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Columbia and *Challenger*: organizational failure at NASA

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Abstract

The National Aeronautics and Space Administration (NASA)—as the global leader in all areas of spaceflight and space science—is a unique organization in terms of size, mission, constraints, complexity and motivations. NASA's flagship endeavor—human spaceflight—is extremely risky and one of the most complicated tasks undertaken by man. It is well accepted that the tragic destruction of the Space Shuttle *Challenger* on 28 January 1986 was the result of organizational failure. The surprising disintegration of the Space Shuttle *Columbia* in February 2003—nearly 17 years to the day after *Challenger*—was a shocking reminder of how seemingly innocuous details play important roles in risky systems and organizations. NASA as an organization has changed considerably over the 42 years of its existence. If it is serious about minimizing failure and promoting its mission, perhaps the most intense period of organizational change lies in its immediate future. This paper outlines some of the critical features of NASA's organization and organizational change, namely path dependence and "normalization of deviance". Subsequently, it reviews the rationale behind calling the *Challenger* tragedy an organizational failure. Finally, it argues that the recent *Columbia* accident displays characteristics of organizational failure and proposes recommendations for the future.

1. Introduction

> "What we find out from [a] comparison between Columbia and Challenger is that NASA as an organization did not learn from its previous mistakes and it did not properly address all of the factors that the presidential commission identified."
>
> —Dr. Diane Vaughan; Columbia Accident Investigation Board testimony, 23 April 2003 [1].

Organizational failure is a fact of organizational life. Failure will happen no matter how elaborate of a system an organization deploys. Nowhere is this more apparent than in high-risk organizations like NASA. NASA has a variety of risk-avoidance systems that all aim to do one thing: ensure that instruments and astronauts sent into space complete their missions safely. NASA has failed in a few instances to fulfill this goal in the realm of human spaceflight.[1] The Space Shuttles *Challenger* and *Columbia* tragedies as well as the Apollo launch pad fire in 1967 are examples of failure at NASA that cost a total of 17 astronaut lives. Where the Apollo accident was a mix of organizational and technical failure,[2] both the Shuttle tragedies are largely organizational failures.

Section 2 acquaints the reader with the unique organizational features of NASA. Section 3 explains the *Challenger* tragedy and the rationale behind calling it an "organizational failure". Section 4 explains the working scenario behind *Columbia*'s disintegration and the parallels with *Challenger*. Finally, Section 5 proposes some possible remedies.

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[1] For the remainder of this paper I will speak specifically about human spaceflight.

[2] The Apollo accident in 1967 was the result of bare wires short-circuiting in the capsule's pure oxygen environment causing an intense fire, toxic gas build-up and pressurization of the spacecraft denying the astronauts egress from the vehicle. It can be argued that this was an organizational failure based on the extremely hazardous conditions of the test capsule. However, Apollo is distinct compared to *Challenger* and *Columbia* considering Apollo took place during NASA's formative years when all vehicles were designated as research and development craft. Notably, the Apollo accident does not display the path dependence (Section 2.2) or normalization of deviance (Section 2.4) characteristic of *Challenger* and *Columbia*.

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doi:10.1016/j.spacepol.2003.08.013

2. Organizational features of NASA

2.1. Overview

The National Aeronautics and Space Administration (NASA) is a unique organization in terms of size, mission, constraints and motivations. Even as one of the smallest of the major federal agencies, NASA is a large organization that directly employs 18,000 people and has an operating budget of approximately US$ 15 billion (out of every US dollar spent in the world on space, roughly 35 cents is spent by NASA [2]). NASA's mission is unique as a leader in all areas of spaceflight and space science. Along with the traditional constraints of a federal agency like annual budget review and organizational complexity, NASA's main endeavor of human spaceflight enjoys no flexibility in terms of risk. Complicating things further, the motivations for NASA's mission have varied from the very specific in the past—winning the US/Soviet space race during the 1960s—to the very abstract today—technology transfer, advancement of scientific knowledge and space development.

2.2. Path dependence

NASA has been described as a heavily "path dependent" organization [3]. Path dependence refers to the tendency for organizations to make decisions based on, and have their present state defined by, their history. A good analogy for this phenomenon is when something—like a cardboard box—is pressed upon and is unable to return to its original form. Organizations are often equally unable to return to their original state given a stimulus.

NASA is very much influenced by its history. The agency was established in 1958 by the National Aeronautics and Space Act of 1958.[3] The aftermath of John F. Kennedy's historic "man on the Moon" speech in 1961 sparked the "space race" between the United States and the Soviet Union as each struggled to prove its technological superiority. Cost concerns were of less importance during this era as nothing could be spared to beat the Soviets to the Moon. However, at the end of the era, NASA experienced substantial budget cuts (see Fig. 1) but retained the organizational structure of the Apollo era. Additionally, human spaceflight was recognized as an important and vital part of the space program's success in the 1960s and as such played a major role in the direction of NASA and human spaceflight. These circumstances led to the NASA of the 1980s: still focused on human spaceflight with a smaller budget and no heavy-lift capability like Apollo's Saturn V.

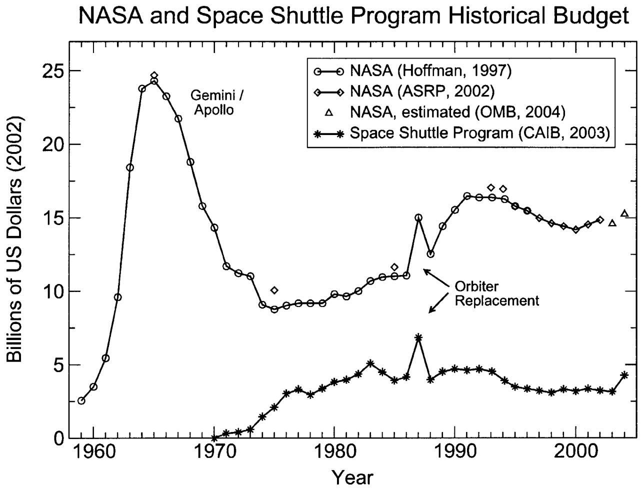

Fig. 1. A plot of the NASA and Space Shuttle Program (SSP) historical budget in billions of US dollars. The figures are constant-dollar amounts based on the year 2002. Note the relatively large amount of funding during NASA's formative years, the spike in 1987 due to replacing the *Challenger* orbiter and the decrease in funding in the past decade. *Source*: Data adapted from Hoffman [24], ASRP [25], OMB [26] and CAIB [27].

2.3. The perpetually "developmental" Shuttle

It is important to understand that—even today—the Space Shuttle is an experimental vehicle. Much is learned from each Shuttle after returning to Earth and during preparation for the next launch. The Space Shuttles flown today are different from those initially flown in 1981. In fact, the Shuttle's official "developmental" stage was from 1980 to 1982. After this point, it was declared "operational" so as to be available to ferry passengers and cargo to the to-be-completed Space Station and to lend legitimacy to the political selling point that the Shuttle could "pay its way" by launching spacecraft for the global telecommunications market. This operational designation was—and still is—in direct conflict with the experience of Shuttle engineers.[4] The Shuttle is still very much a developmental craft with constantly changing technology and mysterious problems that are not predicted from design.

The "operational" designation also sent the message that Shuttle launches were intended to be a routine, regular part of the space program. As Shuttle launches became routine, the excitement of the Apollo-era Moon race abated and NASA was forced by various administrations to cut costs (see historical budget data in Fig. 1). NASA realized that it could contract out portions of the Shuttle program and take advantage of the private sector's business savvy. Unfortunately, this had the

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[3] Public Law 85-568, 72 Stat. 426 (as amended).

[4] In fact, Shuttle engineers pray during launch… in light of *Columbia*, they will likely pray during re-entry as well. This is not a cultural feature of an "operational" vehicle.

effect of injecting production pressures into what was essentially a research and development operation.

2.4. "Normalization of deviance"

Vaughan [4–6] has developed the concept of "normalization of deviance" to explain how technical flaws can escape the scrutiny of the various safety bodies within NASA[5] over time. In many cases, unanticipated problems continue to occur even though nothing particularly catastrophic happens during a given Shuttle mission. This leads to the very pragmatic notion of "acceptable" deviance. That is, it was often very expensive and time-consuming to root out the cause of a given anomaly with some problems being incorporated into the regular maintenance cycle of the Shuttle without detailed examination. Under the production pressures mentioned above, it was unacceptable to spend significant resources on problems that were not "flight safety" risks—that is, if the problem could cause loss of the vehicle.[6] This provided disincentives for the engineers to track down the source of problems, even though many were not part of the Shuttle's design and, if magnified, *could* pose "flight safety" risks. Frequently, a flight was cleared based on previously successful flights that had completed their missions but still exhibited a given problem. This reasoning led physicist Richard Feynman to comment "When playing Russian roulette the fact that the first shot got off safely is little comfort for the next." [7]

3. The Challenger tragedy

3.1. The launch

On 28 January 1986, some 73 s after lift-off, the Space Shuttle *Challenger* exploded. President Reagan appointed William Rogers, an experienced politician, to head a Commission that was charged with investigating the accident (The Rogers Commission [8]). The investigation climaxed with commission member and physicist Richard Feynman dunking "a piece of the rocket booster's O-ring[7] material into a cup of ice water, demonstrating how it lost all resiliency at low temperatures and removing all doubt as to the technical cause of the explosion" (APS [9]). In the abnormal cold ($<-7^{\circ}$C) of the three nights that *Challenger* had spent on the launch pad, an O-ring on one of the solid rocket boosters (SRBs) had become brittle. About 1 min after launch, hot gas exited one SRB and pierced the primary fuel tank causing the colossal explosion that destroyed *Challenger*. What was not destroyed by the initial explosion was crushed by the force of hitting the surface of the ocean at 320 kph.

3.2. The night before launch

There was an ongoing debate in the years before the *Challenger* launch between the low-level engineers and management at Morton Thiokol—the contractor for the SRBs—about the SRB O-rings. The original shuttle design called for two O-rings per SRB segment for redundancy—the primary and secondary O-rings. NASA typically retrieves SRBs from the ocean for inspection (and reuse) and had seen O-ring heating damage and "blow-by" [8] on a number of flights[9].

The night before the fateful *Challenger* launch, there was a teleconference between engineers and officials at Morton Thiokol (Thiokol), Kennedy Space Center (KSC) and Marshall Space Flight Center (MSFC). A group of low-level engineers at Thiokol who were involved with the O-ring problem were concerned that the unprecedented cold temperatures on the launch pad were below the design threshold for the O-rings. The worse case of O-ring damage and blow-by to date had occurred in a similarly strange period of very cold temperatures nearly a year before. The engineers expressed their concerns to the upper management at Thiokol who decided to hold a conference call with the KSC and MSFC officials later that night.

The circumstances surrounding this conference call reek of organizational failure [5]. The engineers had very little time to assemble their presentation on why cold temperatures should be a concern for O-rings. The ground crew had to start pumping liquid fuel into the main fuel tank by midnight that night to launch the following morning. Why was not the launch postponed? Perhaps because the O-ring problem was not considered to be of much concern. Perhaps because this flight had Sharon Christa McAuliffe on it, an educator and civilian. President Reagan was to give his State of the Union address the following night and had planned on using the launch in his speech arguably to highlight the "operational" nature of the Space Shuttle and the educator astronaut in a time of significant educational spending cuts. Even though the Rogers Commission found that there was no direct evidence of an "order" from the Reagan administration, the political pressure felt by upper management and political appointees had to be huge.

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[5] See Vaughan [4] for an extensive discussion of the safety divisions within NASA.

[6] Loss of vehicle assumes loss of crew as the Shuttle has no crew escape capabilities.

[7] An "O-ring" is simply a round rubber washer that is intended to provide a seal.

[8] "Blow-by" refers to hot gas actually getting past the primary O-ring and heating the secondary O-ring.

[9] Vaughan [5] lists all flights and their O-ring conditions on pages 442–444 (Figs. B5.1–5.3).

Further, the engineers were immersed in a culture of proof. That is, they were required to prove at this point that there was a mission critical problem that necessitated the postponement of the launch. However, the production pressures associated with being a NASA contractor did not allow the resources to study the problem in detail in preceding months and they were not going to come up with any monumental calculations or experiments in the 3 h between the decision to have the conference call and the call itself. In their haste to get ready for the call, the engineering team mistakenly included slides that had been used in previous Flight Readiness Reviews (FRR[10]) to argue that the O-rings would *not be a problem* despite damage and blow-by incidents. Tufte [10] shows that the graphics presented in the teleconference were unclear and obfuscated and has since produced his own charts from the data that clearly show a temperature correlation with O-ring damage. The people at KSC and MSFC received mixed signals as Thiokol engineers argued against launch in the extreme cold when they had seen similar charts in previous FRRs to argue the opposite.

In the end, all parties to the call took a break during which the senior manager at Thiokol criticized his engineers for their performance. When the call resumed, a majority of the Thiokol engineers had decided to recommend that the launch go ahead with a minority still insisting that the previous night's cold temperatures had probably caused damage to the O-rings. In addition to bureaucratic and political pressures and normalization of the deviance of O-ring performance, a path-dependent reliance on proof over engineering intuition is also readily apparent.

4. The Columbia tragedy: what went wrong (again)?

On 1 February 2003, *Columbia* disintegrated over Texas during re-entry.[11] Immediately after this tragedy, an independent investigation board lead by retired Admiral Hal Gehman[12] was formed. The charter and make-up of the board underwent a few revisions to ensure that it was directed in the manner of an airplane crash investigation and completely independent of NASA oversight while retaining significant freedom.

4.1. *The CAIB working scenario*

About 81 s[13] after lift-off on 16 January 2003, a briefcase-sized piece of foam—possibly containing ice—somehow detached from the main fuel tank and impacted the left wing of the *Columbia* orbiter. This probably damaged the left wing enough to cause part of the Shuttle's Thermal Protection System (TPS) tiles to be compromised. The damage was magnified by the super-hot plasma that the Shuttle creates as it slows down during re-entry to the Earth's atmosphere. At one point, the left wing skin was pierced, allowing plasma to enter the wing. This seriously damaged the internal structure of the wing and data show that wing sensors began to fail. *Columbia's* landing computer[14] attempted to correct for the increased drag caused by the wing damage, to no avail. With the continued destruction of the left wing, *Columbia* eventually lost aeronautical control and became ballistic at a speed near 20,000 kph. In the words of the CAIB working scenario "main vehicle aerodynamic break-up occurred at 9:00:23 EST" [11].

4.2. *"Normalization of Deviance" Round 2*

As was the case with O-ring damage in the years before the *Challenger* launch, this was not the first time that foam had detached from the main tank and caused damage to a Shuttle. There had been numerous impacts on previous flights—by foam shrapnel much smaller than that which hit *Columbia*. Shuttles would typically return with hundreds of impacts bigger than 2.5 cm.[15] There are numerous reports in the Problem Reporting and Corrective Action (PRACA) system that show thermal tile damage as a likely result of foam shedding (see NASA [12]).

Not only was foam impacting *not* considered in the design of the TPS, but the high level engineering requirements of the Shuttle specifically state that nothing should impact the shuttle during launch.[16] But

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[10] Flight Readiness Reviews are large conferences typically several weeks before launch where the engineers from each Shuttle subsystem validate their system for launch in a highly public, iterative and technical engineering defense.

[11] An animated GIF of the debris trail is available here: http://www.shorl.com/hahetugakyty.

[12] Adm. Gehman recently headed the successful investigation into the terrorist bombing of the USS Cole in Yemen.

[13] The similarity between this time and the explosion 73 s after the launch of Challenger is interesting. It seems that both flights were victims of unexpected cross-winds associated with this altitude that shook loose an O-ring in the latter case and a chunk of foam in the former case.

[14] The landing of the Space Shuttle has always been piloted by a computer. Landing the Shuttle is a very delicate maneuver that likely cannot be performed by a human pilot.

[15] See external tank images and studies of foam impact damage frequency at NASA [12] in particular see Rieckhoff et al. [28].

[16] "It is critical [...] that all sources of debris be controlled to the greatest extent possible." [29]. "The spec for the [External] Tank is that nothing would come off the Tank forward of the 2058 ring frame [low down on the Tank], and it [the Shuttle] was never designed to withstand a 3-pound mass hitting at 700 ft/s. That was never considered to be a design requirement [...]. We paid an awful lot of attention to making sure nothing came off, because we knew if we fractured the carbon–carbon on the leading edge of the orbiter, it was a lost day."—Richard F. Thompson, Excerpt from CAIB testimony 23 April 2003 [30].

foam had been hitting the Shuttle consistently and a team of chemists and engineers were working on the proper kind and application of foam to apply without using an older method that required environmentally damaging freon. The studies of foam impacts all concluded that they did not pose a "flight safety" risk. Of course, the small pieces of foam that had been coming off the external tank flight after flight, and only causing 2.5 cm pits and craters, were not a "flight safety" issue.

However, a briefcase-sized piece of foam that may have contained a percentage of ice and/or ablator[17] is not what researchers and engineers had in mind when they declared foam shedding not to be a "flight safety" issue. This large a foam shedding event was unprecedented (cf. the three days of abnormal cold before the *Challenger* launch). Here, an anomalous event—the shedding of foam that regularly damages TPS tiles on each flight—is not considered to be dangerous because orbiters are coming back unharmed. What was not considered was the possibility of a larger or heavier (ice-laden) piece of foam hitting the Shuttle in a particularly vulnerable area like the leading wing edge. This is a classic example of Vaughan's "normalization of deviance" where an unpredicted anomaly becomes routine.

4.3. Role of hierarchy in Columbia

Hierarchy also seems to have played a role in the post-launch process during the *Columbia* mission. Engineers in Florida were concerned that the debris that impacted *Columbia* could have impacted near the landing gear housing—a particularly vulnerable part of the TPS. They thought if they could image the damaged area using ground-based telescopes or imaging satellites, they could best be prepared for any abnormal landing conditions. If the wheel housings had been damaged, it was quite possible that only one or none of the landing gear would be deployable upon landing. The engineers were discussing what to do given abnormal landing gear deployment (see NASA [13]).

Unfortunately, it appears that the upper management in NASA shut down the imaging request in the belief that the foam incident did not pose a "flight safety" risk[18] (see Readdy [14]) and because of questionable imaging quality. Further, NASA would have had to declare an emergency or high priority investigation to be able to re-task committed instruments. There are also some unverified indications that the request may have been quashed because the requesters did not go "through the proper channels" (see Vaughan [1]). This shows that some of the hierarchical and bureaucratic structure of NASA—also present in the *Challenger* launch decision—directly conflicts with the intuitions of NASA engineers.

It is important to point out that the likelihood of a successful rescue of the *Columbia* crew would have been very small—given that there was imagery or other evidence that showed wing damage, of course. At the time of writing, three general scenarios have been proposed (in order of increasing likelihood of success): (1) patching the wing breach with materials at hand (duct tape, bags filled with water, etc.) and attempting re-entry; (2) jettisoning as much equipment as possible and attempting a rendezvous with the Space Station; (3) rationing resources while waiting for the next orbiter in line, *Atlantis*, to rescue the astronauts. Evaluating the probability of success for these scenarios could be a research paper in itself, but a few points merit mention. Specifically, each of these scenarios are mutually exclusive in that an attempt at one scenario would not allow an attempt at another scenario. Patching a $\sim$25 cm hole in zero-gravity and very cold temperatures or a space-walk to estimate damages would use resources too fast to attempt a rescue by another orbiter. Jettisoning heavy equipment would probably involve throwing spacesuits and other materials out that would have to be used to attempt to patch damage or transfer crew-members to a rescue craft.

However, if data were available early in the *Columbia* mission that showed extensive damage, one could imagine an Apollo 13-like stroke of technical and logistical genius brought to bear on a rescue attempt that would have probably involved the following in gross detail:

- The preparations for the next orbiter launch, *Atlantis*, could have been accelerated—pushing the limits of safety and hopefully not causing another catastrophic accident. Casual estimates fall in the range of four to six weeks until launch could have been possible. Note that the cause of the *Columbia* damage would have been a launch consideration and any modification of the external tank foam application would have added precious time to the launch schedule.

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[17] Ablator material is placed underneath the main fuel tank's layer of foam to provide lightweight protection against high temperatures. A layer of ice may have formed between the layer of foam and ablator as surrounding air and humidity was frozen due to the cryogenic temperatures of liquid fuel. This ice could have been vaporized during launch, causing ejection of the foam. This process is called, "popcorning".

[18] An elementary calculation—that NASA management should be capable of—can show that there was reason for concern. The foam piece that impacted the orbiter was estimated to have a mass, m, of about 0.78 kg and traveling at a relative velocity, v, of 800 kph. The kinetic energy (energy of motion) of the foam piece would have been $E \propto mv^2$. One can ask, how massive would something have to be to impart a similar amount of kinetic energy at a velocity of 15 kph (typical of a fast bicycle). Equating the two energies yields a mass of 2200 kg!

- The *Columbia* crew would severely ration resources (food, water, air, etc.) such that they could survive the wait for *Atlantis*. A resupply of *Columbia* via another launch vehicle could have been possible but it is hard to imagine *Columbia* accepting provisions without needing to open their airlock or burn calories.
- Once *Atlantis* was successfully launched, it would need to rendezvous with *Columbia*—at around 28,000 kph at a close distance of 10 m—and a series of space walks would transfer the *Columbia* crew to *Atlantis*.
- After successful transfer of the *Columbia* crew, *Atlantis* would re-enter with a larger crew than normal.

The relevant point here is that data about the state of the orbiter are very important in the subsequent development of the mission and that these data were specifically considered to be irrelevant by upper management. The CAIB has issued preliminary recommendations that address on-orbit and launch imaging as well as on-orbit repair ability.

5. Recommendations

What could NASA do differently to better avoid the types of organizational failure typified by the two Shuttle tragedies?

5.1. *Flatten hierarchy*

The Apollo-era mission to the moon was a period of significant, focused development in a mission-oriented environment. The organizational and physical infrastructure of today's NASA is largely a result of this period. A hierarchical, bureaucratic cadre of middle and upper management is necessary for an organizational thrust like that of Apollo. However, in NASA's current environment, it would be practical to question these relics of path dependence.

Specifically, there is a large body of research in organizational science about alternatives to hierarchical organizations and firms. There is work on network organizations [15], creating organizational change [16,17] and organizing knowledge [18]. The network organization—where the organization is flattened and assumes an organic structure with collaborative linkages and dynamic flexibility—has proved to be a good organizational structure in R&D environments like biotechnology and information technology.

There are impediments to this magnitude of change. The upper management and political regulators of NASA have no interest in alternatives to hierarchy. The management at NASA would rather not make decisions that would jeopardize their jobs. Further complicating things, certain members of Congress—which is the regulatory oversight body for NASA—have no desire to make decisions that would jeopardize the NASA center in their district. Unfortunately, these are some of the hardest obstacles in the path of NASA's organizational change.

There needs to be a mechanism for engineers to be able to bypass the bureaucracy and hierarchy, especially in the pre-launch process. What would have been the alternative if the engineers had succeeded in getting their point across in the case of *Challenger*? Probably *Challenger* would have had to been taken off of the launch pad and the SRBs disassembled to replace the damaged O-rings. This would have been expensive but not nearly as costly as the loss of crew and vehicle. As well, if an engineer has a special request for a certain type of data, there should be a way to request exceptions to formal bureaucratic procedures to focus on getting the data. Engineers have many intuitions and hunches that take time and resources to translate into analysis and data. These intuitions need to be respected, given credence, explored and welcomed by upper management.

5.2. *Collaboration over contracting*

NASA needs to take the traditional idea of "contracting" out of Shuttle development and maintenance. As it stands now, contracts are awarded and technology and/or services are delivered. Relationships between subsystem contractors and NASA entities should have a very rich interface between them as opposed to production and delivery-oriented relationships. A pragmatically collaborative model of interaction between NASA and private sector firms would benefit both sides and foster "learning by monitoring"—whereby all parties continue to grow and improve their product and processes through joint testing, simultaneous engineering and development and root cause error detection and correction [19].

Interesting research in the biotechnology field has suggested that networks of learning—as opposed to individual firms—are important for innovation [20]. Perhaps the key to innovation in Shuttle operations and development is not found in single NASA centers with their traditional and path dependent specialties. Indeed, the networks of learning that tie NASA centers, contractors, researchers and academics are probably NASA's most valuable and underutilized asset. Many good ideas lie within the NASA network but, without interaction and encouragement, most of them do not have a chance in the current structure.

5.3. ''Normalization of Deviance'' alarms and specific action

The tendency for design deviance to be normalized in the current structure should not go unnoticed. Both the *Challenger* and *Columbia* tragedies occurred through exacerbation of known design defects. The frequency of occurrence of deviant behavior in both cases was regular but poorly understood, researched and controlled and, in both cases, actually worsened with time. This suggests that there should be ''normalization of deviance'' alarms or a task force that specifically tracks deviant behavior. When a subsystem shows signs of deviant behavior, action should be taken and resources committed (in order of time investment required) to:

- determine seriousness of second- and third-order implications[19] and take proper action;
- find out the root cause of the deviance;
- explore parameter space to determine the target problem's response to swings in variables like temperature, wind shear, humidity, etc.

Such ''normalization of deviance'' quality control seems necessary as engineers often do not realize that a given anomaly has been effectively normalized. A discovery task force that had considerable latitude, analysis capabilities and the ability to allocate resources for expedited deviance research would be ideal. Information technology could also be leveraged as part of the PRACA system (see below) so as to have alarms that go off when tracking specific systems.[20]

5.4. Improve PRACA

The relevant section of the Space Shuttle Independent Assessment Team's (SIATs) report (p. 28 of SIAT [21]) and the NASA Ames pilot project assessment [22] concerning PRACA are quite revealing. These documents show that the main piece of information infrastructure that NASA uses for Space Shuttle risk assessment, problem trending and reporting is woefully out of date, cumbersome, complicated and inaccurate. PRACA contains much of the institutional memory of the Space Shuttle program's operations and, as such, can be a very powerful tool if used effectively. Unfortunately, using PRACA ''effectively'' required ''a team of 10 engineers and 3 quality inspectors''[21] working for one week to produce something meaningful because of poor data and unsupported assessment needs.

PRACA should not need a cluster of ''information priests'' to be able to extract information from its five databases and one paper source. It should be able to facilitate meaningful, regular use by all levels of NASA staff. Further, the current state of algorithmic sophistication in terms of search, trending and data mining is years ahead of what PRACA is capable of. PRACA should be dynamic and responsive to user needs as well as connected to incentives to ensure a high-level of data population. Further, methods of *computer-aided* assessment, trending and data quality assurance should be feasible. In general, following the recommendations of the Korsmeyer et al. [22] pilot project assessment of PRACA would be a substantial improvement. However, it is important for PRACA to be seen as a dynamic information system, in the same manner that the Shuttle is not an ''operational'' vehicle.

6. Conclusion

The organizational failures highlighted by the *Columbia* and *Challenger* tragedies show that NASA's human spaceflight program is broken. Sally Ride has been quoted as saying that she hears ''echos of *Challenger*'' in the *Columbia* investigation.[22] This is not mere coincidence. As Dr. Diane Vaughan said at the beginning of her CAIB testimony, ''When you have problems that persist over time, in spite of the change in personnel, it means that something systematic is going on in the organizations where these people work.'' [7].

NASA is in desperate need of organizational change to shake off the lingering remnants of path dependence left over from the days of Apollo. The entrenched bureaucracy inherited from the Apollo/Gemini programs is far from ideal given the present environment. While such change will not happen overnight, it should not take as long as the 17-year period between the Rogers Commission Report and *Columbia*. It is essential for NASA to be able to use its resources as efficiently as possible to effectively develop, explore and promote space. The expense of an aging shuttle and a brand-new space station that has questionable scientific returns have blunted NASA's blade. If the goal is to have an operational space transportation vehicle, then this needs to be a design goal of a new vehicle—much how airplanes were initially brought into commercial service. If the goal is to be able to transport cargo to an LEO infrastructure, the design requirements are different. By

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[19] For example, foam shedding is a first-order problem—foam is shedding when it is not supposed to. Foam damaging tiles is a second-order problem—foam that was not supposed to be shed in the first place has caused spacecraft damage. The destruction of the Shuttle is a third-order problem.

[20] For example, there could be a ''deviance alarm'' that signals when the Shuttle is in danger of going below its lower temperature threshold of 1°C based upon weather data as part of launch preparation.

[21] See p. 32 of SIAT [21].

[22] See Vaughan CAIB testimony [7].

having both such functions built into something like the Space Shuttle, we are bound to come up with something that is not quite a cargo hauler and not quite safe for human transportation. It would appear that the Shuttle is such a vehicle. If the goal is to continue NASA's mission while minimizing failure, then it is on the brink of a significant and necessary period of organizational change.

In the current environment—after a second major loss of life and vehicle—NASA is in a unique position to critically evaluate what organizational structure is appropriate given its current environment and how to make it happen. The organizational failure exposed by the *Columbia* and *Challenger* accidents and the discussion developed in this paper point to two significant—but difficult and complex—facets of the current NASA organization that will soon need direct consideration:

- *Political and bureaucratic pressures*: Drastically changing the organization of NASA in order to flatten hierarchy and increase collaboration will be difficult for political and bureaucratic reasons. Members of Congress do not engender the support of their constituents by facilitating the restructuring of NASA and the NASA centers, especially when such action could mean unemployment or loss of technical prestige. Career bureaucrats and the "love handles"[23] of NASA management will also not feel compelled to make decisions that mean the loss or reassignment of their own jobs or the increased costs of collaboration. This segment of the NASA work force will argue vigorously that the system can be fixed in its current form and will speak about organizational-level approaches as hasty and radical. This kind of resistance has contributed to NASA being in the complicated position it is in today.
- *Contracting and production pressures:* The term "contracting" should be practically dropped in favor of "formal collaboration." The Shuttle is not a business but a research and development spacecraft. Contracting out of shuttle subsystems unintentionally and inappropriately injects production pressures into an R&D effort. Pragmatic collaboration as developed by Helper et al. [19] is a favorable model for interaction between NASA, NASA centers and the private sector. This would allow "learning by monitoring" and a variety of joint evaluation, assessment and engineering relationships that were previously unavailable. The interface between the various actors involved with the Space Shuttle Program (NASA, contractors, researchers, etc.) has to be at least as rich as the interfaces between various parts of the shuttle itself.

If NASA cannot do these things, it may be time for a stand-down in human spaceflight. Current resources could be channeled to specific technical activities in the pure sciences or in preparation for future human spaceflight endeavors. As it stands, the most costly part of a space mission is in getting the mission payload into space. Breakthroughs in propulsion technology will not come easily at our current level of investment. Under such a human-spaceflight hiatus, resources could be focused to further development of human-spaceflight technology or champion a Lewis and Clark-style mission to Mars. Such a mission would employ a craft that would manufacture the fuel needed for the return trip from what is available on the surface of Mars and cost roughly 6% of traditional Mars architectures that require on-orbit construction of a large craft [23].

In fact, a crucial aspect of the current state of affairs has been left out of this discussion. That is, by consciously deciding to focus on LEO orbital infrastructure (the Shuttle and Space Station), much of the excitement of the early space program has been lost. Presumably, we are past the exploratory stage of human spaceflight and it is time to build. However, this author contends that, instead of "risking human lives on the Space Shuttle to launch groceries… to the station",[24] the use of astronauts in risky situations should be reserved for pushing the limits of human spaceflight or where there are no other reasonable alternatives.[25] A return to the Moon to establish a lunar base, telescope or ^{3}H (tritium) processing facility[26] or to Mars for research, mining or colonization are just the kinds of projects to excite the NASA work force, American public and industry and the next-generation engineers and scientists who will make the discoveries of tomorrow. Crippled by path dependence, bureaucratic inertia and normalization of deviance, NASA has lost the prestige and technical charisma that it once had.

There is a strong need for leadership in NASA that is favorable to and capable of organizational change. The NASA leadership has shown a self-interested reluctance in the past to advocate and execute extensive organizational overhaul. Until NASA itself sees that its best interests lie in organizational-level change, the "echoes of *Challenger*" will continue to reverberate.

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[23] As in unnecessary levels of management that are sure signs of inefficiency.

[24] Rep. Rohrabacher [31].

[25] Indeed, the Space Station has always had questionable scientific return and, recently, a scientist who flew shuttle experiments, Matthew B. Koss, in an editorial in the *New York Times* questioned the need for human involvement in Shuttle science. Koss noted that experiments that have astronaut involvement frequently return poorer quality data and are not run as often as automated experiments [32].

[26] Tritium (^{3}H) is an isotope of hydrogen that is rare on Earth but useful for nuclear fusion.

Acknowledgements

I would like to thank AnnaLee Saxenian of the School of Information Management and Systems at the University of California at Berkeley for motivation and review. Soon to be enjoying the distractions of retirement after a prolific, inspiring career, John Logsdon of the Space Policy Institute at George Washington University provided the references for the figure.

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