Incident

# The Challenger Space Shuttle disaster

John Wilkinson, Human Instrumental Ltd, UK


## Summary

The space shuttle Challenger disintegrated 73 seconds after launch on 28 January 1986 killing all seven astronauts aboard. An O-ring seal in the right solid rocket booster (SRB) failed at lift off causing a breach in the SRB joint seal. This let pressurised hot gas escape and ignite, affecting nearby SRB attachment hardware and an external fuel tank leading to structural failure. NASA management knew the design of the SRB had a potentially catastrophic flaw in the O-rings but did not address this effectively. They also appeared to have disregarded warnings from engineers and not to have passed on their technical concerns.


**Keywords:** Production pressure, culture, risk assessment, design, hindsight bias

This review is based on:

- the original (brief) LPB coverage[1] in a wider review of communication failures;
- the original US Presidential Commission's report of the investigation (the Rogers report)[2];
- the US Congress Committee on Science and Technology's review[3] of the Roger's report and NASA's own investigation;
- the seminal account by Diane Vaughan (published in 1997 but recently republished as an enlarged 2016 edition — the only change is a new foreword on Columbia)[4]; and
- the subsequent Columbia Accident Investigation Board's (CAIB) report of the 2003 Columbia space shuttle disaster[5].

In considering the disaster on this 30th anniversary, the author has aimed to stand back from the later Columbia accident. Since 2003 Challenger is mostly seen and studied through the lens of Columbia (as an example of an organisational learning failure) but it is worth looking at what was known before this so that the original accident is seen more clearly. Even though the CAIB report acknowledges this risk explicitly, there is inevitably a risk of hindsight bias and selectivity in such post-Columbia accounts of Challenger. Therefore, the focus here is more on Vaughan's original and exhaustive account of Challenger alone.

Like Andrew Hopkins (of 'Lessons from Longford' fame) Vaughan is a sociologist, appropriate enough for the socio-technical systems involved both in space travel and in the process industries. Explaining major accidents of any kind requires both engineering / technical expertise as well as an understanding of how organisations (as social structures) and people work. This sociological input produces better learning from such events and improves the chances of avoiding future disasters. This paper summarises the accident, its technical and immediate causes and the contributing organisational factors. Clear lessons emerge for the process industries. One of the big enemies of learning from accidents is a defensive 'checklist' approach e.g. 'we don't have that equipment, that process, that goal – so this doesn't apply to us'. This approach screens out potential learning opportunities. It is much better to say 'OK, this doesn't look like a direct correlation, but what can we learn?' This turns learning into a potentially much more productive process rather than a checklist approach.

## The accident

Challenger launched at 11.38 a.m. EST on 28 January. It disintegrated 73 seconds into the first two minute ascent stage killing all seven astronauts on board. They included the well-publicised presence of Christa McAuliffe, a teacher due to teach elementary pupils from space. Rather like the Space Lab today, the shuttle launches were then seen as sufficiently routine to allow such diversity.

The technical explanation for the disaster is relatively straightforward. There were two Solid-propellant Rocket Boosters (SRBs) attached to the space shuttle. The Solid Rocket Motor (SRM) was contained within the four main central segments of the assembled SRB. The SRBs provided 80% of the thrust required at lift-off to get the whole shuttle assembly off the ground and into space. The shuttle itself initially consisted of the orbiter vehicle, the external fuel tank and the SRBs. The solid fuel in the SRBs was reacted to produce very hot high-pressure gas which expanded and accelerated on moving through the rear nozzle to provide thrust. The SRBs were jettisoned two minutes into the ascent and were later recovered and reused. The use of solid fuel was a well-recognised solution to provide the necessary extra thrust required to get the shuttle off the ground and into space. It was also a relatively cheap choice. The third attachment to the shuttle for lift-off was the external liquid fuel tank consisting of a hydrogen tank, an oxygen tank and an inter-tank which fed the three main shuttle rocket engines with a hydrogen-oxygen mix. The external fuel tank was jettisoned once the shuttle had escaped the earth's atmosphere and was not recoverable.

The SRBs were prefabricated by Morton Thiokol (the contractor who designed, manufactured and maintained the SRBs) from seven original sections into four cylindrical segments each with factory-sealed joints. Propellant was poured into each segment where it solidified. The four segments were assembled after transport to the Kennedy Space Centre and so the remaining joints were known as 'field'




0260-9576/16/$17.63 + 0.00

joints. The pressure generated at lift-off ignition created a very small gap in the SRB joints. The O-rings were designed to seal these gaps against the high pressure hot propellant gases developing inside. The seal was achieved by using quarter-inch diameter Viton rubber-like O-rings. There were two of these, the primary and secondary O-rings, the secondary acting as a back-up in case any of the hot propellant gases generated on ignition should erode and pass the primary.

The air temperature at the launch was the lowest recorded for any previous shuttle lift-off. This hardened the O-rings and adversely affected their ability to achieve an effective seal. On the previous coldest launch in January 1985, a primary joint was breached and eroded but the secondary seal worked as intended. For low temperature to impact on the seated seals fully required about three days' exposure — a relatively rare event. On Challenger's launch in January 1986, the hot combustion gases produced on ignition inside the SRM on the right-hand SRB were able to erode and then 'blow by' both the primary and secondary O-rings on the aft field joint. Cameras captured the resulting smoke puffs at the joint showing that the grease, joint insulation and O-ring material were being burned and eroded by the hot propellant gases.The escaping gases ignited and the ensuing flame started to damage the adjacent SRB aft field joint attachment hardware and then was deflected onto the external fuel tank. The hydrogen tank located aft within the external fuel tank either failed or was weakened and the liquid fuel inside subsequently leaked and started burning. The original flames by this time had also caused the SRB lower strut connecting it to the external fuel tank to break. The SRB then rotated away and the external fuel tank itself failed leading to a major release of hydrogen and a subsequent fireball (not an explosion)[4[p39]]. The shuttle was also by then breaking up mechanically in the normal atmospheric turbulence associated with the launch because the external fuel tank was a key structural part (the 'backbone') of the whole shuttle assembly.

## Lessons learned

The lessons are listed here but the detail which underpins the organisational causes is discussed further below.

### *Lessons for the process industries*

- External pressures on organisations, such as the production pressures on NASA, can establish ways of doing things in the organisational culture, structure and processes which incrementally align reality with what the organisation wishes for — its goals. Managing these pressures and being mindful of their potential distorting effects is difficult and requires vigilance over time and a proper sense of chronic unease.
- To prevent such pressures distorting an organisation's arrangements it is important to establish a clear baseline or rationale for e.g. engineering and technical decisions, so that any incremental movement away from this can be spotted.
- Incremental changes can lead to the normalisation process so that each individual anomaly is explained or justified but the full picture is not seen until after a significant adverse event. Each event is rationalised and validated against e.g. risk assessment processes but not evaluated ("Is this really doing what we want? Against what baseline?")
- Risk assessment should not be about maintaining or defending the status quo — the process should not take over from the purpose. A questioning attitude and mind-set is required. There is always the possibility that something new is happening which designers could not foresee.
- Organisations need sufficient checks and balances for safety to ensure that safety is not over-ridden by organisational structures and processes. These can include: sufficiently independent and resourced safety oversight and an adequate baseline for key arrangements such as engineering and design decisions. If key decision makers cannot see the baseline (or if the baseline is wrong) they cannot easily spot significant deviations from it, especially when these are incremental.
- Whether a new design is developed or an old one used or modified, there are risks to be managed. New designs bring in more potential for 'Unknown unknowns'. In the case of the SRBs, the existing designs (such as the Titan rockets) were not a straight 'read across' to the space shuttle, and introduced misunderstandings about redundancy.

### *Lessons for investigators*

- If the full underlying causes (organisational and some extra-organisational) are not understood and learned from, and the organisation's structure and arrangements changed and maintained accordingly, then accidents can and will repeat.
- Just relying on the official investigation reports for major accidents can be misleading and incomplete. Even with good investigations and reports, what the press and others choose to focus on is not necessarily the full picture, and nor is a company digest or flyer. Companies need to think for themselves and exercise judgement about the full range of lessons learned and consider the full picture presented. This implies that they know what good looks like for an investigation and what the underlying organisational factors may be.
- Learning is a process and not just an outcome. Organisations can learn something from most incidents if they view learning in this way. Using a screening out or defensive checklist approach will inhibit learning.
- The hindsight bias can warp investigator judgements and skew the lessons drawn from accidents like Challenger. Investigators need to establish the full baseline against which key decisions and actions occurred. The history of O-ring anomalies and how to interpret them may look obvious after the Challenger failure but was not obvious to those involved at the time. Based on what they knew or was available to them they acted rationally and in line with the prevailing safety processes.
- Investigations which produce stereotypes (heroes or villains in whatever guise, such as 'management') are good stories but unlikely to change anything or produce real learning. People generally behave in ways that make sense to them at the time. The first job in an investigation is to understand things from their viewpoint.
- The full impact of human factor issues on issues such as critical communication arrangements (like those affecting






0260-9576/16/$17.63 + 0.00

IChemE

the final teleconferences) and fatigue can be missed if investigators either do not prioritise human factors or do not value them sufficiently. These factors can be major contributors to poor decision-making.

## The organisational causes

The underlying causes of the disaster are complex and organisational. These are discussed below.

### *Launch delays*

The launch was put back five times from the original 22 January date before the disastrous launch on 28 January. The shuttle before this was delayed seven times over 25 days before finally launching on 12 January. This affected the subsequent Challenger launch. The last two delays were due to weather and a fault respectively. Delays were a major concern for NASA because the launch schedule had become central in their competition for scarce funding. Production pressures were at their peak before the Challenger launch.

### *The O-rings and the launch decision*

The problem with the O-rings was documented from 1977, long before the first shuttle flight in 1981. Evidence accumulated from 1977 to 1985. During a final teleconference running up to around midnight of the day before the launch, engineers from Morton Thiokol, the SRB manufacturer, and NASA managers debated whether the launch should go ahead because of the predicted very low temperatures expected and the likely effect on the O-rings. As the Commission, the Committee, the press and others investigated "*...they created a documentary record that became the basis for the historically accepted explanation of this historic event; production pressures and managerial wrongdoing.*" [4[pxxxiv]] The Rogers Commission "*...found that NASA middle managers had routinely violated safety rules requiring information about the O-ring problems be passed up the launch decision chain to top technical decision makers...*" [ibid[pxxxiv]] The top-down pressures on NASA included competition, scarce resources and production pressures. These led finally to a flawed and deliberate launch decision.

Vaughan's very thorough investigation provides a more nuanced view, and ultimately a more convincing one. Her conclusions also make more sense in the light of the subsequent Columbia disaster. Rather than the simplistic popular account derived from the Rogers Commission and the Committee's reports, she argues that "*No extraordinary actions by individuals explain what happened: no intentional managerial wrongdoing, no rule violations, no conspiracy. The cause of the disaster was a mistake embedded in the banality of organisational life and facilitated by an environment of scarcity and competition, elite bargaining, uncertain technology, incrementalism, patterns of information, routinisation, organisational and interorganisational structures, and a complex culture.*" [ibid [pxxxvi]]

### *The normalisation of deviance*

Vaughan divides this into three elements: the production of culture; the culture of production; and structural secrecy. The gradual and incremental acceptance of the O-ring anomalies was the 'produced culture'; the scarcity of resourcing and the demands of competition over a long period conspired to establish a culture of production; structural secrecy prevented key information from flowing effectively through the organisation. All of these elements affected decision-making including the final fatal launch decision.

- **Accepting more risk**

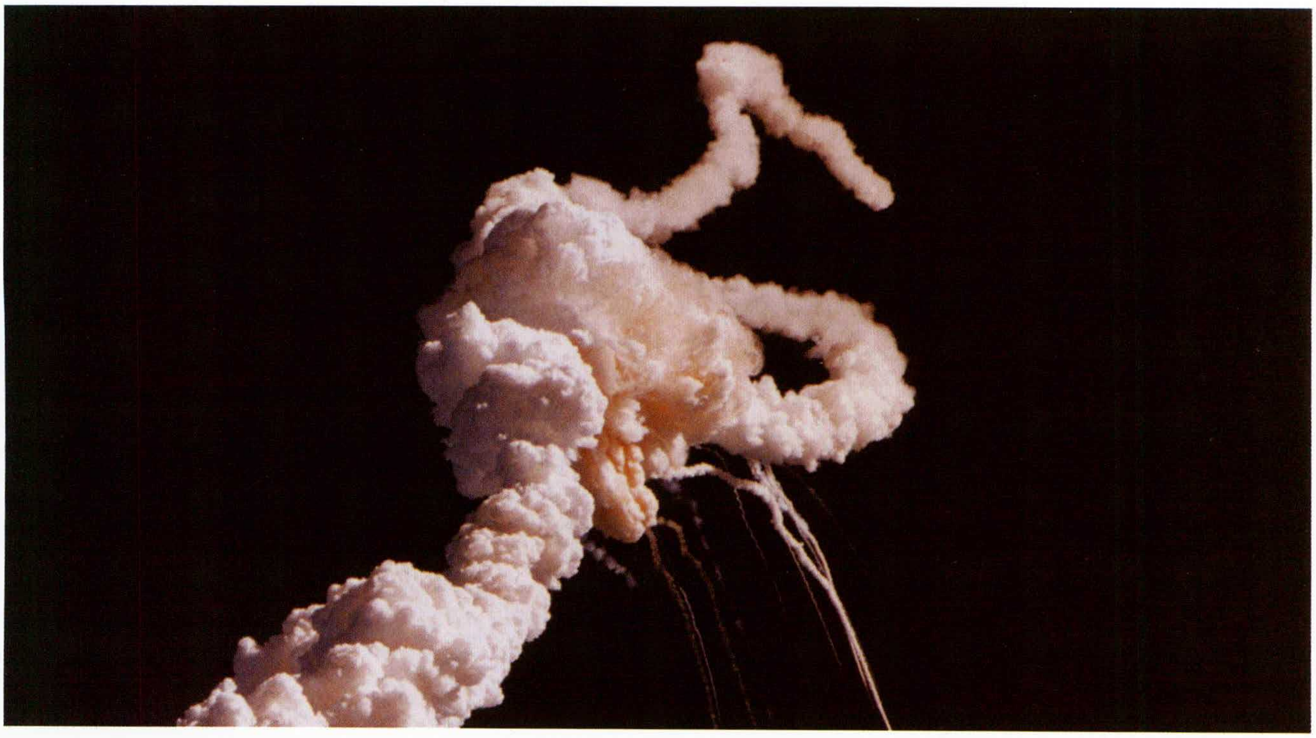
  The normalisation of deviance helps explain:
  - why the evidence of risk in the SRBs was originally accepted in the selected design;
  - why it was assessed as safe when the shuttle was declared operational in 1984;
  - why it continued to be assessed as safe; and
  - why the final launch took place despite some key engineers having and expressing misgivings.

  More risk was accepted incrementally over a long period. The risk was seen as acceptable (and accepted) and anomalies were explained for each case after launch and recovery. Each successful launch reinforced this. Those involved in decisions on the SRB and the launch acted and made decisions that made sense to them (was normal) at each relevant time. Morton Thiokol, Marshall (The Marshall Space Flight Center (MSFC), NASA's rocketry and spacecraft propulsion research centre, who had technical oversight of Morton) and others followed the NASA rules, arrangements and structures for the twin key safety management system procedures — the Acceptable Risk Process (ARP) and the Flight Readiness Review (FRR). There were compounding errors e.g. flawed base data on O-ring temperature limits, no effective demonstration of the correlation of temperature data against O-ring previous failures and in communications such as on the understanding of O-ring redundancy between Marshall and Morton and the way that the O-ring risk was categorised.

- **Redundancy misunderstood**

  The baseline for the redundancy misunderstanding was that the SRB seal design was seen as a significant improvement over previous designs such as the earlier US Titan rocket which only had a primary seal. Failure of a primary was not seen as so significant when a secondary was in place to protect against this. The problem arises through dependency such as the cold temperature issue. In the process sector nowadays, the triggering of any safety or protectives system – such as a pressure relief valve – is a safety event in itself. In the latter case, maintenance could be a common cause factor affecting both operational and safety valves.

  NASA processes, procedures and structures incrementally accommodated the O-ring anomalies to align with the overall goal — of timely and repeated successful shuttle launches and recoveries. These weak signals were seen but were expected and on a case-by-case basis accepted — engineers did risk assessments and communicated the results to managers. The latter were also mostly engineers but with different goals and priorities set by the culture of production. Hindsight does not show so clearly that the context for tuning in to weak signals was against a much wider range of anomalies detected after each launch.




- **Structural secrecy**
  A large organisation generating huge amounts of information, specialised engineering roles and language, the acceptance of risk on a case-by-case basis against established (but flawed) technical criteria and in accord with established risk processes — all of these conspired to prevent key technical information from flowing through the management chain. No individual was hiding anything but the organisation's own structure was acting as a barrier.

- **Oversight**
  The final barrier should have been the safety oversight but NASA's safety programme was famously described as 'silent'. In fact, this was drastically reduced and especially after the shuttle programme entered its operational phase. Internal regulation was also subject to the effects of interdependence, i.e. being part of the same organisation the internal bodies were regulating. The external regulator was even smaller and had a narrow scope. These bodies had in truth little chance of finding the O-ring issue and not least because it was seen and maintained as an acceptable risk.

## *Design and culture*

Design is an inherently uncertain process, the more so in areas of risky technology such as innovative space missions. However, designers in any industry make trade-offs all the time and also are conservative — adopting the solid fuel option for the SRBs was conservative at the time because it was a better tried and tested approach. The fact that there were known risks associated with this was in that sense good because they were 'Known knowns' and could in principle be managed. New designs would potentially have 'Unknown unknowns'. For the SRBs and the shuttle as whole such 'Unknown unknowns' were bound to emerge in such a risky area of technology but NASA generally expected these and was vigilant for them.

There is also the well-rooted view that the transition from an experimental space vehicle to an operational one was somehow also deviant. In terms of the overall space shuttle programme, this was simply an in-built project milestone and the criteria for passing this were met. Hindsight suggests this was a flawed decision and that such an inherently risk enterprise could never be truly seen as operational. Therefore, the original programme could perhaps be criticised but in that context, the decision was rational. In its own terms the mission was a success story. NASA have also been accused of being too 'can do' but if that is reworded as 'being good at solving problems' then it doesn't sound so damming, and problem-solving is what NASA engineers, managers and others were very good at. Culture and control were also eroded by the need to be business-like and put work out to contract. However, the latter was not 'wrong' in itself. Provided that safety, quality and sufficient technical oversight were maintained, this can and did work. The larger problem was that of the ensuing organisational and project complexity — complex organisations can produce surprises, and tightly-coupled systems such as those involved in space flight are particularly prone to this.

## *Cost cutting and mission safety*

One widely-held view of key contributing causes to the accident were NASA cost / safety trade-offs, prompted by budget cuts and other pressures on the organisation. These decisions are held to have adversely affected safety programmes, hardware testing and technical design. Vaughan found it difficult to find concrete evidence that the first two affected mission safety but she investigated the extensive paper trail for the third. The example she chose was the original award of the SRB contract to Morton Thiokol and the consequent decision to not pursue a proposed safety feature,


0260-9576/16/$17.63 + 0.00

escape rockets. Her conclusion is that despite their apparent salience in hindsight "*...these were not the cost / safety trade-offs they appeared to be after the tragedy.*"[4[p423]]

The SRBs were a cheaper option. Rockets using solid fuel have fewer moving parts and so are cheaper to use than liquid fuelled ones even though solid fuel is more expensive. However, solid fuel rockets could not be shut down after ignition which had major implications for mission safety. Previous rockets had escape rockets to allow crews to escape during the dangerous first two minutes of SRB-assisted ascent. Orbiter was too large for this option without significantly reducing its payload so the proposed escape rockets were scrapped.

On the face of it, this looked like a pure cost or business decision that compromised safety but in fact NASA had done an extensive assessment of the option and concluded that escape rockets were simply not viable. Any trigger event that could provide warning that escape was necessary would in effect be the event itself or closely co-incident with it. There was also no practical means identified which would both cover all scenarios during the first two-minute ascent and also significantly increase crew survivability.[4[p424]] NASA concluded that instead "*...that first stage ascent must be assured.* [ibid] In other words they just needed to get this stage right — for example, through conservative design and other tried and tested means. All design involves trade-offs of course, but this example just became more visible than most after the disaster.

The same argument is made in the choice of a segmented over a seamless design for the SRB. Straightforwardly, if a design with no joints is selected, then joints cannot fail — and a joint failed so. But NASA had had the four contract bids and proposals assessed by a source Evaluation Board (SEB) against four 'mission suitability' criteria. There were three segmented designs and one seamless / monolithic one proposed by Lockheed.

However, Vaughan points out that segmented SRBs were more widely used at the time so the bid ratio looks understandable in this 'social context'. [4[p430]] Her closer examination of the SEB assessment also shows that the Lockheed seamless design was rejected not just because it was more expensive than Thiokol's but because the design was inadequate in ways that were significant and not easily correctable. The Thiokol design had issues but these were assessed as 'readily correctable' and the segmented design itself as 'not sacrificing performance quality'. This was confirmed by a subsequent further Governmental Accounting Office (GAO) review after a Lockheed protest that the costs were miscalculated. The GAO agreed a reduction in the original $122 million cost estimates for Lockheed (but did not find any new issue with the Thiokol design) but this was still $56 million more than Thiokol's. The original SEB bid assessment was repeated and found still valid.

Vaughan acknowledges that her analysis of the cost / safety trade-offs is necessarily incomplete even for the SRB contract example despite her painstaking research and analysis. However she concludes that "*...what I found did not affirm either decision [escape rocket scrapping and contract award] as an example of organisational misconduct and amoral calculation on the part of NASA senior administrators.*" [4[p431]] She also strikingly states that "*Production pressures became institutionalised [in NASA] and thus a taken-for-granted aspect of the worldview that all participants brought to NASA decision-making venues.*" [4[pxxxvi]]

## The hindsight bias

Hindsight is tricky to recognise and deal with and after the hugely public failure of one of Challenger's segmented SRBs, the social context looked very different to observers — but all that had changed was that Challenger was lost. People are wired to find stories, to make sense out of events quickly (this is what Daniel Kahneman calls System 1 thinking[6] ) — it is a highly automatic, quick and sometimes dirty process but it has evolutionary advantages. People also like stereotypical characters just as many stories have, so casting heroes and villains (even if labelled collectively as 'NASA Management') is intuitively appealing and inclined to stick in observers' and the public's imagination. The heavier-duty and very effortful System 2 thinking which takes time, energy, patience and application — as shown by Vaughan's epic study over nearly ten years — can really test the evidence, reconstruct the events and look more widely to make sure that the full context is understood. Typically, System 2 thinking comes into play when the world as we think we know it surprises us and System 1 has to look to it for help.

Despite the very unpleasant 'surprise' of a disaster like Challenger however, as Sidney Dekker makes very clear[7[p82]], the hindsight bias can lead investigators and others to be misled by System 2 and ask 'Why didn't people act (think, react, decide etc.) differently?' instead of 'Why did they act as they did?' — a subtle but very important difference. Those involved all acted rationally in the circumstances they found themselves in and with the knowledge, competence and so on that they then had. Only asking the second question will elicit the full context against which to judge causes and contributions, and from which to extract the full lessons. One of the big dangers of hindsight is in not establishing the baseline for what happened — the full landscape in which decisions were made and actions carried out. The O-ring anomalies needed to be seen against a background where anomalies were expected on each flight, and not just for the O-rings. The later Columbia investigators specifically address this issue: "*Rather than view the foam decision only in hindsight, the [CAIB] tried to see the foam incidents as NASA engineers and managers saw them as they made their decisions.*" [5Vol1: [p196]]

## The investigation reports

The Congress report was produced by the Committee on Science and Technology (the Committee) in the US House of Representatives based on the Rogers' Commission investigation and report on the disaster, the NASA investigation, and on its own additional hearings and review. The Committee "*...which authorised the funds and reviewed the lengthy development process which led to the successful Shuttle program, has a responsibility to insure that the tragic accident, and those events that led up to it, are understood and assimilated into all levels and activities of NASA so that safe manned space flight can be resumed.*"[3p2] Clearly this either did not happen or it happened and then the improvements degraded over time. The Committee certainly did not miss the wider implications of the event at the time: "*...the lessons learned by the Challenger accident are universally applicable, not just for NASA but for governments, and for society.*"[3p3]

Neither of the reports are that easy to read and it is difficult to cross-check between them or to find clear and succinct conclusions and recommendations. They are quite discursive e.g. though the use of direct extracts from the hearing testimonies. Although such direct testimony is quite powerful in places, it is not always easy to follow, and the sometimes adversarial nature of the questioning does not help clarity.

The Rogers Commission report itself is separate and the Committee states that it does not always agree with the Rogers' findings[3p4]. For example, the Committee did not agree that NASA middle managers violated rules but the Committee's report came later and did not receive the same level of publicity as the Rogers report.[4[p72]] The Committee also makes some further recommendations of its own to NASA as well as repeating the Rogers' recommendations. It is interesting to look back and see the Committee coming to some significantly different conclusions (and recommendations) to those in the Rogers report. The Committee saw this as their role and felt able to disagree with Rogers (and the report left some areas open for the Committee to conclude on). This is something that did not happen after the CAIB's report. All that said, the conclusions and recommendations make sense even if they ultimately did not prevent the Columbia accident (but may of course have prevented others unknown).

Following the Challenger investigation, when the CAIB investigated Columbia they set a new benchmark for clarity and completeness along with a thorough treatment of the organisational factors, but this is still rare. More recent accidents, such as Macondo, re-emphasise the difficulty of relying solely on official reports — Macondo has multiple reports and the US CSB report is imminent.

## Human factors in the Rogers report

The 'Human Factors Analysis' carried out for the Rogers Commission is relegated to an appendix[4]. It is worth quoting the rationale in full: "*The Commission staff investigators reviewed the work schedules of NASA and contractor personnel involved in the launch processing of the Challenger at Kennedy and of the Marshall managers involved in the 27 January teleconference discussion of low temperature effects on the Solid Rocket Booster joint. The results of the review are presented herein. Although major accident investigations now include human factor analyses, the Commission avoided drawing specific conclusions regarding the effects of work schedules on work performance or management judgment. However, with the concurrence of NASA officials the Commission agreed that the results of the review should be included as an appendix to the Commission report. An evaluation by NASA of the consequences of work schedules should be conducted as part of its effort to reform its launch and operational procedures.*"[4]

Work scheduling, the lack of understanding of what is lost without face-to-face communication, the final teleconferences and other human factor aspects did not receive a sufficient weighting. What is lost in not having limited or unreliable face-to-face communication can be partly compensated for if understood and planned for. In simple terms key decisions were taken by people trying to communicate in a degraded situation (a teleconference or unreliable videoconferences rather than a full face-to-face meeting) and across time zones and after working long hours, sometimes repeatedly.

## Final analysis

Vaughan's account of the Challenger disaster is the most complete and sets the background and baseline very thoroughly and widely — indeed the subsequent Columbia investigation draws heavily on it. Her final analysis is worth repeating here: "*No extraordinary actions by individuals explain what happened: no intentional managerial wrongdoing, no rule violations, no conspiracy. The cause of the disaster was a mistake embedded in the banality of organisational life and facilitated by an environment of scarcity and competition, elite bargaining, uncertain technology, incrementalism, patterns of information, routinisation, organisational and interorganisational structures, and a complex culture.*" [ibid [pxxxvi]]

The 2003 Columbia disaster is eerily signalled in Vaughan's book i.e. written before the book's publication in 1997. She notes that economic pressures were again increasing on NASA, and those at the top were largely not the same people who underwent the Challenger experience and aftermath. She warns that "History repeats, as economy and production are again priorities." [4[422]] These external influences again degraded the NASA culture and its organisation over time despite the lessons learned from Challenger. Even a high reliability organisation may struggle against such forces and weak signals may again be missed.

## References


1. *Carson, P.A. and Mumford, C.J., Communication failure and loss prevention, Loss Prevention Bulletin 218 April 2011 p5-14*
2. *William P. Rogers (Chair), Report of the Presidential Commission on the Space Shuttle Challenger Accident, U.S. Government Accounting Office, Washington, D.C., 1986. In five volumes, available via http://history.nasa.gov/rogersrep/genindex.htm )*
3. *Committee on Science and Technology, Investigation Of The Challenger Accident, Presidential Commission on the Space Shuttle Challenger Accident (Rogers Commission), Union Calendar No. 600, 99th Congress Report 2cnd session, House Of Representatives, 99-1016. Retrieved from https://www.gpo.gov/fdsys/pkg/GPO-CRPT-99hrpt1016/pdf/CHRG-101shrg1087-1.pdf*
4. *Vaughan, D. 2016. The Challenger Launch Decision: Risky Technology, Culture and Deviance at NASA. Enlarged edition with new preface. University of Chicago Press, Chicago and London, 2016.*
5. *Columbia Accident Investigation Board Reports via NASA http://www.nasa.gov/columbia/home/CAIB_Vol1.html*
6. *Kahneman, D. 2011. Thinking Fast and Slow*
7. *Dekker, S. 2015. The Field Guide to Understanding Human Error.*
8. *Rogers Commission report, Volume 2: Appendix G - Human Factor Analysis. Retrieved from http://history.nasa.gov/rogersrep/v2appg.htm*



0260-9576/16/$17.63 + 0.00

IChemE