PLANETARY ENTRY PROBES 1953-2036: A TECHNOLOGIST'S PERSPECTIVE

ALVIN SEIFF MEMORIAL AWARD PRESENTATION

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ABSTRACT

It has been 60 years since the appearance of Allen and Egger's NACA report describing the blunt body concept and 40 years since Alvin Seiff and his co-authors published the results of the Planetary Atmospheric Entry Experiment Test (PAET). PAET clearly demonstrated the use of probes to determine the structure and composition of an unknown planetary atmosphere. This report recounts some of NASA's accomplishments in planetary exploration pioneered by Seiff, the requisite entry technology, the importance of high enthalpy facilities for mission success, and lessons learned by the current community that trace their heritage to Seiff, his peers and his successors. A few "words of wisdom" from "giants" in the space business are also provided. The report concludes with recommendations regarding the challenges and opportunities that lie ahead for the Entry, Descent and Landing (EDL) community prior to a return to Venus, the giant planets and sending humans to walk on Mars, hopefully by 2036.

1. INTRODUCTION

This author is deeply humbled to be a recipient of the 2013 Alvin Seiff Memorial Award, and expresses the most sincere gratitude to he who prepared the nomination, those that provided supporting letters of reference and to the Award Committee. It is noted that the opinions and recommendations herein are the author's and do not represent NASA or UC policy.

In the early 1960s, Seiff was chief of the Supersonic Free Flight Facility Branch at NASA Ames Research Center and had the charter to build a group to develop the aerothermodynamics and aerodynamics technology required for the safe lunar return of astronauts aboard the Apollo entry capsule. This author was very fortunate to be one of Seiff's fresh-out hires. Seiff soon was promoted to chief of the Vehicle Environment Division and served in that position until 1972. At that time, a reorganization abolished the division and Seiff's staff was reassigned to other organizations. During his twelve-year tenure in management, Seiff conceived and led the execution of the Planetary Atmospheric Experiments Test (PAET), whose objective was to demonstrate, in the Earth's atmosphere, that measurements taken on board a probe during entry could be used to deduce the structure and composition of an unknown planetary atmosphere. Seiff's vision and the PAET represent the origins of decades of NASA's exploration of bodies in our solar system with atmospheres. During Seiff's term in management, he led his staff to create innovative solutions for entry technology problems and provided hands-on mentoring to help them meet these challenges.

Seiff and his colleague, Tom Canning were the forces behind the development of ballistic ranges at Ames, becoming key facilities in those days for aerothermodynamics and aerodynamics testing. Fig. 1 taken in 1966 is of Seiff, then 43 years old, with the Hypersonic Free Flight ballistic range.

Fig. 1. Alvin Seiff with Ames' ballistic range

Al Seiff was a modest person and if he were reading this report, would say he was but one of many in his peer group, including Ames' managers like Tom Canning, Dean Chapman and his colleagues from

Langley Research Center (LaRC) like Walt Olstead and Gerry Walberg, who should also be given credit.

In the 1960's, the "scuttlebutt" among Al's staff was that "you can do anything you want, as long as you use a ballistic range." This was not completely true, as discussed below.

It is remarkable that the mentoring that Seiff provided his staff started many of them on their paths to achieve much in their careers. A few examples are: Bill Borucki, Principle Investigator (PI) of the Kepler Mission that has recently been discovering numerous planets orbiting about distant stars, several of which lie in a "habitable" zone; John Givens, the project manager of Galileo Probe Mission and systems engineer (thermal) for Pioneer-Venus; Dale Compton, who became one of Ames' Center Directors; Dave Cooper, who became chief of Ames' Numerical Aerodynamic Simulator (NAS) Division and later director of the Lawrence Berkeley Labs Supercomputing Facility; Ellis Whiting, PAET Radiometer Experiment PI and co-developer of Ames line-by-line synthetic spectrum code; Vic Reis, who later rose to the most senior ranks in the President's Office of Science and Technology Policy and the Department of Energy [3]; as well as Mike Tauber, a senior entry systems engineer (Seiff Memorial Award winner in 2010). After leaving division management, Seiff's mentoring continued with many others including Dave Atkinson and Boris Reagent, both senior planetary atmospheric scientists.

This author was hired in 1962 by Seiff, marking the beginning of his five-decade long career with NASA. Arnold's career was enabled by mentoring and opportunities provided by Alvin Seiff. These included the chance to research bow shock layer radiation with ballistic ranges [4], shock tubes [5,6] PAET flight testing [7,8] and theory (line-by-line synthetic spectra [9] and quantum or computational chemistry [10,11]). Seiff also approved Arnold's NASA supported graduate study and provided an example for excellence in personal research, management of research and career re-invention.

Seiff's encouragement of Arnold's research with a combustion driven shock tube at 6 km/s and later his support for Cooper and Compton's simulations of 60 km/s Jovian entry conditions with a Votienko Compressor-type shock tube [12] proved that he would sponsor research with test facilities other than a ballistic range.

Once Seiff left his post as a division chief, he "reinvented" himself as a space scientist, focusing his attention toward turning his PAET demonstrated vision into the reality of planetary exploration for NASA.

2. CONTRIBUTIONS OF ENTRY TECHNOLOGY TO NASA'S EXPLORATION OF THE SOLAR SYSTEM

2.1 Blunt Body Concept and PAET

Fig. 2 depicts vehicles, based on entry technology, that have enabled NASA successes in planetary exploration. The origin of this bold journey is the pioneering work by Allen and Eggers [1], which provided the "blunt body" solution to the entry physics "problem" in 1953. Seiff's vision as demonstrated by PAET turned the entry physics "problem" into a "solution" [2], enabling the determination of the structure and composition of an unknown planetary atmosphere with entry probes. It should be noted that in the early 1960's the atmospheric composition of the planets in our solar system was not well known, which was the reason for Seiff's emphasis on determining atmospheric composition. In addition to flying the famous atmospheric structure instrument (ASI) based on accelerometers and temperature sensors, PAET incorporated a mass spectrometer and a radiometer to prove that composition could be determined by directly sampling gases, or by observing spectral features of the radiation from the bow shock formed about the vehicle. Hasso Niemann of NASA's Goddard Space Flight Center, recipient of the First Alvin Seiff Memorial Award in 2007, was the PI for mass spectroscopy while Ellis Whiting was the PI for radiometry [7]. Arnold was the PAET radiometer Co-PI.

Some important lessons learned from PAET were: (1) the ASI experiment worked exceptionally well, (2) sampling of gases during high speed entry compromised the composition experiment because of reactions within the hot sampling tube and, (3) shock layer radiometry worked well, even allowing a reasonable determination of the trace amount of CO_2 in the Earth's atmosphere by radiometric analysis of the CN violet band system [7]. Lesson (2) is the basic reason that mass spectrometry experiments at Mars, Venus, Jupiter and Titan (moon of Saturn) were conducted during subsonic phases of the entry. Whiting and Arnold proposed the radiometer experiment for Pioneer-Venus and much later for the Cassini-Huygens Probe mission, but did not qualify in the science selection processes for those flights. In retrospect, those were wise decisions, as evidenced by the spectacular success of mass spectroscopy, e.g., the determination of Jupiter's atmospheric composition via the Galileo mission by Niemann and his colleagues [13].

2.2 Decades of Space Exploration Enabled by Entry Technology

The decades from the 1970's to the present involving entry technology have seen many NASA successes and sadly the tragic loss of Shuttle Columbia and her crew. As denoted in Fig. 2, success with PAET led to ASI and mass spectrometry flight experiments at Mars, Venus and Jupiter via the Viking, Pioneer and Galileo missions, respectively. The following sections contain discussions of the involved entry technology for some of these missions highlighted with yellow borders. These discussions will help deliver this author's intended messages for this paper.

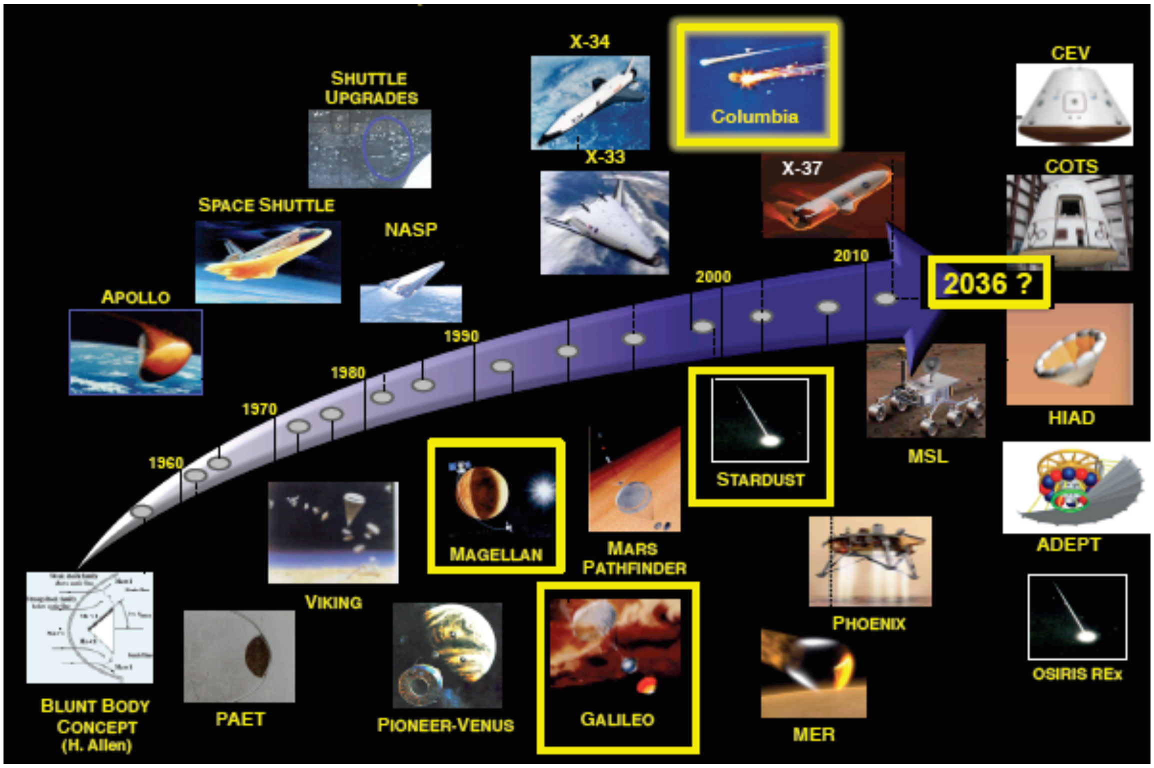

Fig. 2. Vehicles supporting NASA missions enabled by entry technology and key high enthalpy facilities

2.3 Ames Space Technology Division.

In 1985, another reorganization under Ames Center Director, William F. Ballhaus, III led to the consolidation of Ames' residual expertise in entry technology and relevant facilities into a single division. This author was selected as the division chief and remained in that position until his retirement from civil service in 2002. During this time significant contributions by the staff of the division toward NASA's missions beyond Viking continued. Contributions from other institutions, especially from Langley Research Center (LaRC), Johnson Spaceflight Center (JSC) and the Jet Propulsion Laboratory (JPL) were also enabling to the success for these missions, but the focus here is on NASA Ames' work in entry technology.

2.4 Magellan and Aerobraking

Aerobraking is a maneuver where a spacecraft makes many passes at high altitudes to reduce speed by aerodynamic drag. Aerodynamic heating for aerobraking is low enough that the spacecraft does not require a thermal protection system (TPS) and is a mass-efficient alternate compared to the use of orbital insertion via retro-propulsion.

In the early 1990's JPL managers desired to circularize Magellan's orbit to conduct lower altitude scientific observations of Venus. JPL asked Ames to perform rarefied flow simulations to ensure that the maneuver was safe and well conceived. Brian Hass did so [14]. Based in part on Hass' study, this final phase of Magellan's mission was chartered and successfully completed. Aerobraking was later used for mission success by the Mars Global Surveyor; despite a broken hinge on one solar panel [15].

Mission managers have subsequently used aerobraking without hesitation.

There is a powerful lesson to be learned from the Magellan aerobraking experience, and how its success influenced the adoption of the technology for subsequent Mars missions. This lesson will be discussed more in the subsection 5.2 on Aerocapture.

2.5 The Galileo Probe Mission to Jupiter

The Galileo mission was conceived to help understand the formation of the Solar System in part by determining Jupiter's atmospheric composition and structure. Hasso Niemann and Al Seiff played very important roles in the Galileo mission, building on the successes of PAET, leading to the determination of the composition and structure of Jupiter's atmosphere.

From the technologist's perspective, the Galileo mission represented a tremendous challenge because the probe's entry environment is the most hostile ever encountered by a human-made object. The Galileo probe was to be placed in low Earth orbit by a Space Shuttle and then launched from there to Jupiter. Originally, Galileo's entry speed was to be about 41 km/s. Due to the loss of Shuttle Challenger and her crew of seven astronauts during launch on January 28, 1986, the Galileo mission was delayed. This delay led to Galileo's actual entry speed being increased to 47.4 km/s and the entry occurred on December 7, 1995.

The Galileo probe was flown with instruments to determine the amount of TPS recession. The data returned revealed how close this mission came to being a failure. This "near miss" happened, despite the best combined efforts from NASA Ames, Langley and industry to predict the performance of the probe's carbon phenolic TPS. This "story" can be seen by inspection of Fig. 3 based on the report by Milos, Chen, Squire and Brewer [16].

As can be seen from the figure, the recession (orange) was fairly uniform over the heat shield. The black coloring (left) indicates the non-uniform thickness that accounted for the higher predicted recession at the nose region. The nose region recession was over-predicted while that on the conical flank was considerably under-predicted. There was a near TPS burn-through on the conical flank.

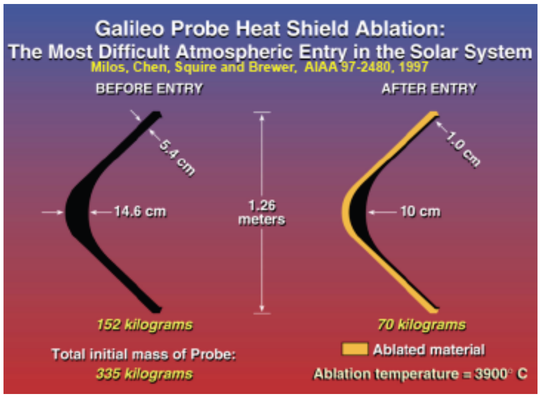

Fig. 3. Cross-section of the Galileo forebody heat shield before and after the Jovian entry.

Recent discussions with Michael Green (retired Ames employee, currently with ERC, Inc.) and Bala Balakrishanan (ERC, Inc.), both of whom were heavily involved with NASA's work on the Galileo Probe [17,18] recalled the challenges of predicting the vehicle's environment and the thermal response of its carbon phenolic TPS. These challenges included the difficulty of simulating the fluid dynamics at these extreme conditions, boundary layer turbulence, radiative transport, boundary layer chemistry and uncertainties in the probe's carbon phenolic TPS materials properties.

In a paper analyzing Galileo's flight data, the authors of [16] stated in 1997 that based on their analysis "Under prediction of the frustum recession may be a direct consequence of the above-nominal helium fraction in the Jovian atmosphere, however the over prediction of the recession near the nose is problematic".

About 3 years ago, Michael Tauber and the late Benard Laub gave a seminar at NASA Ames that included a discussion of the Galileo probe flight data. A key conclusion they made was that turbulent flow on the frustum could cause surface roughening, greater heating and increased recession. They also stated that blockage near the stagnation point is obviously greater than was accounted for in the pre-flight designs, but the underlying thermal physics are not yet fully understood.

A fast, engineering analysis code (fully coupled flow field heating environment, ablation and materials response written by Tauber, et. al. [19]) exists that is suitable for carbon phenolic TPS design for the outer planet missions. This tool was validated against the Galileo probe flight data and is typically used in mission studies [20].

While it is apparent that heat shield designs for outer planet missions could be accomplished with the engineering code [19], it seems important to this author that the EDL community should expend efforts to develop a better understanding of the Galileo flight data. Perhaps, advancements in real gas Computational Fluid Dynamic technology could be applied to solutions that couple materials thermal response, fluid dynamics, and reacting boundary layer gases building on recent work and radiation transport through the boundary layer [21, 22].

Work reported in 1980 by Arnold, Cooper, Park and Prakash [23] may portend one aspect of what could be accomplished today to improve the understanding of Galileo's boundary layer blockage of radiation striking the surface. The purpose of their study was to understand the effects on radiation reaching the probe's surface when realistic, atomic line and line-by-line absorption cross sections for diatomic species were used for radiation transport, as contrasted to results from coupled flow field/radiation solutions that used approximate "picket" fence absorption cross sections. That analysis [23] of Galileo's boundary layer blockage effects used the best available absorption cross-sections and radiation transport tools available at that time. The line-by-line cross sections for the atomic and diatomic species were based on well-known spectroscopic constants. The electronic transition moments used for diatomics were determined from both shock tube experiments and those from ab-intio (first principles) calculations by Ames' computational chemists. The best available continuum-like cross sections for C_3 came from both computational chemistry solutions and experiment. At that time, newly available cross sections for C_2H had just become available from Cooper and Jones [24] and its effects of its blockage was also assessed.

Fig. 4 shows species concentrations and shock layer temperatures at the stagnation point from HYVIS solutions [25] provided by J. Moss of the Langley Research Center for an entry speed of 41.2 km/sec. The study [23] solved the uncoupled radiative transport through the boundary layer conditions using the HYVIS data. Table 1 shows the comparison of the HYVIS solutions with the "picket" fence cross sections to those using the more realistic line-by-line cross sections.

With no boundary layer absorption, the predicted flux impinging on the stagnation point is 56 kW/cm^2. When the boundary layer absorption was "turned on" with no absorption by C_2H, the blockage drops the impinging flux to 26 kW/cm^2. When the C_2H absorption is "turned on" the flux striking the wall is dropped another 3 kW/cm^2. It is interesting to note that the peak heat flux for entry to Venus' atmosphere is about 3 kW/cm^2, giving one a feeling for the magnitude of heat fluxes that are associated with Jovian entries. Note that at the frustum, the line-by-line solutions are close to the HYVIS results and it was concluded [23] that the turbulent boundary layer heating causes dissociation and in these regions the gases are optically thin.

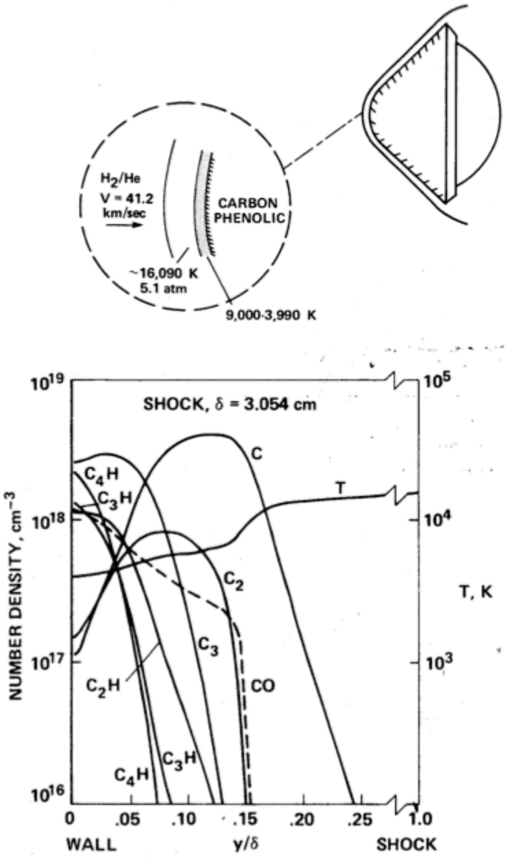

Fig. 4. Species concentrations and temperatures predicted by the HYVIS code [25].

Table 1. Comparison of blockage using line-by-line absorption cross sections with HYVIS

Stag. point	kW/cm^2
No BL	56
No C2H	26
With C2H	23
HYVIS	20

Frustrum	kW/cm^2
No C2H	11.7
HYVIS	11.7

As noted in [23], the higher molecular weight species, C_3H and C_4H were predicted by HYVIS to be present in high concentrations, but were assumed to be transparent in the line-by-line solutions. If these species have strong absorption coefficients, they would absorb more radiation from the invisid shock layer and this results in more blockage. The results would be in the right direction to explain the over prediction of the TPS recession at the stagnation region.

In addition to the theoretical work on Galileo, large effort was expended experimentally with Ames Giant Planet arcjet facility (see section 3.1) and a gas dynamics laser to certify the carbon phenolic heat shield. Neither facility is in operation today.

Presently, a NASA project conducting Hypersonic EDL research under Mike Wright's leadership, funded by the HQ Space Technology Mission Directorate (STMD), is underway. Within this project, computational chemistry research is being conducted on C_3 [26] and other triatomic species. Solutions of the Schrodinger equation for the wave functions and transition moments of C_3H and C_4H should be feasible at this time, and it might be possible to create continuum-like cross sections using these data as inputs.

Further, recent experimental work has been undertaken [27] to measure heating enhancement on pre-roughened TPS flying in a ballistic range. This approach could help quantify the effects of turbulence induced roughness and increased recession for Galileo.

Respectfully, this author recommends that the Entry, Descent and Landing (EDL) community should revisit and understand the Galileo flight data. This understanding could put the EDL community in a better position to design heat shields for new missions to the outer planets. Furthermore, as recently pointed out [21], this understanding could help in designing heat shields for very high speed (up to 15 km/s) capsules returning humans from Mars.

2.6 Stardust and the Phenolic Impregnated Ceramic Ablator

In the early 1990's Dan Rasky [28], then chief of the Thermal Protection Branch at Ames and the author convinced Sam Venerri of NASA headquarters that it would be a good idea for the agency to begin research on lightweight ablative TPS. The proposal was funded under the now defunct Base Research and Technology program. One result of the research led to the development of the phenolic impregnated carbon ablators (PICA). PICA was patented by NASA (number 5,536,562 by Tran, Henline, Hsu, Rasky and S. Riccitiello). PICA was proposed as an enabling technology for a Discovery class mission to return ejecta from Comet Wild II to the Earth. The proposal, led by Lockheed-Martin was accepted and became known as Stardust. Stardust successfully completed its return to the Earth in January 2006, executing the fastest return to the Earth by an object made by human hands (12.7 km/s). Stardust's heat shield was manufactured by Fiber Materials Inc. (FMI).

The Stardust heat shield was recovered, and coring of the heat shield gave valuable insight to the behavior of PICA in extreme heating (~ 1,100 W/cm^2) [29].

Fig. 5. The Stardust PICA heat shield before (left), and after its return to Earth in January 2006 (right).

During NASA's Orion Thermal Protection System Advanced Development Project (ADP) led by J. Reuther and E. Venkatapathy, the objective was to develop a heat shield material for the Orion heat shield. PICA was a strong contender against AVCOAT, the material used for the Apollo lunar return capsule. Considerable improvement in the thermal response model and material properties of PICA were developed during that time. AVCOAT was selected for Orion, principally because PICA has a low strain to failure property, making it difficult to integrate on a "flexible" carrier structure.

In 2007, arcjet testing of the Mars Science Laboratory (MSL) base lined Super Light Weight Ablator (SLA 561-V) uncovered flight-relevant conditions at which SLA 561-V suffered catastrophic failure. Based on an extensive "tiger-team" effort co-led by Robin Beck, Mike Wright and Helen Hwang, MSL project management at JPL decided to abandon SLA and adopt the PICA TPS material, flown previously on Stardust [29]. PICA had no heritage at Mars. This situation necessitated an incredibly intense effort [30] to mature and certify the PICA TPS design in only 12 months to meet MSL's then planned 2009 launch date. This was accomplished, and was an enabling element in the success of delivering the rover Curiosity to the surface of Mars in August 2012.

It is noted that Dave Olynick and this author advocated that the Stardust PICA heat shield should be instrumented with at least bond line thermocouples, but this did not happen. However, James Reuther and Mike Wright were successful in their advocacy to instrument MSL's PICA heat shield [30] and the results are already influencing the design of future Mars entry vehicles. This practice should continue on every entry vehicle in the future for the sake of NASA's future.

The PICA success story had two very "tense" moments. The first was that after Stardust was launched, concerns about arcjet calibrations during its development raised questions regarding the validity of PICA's predicted performance. This led to the formation of an internal PICA Assessment Team (PAT), led by Alan Covington that conducted new arcjet tests and analysis to better understand the PICA's performance for the Stardust mission. Fig. 6 depicts a key result from the PAT team's report [31], which proved that there was ample margin (74 ^{O}C, below the requirement of 190 ^{o}C) in the PICA TPS to withstand the Stardust's heating environment. It is unfortunate that flight data could not be plotted on the figure.

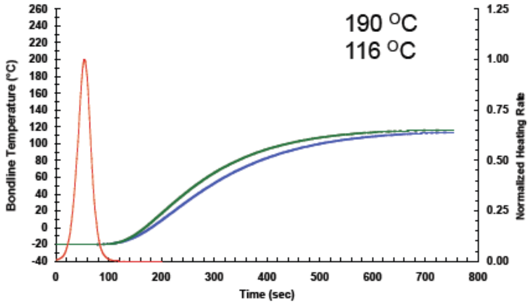

Fig. 6. Result of the PAT team's study showing that Stardust's TPS bond line temperature had ample margin for the fastest Earth entry (12.7 km/s) by a human- made vehicle yet attempted.

The second "tense" moment was during Stardust's Earth entry in January 2006 after being in space for 6 years and capturing ejecta from comet Wild II. This entry was observed with many instruments onboard an aircraft, one of which was a video camera whose images proved the entry was successful.

Fig. 7. Photo of Stardust's successful entry

2.7 Shuttle Columbia Accident – Lesson Learned

The purpose of this section is to illustrate how serious the consequences can be for an accident involving the extreme energies associated with atmospheric entry.

On February 1, 2003 Shuttle Columbia and her crew were lost en route on their return to the Kennedy Space Center. Pre-planned, in the event of such an accident, then Ames Center Director, G. Scott Hubbard was to be the sole NASA person on the Columbia Accident Investigation Board (CAIB). The board's charter was to look into the causes of the accident and to recommend actions to prevent reoccurrence of such a catastrophic event.

Director Hubbard requested this author to join him in Houston to help in investigating the physical cause of the accident. Early on in the investigation, it was observed that a briefcase-sized piece of external tank foam was lost on launch and had travelled in the supersonic flow, striking Columbia's left wing. The author was tasked to help understand what caused the shuttle to break up on entry, assuming that the foam somehow compromised the shuttle's TPS. The author was able to secure two consultants for this investigation and those selected were Howard Goldstein, a developer of the shuttle tile TPS and Don Rigali, retired from the Sandia National Lab and an expert in carbonaceous heat shields.

Several parallel studies by the CAIB led to the conclusion that during entry, a large breech in panel eight of the Reinforced Carbon-Carbon (RCC) Wing Leading Edge System (WLESS) caused by the foam strike, allowed superheated air to enter the aluminium wing box and melt the sub-structure. The subsequent structural failure and loss of Columbia and her crew was a consequence of the foam strike.

Fig. 8 is a collage of two photographs from [32] that helped pinpoint the location of the foam strike. As seen, this is a mock up of the panel 8 and 9 WLESS made from debris recovered from Columbia's wreckage. Other panels from the wreckage served as surrogates for panels 8 and 9. From inspection of the figure, in front of the RCC panels, one can see the recovered LI-2200 close-out tiles that abutted to the RCC. The inset shows a blow-up of the corner where the LI-2200 tile interfaces with RCC panel eight.
Fig. 8 clearly shows significant slumping (shrinking) of the LI-2200 caused by hot debris that was forced to flow out of the void behind RCC panel eight. This flow is also very evident in the other two LI-2200 tiles outboard, below panel 9. The flow direction follows the streamline pattern as discussed in [32].

This debris analysis is one of several pieces of convincing information, which supported the hypothesis for the cause of the accident stated in the CAIB report:
www.nasa.gov/columbia/home/CAIB_Vol1.html

Fig. 8. Photograph of Shuttle Columbia debris that helped pinpoint the location of the foam strike.

Unquestionable proof of the cause of the accident was documented in a ground test led by director Hubbard that fired a briefcase sized piece of foam at a full scale WLESS with a flown RCC panel 8.

Importantly, as documented in the full CAIB report, another cause of the accident was the cultural climate in NASA at the time of the accident.

It is this author's purpose here to remind those involved with entry technology that our work is risky. Consequences of not retiring risk can be heart breaking as based on personal experience of seeing, first hand, the debris from the Shuttle Columbia and realizing that seven astronauts perished in the accident.

3. HIGH ENERGY FACILITES

Several types of high-energy facilities are critical to the success and safety of NASA's missions involving atmospheric entry. This is because they can simulate (not duplicate) entry environments on the ground. As said by Dean Chapman, "It is generally not possible to duplicate flight scale, altitude and velocity in a ground facility."

3.1 Arcjets

Arcjets, depicted in Fig. 9 have an arc heater (essentially a standing lightning bolt) that heats high pressure flowing air that is expanded to supersonic speed by a water-cooled nozzle. Arcjets are in effect, a hot wind tunnel where a model with a candidate TPS material is inserted into the flow. Arcjets can run for durations up to 30 minutes, and can achieve flight-like heating rates and surface pressures allowing the evaluation of TPS materials at flight-relevant conditions.

Arcjets are critical facilities for both the development and flight certification of TPS materials. They have been used for the development of all NASA vehicles depicted on Fig. 2 (with the exception of Magellan that did not require a TPS as explained above in the aerobraking section).

It is noted that the Giant Planet Facility, so important for the Galileo mission to Jupiter had to be torn down for work on the National Aerospace Plane (NASP). This has compromised the consideration of entry probes for new missions to Jupiter. It is unlikely that the Giant Planet Facility could be rebuilt under current fiscal constraints. In the future, piecewise development of TPS will have to be accomplished as described in [33].

3.2 Ballistic Ranges

Ballistic ranges were used heavily in the 1960's for the Apollo and planetary missions. In order to achieve lunar return speeds (11 km/s), the Ames ballistic ranges then typically operated with light gas guns that launched the models into a counter flowing supersonic airstream created by a shock tunnel. Radiometers were used to observe gas cap radiation from small models, and in turn to predict bow shock radiation for full-scale vehicles [4].

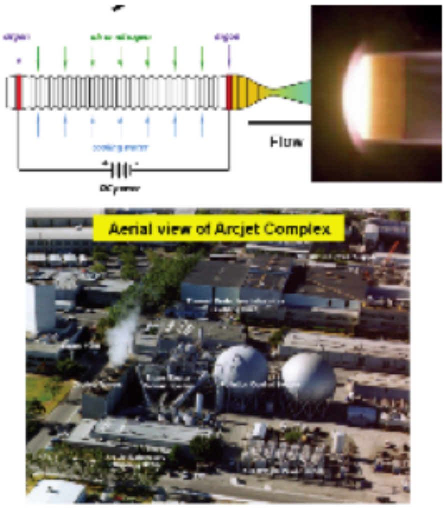

Fig. 9. Upper: Arcjet elements: arc heater, nozzle and test article. Lower: photo of electrical power station, water cooling tower, etc. required to operate the arcjet facility that occupy the size of a small city block.

As shown in Fig. 10, the test sections for some of the ranges were long enough that several cycles of angle-of-attack oscillations of the model in free-flight could be observed. Analysis of the shadowgraph data and angle of attack histories is used to determine the aerodynamic coefficients for full-scale vehicles.

Today, Ames' ranges no longer operate in the counter flow mode, and are not used to investigate radiation physics. They do continue to provide valuable information for the aerodynamics of new designs for planetary probes.

Al Seiff and Tom Canning were very proud of the Ames Ballistic ranges. At one point, Seiff told Arnold that he was pleased to have seen that this author had received stewardship of Ames' ballistic ranges**.**

3.3 Shock Tubes

Shock tubes are capable of producing a nominally one-dimensional flow behind a normal shock wave that can simulate hot gas conditions that occur behind bow shock waves of bodies flying at hypersonic speeds. The speed of the normal shock wave depends upon the un-shocked gas pressure and the type of driver. In the 1960s many shock tubes were in operation across the nation. At Ames, there were three types: a combustion driven shock tube typically operated at 6 km/s, ideally suited for studies of Mars entries [5], several electric arc driven shock tubes that operated in the 6 – 12 km/s range and are ideal for Earth entry missions [34] and finally, a Voitenko compressor operated to simulate Jovian entry environments up to 60 km/s [12].

Today, only one shock tube is operational at Ames, called the Electric Arc Shock Tube (EAST) that uses an electric arc driver. The EAST facility has been extremely valuable in validating first principles predictive radiative heating codes (NEQAIR [35] and HARA [21]). Fig. 11 shows a photograph of the EAST facility and below that is a relatively high resolution spectrum from hot air for an unshocked pressure of 0.1 Torr, and a shock speed of 10 km/s.

Fig. 10. Photograph of the NASA Ames Ballistic Range showing the test section. The light gas gun launched the model into a counter-flowing supersonic air stream created by a shock tunnel. The black and white inset depicts a shadowgraph of a model in hypersonic flight.

It is noted that Cruden, et. al. have made major advancements [36] in the instrumentation of the EAST facility that have enabled measurements further into the UV and IR spectral regions

3.4 Criticality of facilities for mission success and safety

Arcjets have been enabling for the TPS development and certification for all the vehicles shown on Fig. 2. Future vehicles requiring TPS and the development of new TPS materials must have arcjet test services available for success and this includes the new class of deployables that show much promise for future NASA missions. Ballistic ranges are still in use for the determination of aerodynamics for new vehicles and flight conditions. Many aerodynamic coefficients can be calculated with modern Computational Fluid Dynamics (CFD), but some cannot yet be reliably predicted, e.g., time derivatives of pitching moments. Shock tubes are critical for exploring radiative properties of gases and validating synthetic spectrum codes and properties that are beyond the capability of computational chemistry.

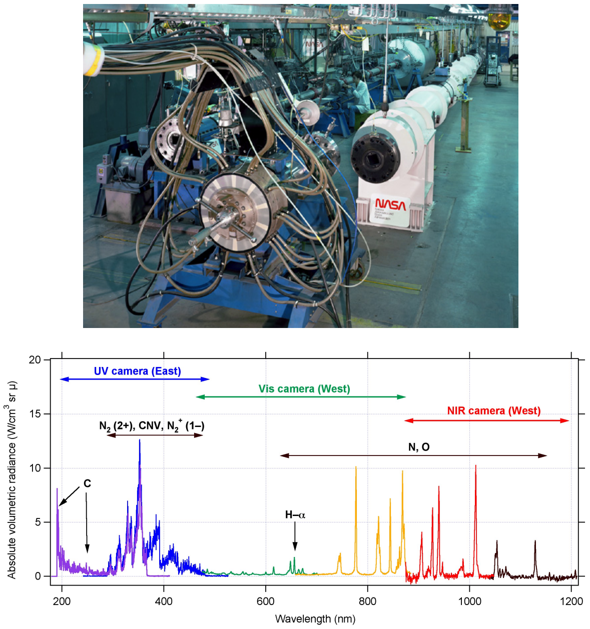

Fig. 11. Photograph of Ames' Electric Arc Shock Tube (upper) and typical high-resolution spectra (lower) used to validate first principles radiative heating codes.

During the span of time this author was in management, NASA funding practices for facilities operation and maintenance shifted from a comfortable "three-pocket" approach to one where facilities operations had to be funded from projects they supported. In this situation, projects come and go, and they typically are on strict budgets. Facilities managers are constantly required to show "relevance," are under the threat of closures and may have to defer prudent maintenance. Project managers "skimp" on testing and this can lead to serious issues regarding retirement of risk and/or carrying extra margins for TPS that can reduce the mass and/or the number of instruments that provide science return.

The bottom line is that high enthalpy facilities are enabling for success in NASA's mission involving hypersonic flight. All parties including space scientists, project managers and decision makers at NASA Headquarters should understand this, and support facility stewards in their endeavours to provide high quality testing services.

4. THE FUTURE – HUMAN MISSION TO MARS

Studies for landing humans on Mars has been underway by NASA for decades [37, 38], but serious development of the transportation system to enable the mission has suffered from a lack of resources. As pointed out by Braun and Manning, if a human landing on Mars' surface is to be accomplished by 2036, serious technology maturation efforts should be underway now [39].

Mission studies [38,40] have identified three important elements of the entry, descent and landing of 40 metric tons required for the human Mars mission: (1) The aerocapture manuever by large rigid or deployable aeroshells to enable landing of 40 metric ton payloads on Mars' surface. Aerocapture would be followed by out-of-orbit entry requiring a dual heat pulse capable TPS. (2) Supersonic retro-propulsion during descent. and (3) the capability to land on an un-prepared surface at Mars. Fig. 12 depicts the concept of operations for three candidates. The rigid vehicle is a 10x29 meter ellipsled. Deployables would be a 23 m diameter Hypersonic Inflatable Aerodynamic Decelerators (HIAD) or the Adaptive Deployable Entry Placement Technology (ADEPT) mechanically deployed decelerator.

Dual heat pulse capable TPS for rigid aeroshells has been demonstrated by the use of PICA atop a Shuttle tile (LI-900) that could be used for the aerocapture and subsequent out-of-orbit entry [41]. ADEPT's carbon cloth has a demonstrated capability well beyond the 110 W/cm^2 and the capability to endure dual heat pulse environments has been shown [42]. Consequently, it is feasible to use an ADEPT vehicle for human Mars missions at the 23 m diameter scale. The flexible TPS for the HIAD has not yet been demonstrated for capability at 75 W/cm^2, well below the required 110 W/cm^2 level, but this limitation could be overcome by going to a much larger vehicle. [38,43].

Recently, work has been initiated by NASA's Space Technology Mission Directorate (STMD) for development of supersonic retro-propulsion, and this gives an important start toward the second element of EDL technology required for the human Mars mission.

This author is not aware of significant work on the formidable task of landing 40 metric tons of payload on Mars, especially on an un-prepared surface. The magnificent work on the Mars Science Laboratory (MSL) sky crane technology is very impressive, but could it be scaled up from its ~ 1 metric ton delivery of the Curiosity rover by 40 times for to meet the needed capability for the human Mars mission?

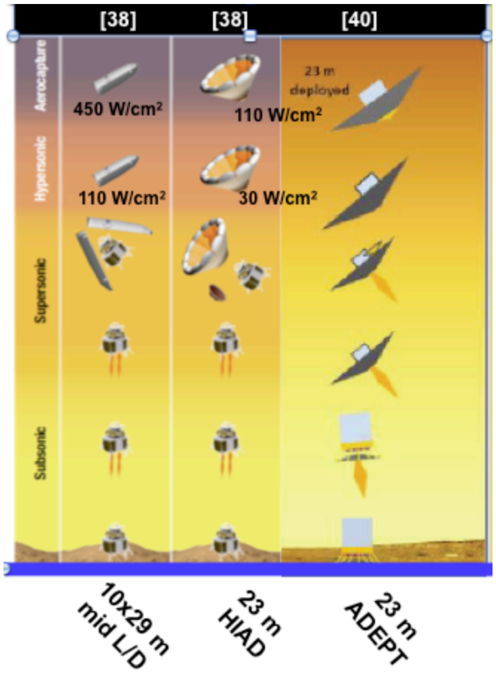

Fig. 12. Three concepts for landing humans on Mars.

It is pointed out that the 23 meter diameter ADEPT described in [40] featured ribs that rotate downward to create a large stabilizer that could be enabling for landing 40 metric tons on Mars. Fig. 13 depicts the concept of rib deployment operations from aerocapture, entry from Mars orbit and finally placement of the ribs to become a landing stabilizer.

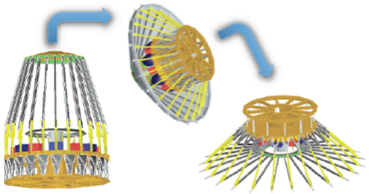

Fig. 13. Operation of ADEPT's ribs throughout launch, entry and landing

The return of astronauts from the Mars mission may require entry speeds up to 15 km/s, and this is another area where currently funded Space Technology Mission Directorate (STMD) research may lead to technology solutions for the final leg of the mission. Fig. 14, showing unpublished work by D. Kinney depicts the heating during direct entry into Earth's atmosphere with a "heavy" version of the Orion capsule with the constraint of a peak deceleration of five "g's." As can be seen, the peak heating rates increase from about 1,000 to over 3,000 W/cm^2 as the entry speed increases from lunar return (11 km/s), up to 14 km/s, respectively. The higher speeds enable shorter return times, important for the rapid return of astronauts.

Currently available TPS materials (AVCOAT and PICA) are not capable of safely performing beyond about 1200 W/cm^2 and this obviates their utility for a "fast" return of astronauts from Mars. As shown in the inset in Fig. 14, the very dense carbon phenolic ablator used for the Galileo and Pioneer Venus probes can easily perform at these heating rates, but sizing studies by K. McGuire show that it would be far too heavy. However, McGuire's sizing also shows that a hypothetical, mid-density carbon phenolic TPS material suggested by Benard Laub could be a solution for the "fast" human Mars return TPS. Recently the STMD has funded work on 3 dimensional woven TPS [44] that could meet the need for this type of heat shield material.

5. NEARER TERM MISSIONS NEEDING ENTRY

Fig. 15 depicts two types of maneuvers that will be required for future missions.

5.1 Direct entry

Direct entry has been accomplished many times over the past five decades, but challenges remain for EDL technologists in the future. Extreme examples include: (1) planet direct entry, e.g., Jupiter entry at high latitudes whose environments are much more severe than Galileo's and (2) sample return missions from Mars. To avoid possible contamination of the Earth's biosphere by a potential Mars biohazard, the entry system will have to be a thousand times more reliable than today's systems. Entry technologists will have to solve these challenging problems to enable such missions.

5.2 Aerocapture

Aerocapture is a maneuver that has been proposed for by U.S. entry technologists for years, but has not yet been used for a NASA mission. Aerocapture test flights have been proposed and actually started i.e., the cancelled project called the Aeroassist Flight Experiment (AFE) [45]. The remarkable benefits of

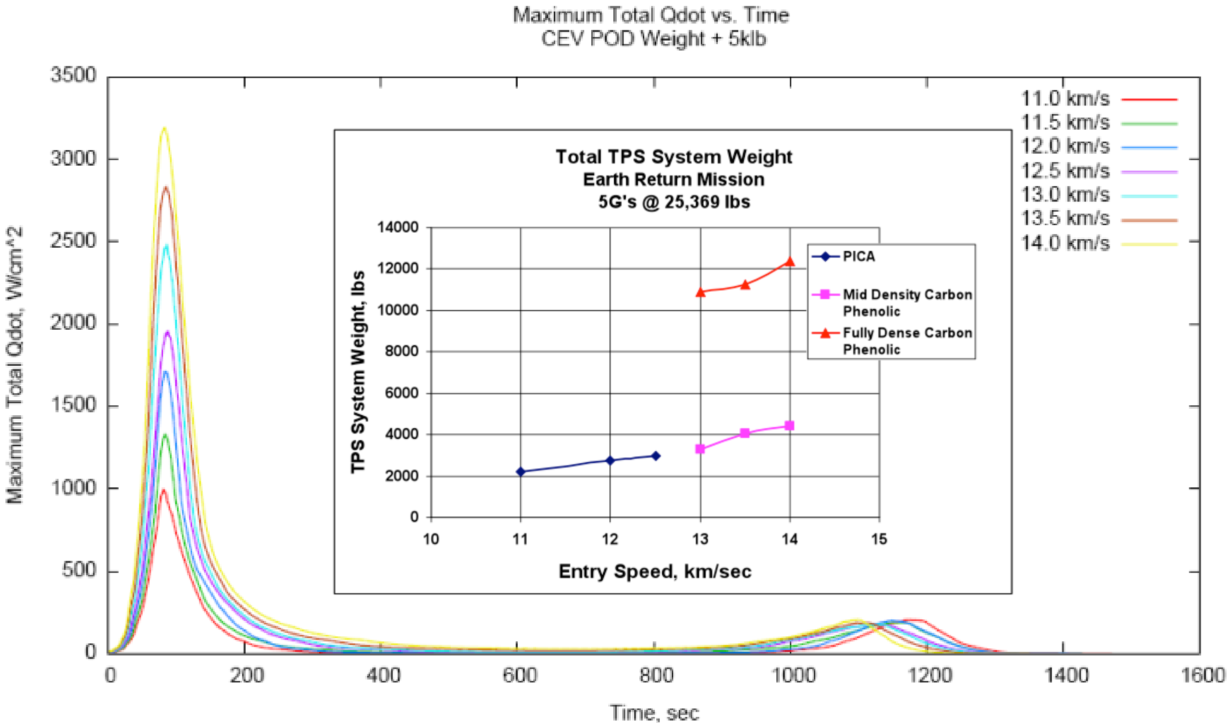

Fig. 14. Plot of entry heating for a "heavy" Orion Vehicle as a function of entry speed. The inset shows the corresponding increase in TPS mass for such entries.

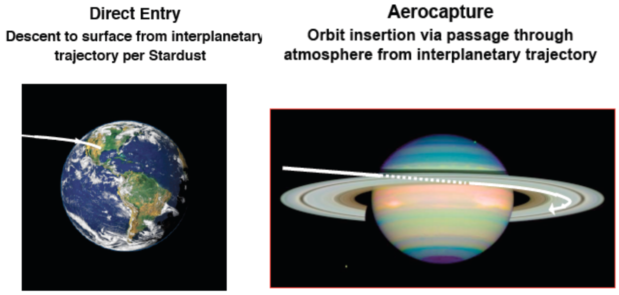

Fig 15. Maneuvers required for future missions.

aerocapture in terms of delivered mass savings for a number of missions have been described in [46]. Examples quoted there by Munk and Kremic for Saturn and Titan are infinite and 280 percent, respectively. Spilker has described [47] an inspirational mission that could be enabled by aerocapture. See Fig. 15, where the vehicle would aerocapture in Saturn's atmosphere and then be inserted into an orbit to observe, close up, the planet's spectacular rings.

The closest the U.S. has come to demonstrating aerocapture occurred during the Apollo 4 test flight where lift was used to increase altitude during a simulated lunar return entry.

During a COSPAR meeting in 2008, Dr. L. Gurvits informed this author that the Soviets had performed aerocaopture with their ZOND 6 and ZOND 7 Lunar return missions in the late 1960's. Later, Gurvits kindly provided documentation and a figure from the Encyclopedia, *Cosmonautics,* [48] that is reproduced in Fig. 16 (translation by Sergey Gorbunov). As can be seen from the figure, ZOND 6 was launched from the Soviet Union, sent on a trans lunar trajectory, circumnavigated the moon, and underwent two mid-course corrections on the return leg. After flying over the South pole, ZOND 6 descended into an entry corridor, skipped out of the atmosphere, entered the atmosphere *again* and then landed on Soviet soil. If a small propulsive burn had been fired, exo-atmosphere, a full aerocapture maneuver would have been accomplished. ZOND 7 flew a similar trajectory.

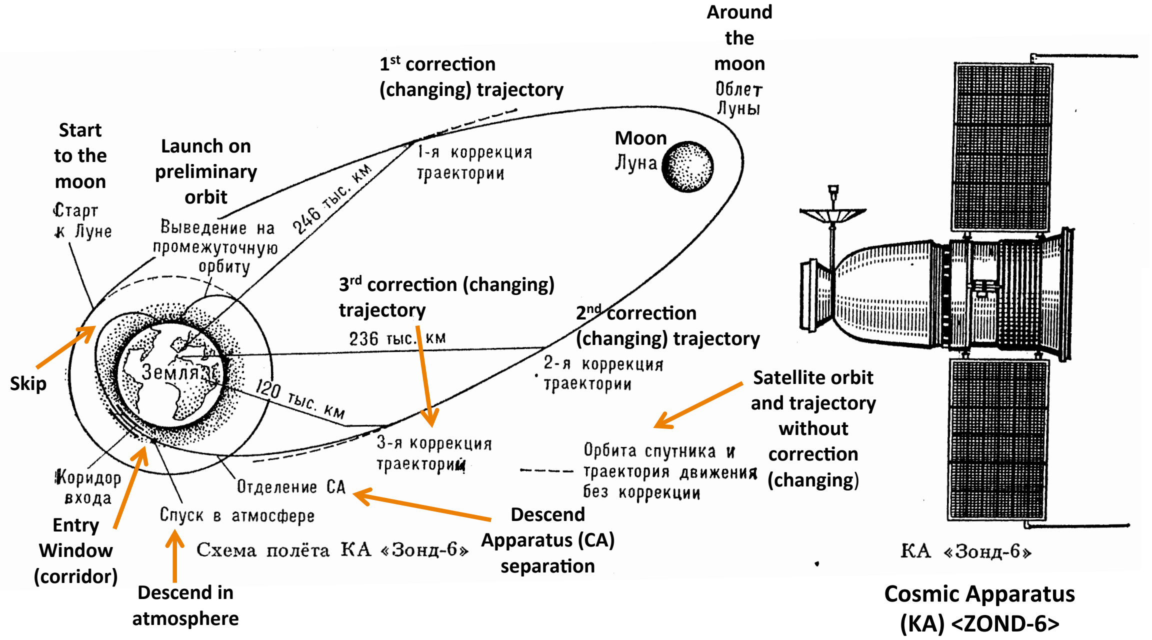

Fig. 16. Zond 6 "Skip" trajectory accomplished by the Soviets in the late 1960's.

It seems to this author that a good understanding of ZOND's success by the current Entry Descent and Landing (EDL) community could help reduce the actual and perceived risks of aerocapture. By analogy to the aerobraking experience with Magellan and its use in subsequent Mars Missions described in section 2.4, perhaps this understanding could encourage mission designers and decision makers to utilize this maneuver for improved efficiencies for future solar system exploration, including the human Mars mission.

6. DEPLOYABLES FOR FUTURE MISSIONS

In recent years, the advantages of systems that are stowed for launch and deployed in space prior to atmospheric entry have led to investments to increase the technical readiness level (TRL) of inflatable [49] and mechanically [40] deployable hypersonic decelerators. The advantage of these systems include factors of ten reduction in deceleration loads that allow use more capable science instruments and similar reductions in heating rates that enable more efficient TPS. Fig. 17 depicts the mechanical deployable known as ADEPT [50]. Arcjet testing [51] has proven that ADEPT's 3 D woven fabric "skin" can serve as both the TPS and structural member that transfers aerodynamic loads to ADEPT's umbrella-like substructure for the ADEPT-Venus mission. That arcjet testing has also shown ADEPT's TPS can function at heating rates up to 256 W/cm^2. A preliminary thermal response model has been developed on the basis of the testing [42,51].

Systems analysis [43] of the Hypersonic Deployable Aerodynamic Decelerator (HIAD) developed by Neil Cheatwood [49] and his colleagues suggests that there are many future missions that could be accomplished with deployables. See Fig. 18. As pointed out in [43] achieving readiness for these missions using HIAD's is dependent upon a third generation, 75 W/cm^2 capable, flexible TPS that is suitable for use with the inflatable HIADs and the assumption that its TPS is non-catalytic.

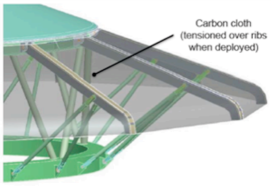

Fig 17. The ADEPT-VITaL mechanically deployable [50]. ADEPT's nose TPS (light blue) is a conventional rigid TPS design.

It is this author's opinion that deployable decelerators will open opportunities to entirely new classes of missions in a fashion that echoes the impact of the original development of the blunt body concept.

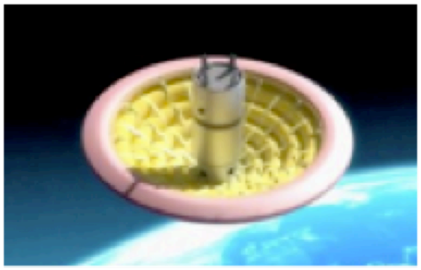

Fig 18 The Hypersonic Inflatable Decelerator concept that has already been flight tested [49].

7. WORDS OF WISDOM FROM "SPACE GIANTS"

Here, the author would like to share a few "Words of Wisdom" from "giants" in the space business that may give guidance to those in the EDL community, present and future. These statements may not have originated with those named, but the author was very impressed by those who said them in his presence

Al Seiff, "Let us turn that problem into a solution."

Hans Mark, "You can judge a research center by the size of its junkyard."

Dean Chapman and Hans Mark, "CFD will replace the need for wind tunnels" – close but not true, yet.

G. S. (Scott) Hubbard as the HQ "Mars Czar," "Follow the water."

Harry McDonald, "When opportunity knocks, don't complain about the noise,"

William F. Ballhaus III, "A research center should always have more on its plate than it can accomplish."

John (Jack) Boyd, "Management is the art of accomplishing things through others."

Tom Young, "In the space business, one strike and you are out." "Test as you fly and fly as you test."

Sally Ride, "I hear echoes of Challenger in Columbia." Have you read the CAIB report?

8. SUMMARY

As depicted in Fig. 2, EDL technology has enabled remarkable accomplishments in Solar System Exploration since the pioneering days of Allen, Seiff, their colleagues and successors. This author believes that the current generation measures up to their 1960's era predecessors. Given adequate resources, it seems likely that they and the following generation can achieve much by 2036; possibly landing humans on Mars, provided the public and the congress see fit to continue the adventures.

Based on this author's experience, suggestions for the current generation involved in solar system exploration EDL are: (1) To meet the challenge of the future, it is important that all involved in the journey understand and mitigate the inherent risks in our work; (2) All those involved should understand the critical nature of facilities for technology development and flight certification so important for mission success and safety, and help facility managers sustain their stewardship; (3) As exemplified by data from the Galileo recession sensors, and recently, the MSL EDL Instrument (MEDLI), flight data are of critical importance for future mission success. Importantly, funding is in place for the post flight analysis of the MEDLI data. This practice should be continued into the future; and finally (4) As exemplified by Alvin Seiff, it is very important for the current generation to mentor the next generation by passing along both their technical and managerial skills to them.

9. RECOMMENDATIONS

(1) The IPPW series is promoting communication between solar system scientists, technology developers, mission managers and decision makers. This work is bearing fruit and needs to be kept up.

(2) More should be done within the IPPW series to promote international collaboration of new missions. Look at the success of Cassini-Huygens as an example of what could be done in the future.

(3) There should be more development of the deployable technology, because it can enable new classes of missions, robotic and ultimately, human Mars exploration.

(4) The current EDL generation should build the tools and data to understand the Galileo Flight Data.

(5) By analogy to the Magellan aerobraking example, there is a need to fully understand the Soviet success with the ZOND skip (aerocapture) missions to help

retire perceived and actual risk for this mission enabling technology. This would be an excellent topic for future IPPW papers.

10. ACKNOWLEDGMENTS

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