aerocapture missions served as the basis for this comparison. A concentrated effort was made to record key attributes into individual spreadsheets with associated page numbers within each study. The advantage of this methodology was that it provided revisits to the source material for verification. These spreadsheets are available from MSFC/NP40 upon request.

While the main goal of this research was to highlight aerocapture at Mars, total mission strategies were investigated. Human aerocapture conditions at Earth were also recorded when available. Of the 17 human studies, 7 yielded information regarding manned aerocapture at Earth and 15 provided Mars aerocapture data. Even though the focus remained on Mars aerocapture, all available aspects were documented for a complete picture of the mission design.

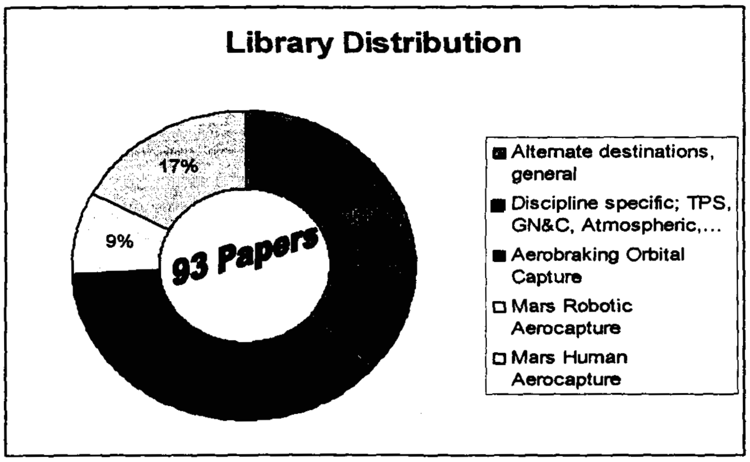

Figure 2 Aerocapture Library Distribution

IV. Documentation Process

Documentation began with identification of common areas of comparison. This effort focused on discovering and recording aerodynamic characteristics such as lift-to-drag ratio (L/D), entry velocity, entry corridor width, aeroshell shape, and the allowable g-load experienced upon aerocapture. Attributes unique to a particular mission study were identified as well in order to depict a comprehensive mission design for future mission planners.

V. Analysis

With the primary focus of this research being to examine the aerocapture process and seek out trends within the data, it was beneficial to view robotic and human mission data concurrently where possible. Robotic and human missions are discussed following the combined chronological assessment.

Robotic and Human Chronological Evaluation

The robotic and human papers supply sufficient data for comparative analysis in the areas of L/D and entry velocity. (Fig 3, 4) Representative papers cover the time period from 1979 to 2003. As the data illustrates, robotic mission studies using aerocapture were published from 1979-1988 and from 2000-2003. The human Mars mission studies embody the 1986 to 1998 time period with one study in 2003.

As shown in Figure 3, eight robotic papers used an L/D from 0.25 to 1.5. Five robotic studies between 2000 and 2003 had an L/D of 0.4 or less. A greater L/D range of 0.2 to 1.5 exists for the 13 human studies that provide L/D data.

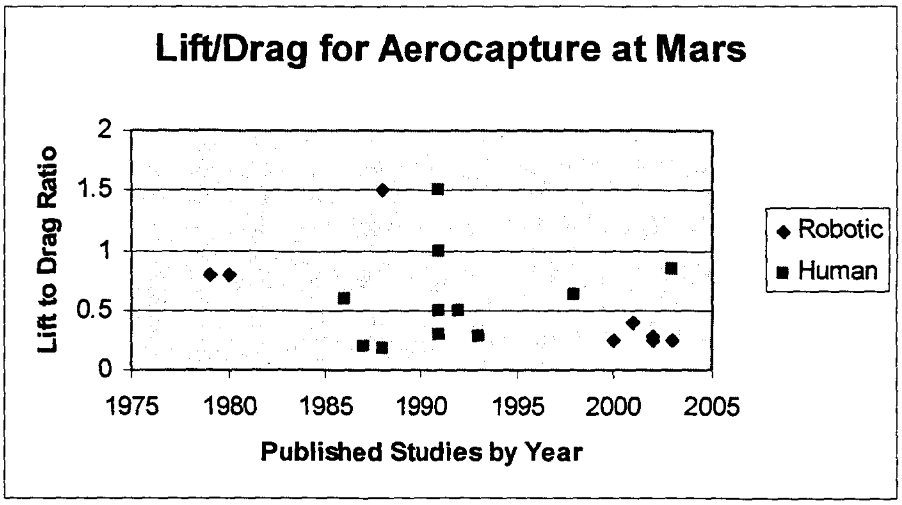

Figure 3 Lift/Drag for Chronological Robotic and Human Aerocapture studies

Figure 4 depicts the entry velocity at Mars aerocapture. Of the 7 robotic papers that identified this parameter, 4 of those required an entry speed limit of approximately 6 km/s. A cluster of human studies in the late 1980s to the 1990s favor an entry velocity of 8 to 10 km/s; this entry speed range results from a desire to limit the trip time for humans, and to reduce zero-g and galactic cosmic radiation exposure. Robotic missions generally have lower entry velocities since they travel on a minimum energy trajectory and trip time is not usually a constraint.

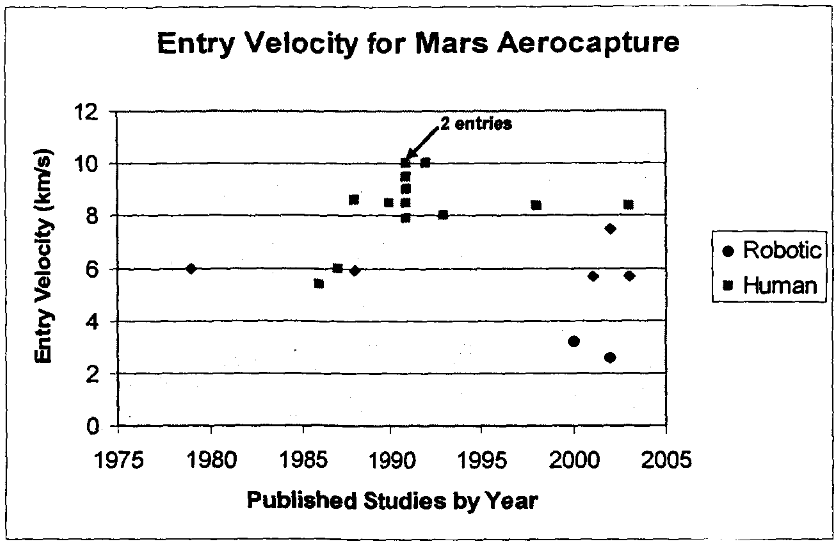

Figure 4 Entry Velocity for Chronological Robotic and Human Aerocapture studies

VI. Robotic

While many Mars robotic missions have flown in the past 4 decades, none of them have used aerocapture to achieve orbit about the Red Planet. The masses of the orbiters sent to Mars thus far have been low enough so that the mass of the propellant needed to capture them into a high ellipse for subsequent aerobraking is about equivalent to the mass of the aeroshell needed for aerocapture. Once the vehicle masses become large enough, aerocapture will be more mass-advantageous.

The robotic papers selected for analysis are shown in Table 2. Each of these papers implements aerocapture as the method of Mars orbital capture.

Study Ref #	Study/Paper	Author	Year
1	Aerocapture Vehicle Mission Design Concept	Cruz	1979
2	Design Integration of Aerocapture Vehicles for MSR	Hassett	1980
3	Design Sty of OnBoard Nav and Guid during aerocapture at Mars	Fuhry	1988
4	CNES-NASA Studies of MSR Aerocapture Phase	Fraysse	2000
5	Mars Sample Return (MSR) Direct Aerocapture Design	Condon	2001
6	Trajectory Analysis for TPS for Mars Aerocapture Vehicles	Jits	2002
7	Aerocapture Guidance Algorithm Comparison Campaign	Rousseau	2002
8	Titan Aerocapture SA (Mars Sample Return Option Used)	Lockwood	2003

Table 2 Selected Mars Robotic Studies

This robotic data set spans from 1979-2003. Only two aerocapture parameters, lift to drag ratio and entry velocity, are represented in the majority of the papers and could be considered for comparison purposes.

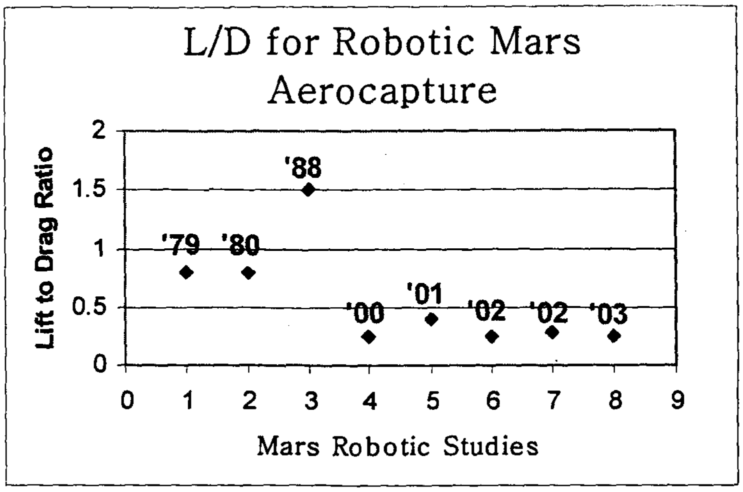

Figure 5 L/D for Mars Robotic Studies

Figure 5 illustrates the L/D for the represented Mars Robotic studies. It appears that an L/D of approximately 0.25 is preferred for studies performed in 2000 and later. This L/D corresponds to a blunt shape, flight-proven for Mars entry on the Mars Pathfinder mission launched in 1996.

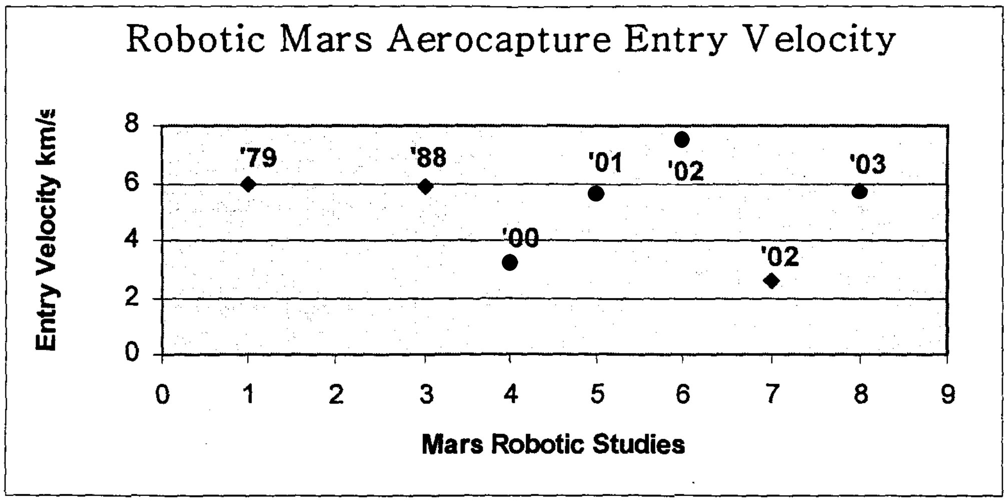

Figure 6 Entry Velocity for Mars Robotic Studies

Entry speed varies from a low of 2.6 km/s to a high of 7.5 km/s (Fig 6). An entry speed of approximately 6 km/s is chosen in the majority of studies.

VII. Human Aerocapture at Mars

While many manned Mars studies were executed in the past, relatively few of them included aerocapture as a way of establishing a Martian orbit. The other architectures either utilize aerobraking for orbit capture, or travel directly to the surface of Mars. The human papers selected for analysis are presented in Table 3.

Study Ref #	Study/Paper	Author	Year
1	Veh Design rqmts for Aerocapture at Mars	Hill	1986
2	Aeroassist Veh human Mars mission	Menees	1987
3	Aerocapture for Manned Mars mission	Wilcockson	1987
4	Mars OEXP-Human Exp to Mars	Mars Expl Ofc	1988
5	90 Day Study	Pres Report	1990
6	Aerodynamic rqmts of Mars Aerobraking Transfer L/D = 1.5	Braun	1991
7	Aerodynamic rqmts of Mars Aerobraking Transfer L/D = .5	Braun	1991
8	Manned Aerocapture Part II	Lyne	1991
9	Physiological Constraints on Deceleration @ Aerocapture	Lyne	1991
10	STCAEM Cryo/Aerobrake	Boeing	1991
11	Technologies for Aerobraking	Cooper	1991
12	Physio const Aerocapture for manned Mars missions	Lyne	1992
13	Mars Aerocapture: Extension & Refinement	Wercinski/Lyne	1993
14	Mars Aerocapture for the DRM	Lyne/Wercinski	1998
15	Blended control, guidance algorithm	Jits/Walberg	2003

Table 3 Selected Mars Human Studies for Mars Aerocapture

Sixteen papers in the data collection that employ aerocapture are chosen for comparison since these are complete mission designs. One paper has two designs with different L/Ds (Braun, 1991); each design is documented separately. Some papers have data for both aerocapture at Mars and return aerocapture at Earth. Fifteen of these include Mars aerocapture while seven papers discuss Earth aerocapture. Both aerocapture at Mars and aerocapture at Earth will be discussed, respectively. Along with entry velocity and L/D, these papers presented sufficient data for other comparison areas including allowable g-load on humans during aerocapture and entry corridor width definition for aerocapture at Mars.

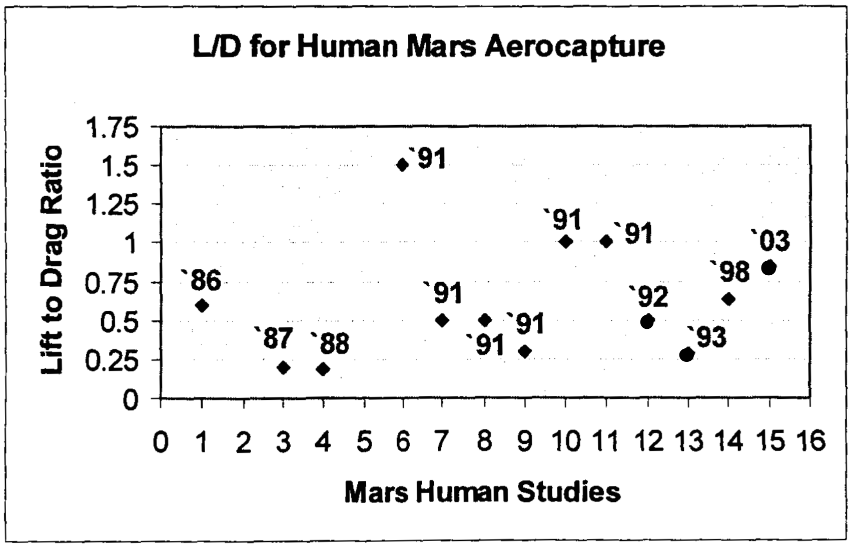

Figure 7 L/D for Human Mars Aerocapture

The L/D values for human Mars studies are wide-ranging as shown in Figure 7. Of the fifteen papers, thirteen listed L/D values from 0.18 to 1.5.

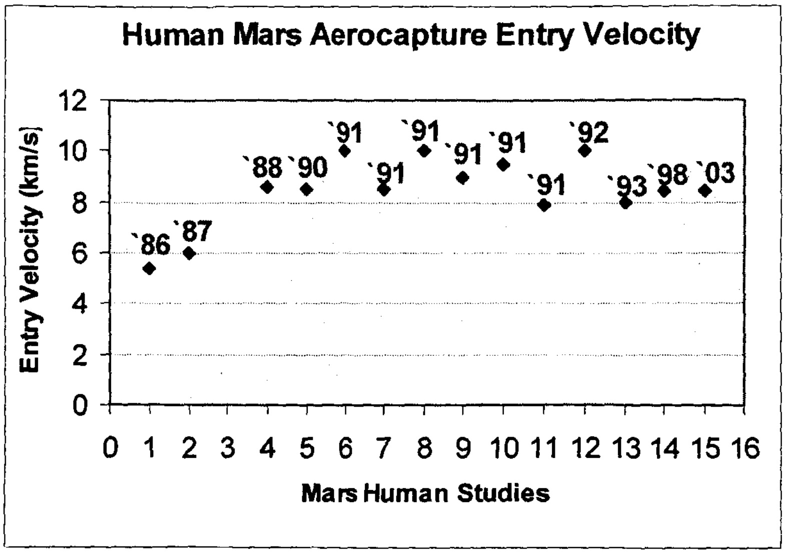

Figure 8 Entry Velocity for Human Mars Studies

Entry Speed at Mars aerocapture is represented in Figure 8. Fourteen studies chose an entry velocity ranging from 5.4 to 10 km/s. Most values appear to be from 8 to 10 km/s; this is likely due to a constraint on the trip time allowed for human transit.

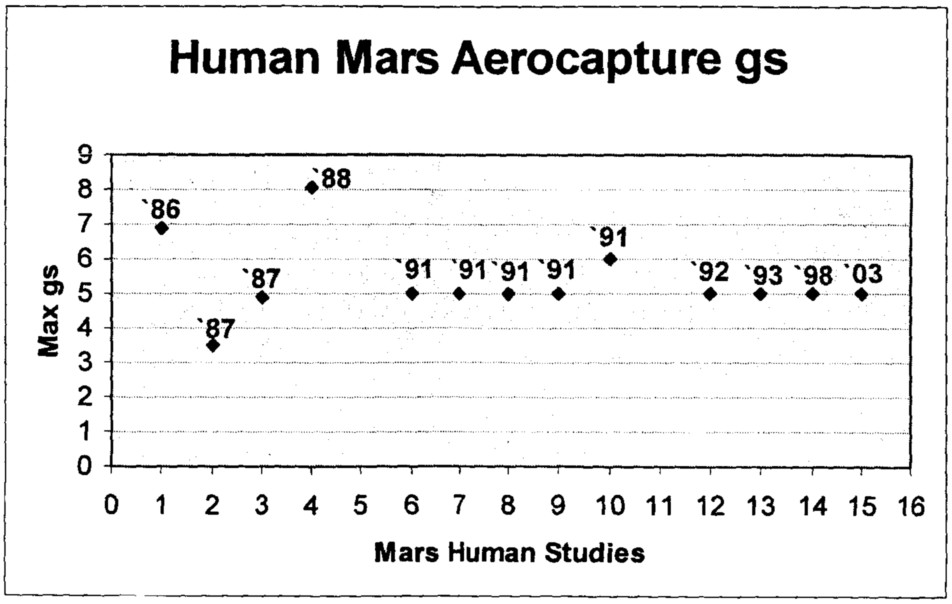

Figure 9 G-load on Humans at Mars Aerocapture

Allowable g-loads upon Mars aerocapture vary from 3.5 g's to 8.08 g's according to Figure 9. Most of the studies establish a maximum g-load of 5. This design criteria is recommended from the medical community based on human tolerance to g-loads following a zero-g transit time to Mars of about six months.

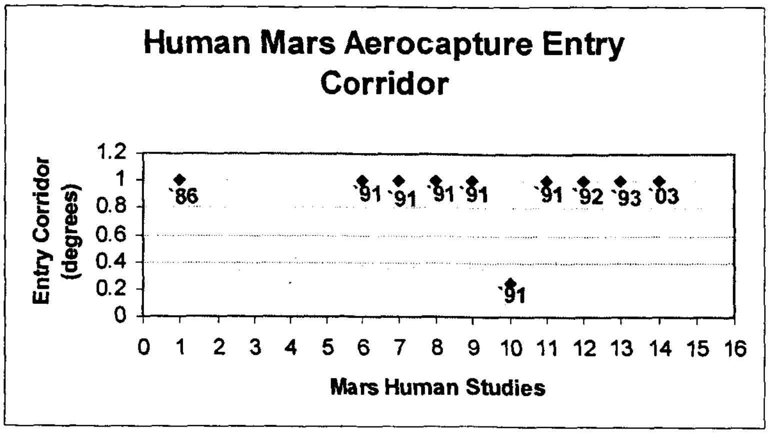

Figure 10 Mars Aerocapture Entry Corridor Width

Figure 10 illustrates the entry corridor width at Mars for aerocapture. Other than an isolated value of 0.25 degrees, an established value of 1 degree seems to be the necessary entry corridor width for a successful Mars aerocapture.

VIII. Human Aerocapture at Earth

Study Ref #	Study/Paper	Author	Year
1	Aeroassist Veh human Mars msn	Menees	1987
2	Aerocapture for Manned Mars msn	Wilcockson	1987
3	Mars OEXP-Human Exp to Mars	Mars Expl Ofc	1988
4	90Day Study	Pres Report	1990
5	Manned Aerocapture Part II Earth Return	Lyne	1991
6	Physio Const Aerocapture for Manned Mars msn	Lyne	1992
7	Earth return for TransHab/Ellipsled	Muth	2000

Table 4 Selected Mars Human Studies for Earth Aerocapture

Seven papers listed in Table 4 are comprehensive mission designs chosen for comparison. Five of the papers discuss aerocapture at both Mars and Earth. The remaining two papers look at Earth aerocapture only. Adequate data for comparison in the areas of L/D, Entry Velocity, and allowable g-load on humans during aerocapture was acquired.

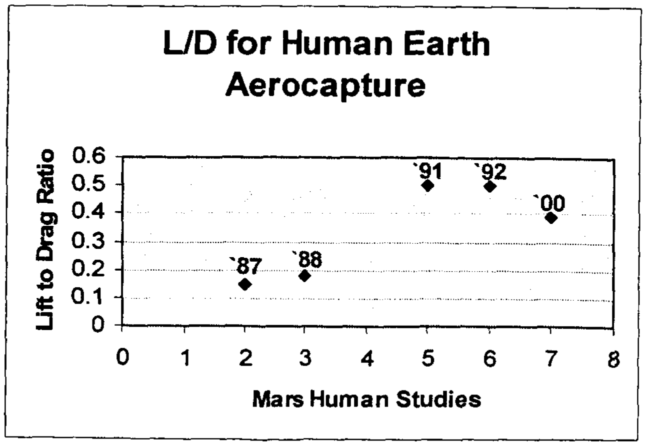

Figure 11 L/D for Human Earth Aerocapture

The L/D values for human Earth aerocapture ranged from 0.18 to 0.5 (Fig 11). L/D values are not available for two of the papers.

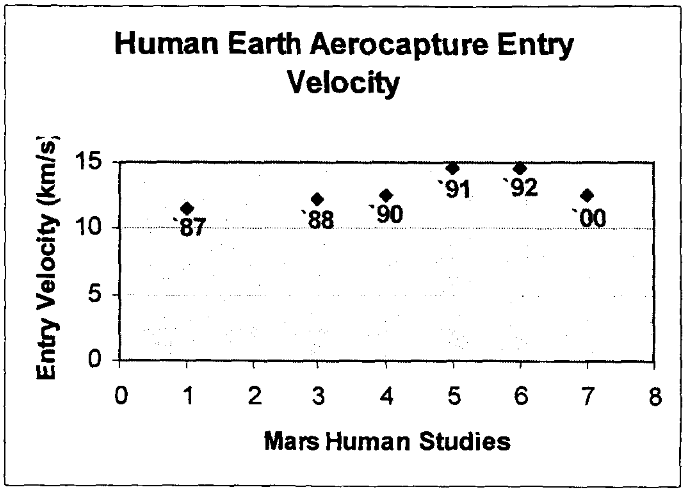

Figure 12 Entry Velocity at Earth

Entry Speed at Earth aerocapture is represented in Figure 12. Entry speed values are consistently between 11.5 and 14.5 km/s.

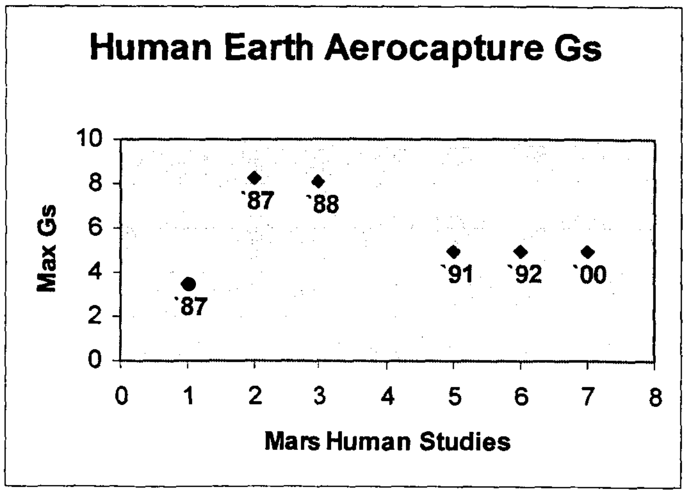

Figure 13 G-load on Humans at Earth Aerocapture

Allowable g-loads at Earth aerocapture vary from 3.5 g's to 8.3 g's according to Figure 13. Half of the studies establish a max g-load of 5. This design limit is recommended from the medical community on human tolerance to g-loads following a zero-g transit time to Mars and return time to Earth of about six months each. A Mars surface stay at about 1/3 Earth g would also be of consideration.

IX. Conclusions

The publications gathered throughout this effort were formed into an aerocapture library for future reference. A bibliography is located in the Appendix (Table 5). Although every effort was made to include all applicable papers into the library, the authors acknowledge that some relevant publications may have inadvertently been missed. In order to make the library as beneficial to the aerocapture community as possible, papers will continue to be added into the library as they become available.

Many interrelated factors contribute to a successful aerocapture at Mars. Of the 93 Mars publications surveyed, 24 studies used aerocapture as the method of capturing into Mars orbit and/or Earth orbit upon return. No robotic published Mars aerocapture mission studies were located between 1989 and 1999. There has been a concentration of human Mars mission study since 1986; however, only 1 human Mars aerocapture mission study was found between 1999 and 2003.

Since the goal of this comparison was to research a complete aerocapture mission to Mars, discipline specific papers and aerocapture papers to other destinations were not included in the data set. While many of the papers discussed a complete mission scenario, all desired parameters were not identified in each paper. Therefore, comparison of the data was limited. In summary, throughout this investigation, entry corridor width for a human Mars aerocapture of one degree appears to be optimal. Also, a 5 g-load limit on humans was imposed in 9 of 13 studies. Many more studies will be required to identify additional trends within aerocapture at Mars.

Appendix

Year	Title	Author Last
1979	The Aerocapture Vehicle Mission Design Concept	Cruz
1980	Design Integration of Aerocapture and Aeromaneuver Vehicles for a Mars Sample Return Mission	Hassett
1986	Manned Mars Mission Vehicle Design Requirements for Aerocapture	Hill
1987	Aeroassisted-Vehicle Design Studies for a Manned Mars Mission	Menees
1987	Aerocapture for Manned Mars Missions	Willcockson
1987	Mars Vehicle TCS and Aerobrake TPS	Comer
1988	A Design Study of Onboard Navigation and Guidance During Aerocapture at Mars	Fuhry
1988	Manned Mars Explorer Project	Nolan
1988	Final Report on the Design of a Fast Crew Transfer Vehicle to Mars	University
1989	Aerobraking Characteristics for Several Potential Manned Mars Entry Vehicles	Tartabini
1989	Mars Rover Sample Return Aerocapture Configuration Design and Packaging Constraints	Lawson
1989	An On-Board Navigation System Which Fulfills Mars Aerocapture Guidance Requirements	Brand
1989	The Office of Exploration: FY 1989 Annual Report Volume V: Technology Assessment (TM 4170)	?
1990	Effect of Interplanetary Trajectory Options on a Manned Mars Aerobrake Configuration	Braun
1990	Aerodynamic Requirements of a Manned Mars Aerobraking Transfer Vehicle	Braun
1990	Equilibrium Radiative Heating Tables for Aerobraking in the Martian Atmosphere	Hartung
1990	Atmospheric Effects on Martian Aerocapture	Ess
1990	Manned Mars System Study (Martin Marietta)	Marietta
1991	Aerobraking Technology Studies	Eldred
1991	TPS Design for Aerobraking at Earth and Mars	Williams
1991	Parametric Study of Manned Aerocapture Part 2: Mars Entry	Lyne
1991	Parametric Study of Manned Aerocapture Part 1: Earth Return from Mars	Lyne
1991	Parametric Entry Corridors for Lunar/Mars Aerocapture Missions	Ling
1991	Applications of Low Lift To Drag Ratio Aerobrakes Using Angle of Attack Variation for Control	Mulqueen
1991	Technologies for Aerobraking	Cooper
1992	Earth Aerobraking Strategies for Manned Return from Mars	Braun
1992	Effect of Parking Orbit Period on Aerocapture for Manned Mars Missions	Lyne
1992	Aerocapture and aeromaneuvering at Mars	Vijayaraghavan
1992	A Generalized Reusable Guidance Algorithm for Optimal Aerobraking	Dukeman
1992	Physiologically Constrained Aerocapture for Manned Mars Missions	Lyne
1993	Mars Aerocapture: Extension and Refinement	Wercinski
1993	The Effect of High Lift to Drag Ratio on Aerobraking	Crouse
1993	Physiological Constraints on Decelereation During the Aerocapture of Manned Vehicles	Lyne
1995	Convective and Radiative Heating for Vehicle Return from the Moon and Mars	Greendyke
1997	Mars Pathfinder Rover - Lewis Research Center Technology Experiments Program	Stevenson

Year	Title	Author Last
1998	Mars Aerocapture Studies for the Design Reference Mission	Lyne
1998	Aerothermodynamics of the Mars Global Surveyor Spacecraft	Shane
1998	DRM 3.0 Addendum: The Reference Mission of the NASA Mars Exploration Study Team	Drake
1999	Mars Missions Using Solar Electric Propulsion	Williams
1999	Application of Accelerometer Data to Mars Global Surveyor Aerobraking Operations	Tolson
1999	Mars Global Surveyor: Aerobraking Mission Overview	Lyons
2000	Earth Return Aerocapture for the TransHab/Ellipsled Vehicle	Muth
2000	CNES-NASA Studies of the Mars Sample Return Orbiter Aerocapture Phase	Fraysse
2000	Reassessment of Effect of Dust Erosion on Heatshield on Mars Entry Vehicle	Palmer
2001	Adv Prop Systems: Mission Scenarios, Critical Overview, Key Technologies for New Demands	Accettura
2001	The Dev and Eval of an Operational Aerobraking Strategy for Mars 2001 Odyssey Orbiter	Tartabini
2001	Afterbody Heating Characteristics of a Proposed Mars Sample Return Orbiter	Horvath
2001	Experimental and Numerical Investigation on Martian Atmosphere Entry	Monti
2001	Architecture Selection: The Key Decision for Human Mars Mission Planning	Donahue
2001	Human Space Exploration in "Earth's Neighborhood" Strategy and Architectural Approach	Joosten
2001	Comparative Analysis of Current NASA Human Mars Mission Architectures	Donahue
2001	Technology for Human & Robotic Exploration & Dev of Space (THREADS) Road Maps Overview	Mankins
2001	Mars Direct Sample Return Mission Design	Condon
2001	Mars Transportation Environment Definition Document	Alexander
2001	Thermal Performance of Advance Charring Ablator Systems for Future Robotic/Manned Missions - Mars	Congdon
2002	Selection and Prioritization of Advanced Propulsion Technologies for Future Space Missions	Eberle
2002	Aerocapture Technology Development Needs for Outer Planet Exploration	Munk
2002	An Overview of the Aerocapture Flight Test Experiment (AFTE)	Hall
2002	Experimental and Hypersonic Aerodynamic Characteristics of the 2001 Mars Surveyor Lander w/ Flap	Horvath
2002	Atmospheric Models for Aerocapture	Justus
2002	High Fidelity Modeling of Semi-Autonomous Attitude Control During Aerobraking	Johnson
2002	Importance of an On-Board Est of the Density Scale Height for Aerocapture Guidance Algorithms	Perot
2002	Corridor Control Guidance and Other Derived Guidance Schemes for Aerocapture	Augros
2002	An Analytical Assessment of Aerocapture Guidance and Navigation Flight Demonstration for Applicability to Other Planets	Graves
2002	Aerothermal Instrumentation Loads For Aeroassist Technology for Human/Robotic Missions to Mars	Parmar
2002	Mars Generation Mission A Manned Mission To Mars	Oliver
2002	Mars Smart Lander Simulations for Entry, Descent, and Landing	Striepe
2002	Mission Design Study for the 2003/2005 Mars Sample Return Mission	Adams
2002	Trajectory Analysis For Thermal Protection System Design of Mars Aerocapture Vehicles	Jits
2002	Demonstration of Integrated Trajectory/Aerothermal/TPS Sizing Design Tools for Mars Smart Lander	Loomis
2002	A Parametric Study of Aerocapture for Missions to Venus	Craig
2002	Aerocapture Guidance Algorithm Campaign	Rousseau

Year	Title	Author Last
2003	Aerocapture Technology Project Overview	James
2003	NASA Development of Aerocapture Technologies	James
2003	Cost Benefit Analysis of the Aerocapture Mission Set	Hall
2003	Comparison of Methods to Compute High-Temperature Gas Viscosity	Palmer
2003	Thermal Protection Concepts and Issues of Aerocapture at Titan	Laub
2003	Planetary Probe Mass Estimation Tool Development & Application to Titan Aerocapture	Dyke
2003	Titan Aerocapture Systems Analysis	Lockwood
2003	Aerocapture Simulation and Performance for the Titan Explorer Mission	Way
2003	An Analysis of the Radiative Heating Environment for Aerocapture at Titan	Olejniczak
2003	Preliminary Aerothermodynamics of Titan Aerocapture Aeroshell	Takashima
2003	Titan Explorer Mission Trades from the Perspective of Aerocapture	Noca
2003	Approach Navigation for a Titan Aerocapture Orbiter	Haw
2003	Guidance Algorithms for Aerocapture at Titan	Masciarelli
2003	Structural Design of the Titan Aerocapture Mission	Hrinda
2003	The Impact of Flowfield-Radiation Coupling on Aeroheating for Titan Aerocapture	Wright
2004	Detached Eddy Simulation of Hypersonic Base Flows w/ Application to Fire II Experiments	Sinha
2004	Analysis of Afterbody Heating Rates on the Apollo Command Modules, Part 1: AS-202	Wright
2004	Collision Integrals for Ion–Neutral Interactions of Nitrogen and Oxygen	Wright
2004	Aerothermodynamic Testing of Aerocapture and Planetary Probe Geometries in Hypersonic Ballistic-Range Environments	Wilder
2004	Global MGS TES data and Mars-GRAM validation	Justus
2004	Blended control, predictor-corrector guidance algorithm: an enabling technology for Mars aerocapture	Jits
2004	N2-CH4-Ar Chemical Kinetic Model for Simulations of Atmospheric Entry to Titan	Gokcen
2004	Uncertainty and Sensitivity Analysis of Thermochemical Modeling for Titan Atmospheric Entry	Bose
2004	Aeroheating Analysis for the Afterbody of a Titan Probe	Olejniczak
?	Explicit Guidance For Aeroassisted Orbital Plane Change	Ma

Table 5 Aerocapture Library Bibliography

Acknowledgments

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References

[1] Griffin, Brand, Thomas, Brent, and Vaughan, Diane, *"A Comparison of Transportation Systems for Human Missions to Mars," AIAA2004-3834*, 2004.

[2] Cruz, M.I., "*The Aerocapture Vehicle Mission Design Concept*," Joint Propulsion Conference, *AIAA 79-0893*, 1979.

[3] Hassett, R.J., *"Design Integration of Aerocapture and Aeromaneuver Vehicles for a Mars Sample Return Mission,"* AIAA 80-0728, 21st Structures, Structural Dynamics, and Materials Conference, 12-14 May 1980, Seattle, Washington.

[4] Fuhry, Douglas, "*A Design Study of Onboard Navigation and Guidance During Aerocapture at Mars*," NASA CR-172053, 1988.

[5] Fraysse, H., Powell, R., Rousseau, S., and Striepe, S., "CNES-NASA Studies of the Mars Sample Return Orbiter Aerocapture Phase", IAF-00.A.6.05, 51st International Astronautical Congress, 2-6 October 2000/ Reo de Janeiro, Brazil.

[6] Condon, Gerald and Braden, Ellen M., "*Mars Direct Sample Return Mission Design*," *AIAA2001-4614*, AIAA Space 2001 – Conference and Exposition, Albuquerque, NM, 28-30 Aug, 2001.

[7] Jits, Roman, "*Trajectory Analysis For Thermal Protection System Design of Mars Aerocapture Vehicles*," *AIAA2002-0818* 40th AIAA Aerospace Sciences Meeting & Exhibit, 14-17 January 2002 / Reno, NV.

[8] Rousseau, Stephane and Perot, Etienne, *"Aerocapture Guidance Algorithm Comparison Campaign," AIAA2002-4822, 2002.*

[9] Lockwood, Mary Kae, *"Titan Aerocapture Systems Analysis,"* AIAA 2003-4799, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 20-23 July 2003, Huntsville, Alabama.

[10] Hill, Oliver and Wallace, Rodney O., "Manned Mars Mission Vehicle Design Requirements for Aerocapture," N87-17731, Houston Space Center, Houston, TX, 1986.

[11] Menees, G.P., "Aeroassisted-Vehicle Design Studies for a Manned Mars Mission," *NASA TM 10003, 1987.*

[12] Wilcockson, W.H. "*Aerocapture for Manned Mars Missions*," Martin Marietta Company, NASA CR-183550 Orbital Transfer Vehicle Concept Definition and Systems Analysis Study, Vol 10, 1987.

[13] NASA. "Exploration Studies Technical Report." NASA-TM-4075, 1988.

[14] NASA. "Report of the 90 Day Study on Human Exploration of the Moon and Mars." NASA internal report. 1989.

[15] Braun, Robert D. and Powell, Richard W., "*Aerodynamic Requirements of a Manned Mars Aerobraking Transfer Vehicle*," Journal of Spacecraft and Rockets, Vol. 28, No. 4, 1991.

[16] Lyne, J.E., Anagnost, A., Tauber, M.E., "*Parametric Study of Manned Aerocapture Part II: Mars Entry*," Journal of Spacecraft and Rockets, Vol. 29, No. 6, 1991.

[17] Lyne, J.E. "*Physiological Constraints on Deceleration During the Aerocapture of Manned Vehicles*," 1991.

[18] Space Transfer Concepts and Analysis for Exploration Missions," The Boeing Co., Volume 2, NAS8-37857, Huntsville, AL, March 1991.

[19] Cooper, David M. and Arnold, James O., "*Technologies for Aerobraking*," NASA TM-102854, 1991.

[20] Lyne, James Evans, "Physiologically Constrained Aerocapture for Manned Mars Missions," NASA TM-103954, August 1992.

[21] Wercinski, P.F. and Lyne, J.E., "*Mars Aerocapture: Extension and Refinement*," NASA TM-111900, Journal of Spacecraft and Rockets, Vol. 31, No. 4, 1993.

[22] Lyne, James Evan, Wercinski, Paul, Walberg, Gerald, and Jits, Roman, "*Mars Aerocapture Studies for the Design Reference Mission,"* NCC2-5198, 1998.

[23] Jits, Roman, and Walberg, Gerald, *"Blended control, predictor-corrector guidance algorithm: an enabling technology for Mars aerocapture,"* IAF-01-A.7.05, 52nd International Astronautical Conference, 1-5 October 2001, Toulouse, France.

[24] Lyne, J. Evans, Tauber, M.E., and Braun, Robert D., *"Parametric Study of Manned Aerocapture Part I: Earth Return from Mars," Paper* 91-2874, Atmospheric Flight Mechanics Conference, New Orleans, La, August 12-14, 1991.

[25] Muth, W.D., Hoffman, C., and Lyne, J.E., "*Earth Return Aerocapture for the TransHab/Ellipsled Vehicle*" Final Study Report for NASA Grant NAG1-2163, October 2000.