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Aerobraking Cost and Risk Decisions

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Four missions have successfully employed aerobraking at Venus and Mars to reduce the spacecraft orbit period and achieve the desired orbit geometry. The propellant mass reductions enabled by the aerobraking technique allow the use of smaller launch systems, which translate to significant savings in launch costs for flight projects. However, there is a significant increase in mission risk associated with the use of aerobraking. Flying a spacecraft through a planetary atmosphere hundreds of times during months of around-the-clock operations places the spacecraft in harm's way, and is extraordinarily demanding on the flight team. There is a cost/risk trade that must be evaluated when a project is choosing between a mission baseline that includes aerobraking, or selecting a larger launch vehicle to enable purely propulsive orbit insertion. This paper provides a brief history of past and future aerobraking missions, describes the aerobraking technique, summarizes the costs associated with aerobraking, and concludes with a suggested methodology for evaluating the cost/risk trade when considering the aerobraking approach.

I. Introduction

AEROBRAKING is a proven approach for shaping planetary orbits, using aerodynamic drag from the planetary atmosphere to slow the spacecraft and gradually lower the vehicle apoapsis. The propellant savings that can be garnered using this technique are substantial; the Mars Global Surveyor (MGS) and Mars Odyssey missions both saved in excess of 300 kg of propellant via aerobraking. The Mars Reconnaissance Orbiter (MRO) project recently realized a propellant savings of 580 kg through aerobraking to the final science orbit in 2006.

The propellant mass reductions enabled by the aerobraking technique allow the use of smaller launch systems, which translate to significant savings in launch costs for flight projects. However, launch cost savings are offset by the costs associated with the planning and execution of the aerobraking phase. There is also a significant increase in mission risk associated with aerobraking. Flying a spacecraft through a planetary atmosphere hundreds of times during months of around-the-clock operations places the spacecraft in harm's way and is extraordinarily demanding on the flight team. There is a cost/risk trade that must be evaluated when a project is choosing between a mission baseline that includes aerobraking, or selecting a larger launch vehicle to enable purely propulsive orbit insertion. This paper suggests a methodology for evaluating this cost/risk trade.

An overview of past and future aerobraking missions, including Magellan, MGS, Odyssey, and MRO is provided in Sec. II. A technical description of the aerobraking technique is given in Sec. III. Key aerobraking risk areas are discussed in Sec. IV, and a straw-man probabilistic risk assessment for a generic aerobraking mission is given. Aerobraking costs are discussed in Sec. V, using Mars Odyssey as an example. Section VI describes an approach for evaluating the cost/risk trade associated with aerobraking versus the selection of a larger launch vehicle. Conclusions are given in Sec. VII.

II. Past and Future Use of Aerobraking

Four missions have successfully used aerobraking to reduce the orbit period and achieve the desired orbit geometry. In 1993, after the Magellan primary science mission was completed, aerobraking was performed to nearly circularize the orbit to enhance subsequent scientific data. This mission proved that substantial modifications to the vehicle would not be required to perform aerobraking. Operational procedures were developed and validated by the Magellan flight team, and substantial experience was gained. The Mars Global Surveyor in 1997 and Mars Odyssey in 2001 launched with propellant deficits and relied upon the aerobraking technique to lower the orbit apoapsis to the desired altitude for the science mission. The propellant savings provided by aerobraking allowed these missions to launch on Delta II 7925 launch vehicles, providing a significant cost savings relative to the larger launch vehicles that would have been required if purely propulsive orbit insertion had been required. Most recently, the Mars Reconnaissance Orbiter completed a 6-month aerobraking phase before the start of the science mission in 2006. Table 1 provides a summary of the key attributes of the pre- and post-aerobraking orbits for these missions, and their effective propellant savings via aerobraking.

A. Magellan

The Magellan spacecraft was launched from the space shuttle in May of 1989. An inertial upper stage injected the spacecraft onto the interplanetary trajectory for arrival at Venus in August 1990. The orbit insertion burn was performed by a Star 48B solid rocket motor. Magellan was placed into an elliptical orbit with an orbit period of 3.2 h. The relatively high eccentricity of this orbit compromised some of the science return during the prime mission. For the first three Venus years, the synthetic aperture radar was used to obtain a global map of the surface.

The desire to obtain higher resolution gravity maps in the polar region led to the 70-day aerobraking phase from late May to early August 1993 [1]. Magellan used atmospheric drag to accomplish a velocity change (DV) of over 1200 m/s to the orbit, achieving a lower eccentricity 540×200 km altitude orbit with a period of about 1.6 h. The Magellan spacecraft is shown in Fig. 1. During aerobraking, the large high gain antenna (HGA) was trailing the spacecraft bus, and the solar arrays were set normal to the

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Table 1 Aerobraking orbits and propellant savings

Mission	Spacecraft dry mass, kg	Pre-aerobraking orbit			Post-aerobraking orbit			DV savings, m/s	Propellant savings, kg
		h_p, km	h_a, km	Period, h	h_p, km	h_a, km	Period, h		
Magellan	1035	170	8,450	3.2	200	540	1.6	1220	490
MGS	677	120	54,200	45	110	430	1.9	1220	330
Odyssey	380	110	26,200	18	120	540	2.0	1090	320
MRO	968	110	44,000	34	120	500	1.9	1190	580

aerodynamic flow. The large area of the HGA moved the center of pressure aft of the center of mass, providing substantial longitudinal stability while in the atmosphere.

Based on pre-aerobraking estimates of 50% orbit-to-orbit variability, the aerobraking dynamic pressure corridor was set between 0.27 and 0.32 N/m^2. The upper boundary of the corridor was limited by the maximum temperatures for solar array solder joints and the potential for HGA delamination. The lower limit was set by the desire to finish aerobraking in less than 100 days and constrain the number of orbit trim maneuvers (OTM) needed to stay within the corridor. Early drag passes showed orbit-to-orbit density variations of less than 20% and lower than predicted solar array temperature increases due to aerodynamic heating, so the main phase corridor limits were increased to 0.29 and 0.35 N/m^2. The corridor and periapsis altitude during the mission [2] are shown in Fig. 2. Fourteen OTMs were required to perform the 70-day aerobraking mission.

Magellan was intentionally entered into the atmosphere for the last time on 12 October 1994. The success of the Magellan aerobraking phase is a credit to the engineers that developed this new technique to maximize the science return from the mission and develop an enabling technology for the future. Many processes and lessons learned from the Magellan aerobraking phase have served as the building blocks for subsequent Mars aerobraking missions.

B. Mars Global Surveyor

The MGS was the first planetary spacecraft to rely on aerobraking as an enabling technology for mission success [3]. The MGS aerobraking configuration is shown in Fig. 3. Drag flaps were incorporated at the end of each solar array, to increase the overall drag surface of the vehicle. In the aerobraking configuration, the solar arrays were to be swept 30 deg to assure aerodynamic stability, and rotated so that the solar cells were on the downstream side of the array.

During deployment of the solar array following launch on 7 November 1996, it was noted that one array did not fully deploy and was tilted about 20 deg from the fully deployed and latched position. After the Mars orbit insertion in September 1997, the aerobraking phase began. On the early aerobraking orbits, the deflection of the array was noted and was within the few degrees expected based on the best estimates of the failure mode at that time. On orbit 15, the density of the atmosphere was twice the prediction and the array deflected about 10 deg, well beyond the expected value. Analysis of flight data and experiments performed on the flight spare led to the conclusion that the composite sheets on one side of the yoke, at the base of the array, had failed in compression and only the face sheets on one side (and perhaps some wires and aluminum honeycomb) were holding the solar array to the spacecraft. Based on this failure mode, it was determined that aerobraking could continue if the broken solar array was rotated with the cells into the flow. This configuration limited aerobraking to about one-third of the originally planned dynamic pressure. The aerobraking phase successfully ended about one year later than planned. The extension in the aerobraking phase duration resulted from the time allocated to troubleshooting activities, replanning of the aerobraking phase, resynchronization of the orbit so that the desired 1400 hrs local solar time would be reached, and slower aerobraking due to the reduced dynamic pressure limitation.

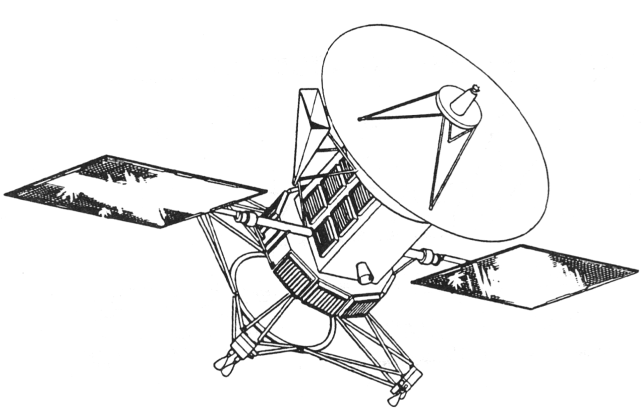

Fig. 1 Magellan spacecraft.

The early phases of MGS aerobraking showed that the statistical orbit-to-orbit density variation was about 30% 1σ, consistent with expectations. Changes of 100% or more occurred over small spatial scales during a single orbit. A regional dust storm occurred in Noachis Terra in November 1997, producing a density increase exceeding 100% from one orbit to the next. This increase occurred over all longitudes at 50° N, the latitude of periapsis. The disturbance slowly decayed over about 75 days. MGS also encountered unpredicted planetary longitudinal waves with maximum-to-minimum density ratios greater than 3. These longitudinal waves are propagated from the lower atmosphere and are influenced by surface topography.

C. Mars Odyssey

The Odyssey aerobraking configuration is shown in Fig. 4. This configuration provided strong aerodynamic stability about the body z axis, which nominally pointed toward the center of Mars during aerobraking. The relative wind is along the Y_M direction. The solar array cells were oriented away from the flow to minimize cell heating.

After orbit insertion on 24 October 2001, the orbital period was 18.6 h. The goal of aerobraking was to reduce the orbit period to 2 h within a 90-day period to assure the proper local solar time in the final science orbit [4]. The reference orbit period decay profile, developed just after orbit insertion, is shown in Fig. 5. Also shown is the actual orbital period reduction profile achieved during aerobraking. The 70% 2σ orbit-to-orbit variations in density anticipated from MGS were clearly present again. The actual orbital decay fell about 50 min behind the target at orbit 75. This was a result of the orbit periapsis precessing toward the North Pole and passing through the highly variable boundary of the polar vortex. While inside the vortex, the variability was substantially lower and aerobraking could be performed more aggressively, so that by orbit 245 the actual orbit period was 13 min ahead of the plan. After 77 days, aerobraking ended on 11 January 2002, 13 days shorter than the expected 90-day phase duration. The processes and methodologies developed by Magellan and MGS allowed Odyssey aerobraking to be performed flawlessly.

D. Mars Reconnaissance Orbiter

As shown in Fig. 6, MRO was the first spacecraft to have a significantly asymmetric aerobraking geometry relative to the flowfield. Drag from the HGA produced a bias in the equilibrium

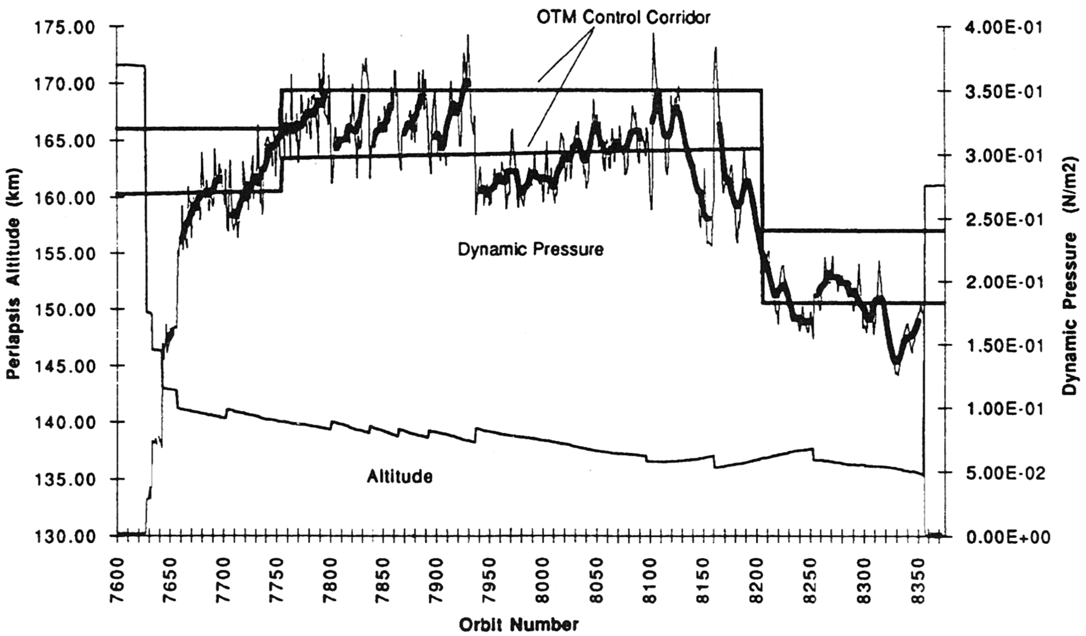

Fig. 2 Magellan dynamic pressure and control corridor.

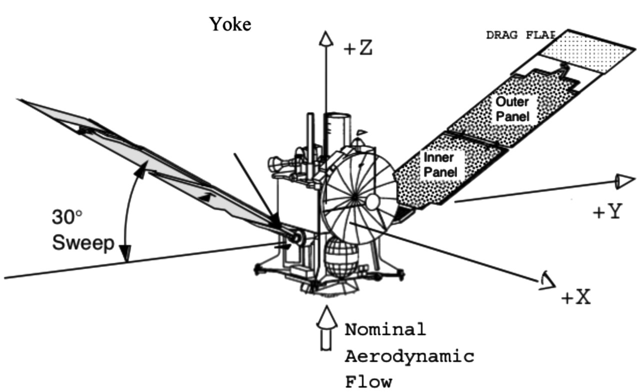

Fig. 3 Mars Global Surveyor in aerobraking configuration.

angle of attack but increased the pitch stability. To achieve the desired local solar time for the science orbit, the aerobraking phase lasted 6 months. As a result, MRO aerobraking heating rates were considerably lower than Odyssey and more like the MGS phase two (post-redesign) aerobraking limits. Odyssey maximum heat rate safety margins were about 100% in the main phase of aerobraking, whereas the MRO margins were about 200%. MRO contributed a major advancement in the movement toward autonomous aerobraking by using onboard measurements to update the aerobraking sequence. The number of temperature sensors on the solar arrays has been increased beyond earlier missions and the locations were strategically placed so that the data will provide validation of aerodynamics and heat transfer methods. These data should provide improved confidence in safety margin calculations.

III. Aerobraking Operations Overview

Aerobraking operations is a highly orchestrated process, requiring close interaction between the navigation team, spacecraft team,

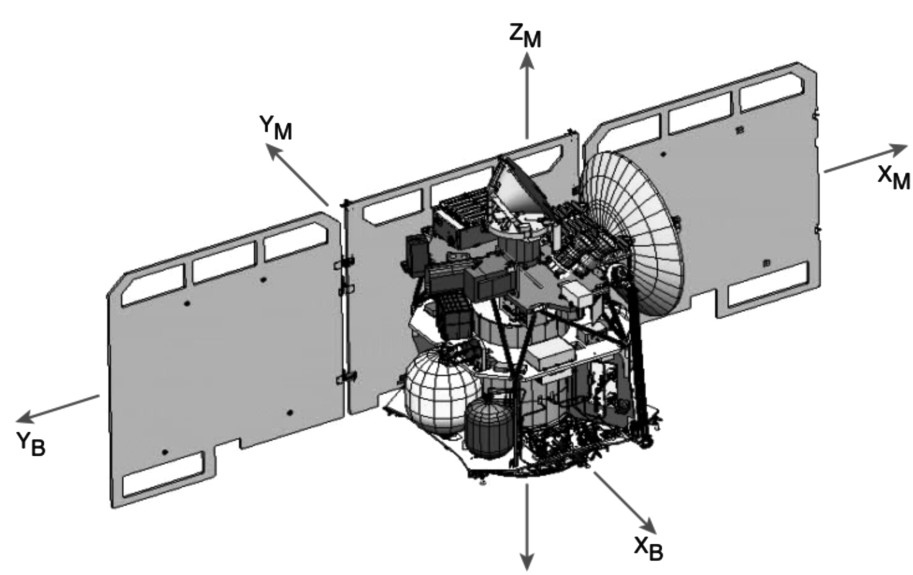

Fig. 4 Mars Odyssey aerobraking configuration.

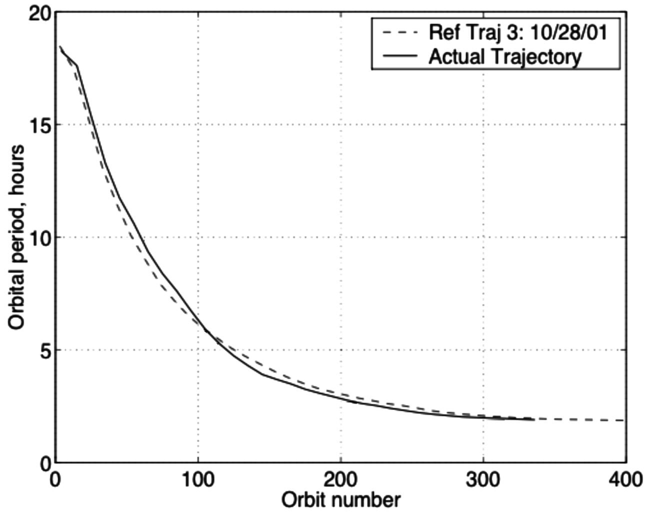

Fig. 5 Odyssey orbit period plan versus actual.

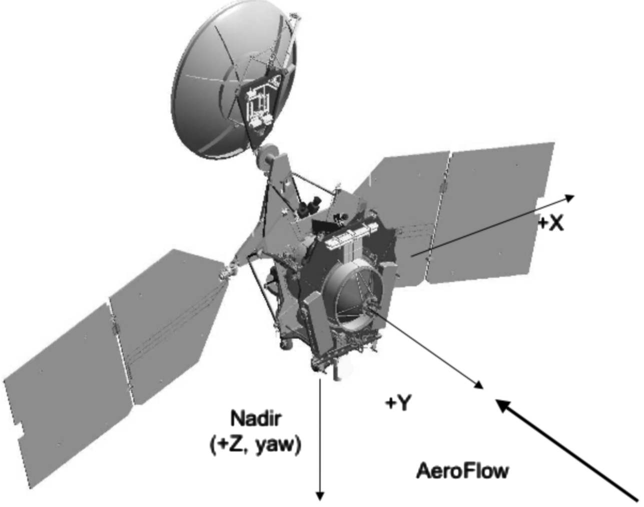

Fig. 6 MRO aerobraking configuration.

atmospheric scientists, and mission management. Key decisions are made on a daily basis, to maintain the orbit periapsis within the desired aerobraking corridor, while being responsive to atmospheric density variations.

Two critical operations must be repeatedly accomplished to complete a successful aerobraking phase: drag passes are performed on every orbit, and orbit trim maneuvers are frequently performed at apoapsis, to maintain the desired periapsis altitude.

A sample drag pass timeline is shown in Fig. 7. The spacecraft configuration process for a drag pass begins 30 min before the start of the drag pass, with the calculation of accelerometer biases. Telecommunications is switched from the HGA to the low gain antenna (LGA), in carrier-only mode. This switch is made because the HGA cannot maintain an Earth point during the drag pass, and telecommunication link capabilities do not support the receipt of telemetry data over the LGA. Carrier-only mode is chosen to maximize the power in the radio's carrier signal for Doppler tracking purposes to support enhanced orbit determination during the drag pass period. The spacecraft slews to the aerobraking attitude 10 min before the drag pass. Attitude control is transitioned from the reaction wheel assemblies (RWAs) to thrusters. Periapsis timing estimation (PTE) is enabled. During the drag pass, attitude and rate control dead bands are relaxed, allowing the spacecraft to trim to its aerodynamically stable attitude. Following the drag pass, the spacecraft turns back to its normal attitude, with the HGA pointed at Earth. Telecommunications is reconfigured back to the HGA, and telemetry playback from the drag pass is initiated.

Figure 8 shows a sample time line for performing an aerobraking maneuver (ABM) at apoapsis. These maneuvers are used to control periapsis altitude to stay within the desired aerobraking heating

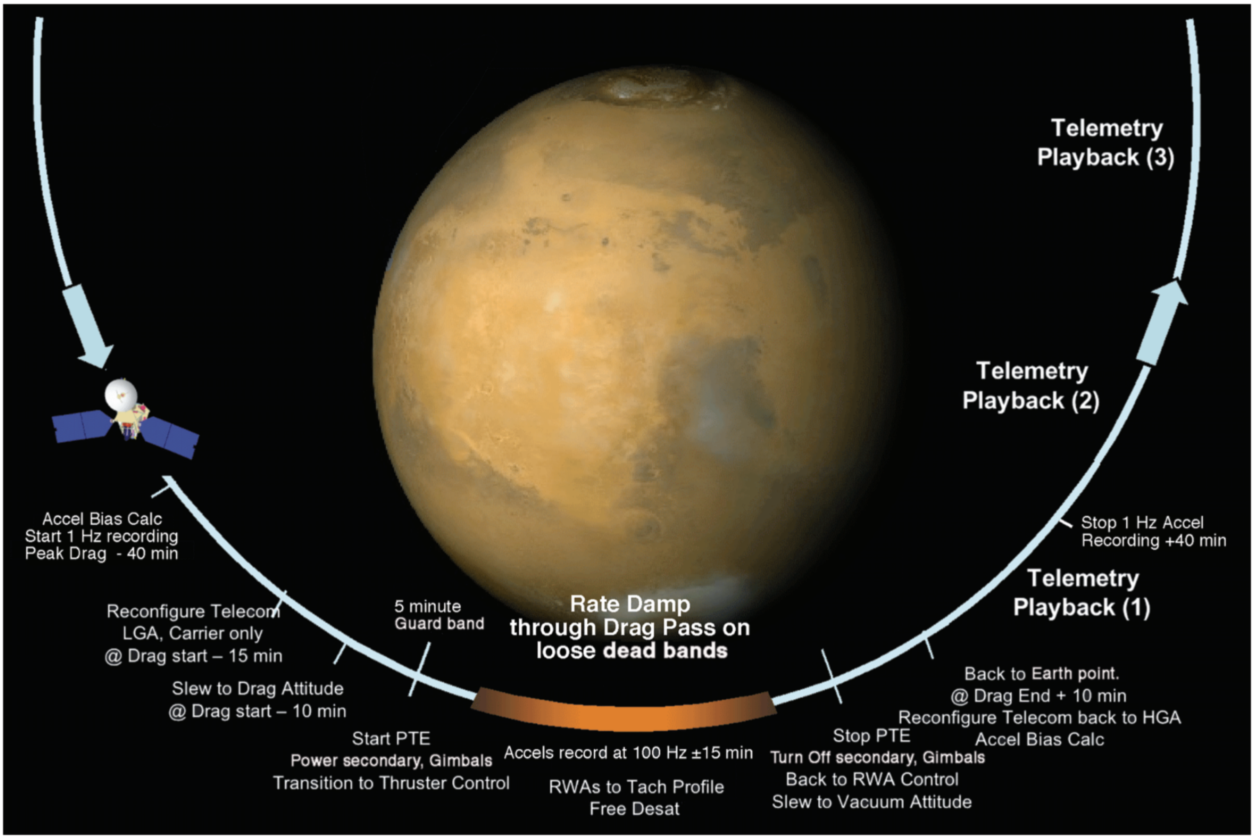

Fig. 7 Sample drag pass time line.

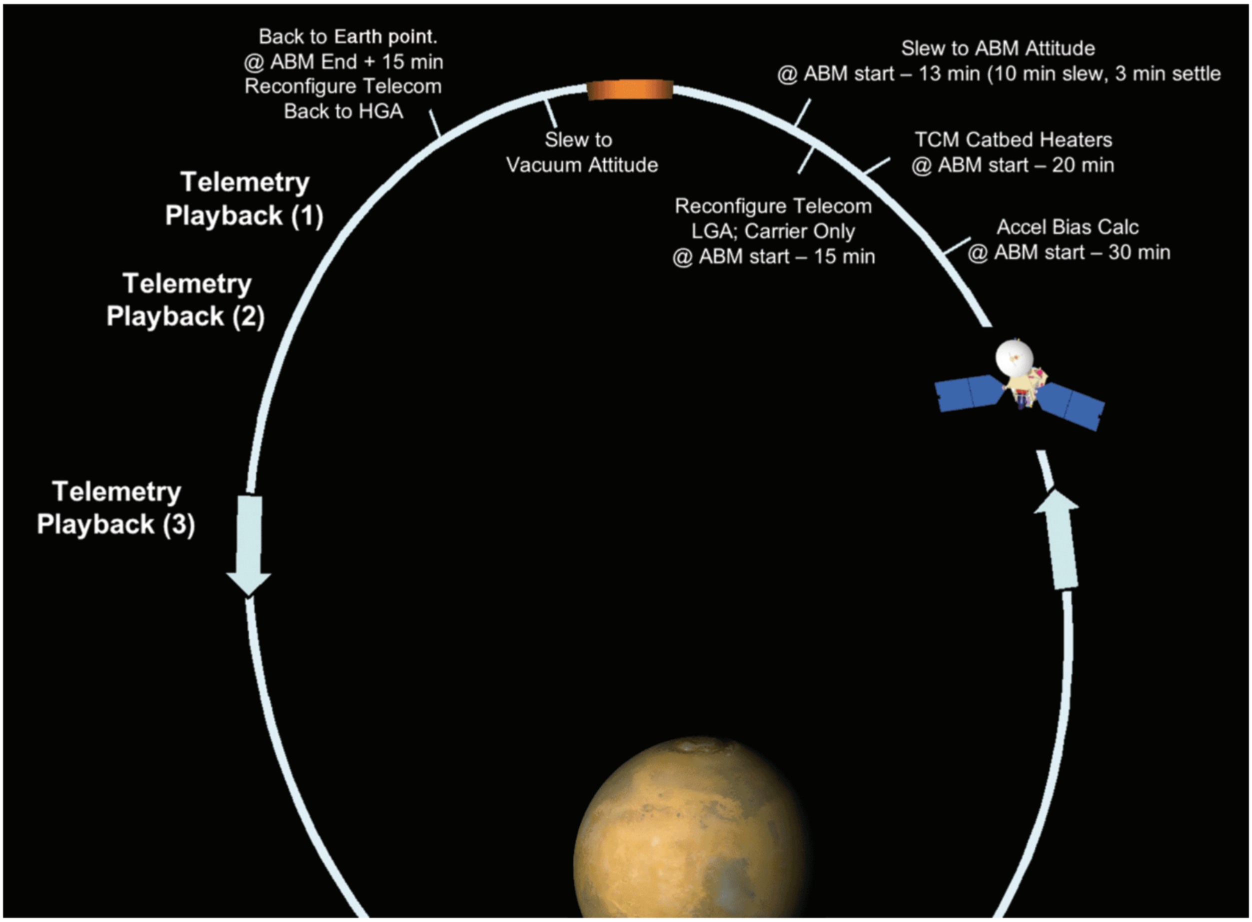

Fig. 8 Sample orbit trim maneuver time line.

corridor. Stored maneuver parameters are often used as a "menu" for ABM selection. The spacecraft heats the catalyst beds for the trajectory correction maneuver (TCM) thrusters and begins the turn to the maneuver attitude 20 min before the burn. Telecommunications is via the LGA during the maneuver. Following the ABM, the spacecraft slews back to the desired orbit attitude and plays back telemetry from the burn.

During the final stage of aerobraking, the orbit period is less than 2.5 h, leaving little time between the orbit trim maneuvers and the drag sequences.

IV. Aerobraking Risk Areas

Flying a spacecraft through a planetary atmosphere hundreds of times during months of human-intensive operations is inherently risky. As described in Sec. III, aerobraking is a highly orchestrated process, requiring frequent maneuvers to maintain the orbit periapsis altitude or dynamic pressure within the desired aerobraking corridor. By its nature, aerobraking requires around-the-clock operations and depends upon reliable communications between the Deep Space Network (DSN) and the spacecraft. The aerobraking thermal environments are difficult to test on Earth, forcing the spacecraft designers and operators to rely primarily on computational analysis for design validation. Atmospheric variability, command errors, and vehicle safing can all pose critical threats to the mission. This section describes the key risk areas involved in aerobraking and concludes with a straw-man probabilistic risk assessment for a generic aerobraking phase.

A. Key Risk Areas

1. Orbit-to-Orbit Density Variations

The most prevalent risks encountered during aerobraking are related to environmental uncertainties. Atmospheric density is highly variable at aerobraking altitudes, and the ability to predict orbit-to-orbit density variations is limited [5]. MGS and Odyssey drew upon expertise from the Mars atmospheric science community for modeling and trend analysis, and folded their input into the Mars Global Reference Atmosphere Model (Mars-GRAM 2000) for atmospheric density predictions. During the course of Odyssey aerobraking, the standard deviation of the actual density at periapsis relative to the predicted density was about 30%, consistent with the MGS experience [3]. Figure 9 shows the ratio of the measured-to-predicted maximum periapsis density during each orbit. Note that factors of 1.5 are not uncommon and two Odyssey drag passes encountered periapsis densities more than 100% greater than predicted. Each point in Fig. 9 represents one drag pass during the 2001–2002 aerobraking phase. The Odyssey aerobraking main phase design incorporated heating rate margins that could accommodate atmospheric densities up to 120% greater than those expected at the top of the aerobraking corridor. In contrast, MRO has a longer period in which to aerobrake, and so the design targets a lower heating rate corridor and is much more tolerant to atmospheric density variations.

2. Structural Loads and Thermal Cycling

Aerobraking is a demanding physical environment for the spacecraft, with the potential to expose structural design flaws or latent mechanical anomalies. An example of this was seen during MGS aerobraking. Significant flexure of a solar panel was noted during the initial orbits of the MGS aerobraking main phase. Aerobraking operations were suspended, pending an investigation of the anomaly and a redesign of the aerobraking phase. It was determined that a solar array damper had likely been damaged during the postlaunch deployment; the solar array could no longer sustain the drag forces planned in the original aerobraking design. Following the redesign, MGS completed aerobraking with a reduced target

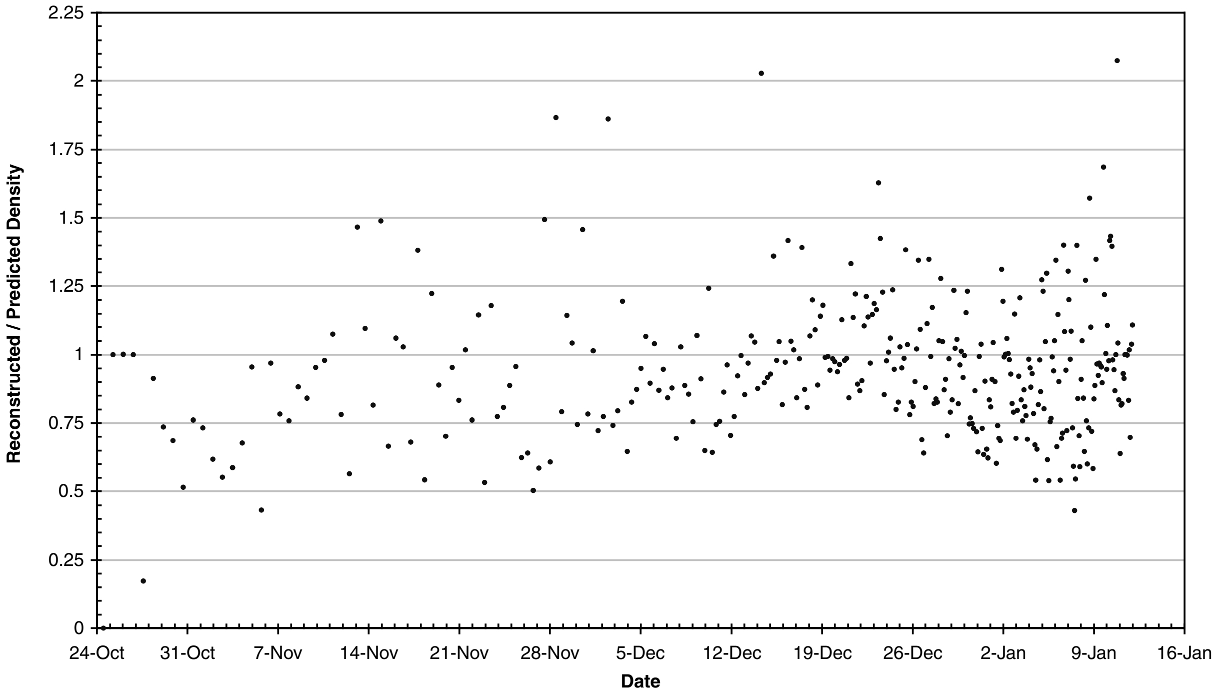

Fig. 9 Mars Odyssey density variations from predictions.

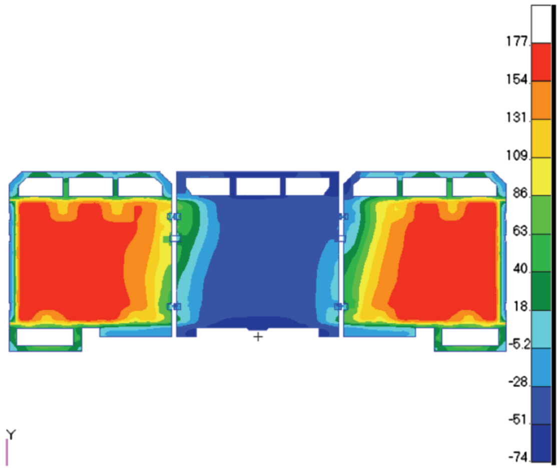

Fig. 10 Modeled temperature of Odyssey solar array during main phase drag pass.

dynamic pressure (roughly 30% of the original target dynamic pressure value). The MGS aerobraking phase, originally planned for 90 days, ultimately took over 400 days to complete.

Figure 10 shows the Odyssey modeled solar array temperatures during a main phase drag pass. Temperature sensors mounted within the solar array structure were used to correlate the thermal models with the actual sustained temperatures on the solar array. Physical delamination of the solar array was thought to be the primary failure mode if corner temperatures of 190°C were surpassed.

3. Communications Failure

Present-day aerobraking methods require near-continuous communications with the spacecraft, for the return of drag pass data and the uplink of command sequences. Aerobraking sequences typically include a set of "primary" drag passes (covering 1–5 orbits) which are intended for use, followed by a "backup" sequence of passes that are not intended for use unless the next sequence uplink is delayed. Periapsis timing errors tend to accumulate, making the backup sequence less reliable than the primary sequence. Near the end of its aerobraking phase, the Odyssey flight team uplinked a new sequence every 6 h. The change in velocity from each drag pass is evaluated, and subsequent apoapsis maneuvers are planned accordingly. Loss of communications for an extended period (greater than 24 h) during the final phase of aerobraking will result in the orbit periapsis decreasing rapidly, as atmospheric drag degrades the orbit. To guard against this possibility, the Odyssey flight team included an autonomous "pop-up" maneuver at the end of each backup sequence of drag passes. This maneuver, which raises periapsis to a higher altitude, would be executed only if the end of the backup sequence was reached before a new primary sequence was uplinked, and would effectively terminate aerobraking until communications with the ground could be reestablished.

4. Spacecraft Safing

A spacecraft safing event can occur at any time during aerobraking. A safe mode is designed to reestablish attitude knowledge onboard the spacecraft, while orienting the spacecraft so that it is in a favorable attitude for communication with Earth while keeping the solar array on the sun [6]. Depending on where the safe mode entry occurs during the aerobraking orbit, the spacecraft may enter the atmosphere in the safing attitude, rather than the planned aerobraking attitude. Aerodynamic stability is not assured while performing a drag pass in the safing attitude, and vehicle tumbling may occur. Aerodynamic heating of sensitive spacecraft components and science instruments will put the hardware at risk.

5. Human Error

The labor-intensive aerobraking process requires command sequences to be built, tested, and uplinked to the spacecraft up to 4 times per day. Human error in the sequence generation process is one of the greatest risks present during the aerobraking phase. For example, a sequencing error that inadvertently commanded a periapsis-lowering maneuver rather than an intended periapsis-raising maneuver could be mission catastrophic. An unintended periapsis-lowering maneuver was actually executed on MGS [7], due to a ground/flight memory management error. An emergency correction maneuver was successfully uplinked and executed, returning the periapsis altitude to the desired value.

The likelihood of a human error occurring is increased by fatigue and stress that accrue during around-the-clock aerobraking operations. Efforts are underway to automate the aerobraking process [8]. The first phase is to reduce the number of sequence uploads required. Odyssey demonstrated a small portion of aerobraking autonomy during short orbit periods, through performing an onboard estimation of the most recent periapsis passage time, and computing an onboard update of subsequent periapsis times [9]. MRO will further develop autonomous aerobraking by implementing this technique in the flight system. However, aerobraking will remain a human-driven process for sequence generation, atmospheric evaluation, and maneuver decisions.

B. Probabilistic Risk Assessment

This straw-man probabilistic risk assessment is intended to provide an estimate of the quantitative level of risk that is involved in a generic aerobraking mission. For this generic mission, it is assumed that a 90-day aerobraking phase is composed of 10 walk-in orbits where the periapsis altitude is gradually lowered to the designed aerobraking corridor, 300 main phase orbits where the periapsis altitude is targeted to stay within the desired heating corridor, and a walkout phase consisting of 150 orbits where lower heating rates are targeted. Each of the primary risk areas described above is evaluated, and the resulting aerobraking reliability is calculated.

1. *Orbit-to-Orbit Density Variations*

For the purpose of this calculation, an aerobraking corridor design similar to that used for Odyssey and originally planned for MGS is assumed. With this design, an unexpected density increase of 120% (4σ) could exceed the vehicle heating limits. This risk is relevant primarily during the main phase of aerobraking, where targeted heating rates are the highest. The probability of a 4σ atmospheric density variation is 0.00006. Considering 300 main phase orbits, the total probability of exceeding the heating rate limits due to atmospheric density variations is $1 - 0.99994^{300}$, or 0.018.

2. *Structural Loads and Thermal Cycling*

If not caused by an extreme density variation, a structural failure during aerobraking would likely be due to a design flaw or a latent structural weakness. The probability of a design flaw is estimated as 10^{-3}, whereas the probability of a latent structural weakness or structural failure (similar to MGS) is estimated as 10^{-2}. The combined probability of a structural load failure is calculated as 0.011.

3. *Communications Failure*

In order for a communications failure to be catastrophic, the autonomous pop-up maneuver placed at the end of the aerobraking backup sequence must fail. If we assume that the probability of an extended communications outage during the 90-day aerobraking phase is 10^{-3}, and the probability of a failed pop-up maneuver is also 10^{-3}, then the combined probability of failure due to a telecommunications outage is 10^{-6}.

4. *Spacecraft Safing*

If we assume that spacecraft safing events occur twice yearly on average, the likelihood of a safing event occurring during a 75-day aerobraking main phase is 0.34. The probability of a mission failure due to an aerobraking drag pass while in safe mode is difficult to assess, but it is not likely to be less than 10^{-3}. Assuming this value, the resulting probability of a mission failure due to spacecraft safing during aerobraking is 3×10^{-4}.

5. *Human Error*

The probability of a human error in the sequence development process is estimated to be 10^{-5} per sequence. During the course of the aerobraking phase, roughly 250 sequences are sent to the spacecraft. The likelihood that a given sequence error will be mission catastrophic is estimated as 10^{-2}. The resulting probability of a catastrophic failure due to human error is 2×10^{-5}.

Table 2 Generic Orbiter Mission probabilistic risk assessment

Mission phase	Success probability
P (launch)	0.96
P (cruise)	0.99
P (orbit insertion)	0.95
P (aerobraking)	0.97
P (science)	0.99
***P* (success|aerobraking)**	**0.867**
***P* (success|no aerobraking)**	**0.894**

6. *Combined Probability of Failure During Aerobraking*

If we statistically combine the probability of failure due to the modes described above, the resulting reliability of the aerobraking phase is assessed to be 0.97. There is a 3% chance of catastrophic failure during the aerobraking phase for our generic mission. Atmospheric density variation is the dominant risk area.

It should be noted that the MRO mission is mitigating the risk associated with atmospheric density variations by designing to a much lower target heating rate during the aerobraking main phase than was done on previous missions. This approach dramatically reduces the risk associated with atmospheric density variations, but it results in a longer aerobraking phase (roughly 170 days) and requires many more sequence builds.

7. *Generic Orbiter Mission Risk*

In Sec. VI, we will evaluate the aerobraking cost/risk decision for a generic orbiter mission. To provide context for the cost/risk analysis, a high-level probabilistic risk assessment for a generic orbiter mission is given here. Table 2 shows straw-man probabilities of successfully completing each mission phase. These numbers are representative; actual mission probabilities will vary with the design and hardware components used [10].

As seen in Table 2, for our generic orbiter mission, the inclusion of aerobraking lowers the overall probability of mission success from 89.4 to 86.7%. This 2.7% reduction in success probability is a price that the project pays when selecting the aerobraking approach; a method for assigning a financial cost to this risk is discussed in Sec. VI.

V. Aerobraking Costs

Aerobraking represents an additional mission phase between orbit insertion and the onset of the science mission. The costs associated with aerobraking can be subdivided into four major categories: aerobraking planning and development, aerobraking operations, science, and DSN tracking. Aerobraking planning and development represents the labor associated with preparing for aerobraking before launch and during cruise. It includes the aerobraking corridor design, navigation development, atmosphere modeling, tool development, testing, and flight team training. Aerobraking operation costs include the labor charges of the flight team, atmospheric advisory group, and mission management during the actual aerobraking phase. The science team is a standing army that is fully assembled and charging to the project during the aerobraking phase. Science team costs are reported separately from the flight team costs. Radiometric tracking and telemetry provided by the DSN also represents a major cost, as aerobraking typically requires continuous coverage by the DSN.

Table 3 provides a summary of the Odyssey aerobraking costs. The costs are estimated based upon the number of people involved and the duration of the work period. Costs are given in fiscal year 2002 dollars (FY'02$) and shown in thousands (K) of dollars.

DSN tracking costs were not charged directly to the Odyssey project, so that they are not accounted for in Table 3. Based upon current DSN aperture rates (FY'06), the estimated cost for continuous 34-m DSN station coverage for a 77-day aerobraking phase is $2.25 million.

Table 3 Mars Odyssey aerobraking cost summary

Category	Cost (FY'02$)
Aerobraking planning and development	$1450K
Navigation, spacecraft team, mission planning & sequencing, test & training	
Aerobraking operations	$4810K
Mission management, navigation, spacecraft team, mission planning & sequencing, atmospheric advisory group, DSN scheduling, ground data system	
Science Team	$3050K
Science operations and data analysis	
Total Odyssey aerobraking cost	**$9310K**

VI. Cost/Risk Decisions on the Application of Aerobraking

The successfully completed aerobraking phases for the Mars Global Surveyor and Mars Odyssey missions have validated the propellant-saving aerobraking technique as a viable, low-risk approach for reducing launch costs. With today's launch systems, the cost savings can be significant, on the order of $10–$30 million. This level of potential savings on launch costs is quite attractive, particularly for highly cost-constrained competed missions. In the 2007 Mars Scout competition, nearly every proposal that required orbit insertion baselined the aerobraking approach.

Is this prudent? The aerobraking approach unquestionably entails more risk than a purely propulsive orbit insertion. Any mission that intends to use aerobraking to reduce the orbit period still needs to capture propulsively. As we have discussed in Sec. IV, the aerobraking technique exposes the spacecraft structure to a stressing environment, in which any design flaws or latent structural defects can manifest themselves in failure. The vagaries of the planetary atmosphere introduce large uncertainties on structural heating during a drag pass, and the around-the-clock nature of aerobraking is stressing to the flight team, increasing the potential for commanding errors that could be mission catastrophic.

If actual costs were the only consideration, the decision on whether to baseline the aerobraking approach would be straightforward. Careful accounting of the costs associated with aerobraking, as shown in Sec. V, would be compared with the launch costs associated with going to a larger launch vehicle to enable a purely propulsive capture. This comparison is typically what is done when a preproject decides whether to baseline aerobraking (workforce costs associated with aerobraking development and flight operations are often underestimated during pre-phase A).

However, this decision process completely ignores the added risk introduced by the aerobraking approach. The key question is *how much is it worth to "buy down" the risk of aerobraking through buying a larger launch vehicle?* If aerobraking were 100% reliable, then the equation would reduce to a simple cost comparison. If, however, aerobraking introduces a 50% chance of a mission catastrophic failure, then aerobraking would clearly be a nonstarter, as the project risk posture would be unacceptably high. Put another way, the high probability of failure would put the investment at an unreasonable risk.

The straw-man probabilistic risk assessment shown in Sec. IV indicates that the probability of a successful aerobraking phase during a 3-month aerobraking period could be roughly 97%, which, when multiplied by the probability of successfully completing the other mission phases, lowers the overall probability of mission success from 89.4 to 86.7%. Aerobraking risk can be mitigated through flying higher in the aerobraking corridor at lower heat rates, as was done in the MRO mission. However, if we assume for the sake of argument that a generic project is taking on an additional 2.7% of mission risk through employing aerobraking, we can estimate the "effective cost" of aerobraking. The effective cost is defined as the actual cost associated with aerobraking planning, support, and execution (as shown in Sec. V), in addition to the probabilistic cost of failure during aerobraking.

The Odyssey aerobraking operations and science team costs from Table 3 can be reasonably scaled upward to our 90-day mission, and inflated to FY'06 dollars (a flat 4% inflation rate is assumed). The resulting project cost for aerobraking is $12.4 million. Scaling the DSN costs for continuous coverage from 77 to 90 days results in a cost for DSN tracking of $2.6 million. The actual cost of aerobraking for our generic mission is $15 million.

The probabilistic cost of aerobraking failure is equal to the total cost of the project from inception through the aerobraking phase (i.e., the amount invested) multiplied by the incremental mission risk due to aerobraking (in our case, 2.7%).

For a generic $450 million mission, roughly $425 million will be invested in the mission by the point of aerobraking completion. The remaining $25 million represents the cost of flight operations and data analysis during the science phase. To determine the probabilistic cost of failure associated with aerobraking, the $425 million investment is multiplied by the 0.027 reduction in mission success probability due to aerobraking, with a resultant probabilistic cost of $11.5 million. Thus, when evaluating an aerobraking mission with a smaller launch vehicle against a purely propulsive orbit insertion and a larger launch vehicle, we should calculate the effective cost of aerobraking as the planned cost of aerobraking ($15 million) plus the probabilistic cost of failure ($11.5 million). The effective cost of aerobraking is therefore $26.5 million. For this generic mission, the project manager should be willing to spend up to $26.5 million to procure a larger launch vehicle to enable purely propulsive capture.

Without consideration of the probabilistic cost of failure due to aerobraking risk, the effective cost of aerobraking will be considerably underestimated, leading to poor cost/risk decisions in launch vehicle selection. An understanding of this simple concept is necessary when performing mission trade studies early in the project life cycle, as well as in the proposal evaluation process.

VII. Conclusions

Aerobraking is an enabling technology that allows significant propellant savings (historically, on the order of 300–600 kg for Mars missions). These propellant savings allow reduced launch mass, which translate into savings in launch system costs. However, the aerobraking process is quite complex and not without risk. A straw-man probabilistic risk assessment indicates that the probability of failure for a 90-day aerobraking phase with Odyssey-like heating rates is about 0.03. This increase to the mission risk posture should be considered when making the aerobraking cost/risk decision at the inception of the mission. For the generic $450 million orbiter mission considered in this paper, the planned cost of aerobraking is estimated to be $15 million, and the probabilistic cost of failure is $11.5 million, for a combined effective cost of aerobraking of $26.5 million. If a larger launch vehicle can be procured to allow purely propulsive capture, and if the cost increment for the larger launch vehicle is less than the effective cost of aerobraking, the larger launch vehicle is a wise investment. Applying this concept to early mission trade studies and proposal evaluations is a necessary step toward making appropriate cost/risk decisions.

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