Aerobraking Cost/Risk Decisions

David A. Spencer
Jet Propulsion Laboratory
California Institute of Technology

Robert Tolson
North Carolina State University
National Institute of Aerospace

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Agenda

- Motivation for this Paper
- A Brief History of Aerobraking
- Aerobraking Risk
- Cost
- Aerobraking Cost/Risk Trades
- Conclusions
Discover Magazine Award for Technological Innovation, 1994
Odyssey Orbit Period During Aerobraking

- Actual
- Plan
Odyssey Aerobraking Periapsis Altitude
Key Aerobraking Risk Areas

- Orbit-to-orbit density variations
- Structural loads and thermal cycling
- Communications failure
- Spacecraft safing
- Human error
Orbit-to-Orbit Density Variations
Probabilistic Risk Assessment

• Assumptions: Generic aerobraking orbiter
  – 90-day aerobraking phase
  – 300 main-phase orbits with Odyssey-like heating corridor
  – 150 walk-out orbits targeting lower heating

<table>
<thead>
<tr>
<th>Aerobraking Risk Area</th>
<th>Prob. of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit-to-orbit density variations</td>
<td>0.018</td>
</tr>
<tr>
<td>Structural loads &amp; thermal cycling</td>
<td>0.011</td>
</tr>
<tr>
<td>Communications failure</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Spacecraft safing</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Human error</td>
<td>$2 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

• Estimated reliability of aerobraking phase: 0.97
## Generic Orbiter Mission Risk

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Success Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(Launch)</td>
<td>0.96</td>
</tr>
<tr>
<td>P(Cruise)</td>
<td>0.99</td>
</tr>
<tr>
<td>P(Orbit Insertion)</td>
<td>0.95</td>
</tr>
<tr>
<td>P(Aerobraking)</td>
<td>0.97</td>
</tr>
<tr>
<td>P(Science)</td>
<td>0.99</td>
</tr>
<tr>
<td>P(Success</td>
<td>Aerobraking)</td>
</tr>
<tr>
<td>P(Success</td>
<td>No Aerobraking)</td>
</tr>
</tbody>
</table>

- Inclusion of aerobraking for our generic orbiter mission lowers overall probability of mission success from 89.4% to 86.7% (2.7%)
# Odyssey Aerobraking Cost Summary

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost (FY’02$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobraking Planning &amp; Development</td>
<td>$1450 K</td>
</tr>
<tr>
<td>Navigation, Spacecraft Team, Mission Planning &amp; Sequencing, Test &amp; Training</td>
<td></td>
</tr>
<tr>
<td>Aerobraking Operations</td>
<td>$4810 K</td>
</tr>
<tr>
<td>Mission Management, Navigation, Spacecraft Team, Mission Planning &amp; Sequencing, Atmospheric Advisory Group, DSN Scheduling, Ground Data System</td>
<td></td>
</tr>
<tr>
<td>Science Team</td>
<td>$3050 K</td>
</tr>
<tr>
<td>Science Operations &amp; Data Analysis</td>
<td></td>
</tr>
<tr>
<td><strong>Total Aerobraking Costs (FY’02$)</strong></td>
<td><strong>$9310 K</strong></td>
</tr>
</tbody>
</table>

Note: Costs are estimated based upon number of people and duration of work period. Costs shown are in FY’02$. DSN costs not included.
Generic Orbiter Aerobraking Cost

• To generate a cost estimate for a generic (Odyssey-like) 90-day aerobraking phase…
  – Odyssey aerobraking ops and science costs are scaled up to a 90-day mission phase; planning costs stay the same
  – Costs are inflated from FY’02$ to FY’06$
  – DSN costs are estimated assuming continuous 34m coverage, based on DSN rate table ($2.6M)

• Resulting estimated cost is $15M.
Aerobraking Cost/Risk Trade

• If actual costs were the only consideration, the decision on whether to baseline aerobraking would be straightforward.
  – Compare estimated cost of aerobraking ($15M for our generic mission) with the cost of a larger launch vehicle to enable purely propulsive capture. Choose the lower cost option.
  – This is the approach commonly taken by proposal teams.

• However, this decision process completely ignores the added risk introduced by the addition of the aerobraking phase.

• The key question is: how much is it worth to “buy down” the risk of aerobraking through buying a larger launch vehicle?
How Much is it Worth to Buy Down Aerobraking Risk?

• Assume our generic mission has a total mission cost cap of $450M.
  – Roughly $425M (including L/V) will be invested in the mission by the point of aerobraking completion.
  – Remaining $25M represents cost of flight operations and data analysis during the science mission.

• The Probabilistic Cost of Failure is calculated by multiplying the amount invested ($425M) by the reduction in mission success probability due to aerobraking (0.027). Result: $11.5M
  – This is how much aerobraking risk is worth.

• The “effective cost” of aerobraking is equal to the planned cost of aerobraking ($15M) plus the probabilistic cost of failure ($11.5M). Result: $26.5M

• The Project Manager should be willing to spend up to $26.5M to procure a larger launch vehicle, to enable purely propulsive capture.
Conclusions

- Aerobraking is an enabling technology that allows significant propellant savings (typically 300-600 kg), and lowers launch costs.

- There are inherent risks with aerobraking.
  - Strawman PRA indicates that the probability of failure for a 90-day aerobraking phase with Odyssey-like heating rates is about 3%.

- The increase to the mission risk posture should be considered when making the aerobraking cost/risk decision at the inception of the mission.

- The “effective cost” of aerobraking is the planned aerobraking cost plus the probabilistic cost of failure.

- The effective cost of aerobraking should be compared with the incremental cost for a larger launch vehicle to enable purely propulsive capture.
  - If the incremental cost for a 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...and it’s good system engineering!