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The case for a Leading Edge Reinforced Carbon-Carbon (RCC) segment failure on the Columbia Space Shuttle

A lot of evidence to date points to a failure of the Leading Edge (LE) of the left wing as the primary cause of the shuttle failure, not damage to Thermal Protection System (TPS) tiles on the bottom of the wing. NASA has considerable experience with TPS tile damage, with tiles being damaged on virtually every mission since 1981. I would like to discuss a few possibilities relating to the Columbia accident that I have not yet seen discussed.

Background

The video shot near Bishop, Calif shows debris leaving the Columbia, and an unusual color in the re-entry trail. Note: additional study should be done to determine if this unusual color of the re-entry trail could have been caused by the materials present in the RCC, RCC seals, structural aluminum, or iconel structural material.

The recent finding of aluminum residue on the shuttle thermal tiles supports the theory that the wing structure underneath the LE RCC was compromised.

Some analysts think that the external tank foam or ice debris that impacted the shuttle during ascent (81 seconds after liftoff) hit first on the leading edge, based on the video image and the size of the "particle cloud" of external tank foam debris on the subsequent video frames. Some of the significant factors in this impact, relative to the LE RCC, are:

- It appears to have hit near the most inboard section of the LE, where the impact angle (relative to the flight path) was the greatest.
- It hit during a period of high dynamic pressure, shortly after maximum "Q".
- It hit during a period of high acoustical stress, on a section of the LE exposed to very high levels of acoustical stress
- The stress on the leading edge could have been increased if the wing was at a positive Angle of Attack (AOA): this would increase the severity of the debris impact on the lower portion of the leading edge, due to the aerodynamic loading of the RCC.
- It hit somewhere between RCC segments 8-11: the safety margin for RCC vertical shear is slightly reduced near segments 9-11 (see diagram later in these notes).

There are two possible RCC failure modes that have not been discussed in the Columbia accident investigate to date (in the open press material I have seen):

1. Material Degradation
2. Aerodynamic loading

Material Degradation

The possibility that the wing LE RCC failed on this mission due to material degradation of the RCC or RCC segment seals cannot be discounted. Some factors include:

- The Columbia had the greatest re-entry experience (28 missions, I believe) of the entire fleet (e.g., the highest number of re-entry heating cycles). I have no data indicating whether any of the RCC on Columbia had been replaced: if it is original material, then from a materials viewpoint, the RCC (and/or RCC T-seals) on Columbia should be expected to be the first to fail. RCC segments 8-10 would be the most likely portion of the leading edge to fail due to re-entry heating[2].
- The left wing of the Columbia experienced[4] a significantly earlier transition to turbulent flow than the right wing, or other shuttles. This dramatically increases the amount of time the RCC would be exposed to high heating levels, and would therefore accelerate any adverse material degradation trends, especially oxidation. It can be expected that oxidation would occur most rapidly in the RCC segments exposed to the greatest heating: as the STS-2 isotherm[1] below shows, the highest re-entry temperatures occur exactly at the point where the debris appears to have hit (segment 9-10).

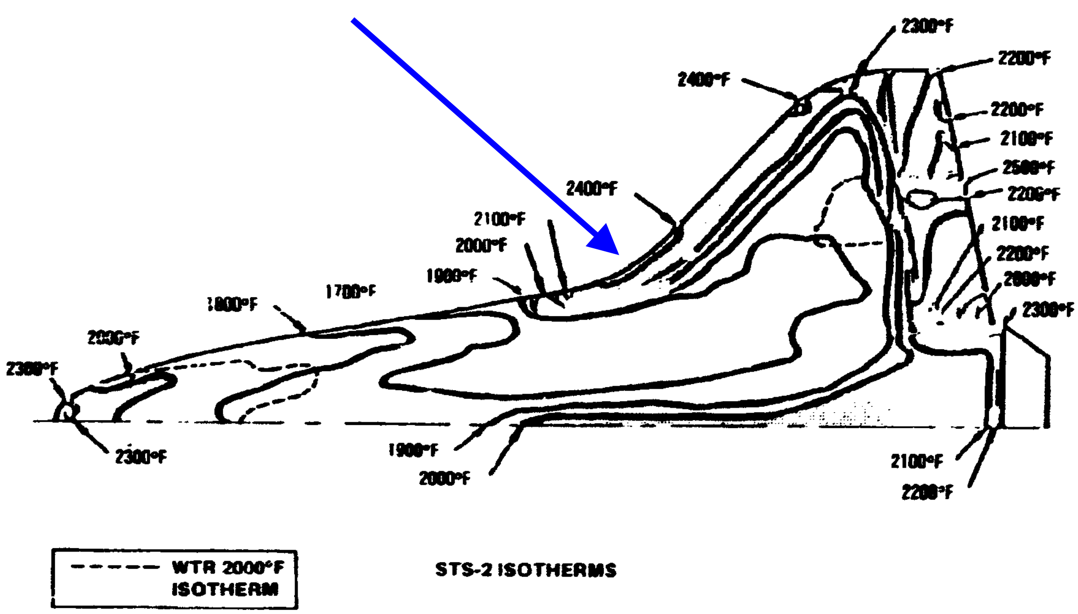


Figure 10.- Orbiter lower surface isotherms (STS-2).

This section of the LE experiences the greatest re-entry heating, and is therefore the most likely to have experienced RCC material degradation due to multiple re-entries.

- It is interesting to note that in the NASA study from which this diagram is taken, the RCC oxidation study is taken at a mid-span (55%) RCC segment, not at the wing root, where the worst case re-entry heating is experienced.

<u>Mass loss due to oxidation</u>

A 1986 NASA report[1] predicted RCC material loss due to oxidation. From this report :

" RCC material properties are degraded when exposed to mission environments of the Orbiter, especially for the re-entry conditions. This degradation is relative to subsurface oxidation occurring in the material substrate and is measurable in terms of mass loss. (Lug regions restricted to 0.1 psf maximum…).

Other quotes from this report:
"The effects of mass loss are typically illustrated by the flexure strength date. <u>RCC mechanical properties are a direct function of the accrued mass loss.</u>"
"The lug allowables are particularly important since the critical feature of the RCC components in terms of mission life is lug capability."
"Lug allowables are one of the most important structural parameters for the RCC components. Affected by oxidations rates, acoustic exposure history, geometry attachment technique and load direction, they are also the most difficult to develop. "

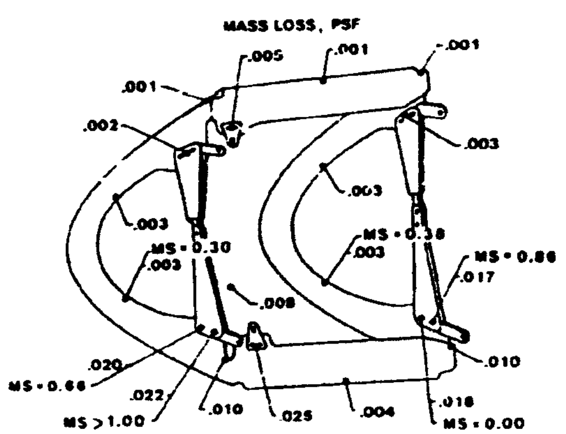


Figure 25 Panel 17 Mass Loss Distribution (After 20 Missions)

It is very interesting to note that on this diagram, the mass loss in the RCC and attachment hardware is greatest on the bottom sections of the hardware (which would have absorbed the ascent debris impact).

It is also significant to note that:

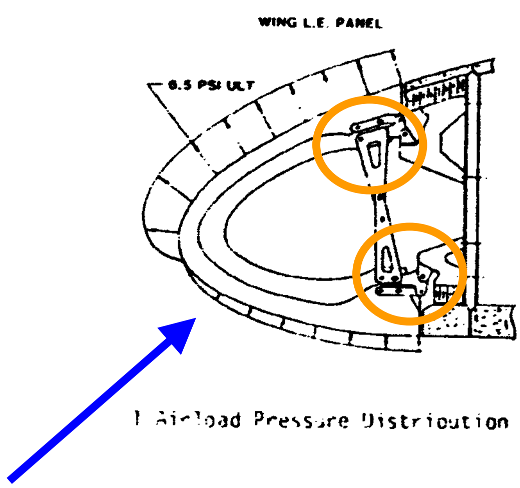
- this mass loss (oxidation) is based on 20 missions using nominal re-entry heating, not increased heating due to asymmetric boundary layer transition heating
- the analysis in this NASA paper utilized RCC panel 17, which has lower re-entry heating (see isotherm diagram)

Obviously, a detailed review of the remaining shuttle's RCC materials is in order to compare theoretical oxidation and that actually experienced.

Aerodynamic Loading

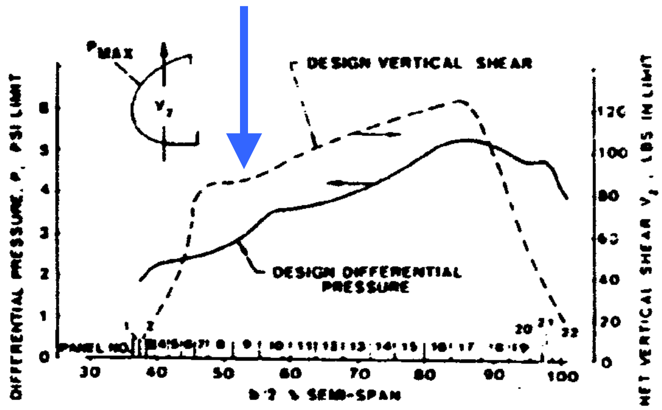
From the 1986 NASA report[1], "Dynamic loads are also imposed on the RCC components due to acoustic response during lift-off and the max Q/transonic regime during ascent. Vibroacoustic analyses resulted in a statistical derivation of attach point RMS loads that are basically used in the determination of lug allowables. Although the acoustic reactions and internal loads are small within themselves, their consequence is important. When coupled with muti-mission mass loss, the acoustic environment becomes a significant parameter in reducing the allowable lug loads and thereby restricting mission life."

The ascent debris impact appears to have hit the wing Leading Edge (LE) at the wing root (approximately RCC segment 9), and most of the impact appears to have been at the bottom of the wing. This diagram shows the aerodynamic loading[1] of the wing leading edge (assumed impact angle and point shown with arrow).



It appears that any stress from the debris impact added to the aerodynamic loads (assuming positive AOA). Further investigation of the actual aerodynamic loading at the time of debris impact should be computed.

It would also be interesting to compute the debris impact load on the RCC lugs (circled in the diagram above), add it to the pre-existing loads, and use the worst case oxidation of the RCC lug attach points and see if the debris impact could have caused an lug attachment failure.



The arrow above indicates RCC panel 9 design vertical shear[1]: it is possible that the debris impact could have exceeded this shear, especially if there was any degradation in RCC material at the lug attach points at the point of impact. It is also interesting to note (in the diagram above) that the design differential pressure seems to “spike” slightly at RCC segment 10 (in the suspect area), with a corresponding slight reduction in the design vertical shear margin at that point.

Recommendations for further investigation

1. Determine if the unusual color of the re-entry trail in the Bishop, Calif video was due to specific shuttle materials (RCC, RCC seals, wing LE insulation, aluminum, wing honeycomb materials, Iconel LE structural materials.
2. Determine the life history of each RCC panel on the left wing. Re-accomplish the oxidation analysis on each panel by applying the worst case (not mid-span) historical re-entry heating experience (especially taking into account early transition to turbulent flow, and actual re-entry heating of RCC segments 8-10).
3. Re-examine the total load on each RCC panel during ascent; especially on RCC panels 8-10. Add the worst case debris impact stress to the accumulated acoustical and aerodynamic loading; then take the worst case oxidation of the RCC at each attach lug and determine if any design loads were exceeded.
4. Model aerodynamic drag experienced by the Columbia (from telemetry data) to various RCC segment failure scenarios: I think it is extremely unlikely that the penetration of the left gear door area only could cause the amount of control inputs experienced. However, it may be impossible to separate asymmetric boundary layer transitions from damaged leading edge drag data.

References:

1. AIAA paper 86-0949 Space Shuttle Orbiter – Leading Edge Structural Design/analysis materials allowables
2. AIAA 96-0808 Space Shuttle Orbiter Aerodynamics Induced by Asymmetric Boundary Layer Transition
3. NASA TP-2000-209760 "Oxidation of Reinforced Carbon-Carbon Subject to Hypervelocity Impact", by Curry et al., 2000
4. Aviation Week & Space Technology Magazine, Feb 24, 2003 Craig Covault

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Thank you for considering my comments regarding the possible causes of this accident.