Managing *Columbia* to disaster

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The NASA Space Shuttle operates under difficult conditions. It is subject to the harshness of space, severe mechanical, thermal and aerodynamic loads, and handles high kinetic and chemical energy. These are sufficient to explain the physical failure of *Columbia* at re-entry early this year. However, there is more to failure than the engineering domain. Dr Dirk Pons (MIPENZ) explores the contribution of management and organisational culture.

Figure 1: Columbia lifts off on mission STS-107. The 'stack' consists of the Space Shuttle (with three main engines burning liquid fuel), the external tank (large orange vessel) containing propellant for the Shuttle engines, and two rocket boosters. Once ignited the booster rockets cannot be stopped as they contain a solid propellant [1].

The Shuttle (Figure 1) is well designed, has multiple redundant control and protective systems, and each mission is a major management project on its own, so opportunities for failure should be rare. That sense of technical and management success was abruptly shattered with the spectacular loss of *Columbia* and crew during re-entry on 1 February 2003 (Figure 2).

The physical cause was impact with a piece of soft foam shortly after launch, which severely damaged the reinforced carbon-carbon (RCC) panels of the leading edge of the left wing (Figure 3). During later re-entry, super heated air penetrated the wing, melting internal structures (Figure 4), and upsetting the aerodynamic characteristics. Eventually the

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control system was overwhelmed and *Columbia* turned sideways into the hypersonic airflow, which ripped it apart.

Figure 2: This video was captured by a Danish crew operating an AH-64 Apache helicopter near Fort Hood, Texas. It was taken about 40 sec after loss of control, and shows the breakup of the main body of Columbia at an altitude of about 40 km. Aerodynamic deceleration would have been about 4g at this point, to rise later to a peak of 7.7g [2].

Now that the physical root cause is known, the remedy seems quite simple: prevent the foam from detaching in the first place. This is quite easily done by removing it, and placing heaters in its place to prevent ice build-up (the foam is an insulator for the cryogenic propellants). As a back-up solution, have future astronauts inspect all leading edges when on orbit, and provide them with the capability to repair RCC panels on orbit. Problem solved?

Not quite. The failure of any engineering system is inevitably finally manifest as a physical failure. Consequently there is a tendency to search for root causes based only in engineering mechanics and operator error. However, there are other subtle influences. The psychology dimension, involving management, personality and organisational behaviour, makes potentially large contributions to system failure [4].

In the case of *Columbia* the startling conclusion is that management practice was to blame for the foam detachment.

To make the links from management to foam, we need to start with the foam. It is placed on the external tank to insulate the cryogenic liquid oxygen and hydrogen, preventing ice build up on the outside. Unfortunately, small pieces of foam come off at most launches, due to the supersonic airflow and imperfections within the foam. Every Space Shuttle flight has been damaged by impact with debris at launch, though not necessarily by foam alone, and sustains an average 143 debris strikes per launch, with most of these on the lower surface, and most less than an inch in diameter [2: 122]. NASA engineers and managers began to see debris damage as

Figure 3: Soft foam was fired by a gas gun at supersonic speed onto this rig, which simulates the leading edge of a space shuttle. The gaping hole that resulted (centre) shows the type of damage that Columbia could have sustained at launch (CAIB Photo by Rick Stiles 2003, www.caib.us).

inevitable, and only a maintenance issue [2: 122]. Managers marginalised the risk: they began to perceive the Space Shuttle as a physically robust operational vehicle rather than a research and development one. A similar perspective had contributed to the loss of *Challenger* many years ago.

The worst culprit for foam detachment was the bipod attachment. This connects the external tank to the nose of the Space Shuttle. The foam here is thicker, is laid up by hand and therefore has internal imperfections (elsewhere it is laid up by machine), stands proud of the surface, and there are complex air flows over this region. Major pieces of bipod foam have detached on at least six missions prior to fateful mission STS-107.

Two missions prior to STS-107, *Atlantis* flew mission STS-112 and bipod foam detached, causing significant damage to a Solid Rocket Booster [2: 124]. The technical experts recommended that the STS-112 incident be treated as an 'in-flight anomaly'. However, shuttle managers declined, and instead classified it as a matter requiring non-critical investigation. The CAIB wondered: '*Why did they take the unprecedented step of scheduling not one but eventually two missions to fly before the External Tank Project was to report back on foam losses?'* [2: 125].

From a management perspective, the disadvantage of a 'in-flight anomaly' is that it requires a major investigation, which can delay or even ground the next few launches. With a rationale that was '*seriously flawed*', some '*sleight-of-hand*' statistics, and '*with no engineering analysis, Shuttle managers used past success as a justification for future flights'* [2: 126]. The way was now clear for any future foam strikes to be considered simply a maintenance issue. When *Columbia* mission STS-107 was being reviewed for flight readiness, the outstanding foam issue from STS-112 was not even discussed by engineers and managers.

Why did presumably excellent managers marginalise the risk of the foam problem? The answer is that there was *'pressure to meet an increasingly ambitious launch schedule*' [2: 131]. This came about since NASA's financial backers, the White House and Congress, had put NASA on financial probation back in 2001, requiring the completion of the core of the International Space Station (ISS) failing which the ISS would not be developed further. The target was to launch 'node 2' (a docking adapter for European and Japanese modules) and thereby get to 'core complete' by a specific date: 19 February 2004. This date was suggested as feasible by project planning at the time.

Simultaneous with setting this target, a new appointment was made to the top post in NASA. A new organisational culture began to flow down from senior management, creating different organisational behaviour in middle managers and engineers. A large amount of management meeting content was devoted to the schedule margin (the number of days delay that could be accommodated without adversely affecting the target launch), and '*any suggestions that it would be difficult to meet that launch date were brushed aside*' [2: 117]. A fixed and tight schedule of Shuttle launches was required to meet an International Space Station date that was technically arbitrary but politically important for senior managers. Unfortunately, the schedule margin kept evaporating. To compensate, some testing was reduced, more tasks were done concurrently, and a third work shift was added [2: 132]. The launch schedule became increasingly compressed and critical as the target date approached. By the end of 2002 there was zero margin left.

With a new organisational culture preoccupied with schedule, rational people started interpreting old things differently. Many of the Shuttle program managers who were involved with STS-107, the final flight of *Columbia,* had been involved with the previous missions and the decisions about foam. When it was found out mid-mission that *Columbia* had sustained a large foam strike, the management team marginalised the severity. The CAIB was severely critical of the STS-107 mission Chair, stating that '*most of Linda Ham's inquiries about the foam strike were not to determine what action to take during Columbia's mission, but to understand the implications for [the next mission] STS-114* [for which she would be a manager again]' [2: 139].

With the schedule pressure entrenched in the organisational culture, the '*Shuttle Program management declined to have the crew inspect the Orbiter for damage, declined to request on-orbit imaging, and ultimately discounted the possibility of a burn-through*' [2: 127]. During the mission Ham stated that '*it's not really a factor during the flight because there is not much we can do about it*' [2: 147]. These were deliberate decisions, i.e. errors of commission, and persistent in that managers missed several opportunities to make alternative decisions. Ham even actively ordered a halt to requests for telescope imaging of *Columbia*, because the requests had not first gained her permission, and the necessary repositioning of *Columbia* would affect the mission schedule [2: 153]. There were other aspect of poor organisational behaviour, like managers and engineers putting more emphasis on their relationships or command structures than on their own professional diligence.

Large organisations all experience office politics, but it is tragic that pathological organisational behaviour contributed to this accident. The CAIB report concludes with stinging criticism of the Mission Management Team for *Columbia*, their lack of effective leadership, their lack of interest in solving problems other than schedule, and their behaviour in keeping dissenting views at bay. Managers defence was that '*if engineers had a safety concern, they were obligated to communicate their concerns to management*'. However, CAIB stated that '*Managers did not seem to understand that as leaders they had a corresponding and perhaps greater obligation to create viable routes for the engineering community to express their views and receive information*' [2: 169].

It is easy to demonise the Shuttle managers, to view their actions as abnormal, reprehensible, professionally negligent, and alien to anything we would do in similar circumstances. However, that would be unfair use of hindsight, and perhaps even dishonest. What can we learn from *Columbia*?

In my opinion, the lessons are:

(1) Leaders (e.g. the senior management team) need to be aware that the key performance indicators (in this case schedule) that they set will subtly change the behaviour and decision making priorities of subordinates. Excessive focus on the bottom line can compromise professional due diligence.

(2) Managers must correct for the fact that subordinates will interpret specific directives as taking precedence over standard organization procedures (e.g. safety), sometimes resulting in violation of those procedures [3].

(3) Leaders and managers need to be aware that their position gives them the authority to marginalise and ignore contrary points of view that are inconsistent with their beliefs. However, such beliefs may lack robustness and validity. Leaders and managers must maintain their intellectual curiosity and skepticism [2: 181].

(4) Organisational success will cause unjustified optimism, complacency, and desensitisation to risk, unless leaders actively de-bias the organisation.

(5) Leaders must encourage minority opinions, and if these are not present the responsibility for a thorough and critical examination falls back on them [2: 183]. Leaders must ensure that adequate communication channels exist, and the organisational culture does not informally penalise those with reservations.

(6) There must be a separation of technical and management authority in safety matters.

The CAIB concluded that the '*organizational culture has as much to do with this accident as the foam*' [2: 97]. Leaders have a responsibility to ensure that the organisational culture, which originates with them, is not adversely affected by their politics, personalities or relationships. The common practice of raising up an inner circle of supportive and like-minded people seems an increasingly fragile leadership concept. Leaders would do better to encourage cognitive and personality diversity, as a dynamic organisation ('learning organisation') needs to encourage openness and find value in disagreements [5: 543].

The conclusion from *Columbia* is that leaders and managers of all organisations need to be more aware their potent effect on organisational behaviour, and how that in turn can drive complex engineering systems to catastrophic failure.

Images courtesy CAIB.

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