Resting among stars

The NASA Space shuttle must be the most sophisticated engineering accomplishment of humankind. The catastrophic loss of *Columbia* and crew at re-entry early this year was totally unexpected and a blow to manned space exploration. DIRK PONS looks into the final moments of *Columbia*.

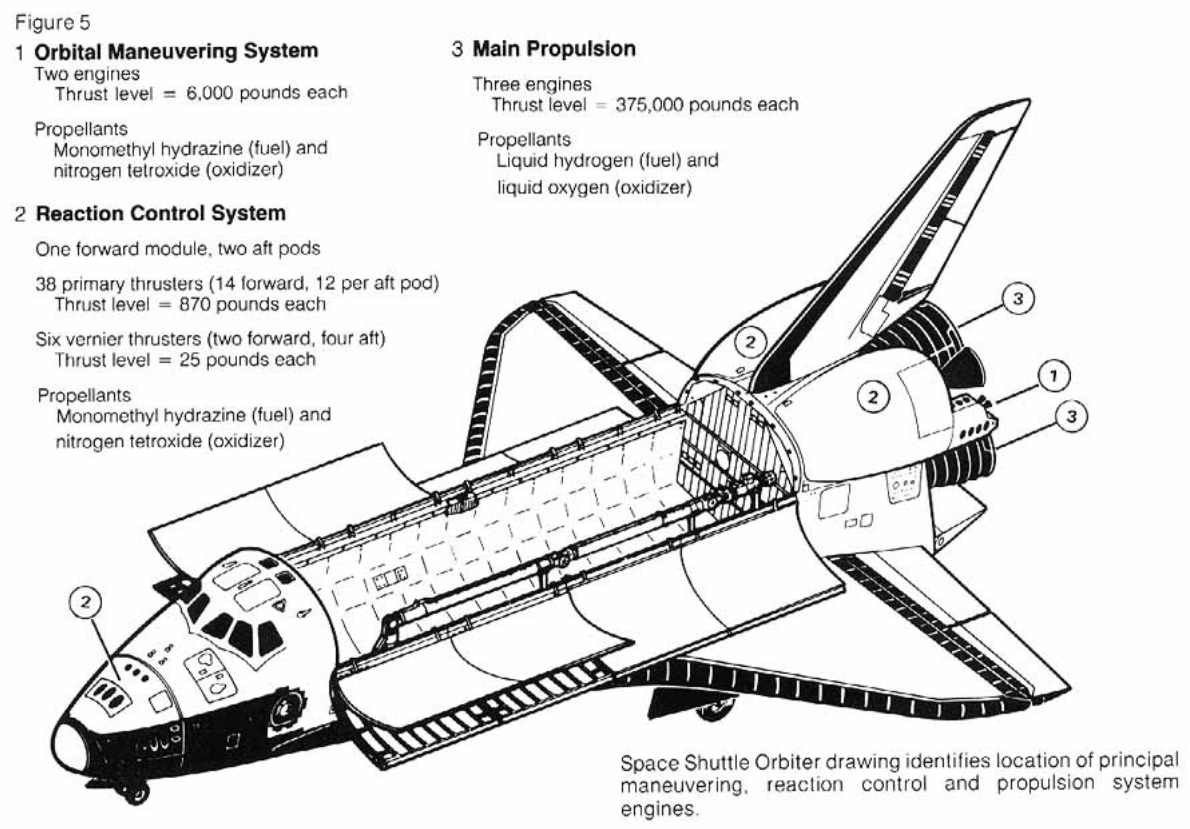

Figure 1: Diagram of Space Shuttle showing principal flight control engines. The rudder and ailerons are also visible, and are aerodynamically effective in the latter part of re-entry. Courtesy NASA (1986).

Introduction
Our planet is the most benign place we know in the Universe. Earth is cocooned in a thin blanket of air, protecting us from the harshness of space. It would be comforting to think that returning to such a safe haven would be an easy passage. Unfortunately, that was not to be for space shuttle *Columbia* and her crew.

Return to Earth
Columbia (Figure 1) had been on an uneventful low-orbit science mission for 17 days. Uneventful except for a minor impact with a piece of soft foam shortly after launch that had been analysed and wasn't expected to be problematic. At the end of the orbital mission, the onboard experiments were stowed. The astronauts had studied living aquatic systems, plant growth (including flax) osteoporosis (bone de-densification), astroculture (harvesting oils from rose and rice flowers), surface tension, crystal growth, dust observations over the Mediterranean,

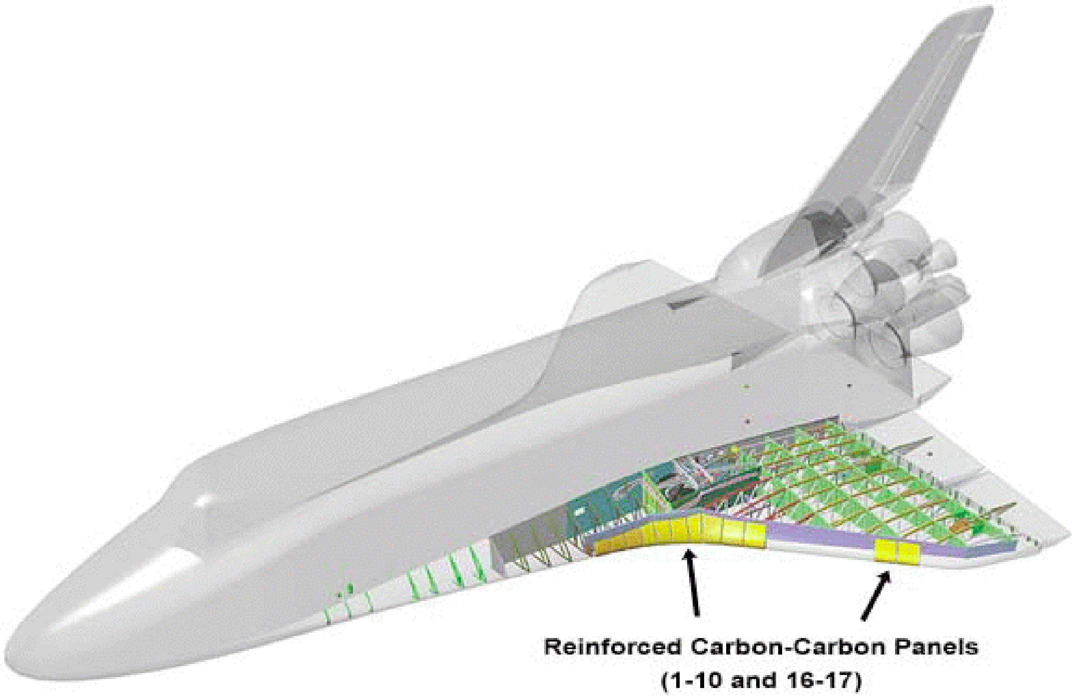

Figure 2: Diagram of Space Shuttle showing position of left wing structures relative to the vehicle. The RCC tile #8 was damaged by a foam strike at launch. Courtesy NASA (2003a).

photographed elves (electromagnetic discharges in the upper atmosphere), grew a cancer tumour (golf ball size), and more. On 1 February 2003, when all was done, Commander Husband and Pilot McCool activated the de-orbit software. *Columbia* was upside down and flying tail first over the Indian Ocean when the engines were fired (de-orbit burn) to slow the vehicle from 28,000 km/hr (Mach 24.56)[1]. There were no problems. Then *Columbia* was repositioned the right way up, facing forward, and with the nose pitched up steeply (about 40°).

Entry interface (EI) for *Columbia* was over the Pacific Ocean. EI is the nominal start of the atmosphere, arbitrarily defined as 400 000 ft. Nine minutes later *Columbia* streaked over the pre-dawn California coast at Mach 23, with everything normal. This speed was enough, despite the thin atmosphere, to superheat the air into a light-emitting plasma, and eventually heat the leading edges to about 1650°C. The light display was visible from inside the vehicle and from the ground, and some ground spectators make a point of watching out for these spectacular Shuttle re-entries. Of course the vehicle was designed for exactly this environment, with reinforced carbon-carbon (RCC) panels on the leading edges and other hot-spots, and silica tiles over the rest of the wing and underbody.

Lost at re-entry

By time EI+10min *Columbia* was over Nevada and ground-based Mission Control noticed a

[1] Mach 1 is the speed of sound. From Mach 1 to Mach 5 is supersonic, and anything greater is hypersonic. Commercial jets, e.g. Boeing 747, fly in the subsonic regime. Fast military aircraft fly in the supersonic regime, as did the recently retired Concorde.

minor problem with some hydraulic sensors in the left wing. Not long to landing in Florida though. A little while later, EI+15min now over Texas, the pressure readings from both left main wheels were lost. Surprising, but not alarming, as it seemed an instrumentation artefact. '*Roger,* ...' replied Commander Husband to the notification from Mission Control. And then nothing. Columbia was at 200,700 ft and doing Mach 18.1 (CAIB, 2003b: 43). At this point in the flight the Shuttle routinely has some communication drop-outs, due to plasma interference and switching antennae. This one seemed a bit long, so Mission Control tried to regain communication via other channels. Nothing came back from the ether.

Columbia and her crew had inexplicably been lost at re-entry.

Mission Control first heard this from someone outside on a cell phone who reported seeing live television coverage of the breakup (CAIB, 2003b: 44). Immediately the Flight Director issued the instruction to '*Lock the doors'* of Mission Control (to protect data), and NASA swung into emergency mode. For the crew, there was no chance of survival at that altitude and speed. Their deaths were caused by blunt impact and lack of oxygen within about 24 sec after loss of aerodynamic control rather than acceleration or explosion (remains of all the crew were recovered) (CAIB 2003b: p77). Debris from *Columbia* was strewn in a fuzzy line across Texas. Miraculously, no-one on the ground was injured, and there was only US$50k of property damage.

Failure analysis on a grand scale

Recovering the *Columbia* debris, and determining the cause of the accident, ranks as one of the wonders of the failure-analysis world. They searched 700,000 acres for pieces, and dived in lakes to check 3100 targets identified by sonar mapping. In the end they, the Columbia Accident Investigation Board (CAIB), recovered 38% of *Columbia* (CAIB, 2003b: 43). The rest was vaporised in the heat, and some small pieces are still expected to be discovered in the woods during the hunting season. Importantly, there were also many eye-witness accounts of the re-entry, including home video from various angles. Back at Mission Control there was also a heap of data, since the Shuttle constantly downloads data on its critical systems to ground. However, the single biggest find was the discovery of the on-board modular auxiliary data system (MADS) which records data from 800 sensors and stores them on tape. This survived re-entry with surprisingly little damage. There is no black-box flight recorder as on commercial planes, but with the downloaded and MADS data they had more than any black box provides. There was even a piece of video camera tape that tumbled down, showing the astronauts during the re-entry, and marvelling in the display of light outside. A poignant moment, since it was that very plasma that would destroy *Columbia*, and was indeed eating into the wing at the very moment. The tape fragment did not run through to the point of destruction, and I for one am grateful of that.

However, I'm fascinated by the cause of the accident as I think there are lessons in there for failure analysis in general. I'm impressed, amazed really, at the openness and honesty of NASA and the CAIB in making public the failure analysis reports right down to the internal e-mails. Most other failure analyses do not release the really interesting bits. Also, the CAIB investigation was so large and had so many resources that it shows the state of the art for failure analysis. The full CAIB reports are freely available on the web, but as it takes a while to get through them, I'll summarise the cause of the failure below.

So what went wrong with *Columbia*? The final sequence of *physical* failure events started with the piece of foam. It detached from the external tank, where it was providing cryogenic insulation for the propellents, and struck the leading edge of the left wing, approximately on panel 8, making a hole about 8x10 inches in the panel, Figure 2. During re-entry, this breach permitted hot plasma to enter into the cavity behind the leading edge, and then melt into the aluminium wing structure. The drag increased, and the lift changed (first decreased, then increased), until the control system was overwhelmed. Once the attitude of *Columbia,* especially yaw and roll, changed sufficiently, the vehicle became aerodynamically unstable.

How the CAIB got to that conclusion is a fascinating story. But first, how could a piece of foam destroy such a strong RCC panel? That the foam strike had occurred was never in doubt, as it had been captured on video.

However, initial engineering analysis (during the flight) had concluded it would not penetrate the RCC panel, and would do only non-critical damage to the silica tiles. Nonetheless, the CAIB demonstrated by physical tests that foam could blow a hole in the RCC. Of course, the Shuttle was doing Mach 2.5 (the speed of a bullet) when the foam came off, so that makes a difference. The relative impact velocity was about 870 km/hr (CAIB, 2003b: 60), and even soft light foam has significant kinetic energy at that speed.

Columbia made a three dimensional stumble into hypersonic airflow.

All the evidence suggests panel 8 (or maybe 9) as the location of the breach. Image analysis suggests this location, as does computational fluid mechanics. A breach here also reconciles the temperature and strain data found from the on-board data storage.

While on orbit a mysterious piece of something appeared alongside *Columbia* after a manoeuvre, and was picked up on ground-based radar, though only noticed afterwards. The object slowly drifted away, for its own rendevous with the atmosphere. After much testing, CAIB concluded that the object was most likely a fragment of RCC panel that had been knocked into the leading edge cavity during the foam impact, and subsequently floated away when in orbit. When *Columbia* engaged the atmosphere, the hot plasma entered this hole. The hole was in an unfortunate location, as this region of the wing gets the hottest.

The data from the on-board MADS was particularly valuable in identifying the failure sequence. Data clearly showed an increase in wing temperature and strain behind panels 8/9 soon after re-entry (CAIB 2003b: p64). Recovered parts from this region of the wing (yes, some of the crucial parts were miraculously found) show high temperature erosion and deposition of Inconel alloy (ex RCC attachment fittings). It was even possible to determine the time and location at which the aluminium spar behind the leading edge burned through, from MADS data and the progressive failure of the wing instrumentation.

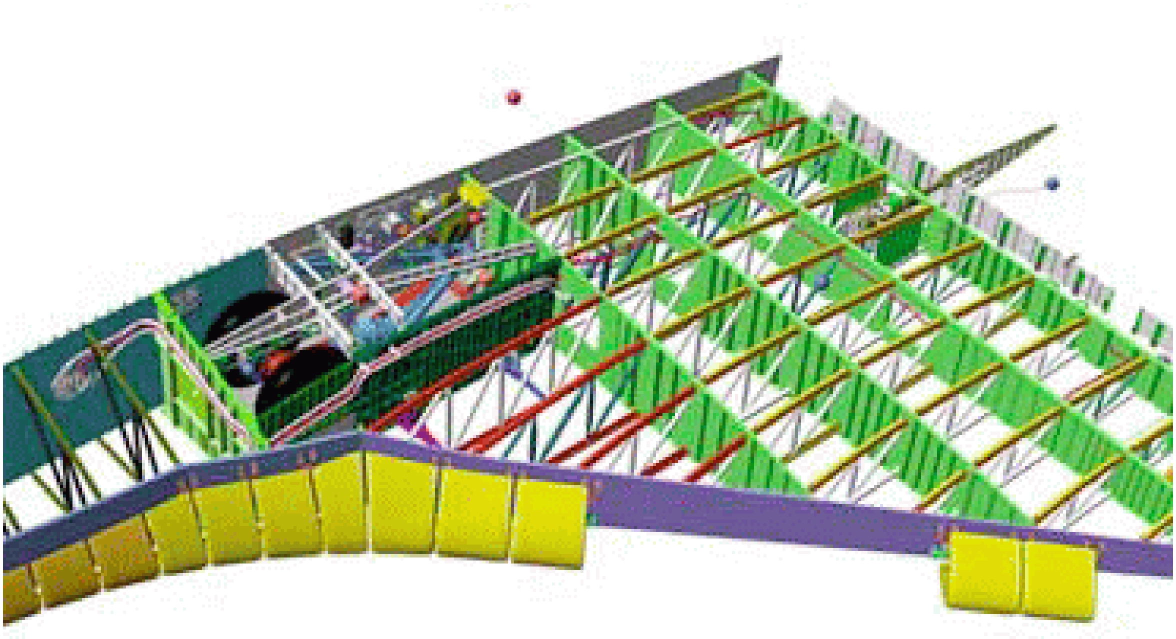

Figure 3: Internal detail of left wing, showing the RCC leading edge panels, the wing structural members, and the wheel well with instrumentation and cables. The breach was in the underside of RCC panel #8, and allowed superheated air to enter the internal structure of the wing at re-entry. This heat rapidly caused structural damage, changed the shape of the wing (and hence the aerodynamic flight characteristics), debonded the protective thermal tiles, and eroded instrumentation cables. Towards the end, the air flow penetrated the wheel well, causing further damage there. Courtesy NASA (2003a).

The sensor problems detected by Mission Control were of course progressive burn through of the wiring bundles. However, the MADS data were unavailable to either the crew or Mission Control at the time.

The first wing spar would have burned through in a *few seconds* and would be '9 inches from top to bottom by EI+522 seconds' (CAIB, 2003b: 67). Thereafter the plasma was jetting into the wing internal structure. Some plasma also apparently escaped out the top of the leading edge, assisted by the natural cavity behind the leading edge, and sprayed Inconel alloy on the pod at the tail (remember that the Shuttle is pitched up at 40°). This also disrupted the air flow over the top of the wing.

Final moments
The drag on the left wing started to increase, causing the vehicle nose to yaw towards the left. At this air density the rudder is ineffective, and steering is by thruster jets in the nose. The control system used these to keep *Columbia* at the correct angle to the air flow.
Reconstruction from the known thruster firings enabled the aerodynamic moments to be determined. Initially the lift on the left wing also decreased, causing the vehicle to attempt to roll with the left wing down. Again the control system compensated, in this case using the elevons to keep the left wing up. By this time (EI+9 min) people on the ground were already noticing bits falling off the orbiter, and bright flashes in the plasma envelope. However, Mission Control did not know this, nor did the crew.

The air entering the wing was at about 4400 deg C, more than enough to melt the internal aluminium structure, and it seems that the wing started to collapse internally. The plasma even managed to penetrate the wheel well, heating up the tyres and causing sensors there to fail too, Figure 3.

Strangely, the reconstructed aero moments show that while the drag continued to increase, the lift on the left wing actually *increased* (rather than deceased) from this time onwards. NASA analysis suggests that this was probably caused by a large area of the underside of the wing collapsing inwards, forming a concave surface (CAIB, 2003b: 71). *Columbia* continued to shed debris, including silica tiles. These were debonded by the heat inside the wing.

As *Columbia* sank deeper into the atmosphere, the air density increased, and the aerodynamic forces grew. Right at the end, the data shows that the control system had to fire all available yaw thrusters to try and keep the heading straight (CAIB, 2003b: 73). However, even this was not enough: the powerful control system had reached the limits of its operating envelope and was overwhelmed. At EI+16 min control was lost. The yaw increased rapidly, and soon exceeded the limits for stable flight. Part separation began.

Columbia made a three dimensional stumble into hypersonic airflow. The aerodynamic forces blasted chunks off the outside, while internal inertial forces tore heavier parts away from lighter ones. Nor was there mercy in the cold high-altitude atmosphere, since the stagnation temperature was high enough to vapourise material. Each piece of debris followed its own ballistic trajectory, determined largely by its density, so pieces rained down over a long footprint.

Comment
It is remarkable that the vehicle could take such a severe mechanical assault, and yet still be so much in control that the flight and ground crew were unaware of the damage. This is a credit to those who designed and built the space shuttle. However, it's apparent that the control system degraded abruptly at the limits of its operating envelope. It provided no warning to the crew or ground control of the impending limits of operation, and I find this tragic. Not that anyone could have done much at that late stage anyway. I also detect a fixed control strategy, something like: fly this vehicle down <given> 3D pipe. Clearly the controller was programmed using a single model of vehicle behaviour: there was no facility to detect the validity of the current control model and transition to an alternative control strategy if necessary. We humans have the flexibility to adapt our strategies, e.g. we drive differently on gravel vs tarred roads. Although, it also has to be said that we make imperfect transitions from one strategy to another, as risk studies on plant control show.

Columbia was so close to the end of peak heating that I wonder whether another control strategy, implemented early enough after entry-interface, might have brought her crew through. Perhaps a vain hope, and certainly the prognosis would have been better if (a) the wing damage had been detected while in orbit, or better still, (b) the foam prevented from detaching in the first place. That neither (a) nor (b) happened was due to a failure of professional engineering diligence and inept engineering management respectively. A dismal day for the status of engineers. Space does not permit further discussion of these interesting topics now.

Memories

Columbia, the first shuttle into space, should have rested in the Smithsonian museum, for future generations to look at fondly. That was not to be. Most of her was vaporised and will slowly return to earth from the upper atmosphere only as atomic fragments. As for the astronauts on *Columbia* who considered it an honour rather than a risk to fly into space, their names will be written in the star charts far into the future. Seven asteroids (diameters 5-7km) orbiting between Mars and Jupiter have been named in their honour (NASA 03-259, 2003). May they rest among the stars forever.

Dirk Pons (MIPENZ, PhD) has special interests in mechanical design, reliability and risk analysis. Contact him at pons@xtra.co.nz

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