ALVIN (AL) SEIFF: THOUGHTS ABOUT AND LESSONS FROM A GREAT ENGINEER

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ABSTRACT

Alvin (Al) Seiff was known as a world-class atmospheric scientist during the last three decades of his life. Equally deserving, however, were his prior achievements as an innovative engineer, an exceptional technical manager, and a mentor of young engineers at NASA Ames Research Center. This paper outlines Al's role in developing Ames' ballistic range facilities, probably the most advanced in the world at that time, and his seminal 1963 report that contained the concepts used to reconstruct the atmospheres of Mars, Venus, Jupiter and Titan. Also discussed is my affiliation with Al after he hired me in 1962, including our joint work on Mars missions and investigating the feasibility that a Jupiter probe could survive entry, work that eventually led to the development of the Galileo probe. Finally, suggestions are offered for speeding the analysis and design of thermal protection systems based on lessons learned from successful probes and landers.

1. INTRODUCTION

Alvin (Al) Seiff (Fig. 1) was a multi-talented person who made major contributions in every field that he worked in. Although Al was known primarily as an outstanding atmospheric scientist during the latter part of his nearly 58 year long career, he was also an exceptionally innovative engineer and a fine technical and personnel manager. His interpersonal skills are reflected in his mentoring of young researchers, many of which rose to high technical and managerial positions. Al graduated with a degree in Chemical Engineering during World War II at the age of 20. He worked for a government agency and taught at the University of Tennessee prior to joining Ames Research Center in 1948. He retired from Ames in 1986, but became an Ames Research Associate and continued his work under the auspices of the San Jose State University Foundation until his passing in December 2000. In his personal life, Al was a skilled musician who enjoyed playing chamber music and jazz with a small group of friends and acquaintances. Both on a personal and professional level, Al was a gentleman in the finest sense of that word.

Al used his strong background in gas dynamics, aerodynamics and dynamics to develop the concept that measurements made on-board an entry probe could be used to reconstruct the atmosphere's properties. The concept was eventually flight-tested at Earth, and its complete success led to its application on-board multiple planetary probes. The results of Al's ideas led to a vast increase in our knowledge of the atmospheres of Mars, Venus, Jupiter and Saturn's moon, Titan.

I became acquainted with Al when he hired me in the fall of 1962 to work in his Branch at NASA-Ames. I was fortunate to work directly with him on an early study of the atmospheric entry problem encountered by a human mission to Mars and on return to Earth. Later, he asked me to investigate the likelihood that a probe could survive atmospheric entry at Jupiter at a speed of nearly 60 km/s. This work eventually led to development of the Galileo probe, and I will mention a lesson learned from that mission.

Lastly, I will discuss some simple engineering concepts and observations that can be used to save time and effort during the initial analysis and design of heat shields for entry probes.

Fig. 1. Al Seiff (1973)

2. AL SEIFF AS ENGINEER, MANAGER, AND ATMOSPHERIC SCIENTIST

Al's career spanned nearly six decades and many technical and scientific disciplines. He was an articulate and prolific writer with approximately 200 publications. Because lack of time and space preclude discussing and listing his many contributions, only the briefest discussion of Al's career and a tiny sampling of his output will be presented here.

2.1 Ballistic Ranges

In 1957, Al was appointed Chief of the Supersonic Free-Flight Branch, that later became the Hypersonic Free-Flight Branch. The primary test facilities of the branch were ballistic ranges, consisting of light-gas guns that were used to launch small models up to about 8 km/s into still air. The velocities could be further increased up to a relative speed of about 13 km/s, by launching the models into the oncoming air stream from a hypersonic shock tunnel that was located at the opposite end of the ballistic range (Ref. 1). Optical techniques were used to photograph the models during flight and measure their attitudes, deceleration, ablation, etc. (Ref. 2). The facilities yielded unique data for lift, drag, dynamic stability, boundary layer transition and aerodynamic heating at speeds and under conditions not available by any other means (Ref. 3-5) and helped make Ames the NASA lead center for entry technology.

2.2 Atmospheric Reconstruction

When designing entry probes and their heat shields, especially, it is essential to know as much as possible about the atmosphere of the target planet. Al devised an ingenious method of obtaining such data during the early entry missions so that subsequent ones could benefit from the information.

Al's concepts for reconstructing atmospheric properties from on-board measured data during entry were first published in his 1963 NASA Technical Note D-1770 (Ref. 6). A summary of his basic concepts follows below. It is impossible to measure the pressure and temperature directly because of the extremely high temperatures of the shock layer that surrounds the probes during entry. However, by measuring the probe's deceleration history along three-axes and knowing the drag coefficient as a function of angle of attack from ground facility tests or CFD, enables one to calculate the ambient atmospheric density as a function of time. Since the probe's initial velocity and flight path angle at entry are known from deep-space tracking, the velocity during entry can be computed as a function of time from the axial deceleration. With the above information, the corresponding altitude is found by integrating the vertical component of the velocity. Having defined the density as a function of altitude permits one to calculate the ambient pressure from the equation of hydrostatic equilibrium. The atmospheric temperature profile is computed from the equation of state, once the mean molecular weight has been determined from mass spectrometry (Ref. 7).

A series of tests were conducted in the 1960s to demonstrate and verify the method. Initially, models were dropped from a helicopter, followed by a high-subsonic drop from an airplane and finally from a balloon at 40 km altitude. The successful culmination of the tests was the PAET, Planetary Atmosphere Experiments Test, which consisted of a 6.6 km/s entry into the Earth's atmosphere of a fully instrumented probe in 1971 (Ref. 8). The success of PAET led to the application of the technique to at least nine entry vehicles, consisting of three at Mars (Ref. 9) (Viking 1 and 2 and Mars Pathfinder), the four Pioneer-Venus probes (Ref. 10), the Jupiter Galileo probe (Ref. 11) and Huygens at Saturn's moon, Titan (Ref. 12). In all cases the experiments worked flawlessly and valuable scientific data were obtained. In addition, the atmospheric information that was gained has been and will continue to be used to facilitate the design of future probes and landers. Al's measurement concepts and his meticulous analysis of the data caused him to be considered the foremost expert on the atmospheric structures of Mars, Venus and Jupiter. The results of his work set the standard and are used by the scientific community worldwide.

2.3 Human Mars Missions

In 1962 while I was working at Boeing, Al hired me to work in his Hypersonic Free-Flight Branch. It was a move that offered me unprecedented research opportunities. Within a few months, Al was promoted to Chief of what became the Vehicle Environment Division. At that time, the Apollo lunar landing program was still in its infancy. Nonetheless, the Mission Analysis Division at Ames was already studying human missions to Mars; a (optimistic!) 1975 launch date was assumed. One major conclusion of the study was that using atmospheric braking instead of retro propulsion at Mars could reduce the initial launch mass by about 50%. With that incentive, Al asked me to work with him on the heating problems posed by entry at Mars and on return to Earth while observing a 10g deceleration limit, thought to be sustainable by a human crew.

As entry speeds increased above that for orbital return, radiative heating became a major concern. Ames Assistant Director, H. J. (Harvey) Allen was well known already for having proposed, in the early 1950s, the use of blunt bodies to limit entry convective heating. In the early 1960s, Harvey Allen showed that the oblique shock waves formed by conical bodies produce much lower shock layer temperatures, and thus much less radiative emission, than the shock layer of a blunt body; this concept offered a means to control the radiative heating on the conical frustum (Ref. 13). Because ballistic range tests at speeds representative of Mars entry and Earth return (Ref. 14) had yielded very high radiative heating rates, conical bodies were actively studied for human Mars missions. The composition of the Martian atmosphere was largely unknown in the early 1960s. Approximately 10 mb of carbon dioxide had been identified near the surface, but a large amount of nitrogen was assumed to be present also. Therefore, nitrogen-rich gas compositions were used in tests to simulate the Mars atmosphere, resulting in large amounts of radiation from the excessively high concentration of CN molecules.

The high drag coefficient that results from a large cone angle is needed to shorten the duration of the entry heating pulse. However, the shock layer temperature and thickness both increase with cone angle and radiative emission increases non-linearly with temperature. Additionally, the requirement to limit the maximum deceleration to 10g resulted in an interesting optimization problem. Our understanding of and data for heat shield materials was somewhat simplistic; we considered only Teflon, vaporizing quartz and graphite. However, we did prove that, theoretically, the heat shielding problems were manageable over a wide range of entry conditions. I did the calculations under Al's guidance and he wrote the text and I presented my first paper at a national meeting of the AIAA (Ref. 15). Subsequently, we published two more papers together on similar topics (Ref. 16 and 17). It was a great privilege for a young engineer like me to be able to work on and author papers with Al, who was the Division Chief.

2.4 Jupiter Probe Study

In about 1966, the scientific community expressed strong interest in a probe mission to Jupiter. Al asked me to look at the feasibility that a probe could survive entry into the giant planet. When I calculated the entry speed and found that it was nearly 60 km/s, I went to Al's office and told him that the mission was infeasible. (To put the Jupiter entry in context, one should recall that at this time NASA still had some problems with the Apollo lunar return capsule's heat shield that was designed for an 11 km/s entry speed.) In his usual patient manner, Al's response was that I should not prejudge the problem, but perform the best analysis that was possible under the circumstances. When discussing the composition of Jupiter's light-gas atmosphere, we decided that I should consider hydrogen, helium and several mixtures of these gases. (From a 1953 photometric measurement of a stellar occultation by Jupiter's atmosphere, a mean molecular weight of 3.3, with an uncertainty of about plus or minus 1, had been derived previously in Ref. 18.) Although some information on thermodynamic and transport properties of helium and hydrogen was available, there was none on the mixtures. Therefore, I gave a modest contract to a post-doctoral fellow at Stanford University to compute high-temperature properties of two gas mixtures. Knowledge of the high-temperature gas properties was essential to computing the radiative emission and the Reynolds numbers, since boundary layer transition was based on the latter.

It soon became apparent that we should take advantage of Jupiter's high equatorial velocity by entering the planet in that region in the direction of planetary rotation and at a shallow flight path angle; doing so would reduce the relative entry velocity by 20%. The resulting reduction in laminar convective heating would be about 50% and the benefits would be even greater for turbulent and radiative heating. Therefore, the entry speed was limited to 50 km/s in most of my calculations. A carbonaceous ablator was assumed and the non-adiabatic nature of the massively radiating shock layer was accounted for. Briefly, it was found that in a helium atmosphere the maximum heating rate with ablation was excessively high, being over 50 kW/cm^2. In contrast, the maximum heating rate in a pure hydrogen atmosphere was a relatively modest 5 kW/cm^2. The results of the study were presented at an AIAA conference in late 1968 and published the following year (Ref. 19).

With Al's encouragement, the Jupiter probe study was refined. One major difference was using primarily a more realistic atmospheric volumetric composition of 85% hydrogen and 15% helium. (In retrospect, this mixture proved to be remarkably close to the 86.3% H_2 and 13.6% He measured 25 years later by the Galileo probe.) Additional major refinements consisted of accounting for the blockage effects of shock layer radiation by ablation products near the wall, and using a charring ablation material code to compute heat shield mass fractions, including insulation thickness, by my co-author, Roy Wakefield. A range of flight path entry angles were investigated and it was found that shallow entries minimized the heat shield mass fraction, as also confirmed by Ref. 20. A minimum forebody heat shield mass fraction, without any margins, of one-third was found. (The corresponding as flown value, including all margins, for Galileo was 45%.) The final results of our study were presented at an AIAA meeting in the fall of 1970 and published in 1971 (Ref. 21). It was gratifying that our most important findings were subsequently applied in the design of the Galileo probe.

Unfortunately, during a center-wide reorganization, Al Seiff's Vehicle Environment Division was abolished in 1972. Al relinquished his managerial duties and became a full-time atmospheric scientist, and I was transferred to the Aeronautics Division. However, I never lost my interest in problems of atmospheric entry and wrote and coauthored a number of papers on my own time, on this and related topics. Also, I tried to maintain an active interest in the Jupiter probe and served on review boards, etc.

3.0 GALILEO PROBE

The design and manufacture of the Galileo probe's heat shield involved several NASA Centers and industrial organizations. Chief among these were Ames, Langley, General Electric and Aerotherm. The primary analysis, design and construction of the Galileo probes heat shield was done starting in the mid-1970s and completed by 1983. The entry into Jupiter was in December 1995, after a six year- long journey. The probe was a blunted 45 deg angle cone with a maximum diameter of 1.26 m and a mass at entry of 335 kg. A cross-sectional sketch of the probe is shown in Fig. 2, as are the entry conditions at an altitude of 450 km above the one bar atmospheric pressure level. The stagnation point maximum heating rate in the absence of ablation was 61 kW/cm^2, of which two-thirds was radiative and one-third laminar convection. However, the massive ablation reduced the radiative heating to a peak value of 16.5 kW/cm^2 and essentially eliminated the convection. Of great value to the engineering community, were five sets of surface recession gages that were embedded in the forebody's heat shield. The gages were located symmetrically about the centerline, with one set on the blunt nose and the remaining four sets on the frustum. From the recessions measured by the gages, it was calculated that about 24% of the probe's entry mass, or at least 80 kg of the forebody's heat shield, was vaporized during entry (Ref. 22).

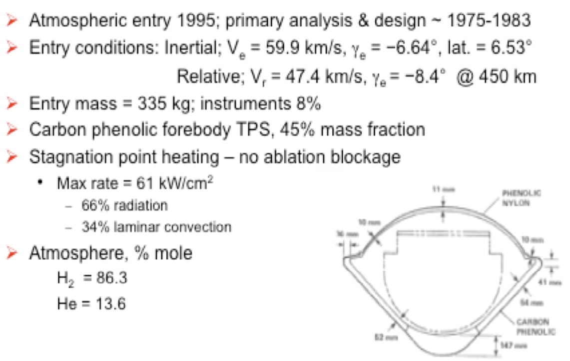

Fig. 2. Galileo probe design and entry conditions

It was a great achievement, that the probe survived entry and returned valuable scientific and engineering data. However, concern arose that the surface recession on the cone's frustum, where most of the body's surface area is located, was under predicted by 20-23%, or by about 27% of the ablated mass, during the design stage. Although the frustum experienced much less radiative heating than the stagnation region, it was exposed to severe turbulent boundary layer heating and shear. The heating pulses at the approximate centroid of the frustum's surface area are shown in Fig. 3; the rates shown were based on calculations using Ref. 23. The peak value of the sum of radiative and turbulent convective heating approached 28 kW/cm^2 in the absence of ablation, but with ablative vapor blockage the maximum total heating rate was reduced to 12 kW/cm^2. Note that radiative heating accounted for about 40% of the heat load, while the turbulent convective heating pulse lasted much longer and was responsible for about 60%. When the probe's carbon-phenolic heat shield material was exposed to heating rates comparable to those during Jupiter entry, it was found that the material spalled, i.e., mass was lost by thermomechanical erosion, in addition to the expected vaporization. The test results are presented in Fig. 4 (Ref. 24) and show a 30% reduction in the ablator's effectiveness at peak heating. An additional problem that accompanies spallation is an increase in surface roughness, thus further enhancing turbulent heating rates and shear stress. Since the test results were not available at the time the probe's heat shield was being designed and built, the multiple deleterious effects of spallation were not fully accounted for. Therefore, the ablative mass loss was significantly under predicted.

So far, I have concentrated on historical events and past missions. In the following section, a few lessons learned will be presented in the hope that these can be applied to improve the efficiency of future mission studies and the design of entry probes and landers.

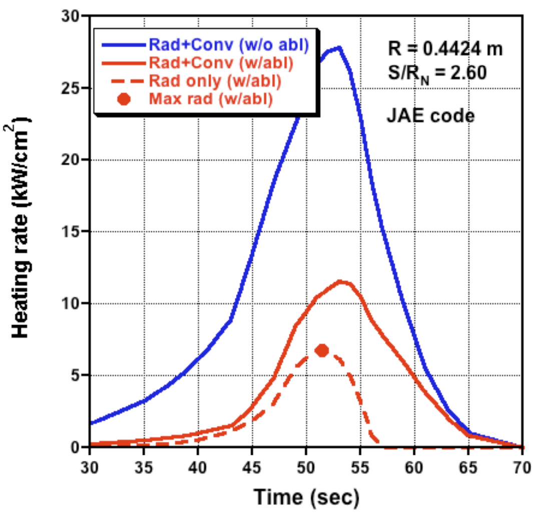

Fig. 3. Galileo probe cone frustum heating including effects of ablation

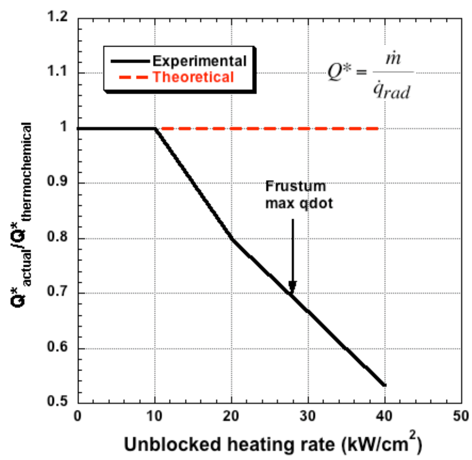

Fig. 4. Effective heat of ablation of carbon phenolic at high heating rates

4.0 MAKING PROBE STUDIES AND DESIGN MORE EFFICIENT

Ballistic entries are characterized by three sets of parameters. These describe the body, the flight path and the atmosphere and are, respectively, the ballistic coefficient, m/C_dA, the entry velocity, V_e and flight path angle, and the atmospheric composition and density structure. We will concentrate here on the effect that the ballistic coefficient has on the heat load and thus the heat shield mass. In Ref. 20, it was shown that the heat load is proportional to the ballistic coefficient to the n power, $(m/C_dA)^n$, where n is the exponent on the free-stream density in the simplest form of the heating rate expression (see Fig. 5). Note that n=0.5 for laminar flow, 0.8 for turbulent flow and always exceeds 1 for radiative heating. Therefore, for high-speed entry bodies that experience turbulent convective heating and significant radiative heating, the ballistic coefficient has a very large influence on the heat load and heat shield mass.

Entry trajectory $$-\frac{dV}{dt} = \frac{D}{m} = \frac{1}{2\rho_1 V_1^2}\left(\frac{C_D A}{m}\right)$$

and heating $$\frac{dq}{dt} \sim \rho_1^n V_1^m$$

and heat load $$q \sim \left(\frac{m}{C_D A}\right)^n$$

Boundary layer; lam n = 0.5, turb n = 0.8
Radiation; inner planets n = 1.19-1.22
Radiation; outer planets n = 1.17-1.45

But $$\frac{m}{C_D A} = \frac{(density)(vol.)}{C_D A} = \frac{(density)f(d)}{C_D}$$

Fig. 5. Effect of ballistic coefficient on heat load

4.1 Initial Estimates of Ballistic Coefficients

In the early stage of an entry probe study, frequently few details are available about the body's size and mass. Therefore, it is typical to use a matrix of ballistic coefficients in the trajectory codes (for example, Ref. 25) that usually also calculate the stagnation point heating rates and may have an option to calculate a heat shield thickness for a specified material. Although the codes are very fast, it may become a time consuming task for the user to evaluate the output and extract the physically realistic cases. The process of finding a realistic narrow range of ballistic coefficients can be speeded up by using information from similar past probes (Ref. 26). This information can be used to determine a representative average body density (see Fig. 6) that when combined with an approximate body size and geometry, i.e., cone angle (see Fig. 7) for a similar mission, can yield an approximate, but realistic, ballistic coefficient. Note that the average densities for two groups of probes are shown in Fig. 7. For probes that experience high heating rates and turbulent boundary layer shear such as Galileo and Pioneer-Venus, very dense heat shield materials (for example, 1450 kg/m^3 carbon-phenolic), are needed that are about three times denser than the remainder of the body. (For example, the over-all density of the Galileo probe, including its massive heat shield, was in the vicinity of 1000 kg/m^3.) Therefore, the heat shield mass must be estimated, by an iterative process, for a given body size and added to the mass found from using Fig. 7, to find an approximate total body mass. However, the probes shown on the right-hand side of Fig. 7 had heat shields with densities that were comparable approximately to the remainder of the body. Therefore, the heat shield was included in calculating the probes' over-all densities.

4.2 Mass Increase from Inception to Launch

Most bodies, including human ones, gain weight as time progresses and planetary entry probes are no exception. The earlier in the analysis and design process estimates of the mass gain are accounted for, the more time and expense can be saved later. The database on mass growth is both limited and imprecise. However, the missions that I am familiar with fell into two broad groups.

Those in group number one experienced a modest mass growth of about 20%. This group consisted of vehicles that could draw on the heritage of previous, similar, successful missions. Examples of this group were the Mars Exploration Rover landers and the current Mars Science Laboratory.

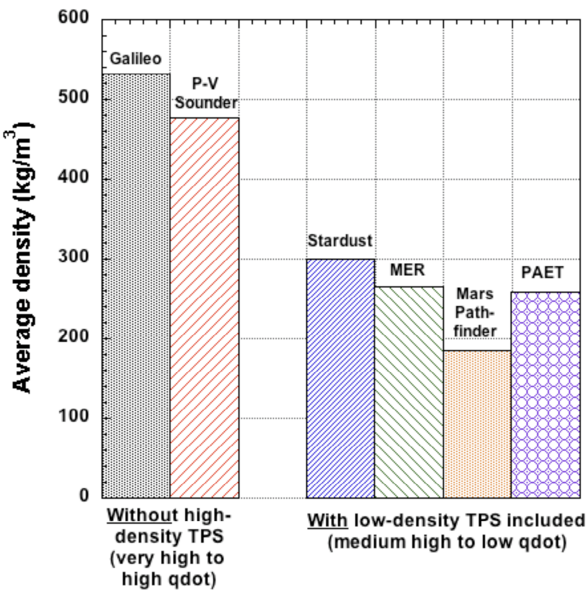

Fig. 6. Average density of entry probes

Cone Angle	Planet(s)	V_E km/s	Atm.	Press. Vessel	Max. Heating w/o Ablat. kW/cm2	Rel. Time	C_D
70°	Mars	6-7	Thin triatom.	no	Low (~0.1)	short	1.7
60°	Earth	11-13	Med. Diatom.	no	Med (~1.0)	Med.	1.5
45°	Venus	11-12	Dense triatom.	yes	High (~5.0)	Very long	1.0
45°	Jupiter	48	Med. Diatom.	yes	Severe (~50.0)	long	1.0
45°	Other outer planets	25-30	Med. Diatom.	yes	High (~5.0)	Very long - long	1.0

Fig. 7. Cone angle choices

By contrast, the second group consisted of new, or significantly more difficult missions. These had mass growths in the neighborhood of 60%, for a variety of reasons. One example was the Galileo probe that entered a poorly defined atmosphere at an unprecedented speed and experienced extreme heating rates. Since the heating could not be adequately simulated, understanding of the heat shield material's response was limited. To some degree, the Pioneer-Venus probes may have been in a similar category.
Another example was the Stardust sample return capsule that made the highest speed entry yet at Earth and used a new heat shield material. Another reason for a large increase in mass can be due to a change in the mission objective(s). An example was the Mars Pathfinder that originally began as a basic meteorological mission, but became much more complex when the rover was added. Although Mars Pathfinder was not the first lander, its direct entry was 70% faster than those of the Vikings that entered from orbits two decades previously.
It would be very useful if additional data on mass growth became available, especially from non-US missions about which I know few details.

5.0 CONCLUDING REMARKS

The methods conceived, tested, and implemented by Al Seiff to reconstruct the atmospheres of Mars, Venus, Jupiter and Titan have greatly increased our knowledge of these heavenly bodies. Furthermore, the detailed atmospheric information that became available has and will continue to facilitate designing lighter, more efficient heat shields for entry vehicles, thereby increasing the mass that is potentially available for scientific instruments and data return. Remarkably, Al remained productive to the end of his life; his last paper was published in Nature (Ref. 27) just ten months before his untimely passing.
It was my good fortune that Al hired me in 1962 and to have worked under and with him for a decade. Our association enriched my professional development and later my personal life during the 38 years that I was privileged to have known Al Seiff.

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