CHAPTER 12

ACCIDENTS, ENGINEERING, AND HISTORY AT NASA, 1967–2003

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Section 203(a)(3) of the National Aeronautics and Space Act directs NASA to "provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."[1] To fulfill that mandate, NASA Administrator T. Keith Glennan instituted the NASA History Office in 1959.[2] The office has stayed open ever since, collecting archival materials for NASA staff and outside researchers, writing history, and commissioning a wide range of works on NASA's history. Over the last decade, the budget of NASA's history office has remained constant at around $335,000 per annum, although funds allocated to the history office from project offices vary from year to year. Even assuming such a level over the lifetime of the office, and not adjusting for inflation, NASA's commitment to telling its own history has cost the organization at least $15 million. But this figure is dwarfed by three official histories of NASA not commissioned by the history office. In 1967, 1986, and 2003, NASA spent $31 million, $75 million, and $152.4 million to produce multivolume accounts of fatal accidents in the manned space program.[3] These three accident reports examined the fatal fire in Apollo 204 (Apollo 1) in 1967, the explosion of the Solid Rocket Booster in STS-51L (*Challenger*) in 1986, and the destruction of the orbiter in STS-107 (*Columbia*).

Fatal accidents in publicly funded systems catch particular media and public attention.[4] Governments become compelled to conduct wide-ranging

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[1] John M. Logsdon et al., eds., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program*, vol. 1, *Organizing for Exploration* (Washington, DC: NASA SP-4407, 1995), p. 337.

[2] Roger D. Launius, "NASA History and the Challenge of Keeping the Contemporary Past," *Public Historian* 21, no. 3 (summer 1993): p. 63.

[3] For Apollo 1, see Ivan D. Ertel and Roland Newkirk, with Courtney G. Brooks, *The Apollo Spacecraft: A Chronology*, vol. 4 (Washington, DC: NASA SP-4009, 1978); for *Challenger*, see Frank Oliveri, "NASA gets $50 million for Shuttle Investigation," *Florida Today* (21 February 2004); for *Columbia*, see Paul Recer, "NASA: Columbia Cleanup costs near $400M," *Newsday* (11 September 2003).

[4] Thomas White, Jr., "Establishment of Blame as a Framework for Sensemaking in the Space Policy Subsystem: A Study of the Apollo 1 and Challenger Accidents" (Ph.D. diss., Virginia Polytechnic

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investigations to reassure the public of the safety of the system and the integrity of the funding process. Accidents at NASA are particularly public and so demand an investigation process that is accountable not only to the Congress but also to the American people. NASA accident investigation boards are forced to draw connections between national politics and engineering design and operations. The process of writing a final report also forces an accident investigation body to tell one coherent story about the accident—how the accident happened, what and who was at fault, and how steps can be taken to ensure the accident cannot happen again.

But as Peter Galison has observed in his study of aircraft accidents in the 1980s, accident reports are inherently unstable. They are multicausal in their historical explanations, and yet embedded in the very process of investigation is a drive for a single point of culpability upon which to base moral responsibility and recommendations for corrective action. Accident reports, then, are always ambiguous about the appropriate explanatory scale, so that it is never clear which is the right scale for analysis—whether the small scale or the large scale, the inflexible O-ring or the schedule pressure imposed on NASA by the White House and Congress.[5]

Galison is certainly correct to assert that reports show an explanatory tension, but this instability between frames of analysis is not just a function of the particular genre of accident reports. Engineering has changed such that there is now a social and epistemological gap between the management of engineering and engineering practice. The analytical tension in the investigation reports mirrors the real gap between engineers and managers at NASA. Furthermore, the reports are analytically asymmetrical, treating engineering as a context-free activity while explaining management in a sophisticated historical and cultural framework.

These gaps are not just a phenomenon inherent to accident reports, but the outcome of a set of historical and historiographical changes. The Apollo 204 accident shows the disjuncture between the engineers designing and managing the project and the technicians manufacturing the spacecraft. The *Challenger* and *Columbia* accidents show that disjuncture has shifted to the gap between managers controlling the project and engineers maintaining and analyzing the spacecraft. Similarly, since the 1980s, the organizational theory and organizational communications communities have joined the aeronautical engineering community in paying significant scholarly attention to

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Institute and State University, 2000). White's thesis analyzes the ways in which blame was allocated in these two accidents but also makes it very clear that public and political concern and outrage were extremely high in both cases.

[5] Peter Galison, "An Accident of History," in *Atmospheric Flight in the Twentieth Century*, ed. Peter Galison and Alex Roland (Dordrecht, Netherlands: Kluwer Academic Publishers, 2000), pp. 3–43.

accidents at NASA. Their engagement has shifted attention to the historical and organizational context of management decision-making surrounding the accidents. No historians of engineering and technology have matched this contextualization of management with a history of the engineering involved in the accidents or an attempt to integrate the two.

This paper will briefly lay out the accidents and discuss the findings of their investigative bodies. The changing historiographical styles, frameworks, and conclusions of the reports will be analyzed. These changes will be linked to changes in the practice of engineering by NASA and its contractors. Finally, some suggestions will be made for future research into accidents and changes in engineering.

APOLLO 204

On 27 January 1967, Spacecraft 012, assigned to the Apollo 204 mission, was undergoing a Plugs-Out Integrated Test on Pad 34 at Kennedy Space Center in Florida. The internal power systems of the newly delivered Command and Service Module were being tested, and so the crew cabin was pressurized to 16 pounds per square inch (psi) of pure oxygen. There were three astronauts on board: Gus Grissom, Ed White, and Roger Chaffee. At around 6:31 p.m. EST, the crew reported a fire in the spacecraft. Less than 20 seconds later, the spacecraft heatshield had ruptured and flame had burst into the service tower. The crew in the Command and Service Module (CSM) level of the support tower immediately evacuated the area but quickly returned with what firefighting and protective gear they could find. However, they were unable to extinguish the fire immediately or remove the crew from the cabin. Meanwhile, the crew had attempted to remove the middle hatch of the spacecraft but had been overcome before doing so. Firefighting crews and medical support arrived approximately 20 minutes later.

NASA Deputy Administrator Robert Seamans had already considered the possibility of an accident in the manned spaceflight program, after Neil Armstrong and Dave Scott in Gemini VIII had lost control of their capsule after docking with an Agena booster.[6] In the aftermath of Gemini VIII, he developed a set of procedures to be followed should an accident ever occur. On the evening of 28 January, he followed those procedures and immediately convened an accident review board.[7] The board convened at Kennedy Space Center in Florida and was

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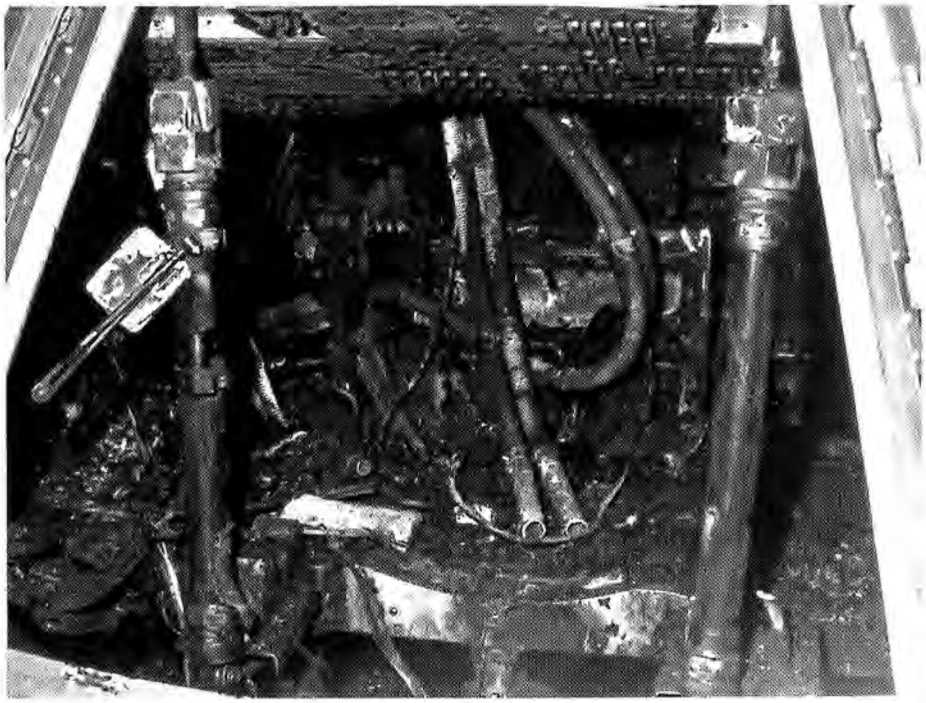
[6] Robert C. Seamans, *Aiming at Targets* (Washington, DC: NASA SP-4106, 1996), pp. 135–136; Barton C. Hacker and James M. Grimwood, *On the Shoulders of Titans: A History of Project Gemini* (Washington, DC: NASA SP-4203, 1977), pp. 308–319.

[7] Apollo 204 Review Board, appendix a-G, "Board Minutes," in *Report of Apollo 204 Review Board to the Administrator, National Aeronautics and Space Administration* (Washington, DC: GPO, 1967), pp. 1-5–1-6.



The mission officially designated Apollo/Saturn 204 is more commonly known as Apollo 1. This close-up view of the interior of the Command Module shows the effects of the intense heat of the flash fire that killed the prime crew during a routine training exercise. While they were strapped into their seats inside the Command Module atop the giant Saturn V Moon rocket, a faulty electrical switch created a spark that ignited the pure-oxygen environment. The speed and intensity of the fire quickly exhausted the oxygen supply inside the crew cabin. Unable to deploy the hatch due to its cumbersome design and the lack of breathable oxygen, the crew lost consciousness and perished. They were astronauts Virgil I. "Gus" Grissom (the second American to fly into space), Edward H. White II (the first American to "walk" in space), and Roger B. Chaffee (a "rookie" on his first space mission). *(JSC image no. S-67-21294, 28 January 1968)*

chaired by Floyd "Tommy" Thompson, Director of NASA's Langley Research Center.[8] The board was made up of three senior NASA engineers, a chemist from the Bureau of Mines, an Air Force officer from the Inspector General's office, NASA Langley's general counsel, and an astronaut.[9]

On 5 April 1967, the Apollo 204 Review Board presented its report to NASA Administrator James Webb. They concluded that the fire was caused

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[8] James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958* (Washington, DC: NASA SP-4305, 1987), pp. 387–391.

[9] Apollo 204 Review Board, appendix a-G, "Board Minutes," pp. 2-1–2-17.

by an unknown source of electrical arc, probably malfunctioning wire insulation around the environmental control unit on the floor of the spacecraft, although the cause would never be definitively known. The spark then ignited nylon netting, Velcro strips, and other combustible materials inside the spacecraft. These materials would have been removed before spaceflight, but under test conditions were not seen as hazardous. The coolant inside the spacecraft, water-glycol, was flammable and left a flammable residue in the cabin after evaporation. As the pipes melted, coolant leaked and ignited, further fueling the fire. The fire was rendered particularly dangerous by the high-pressure, pure-oxygen environment inside the spacecraft during the test. The crew was unable to use the inward-opening inner hatch under the pressurized conditions. The Board determined that the crew had died from asphyxiation caused by fumes from the fire.[10]

The Board told a story of engineering failure, identifying six conditions that led to the fire, and provided recommendations to fix the engineering problems they identified. These conditions were a sealed cabin with a pressurized atmosphere, extensive distribution of flammable materials in the cabin, vulnerable wiring carrying spacecraft power, vulnerable plumbing containing combustible and corrosive coolant, inadequate escape provisions, and an inadequate provision for rescue or medical assistance.[11]

After the Board made their engineering recommendations, they spoke briefly about the larger circumstance surrounding the accident:

> Having identified the condition that led to the disaster, the Board addressed itself to the question of how these conditions came to exist. Careful consideration of this question leads the Board to the conclusion that in its devotion to the many difficult problems of space travel, the Apollo team failed to give adequate attention to certain mundane but equally vital questions of crew safety. The Board's investigation revealed many deficiencies in design and engineering, manufacture and quality control. When these deficiencies are corrected the overall reliability of the Apollo Program will be increased greatly.[12]

On 27 February 1967, the Senate Committee on Aeronautical and Space Sciences started to hold hearings on the Apollo 204 fire, and on 11 April, the House Committee on Science and Astronautics started to hold hearings into the Apollo 204 fire.

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[10] Ibid., pp. 5-1–5-12.

[11] Ibid., p. 5-12.

[12] Ibid., p. 5-12.

On the first day of the hearings before the Senate, NASA Administrator James Webb, Deputy Administrator Seamans, and Associate Administrator George Mueller were sandbagged by the Democratic Senator from Minnesota, Walter Mondale. Mondale asked them about a report that Apollo Program Director Major General Sam Phillips had prepared in 1965 after visiting North American Aviation (NAA), manufacturers of the spacecraft.[13] Mueller first denied any knowledge of the report, arguing that Phillips had prepared many reports on many NASA contractors. Webb then argued that he was not going to release the report for reasons of commercial confidentiality, as it contained details of contract negotiations between NASA and NAA.[14] Senators Brooke, Percy, and, in particular, Mondale became highly critical of NASA's unwillingness, as they saw it, to be accountable to elected officials.[15]

The Phillips report was damning. Phillips had written:

> I am definitely not satisfied with the progress and outlook of either program and am convinced that the right actions now can result in substantial improvement of position in both programs in the relatively near future.
>
> Even with due consideration of hopeful signs, I could not find a substantive basis for confidence in future performance. I believe that a task group drawn from NAA at large could rather quickly verify the substance of our conclusions, and might be useful to you in setting the course for improvements.[16]

Phillips recommended that NAA thoroughly revise (and in many cases implement) systems management and engineering procedures. He called for them to implement a program management system and to significantly improve their manufacturing and quality control.[17]

The House hearing subcommittee was chaired by Representative Olin Teague of Texas, a long-term supporter of the space program. The hearings were contentious—with a Republican from Illinois, Donald Rumsfeld, taking particular aim at NASA senior officials Webb, Seamans, and Faget. Rumsfeld took objection to the constitution of the Board, arguing that it

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[13] Senate Committee on Aeronautical and Space Sciences, *Apollo Accident*, Hearing, 90th Cong., 1st sess., 7 February 1967, pp. 125–127.

[14] Ibid., pp. 131–132.

[15] Ibid., pp. 217, 331–332; Senate Committee on Aeronautical and Space Sciences, *Apollo 204 Accident. Report of the Committee on Aeronautical and Space Sciences, United States Senate, with Additional Views* (Washington, DC: GPO, 1968), pp. 13–16.

[16] Samuel Phillips, cover letter to Lee Atwood, in "NASA Review Team Report," 1965.

[17] Ibid., pp. 1–20.

was made of people responsible for the areas of work whose failure they were investigating. NASA was, in effect, investigating itself. Rumsfeld was also concerned about the narrow focus of the Board's report, suggesting that they had defined their terms very specifically to avoid investigating larger problems within NASA management. Finally, he wanted to know why NASA did not have a separate and independent safety organization.[18] Webb and Seamans gave fairly weak responses to Rumsfeld's questions and were only saved by Teague's interruptions.

But the worst was still to come for NASA. It was revealed that in the initial awarding of the CSM contract to NAA, NAA had scored lower in the technical assessment than Martin. The Congressmen used this revelation to imply some sort of improper relationship between NASA and NAA.[19] In the final days of the House hearing, Thomas Baron, a quality-assurance inspector from NAA, presented to the Committee a detailed report of deficiencies, official malfeasances, and general complaints about the standard of workmanship and care at NAA.[20] While the Baron report was eventually proved to be largely personal grievances and unproven accounts of interactions between workers at NAA, it all contributed to a larger picture of poor management and workmanship at NAA and poor supervision at NASA.

Although the Apollo 204 Board did not blame any individuals for the fire, there were consequences. Joseph Shea, manager of the Apollo Spacecraft Program Office, and Harrison Storms, NAA's vice president in charge of the Space and Information Division, were both moved out of their positions.[21] Deputy Administrator Seamans also resigned soon after the investigation had concluded, his personal relationship with James Webb having deteriorated dramatically over the fire.[22]

CHALLENGER

On 28 January 1986, the Space Shuttle *Challenger* launched from Kennedy Space Center on mission 51-L. There were seven astronauts on board: Dick Scobee, Michael Smith, Ellison Onizuka, Judith Resnik, Ronald McNair, Christa McAuliffe, and Gregory Jarvis. Their mission was to deploy and

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[18] House Committee on Science and Astronautics, *Investigation into Apollo 204 Accident*, Hearings before the Subcommittee on NASA Oversight, 90th Cong., 1st sess., 10 April 1967, pp. 10–14.

[19] Ertel and Newkirk, *The Apollo Spacecraft: A Chronology*, vol. 4, entry for 11 May 1967.

[20] Thomas Ronald Baron, "An Apollo Report," in House Committee on Science and Astronautics, *Investigation into Apollo 204 Accident*, pp. 483–500.

[21] Ertel and Newkirk, *The Apollo Spacecraft: A Chronology*, vol. 4, entry for 7 April 1967; Mike Gray, *Angle of Attack: Harrison Storms and the Race to the Moon*, 1st ed. (New York: W. W. Norton, 1992), pp. 254–255.

[22] Seamans, *Aiming at Targets*, pp. 145–147.

recover a satellite in orbit and to conduct flight-dynamics experiments.[23] Christa McAuliffe, a teacher from New Hampshire, was to conduct a science lesson in orbit.[24] The 28th of January was a very cold morning. The temperature at Kennedy Space Center in Florida had dropped below freezing overnight, and ice teams had been sent out three times to examine potential damage. Parts of the Space Shuttle, including the Solid Rocket Boosters, were still below freezing point at launch. The ambient air temperature was 36°F, 15 degrees lower than any previous flight.[25]

Less than a second after launch, at 11:38 a.m. EST, a puff of gray smoke emerged from the right Solid Rocket Booster (SRB). Over the next 2 seconds, eight more puffs of smoke, blacker and more dense, emerged from the same place on the SRB. Thirty-seven seconds after launch, the Shuttle experienced a 27-second period of severe wind shear, stronger than any other Shuttle launch had experienced. Fifty-eight seconds after launch, a small flame appeared on the aft field joint of the right SRB. Over the next 14 seconds, the flame grew rapidly, burning through the lower strut holding the SRB to the External Tank. Seventy-two seconds after launch, the strut burned through and the right SRB rotated around the upper strut, crashing into the External Tank. The tank collapsed, venting the hydrogen fuel into the atmosphere. The fuel immediately ignited, and the entire Shuttle flew into the fireball. The orbiter entered the fireball, broke up under severe aerodynamic load, and fell back into the Atlantic Ocean. There were no survivors.[26]

On 3 February 1986, President Ronald Reagan appointed the Presidential Commission on the Space Shuttle *Challenger* Accident.[27] The Commission was chaired by William Rogers, Secretary of State under Richard Nixon and an attorney by training and experience. The Commission included two astronauts, a test pilot, two physicists, another attorney, three engineers, a senior Air Force officer, an aerospace journalist, and an astronomer. Another engineer was executive director. The Commission conducted public and private hearings over the early part of 1986 and presented its report to President Reagan on 6 June 1986.

Like the Apollo 204 Review Board, the Commission understood its objectives to be investigating the accident and providing a series of rec-

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[23] Presidential Commission on the Space Shuttle *Challenger* Accident, *Report to the President*, 5 vols. (Washington, DC: GPO, 1986), p. 16; "John F. Kennedy Space Center—51-L Shuttle Mission," *http://www-pao.ksc.nasa.gov/kscpao/shuttle/missions/51-l/mission-51-l.html.*

[24] For Christa McAuliffe's official NASA biography, see *http://www.jsc.nasa.gov/Bios/htmlbios/mcauliffe.html.*

[25] Presidential Commission on the Space Shuttle *Challenger* Accident, *Report to the President*, vol. 1, pp. 16–21.

[26] Ibid., pp. 20–21.

[27] Ibid., pp. 212–213.

The STS-51L crew members. In the back row, from left to right: mission specialist Ellison S. Onizuka, Teacher in Space participant Sharon Christa McAuliffe, payload specialist Greg Jarvis, and mission specialist Judy Resnik. In the front row, from left to right: pilot Mike Smith, commander Dick Scobee, and mission specialist Ron McNair. *(JSC image no. S85-44253,15 November 1985)*

ommendations for a return to safe flight.[28] And like the Apollo Board, the Commission examined the physical causes of the accident but was also critical of NASA and its contractors as organizations:

> The genesis of the Challenger accident—the failure of the joint of the right Solid Rocket Motor—began with decisions made in the design of the joint and in the failure by both Thiokol (manufacturer of the Solid Rocket Motors) and NASA's Solid Rocket Booster project office to understand and respond to facts obtained during testing.[29]

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[28] Ibid., p. 1.

[29] Ibid., p. 166.

The Commission determined that a combustion gas leak through the aft field joint on the right Solid Rocket Motor caused the flame plume. The field joint was designed to be sealed by O-rings. On STS-51L, the O-rings failed to work because ambient temperature was too cold and the O-rings lost resilience and hence their ability to seal quickly.[30] The Commission's report took aim at poor management decisions, arguing that schedule- and cost-conscious managers misunderstood and overruled the safety judgments of engineers. They concluded that flaws existed in NASA's decision-making process and that these flaws had caused NASA to decide to launch STS-51L when there was reason to believe that launching would be risky and potentially catastrophic. NASA's safety system was indicted as silent and ineffective in the face of increasing pressure on the launch schedule. Finally, the Commission suggested that these flaws were rooted in the history of the Space Shuttle program and the history of NASA.[31]

Commissioner Richard Feynman went further in appendix F to the report. This appendix contained Feynman's personal observations from his service on the Commission and particularly addressed the difference he had observed between NASA and Thiokol engineers and managers. Feynman observed that managers and engineers tended to calculate risk in very different ways—managers determining risk from a number of qualitative factors, whereas engineers calculated risk quantitatively, using standard statistical methods. He also observed that these two methods tended to produce widely divergent results. Managers generally understood risks to be orders of magnitude less than engineers.[32] Feynman was highly critical of this gap, arguing that there were only two ways to understand it. The first was dishonesty on the part of managers, designed to ensure a continuous flow of funding for the Shuttle. The second was an incredible lack of communication between engineers and managers.[33] He argued that to ensure safe operation of the Shuttle, NASA managers needed to understand the realities of risk involved in flying high-performance vehicles like the Shuttle. After all, he concluded, "for a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."[34]

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[30] Ibid., chaps. 3, 4.

[31] Ibid. Chapter 5 discusses management decisions; chapter 6, the historical background of the accident; and chapter 7, NASA's safety program.

[32] Richard Phillips Feynman and Ralph Leighton, *What Do You Care What Other People Think? Further Adventures of a Curious Character*, 1st ed. (New York: Norton, 1988), pp. 179–184. This volume also contains a version of appendix F edited for clarity, pp. 220–237. For the original version, see Presidential Commission on the Space Shuttle *Challenger* Accident, *Report to the President*, pp. F-1–F-5.

[33] Feynman and Leighton, *What Do You Care What Other People Think?* pp. 236–237.

[34] Presidential Commission on the Space Shuttle *Challenger* Accident, *Report to the President*, p. F-5.

The Commission's report echoed Feynman's findings, even though he felt upset that his opinions had not been adequately incorporated into the final document.[35] The report suggested that NASA management and NASA engineers saw the material world in very different ways—the engineers understanding risk as quantifiable and determined by the material world, whilst managers understood risk as flexible and manageable in commercial and political contexts. The cause of the accident, the report concluded, was the failure of communication between these two perspectives. The ultimate expression of this philosophy was the statement by Jerald Mason of Morton Thiokol telling Robert Lund, vice-president of engineering, "You've got to put on your management hat, not your engineering hat" in order to determine whether the *Challenger* would launch the next day despite engineers' concerns over the safety of the Solid Rocket Motor.[36] In its final recommendations, the Commission wanted design changes to the Solid Rocket Motor, reform of the Shuttle program management structure, and the establishment of a Shuttle Safety Panel and an independent Office of Safety, Reliability and Quality Assurance.

The House Committee on Science and Technology started holding hearings on the *Challenger* accident on 10 June 1986. As in Apollo 204, from which the Committee drew its precedent, hearings were delayed until the Commission report was published. The Committee conducted 10 days of hearings, questioning senior NASA and Morton Thiokol officials, as well as members of the Commission, astronauts, and Morton Thiokol engineers.[37] While the Committee endorsed the findings of the Commission, their report went further:

> The Committee feels that the underlying problem which led to the Challenger accident was not poor communication or inadequate procedures as implied by the Rogers Commission conclusion. Rather the fundamental problem was poor technical decision-making over a period of several years by top NASA and contractor personnel, who failed to act decisively to solve the increasingly serious anomalies in the Solid Rocket Booster joints.[38]

Neither the Commission nor the Committee explicitly laid blame at the feet of any individuals. However, their criticisms of management at NASA's

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[35] Feynman and Leighton, *What Do You Care What Other People Think?* pp. 199–205.

[36] Presidential Commission on the Space Shuttle *Challenger* Accident, *Report to the President*, p. 94.

[37] House Committee on Science and Technology, *Investigation of the Challenger Accident: Report of the Committee on Science and Technology, House of Representatives*, 99th Cong., 2nd sess., 1986, pp. 37–38.

[38] Ibid., p. 5.

Marshall Space Flight Center and at Morton Thiokol were duly noted by those organizations. Most of Morton Thiokol management involved in the launch decision were reassigned, retired, or resigned, including Jerald Mason and Robert Lund. At NASA, Associate Administrator for Space Flight Jesse Moore resigned, while MSC Director William Lucas and booster project manager Lawrence Mulloy both retired early.[39]

COLUMBIA

On 16 January 2003, the Space Shuttle *Columbia* launched from Kennedy Space Center on mission 107. There were seven astronauts on board: Rick Husband, William McCool, Michael Anderson, David Brown, Kalpana Chawla, Laurel Clark, and Ilan Ramon. Fifty-seven seconds after launch, at around 10:40 a.m. EST, the *Columbia* entered a period of unusually strong wind shear, which created a low-frequency oscillation in the liquid oxygen in the External Tank.[40] At 81.7 seconds after launch, at least three pieces of Thermal Protection System foam detached from the left bipod ramp of the External Tank and fell backwards at between 416 and 573 miles per hour, smashing through the leading edge of the left wing of the orbiter. The largest piece of foam was around 2 feet long and 1 foot wide. The launch was otherwise without incident, and *Columbia* arrived in orbit by 11:39 a.m. EST.

On 23 January, Mission Control e-mailed commander Husband and pilot McCool to inform them of the foam strike, informing them that some foam had hit the orbiter but reassuring them that "we have seen this phenomenon on several other flights and there is absolutely no concern for entry."[41]

On 1 February 2003, after a successful 17-day mission, the orbiter reentered the Earth's atmosphere for a landing at Kennedy Space Center. As the orbiter reentered, superheated air penetrated the left wing through the foam strike in the leading edge and started to melt away the wing from the inside. At around 9:00 a.m. EST, the orbiter broke up under severe aerodynamic load and disintegrated over the Southwest of the United States. There were no survivors.

Around 10:00 a.m. on 1 February 2003, NASA Administrator Sean O'Keefe declared a Shuttle Contingency and, acting under procedures set in place after the *Challenger* accident, established the International Space Station

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[39] Claus Jensen, *No Downlink: A Dramatic Narrative About the Challenger Accident and Our Time*, 1st ed. (New York: Farrar, Straus and Giroux, 1996), pp. 354–355; Richard S. Lewis, *Challenger: The Final Voyage* (New York: Columbia University Press, 1988), pp. 222–223.

[40] Columbia Accident Investigation Board, *Report*, vol. 1 (Washington, DC: NASA and GPO, 2003), pp. 33–34.

[41] Ibid., p. 159.

and Space Shuttle Mishap Interagency Board.[42] O'Keefe named Admiral Harold Gehman as Chair of the Board. Gehman was retired from the Navy and had recently headed the investigation into the terrorist attack on the USS *Cole*.[43] Ex officio, there were immediately seven Board members: four military officers with responsibilities for safety in their home services, a Federal Aviation Administration representative, a Department of Transportation representative, and a NASA Center Director. O'Keefe soon thereafter named both NASA's Chief Engineer and the counsel to Glenn Research Center to the Board. Over the next six weeks, five more members were appointed to the renamed Columbia Accident Investigation Board. They included an aeronautical engineer and former Air Force Secretary, a physicist, a former astronaut and *Challenger* Commission member, a space policy expert, and the retired CEO of a major defense contractor.[44] Over the first six months of 2003, the Board held hearings and conducted investigations into the *Columbia* accident and, on 26 August 2003, released its report.

The CAIB report identified the physical cause of the accident as the foam strike on the left wing leading edge. But unlike the Apollo 204 Board, which briefly mentioned organizational and other factors, or the *Challenger* Commission, which described these factors as contributory, the CAIB emphasized that factors other than the proximate physical cause were as, if not more, important in understanding the *Columbia* accident:

> Many accident investigations make the same mistake in defining causes. They identify the widget that broke or malfunctioned, then locate the person most closely connected with the technical failure: the engineer who miscalculated an analysis, the operator who missed signals or pulled the wrong switches, the supervisor who failed to listen, or the manager who made bad decisions. When causal chains are limited to technical flaws and individual failures, the ensuing responses aimed at preventing a similar event in the future are equally limited: they aim to fix the technical problem and replace or retrain the individual responsible. Such corrections lead to a misguided and potentially disastrous belief that the underlying problem has been solved. The Board did not want to make these errors. A central piece of our expanded cause model involves NASA as an organizational whole.

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[42] Ibid., pp. 231–232.

[43] William Langewiesche, "Columbia's Last Flight," *Atlantic Monthly* (November 2003): 65–66.

[44] CAIB, *Report*, p. 232.

> The organizational causes of this accident are rooted in the Space Shuttle Program's history and culture, including the original compromises that were required to gain approval for the Shuttle Program, subsequent years of resource constraints, fluctuating priorities, schedule pressures, mischaracterizations of the Shuttle as operational rather than developmental, and lack of an agreed national vision. Cultural traits and organizational practices detrimental to safety and reliability were allowed to develop, including: reliance on past success as a substitute for sound engineering practices (such as testing to understand why systems were not performing in accordance with requirements/specifications); organizational barriers which prevented effective communication of critical safety information and stifled professional differences of opinion; lack of integrated management across program elements; and the evolution of an informal chain of command and decision-making processes that operated outside the organization's rules.
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> In the Board's view, NASA's organizational culture and structure had as much to do with this accident as the External Tank foam.[45]

Seventeen years after *Challenger*, the Board concluded that many of the findings of the *Challenger* Commission were still applicable to the Space Shuttle program in the early 21st century. They were critical of the similarities between the *Challenger* and *Columbia* accidents, noting in the *Columbia* accident flawed decision-making processes, a silent safety program, and schedule pressure. The Board also observed that the causes of these failures were rooted in NASA's history and culture; the history of the Space Shuttle program had been a history of the normalization of deviance. Increasingly large engineering problems that had not caused catastrophic failures had been incorporated into NASA's experience base instead of raising safety concerns. NASA had come to rely on past success (or lack of past catastrophe) rather than rigorous testing and analysis. NASA's safety system was still silent. Decision-making was still flawed, with managers and engineers still unable to communicate effectively about risk.

The Commission recommended design changes to the Thermal Protection System on the External Tank, reform of the Space Shuttle Integration Office, training for the Mission Management Team, the establishment of an indepen-

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[45] Ibid., p. 177.

dent Technical Engineering Authority with safety responsibilities, and rendering the NASA Office of Safety and Mission Assurance independent and with total oversight of the Space Shuttle program safety organization.[46]

READING ACCIDENT REPORTS AS HISTORY

The Apollo 204 report is almost exclusively devoted to an analysis of the engineering problems that the Board argued caused the fire. It divides its analysis into two parts, parts IV and V of the report.[47] Part IV, "History of the Accident," provides a chronology of the accident from August 1964 until 28 January 1967. The sections discussing the fabrication, delivery, and inspection of the CSM spacecraft, which cover the period from August 1964 until December 1966, take up less than 10 percent of the report. The remainder of the history of the accident is a detailed chronology of the Plugs-Out Integrated Test of CSM 012, starting around 5 hours and 30 minutes before the accident. Part V, "Investigation and Analysis," has four sections: "Inspection and Disassembly," "Chronology," "Data Analyses," and "Cause of the Fire." Both the "Inspection and Disassembly" and "Chronology" sections are strictly narrative. "Data Analyses" discusses analyses of spacecraft telemetry data and crew voice transmissions from less than a minute before the accident, while the "Causes of the Fire" section notes deficiencies in electrical equipment and wiring insulation, the effects of electrical arcs on wiring and coolant on other equipment, and the effects of a cabin environment of pure oxygen under pressure. The sole mention of other, larger contributory factors is the final paragraph, noting that these engineering problems came about through deficiencies in design and manufacturing.[48]

But none of the political circumstances surrounding the Apollo program—its iconic status as the martyred President Kennedy's legacy, as a visible symbol of American technical prowess, as a marker of position in the Cold War—were identified as contributory. Nor was NASA's organizational structure or its culture. No individuals were identified as bearing particular responsibility for the accident. The report makes clear that poor engineering practice, whether design, management, or operation, was to blame.

The report of the Presidential Commission on the Space Shuttle *Challenger* Accident is a striking contrast to the Apollo 204 report. Even superficially, the reports are dissimilar. The Apollo 204 report looks like a report—it is

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[46] Ibid., chap. 11.

[47] Parts I, II, and III describe the Board's legal authority, the biographies of its members, and the proceedings of the Board.

[48] Apollo 204 Review Board, *Report to the Administrator, National Aeronautics and Space Administration* (Washington, DC: GPO, 1967), pp. 5–12.

monochromatic, printed in standard Government Printing Office format, and appears very similar to a multitude of other NASA reports. The report on the *Challenger* accident looks more like a magazine or coffee table book. It has large sections of color photographs used as visual evidence by the Commission, was printed on glossy paper, and was written in a narrative form familiar to readers of nonfiction. It opens with a preface and an introduction, outlining the task of the Commission and contextualizing the development of the Space Shuttle. The report goes on to outline the events of 28 January 1986 and from there leads into its analysis of the physical cause of the accident in a chapter simply titled "The Cause of the Accident."[49] The remainder of the report analyzes the series of events that contributed to the accident: the chain of decisions that led to the decision to launch, the history of design problems with the O-ring system, the political and organizational pressures to launch, and the failure of the safety system.[50] In seeking to understand the contributory causes of the accidents, the Commission's report does not explicitly draw on any theoretical work. The report's footnotes are to transcripts of Commission hearings or to original NASA and Morton Thiokol documents, rather than any other writings on accidents or safety.

The Presidential Commission was clear that there were physical causes for the accident—in this case, the failure of the O-rings to seal correctly. But unlike the Apollo 204 Review Board, the Commission saw secondary contributing causes. These secondary causes were the flawed launch decision, political pressures on the launch schedule, and a silent safety system. The 1967-model report, setting out an understanding of engineering failures to be fixed with engineering solutions, was changed into a critique of both engineering and management with separate solutions for each area of endeavor.

The report of the Columbia Accident Investigation Board (CAIB) was even more like a magazine. Unlike the Apollo 204 and *Challenger* reports, the CAIB report has its own logo and its own page headers and footers. The report contains sidebars to provide contextual or background material and is illustrated with images of the *Columbia* in preparation and in flight and images of the *Columbia* crew both before and during the 107 mission.

Like the *Challenger* report, the CAIB report devotes only one chapter, chapter 3, to the proximate physical cause of the accident—the separation of Thermal Protection System (TPS) foam from the External Tank and its subsequent impact on the leading edge of the orbiter. But the report has four chapters, chapters 5 to 8, discussing the context of the decision-making that led to the breakup of the orbiter on reentry. Chapter 3 discusses the engineering

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[49] Presidential Commission on the Space Shuttle *Challenger* Accident, *Report to the President*, vol. 1, chap. 4.

[50] Ibid., chaps. 5 through 8, respectively.

analyses the Board performed, the history of External Tank design decisions, and the conclusions to be drawn from these, but it does so without using any theory, simply presenting this engineering section as needing no context or justification. It is only where the Board starts to examine the decision-making of NASA engineers and managers that led to the *Columbia* disaster that more sophisticated explanatory frameworks are needed. The Board drew on a variety of theoretical perspectives, considering Charles Perrow's theory of normal accidents and the work of both Scott Sagan and Todd La Porte on high-reliability theory.[51]

Perhaps most interestingly, the CAIB report drew heavily on the work of Diane Vaughan. Vaughan's 1996 book, *The Challenger Launch Decision*, set out a sociological explanation for the flawed decision, arguing that, far from the managerial misconduct identified by the *Challenger* report, the accident can best be understood in terms of the normalization of deviance, the culture of production at NASA and Morton Thiokol, and structural secrecy.[52] Vaughan argued:

> This book explicates the sociology of mistake. It shows how mistake, mishap and disaster are socially organized and systematically produced by social structures. No extraordinary actions by individuals explain what happened: no intentional managerial wrongdoing, no rule violations, no conspiracy. The cause of disaster was a mistake embedded in the banality of organizational life.[53]

This perspective informed chapter 8 of the CAIB report, where the Board drew explicit links between the *Challenger* and *Columbia* accidents, applying the components of Vaughan's analysis to *Columbia*. The Board concluded:

> First, the history of engineering decisions on foam and O-ring incidents had identical trajectories that "normalized" these anomalies, so that flying with these flaws became routine and acceptable. Second, NASA history had an effect. In response to White House and Congressional mandates, NASA leaders took actions that created systemic organizational flaws at the time of Challenger that were also present for Columbia.[54]

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[51] CAIB, *Report*, p. 180.

[52] Diane Vaughan, *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA* (Chicago: University of Chicago Press, 1996).

[53] Ibid., p. xiv.

[54] CAIB, *Report*, p. 195.

Unlike the *Challenger* report, the CAIB report gives equal weight to the organizational causes of the accident, arguing that while mistakes were made, the organizational structure of NASA was more to blame that any individual failings.

The three reports suggest a story of growing separation of management and engineering. As Peter Galison has suggested, this may simply be a result of the instability between frames of analysis: the desire both to localize and to diffuse the locus of causation, to find a single physical cause, and to explain the accident in terms of larger organizational and cultural problems.[55] But it is interesting to note that these two activities are not only juxtaposed as possible sources of accidents, but also understood and analyzed in different ways. There has been a growing sophistication in the ways that decision-making and its contexts have been understood. There is a transition from Apollo 204's one-paragraph analysis of larger causes, to *Challenger*'s inclusion of organizational and political factors as contributory, to *Columbia*'s equal pairing of technical and social causes. There is a corresponding increase in the contextualization of these social elements of the analysis, from rudimentary mentions in Apollo 204 to a full examination and consideration of sociological and organizational theory literature in *Columbia*.

But there is an interesting asymmetry in these reports as well. As analyses of decision-making and its historical and cultural contexts have grown ever more sophisticated in these accident reports, the discussions of physical causes have remained remarkably similar. In each accident report, a number of possible causes are considered and eliminated before attention is turned to the actual cause. In each of the sections of the reports dealing with physical cause, there is little or no contextualization of engineering and design decision-making and no attempt to locate the discussion in a body of literature. This separates the physical and technical causes of accidents from their contexts and sets up the two activities—engineering and decision-making about engineering—as two quite different activities, to be understood and analyzed in different terms. In this formulation, engineering seems to be understood on its own terms, as a context-free and ahistorical activity, whereas management decision-making is understood as contingent and located within a complex historical and cultural framework.

This asymmetry immediately opens two questions. First, what historical processes caused the separation of engineering and management in the manned space program from 1967 to the present day? Second, what changes in engineering over the same period can be seen in the three accident reports and might provide the basis for understanding engineering in its own historical and cultural context? The disciplines of the history of technology and the history of science provide some directions to go look for answers to these questions.

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[55] Galison, "An Accident of History," p. 4.

Engineering accidents can be understood in a similar way to scientific controversies. A scientific controversy is resolved when the winners declare that their account is true and opponents are no longer taken seriously by the relevant scientific community.[56] Just as scientific controversies open up the inner workings of a laboratory or research group, so accidents open up the internal practices and politics of engineering. But accidents also provide a way to examine how engineers go about activities other than design and innovation. Most studies of engineers and engineering focus on design because it is the most creative and innovative element of the engineer's craft.[57] However, the vast majority of time spent by engineers is taken up with the development and operation of technologies rather than their design. Accident investigations take a comprehensive look at the design, manufacture, and operation of the broken artifact or system and so provide a way to look at engineering work at the routine, everyday level, as well as at the creative design level. The process of investigating an accident results in the extensive description of these everyday routines, routines that are often seen as so mundane as to leave little trace in the documentary record of the project. Thus, if these NASA accident reports are examined as a historian might examine them, they can trace changes in both design and routine engineering.

By treating accidents and their investigations as windows into engineering at NASA, there are at least three aspects of engineering at NASA that have changed since the 1960s—the widespread use of computers in engineering, the emergence of astronautical engineering as a new discipline, and a move away from systems engineering as an organizing philosophy for large projects.

Computing

Since the 1960s, computers have become ubiquitous, and there is a growing literature that points to the ways in which interaction with computers reshapes

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[56] This particular interpretation of scientific controversy is taken from the works of Bruno Latour and Wiebe Bijker in particular. See Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Cambridge, MA: Harvard University Press, 1987); Bruno Latour and Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton, NJ: Princeton University Press, 1986); Wiebe E. Bijker, Thomas Parke Hughes, and T. J. Pinch, *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge, MA: MIT Press, 1987).

[57] This point was well made by John Staudenmaier in his surveys of the field of history of technology. See John M. Staudenmaier, *Technology's Storytellers: Reweaving the Human Fabric* (Cambridge, MA: Society for the History of Technology and the MIT Press, 1985); John M. Staudenmaier, "Recent Trends in the History of Technology," *American Historical Review* 95, no. 3 (1990). For examples of this focus on design to the exclusion of other aspects of engineering, see, for example, Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*, Johns Hopkins Studies in the History of Technology (Baltimore: Johns Hopkins, 1990); Henry Petroski, *To Engineer Is Human: The Role of Failure in Successful Design* (New York: St. Martin's Press, 1985).

the ways people live and work.[58] Just like scientists, the engineering profession has adopted computing extensively, with almost all elements of engineering activity now mediated through computers—design, simulation modeling, communications, logistics, financial management, and administration.[59] Over the period 1967–2003, modeling, testing, and simulation moved from being largely hand-calibrated to being almost exclusively computer-mediated.[60] The Columbia Accident Investigation Board report shows, however, that this process involved the loss of much of the transparency of older techniques.

A brief history of the modeling tool Crater illustrates this process well. Crater was originally built in 1966 by Allen Richardson at Rockwell. It was designed in conjunction with NASA engineers to predict the effects of hypervelocity impacts on multilayer surfaces like those of the Apollo CSM. Crater was a curve fit from a data set generated in part from Gemini experience and in part from testing performed by General Motors and NASA on aluminum honeycomb materials. Crater could predict threshold velocities and penetration damage but was complex to use; the number and complexity of calculations needed to derive a result made it time-consuming and prone to error. Crater was validated using small pieces of foam and ice on single tiles. During the process of turning empirical data into a predictive equation, the limitations and contingencies of these initial data sets were lost.[61] Furthermore, the process of computerization of Crater rendered the uncertainties inherent in the tool even more invisible, and the specific mode of computerization, a plug-in-the-numbers spreadsheet, gave a false sense of clarity and certainty to the results. Thus, an engineer unaware of the history of the tool and its limita-

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[58] See Sherry Turkle, *The Second Self: Computers and the Human Spirit* (New York: Simon & Schuster, 1984); and Sherry Turkle, *Life on the Screen: Identity in the Age of the Internet* (New York: Simon & Schuster, 1995), for an examination of how interaction through the mediation of computers changes identity. More specifically, Dominique Vinck and Eric Blanco, *Everyday Engineering: An Ethnography of Design and Innovation, Inside Technology* (Cambridge, MA: MIT Press, 2003), and Susan Leigh Star, *The Cultures of Computing* (Oxford, U.K., and Cambridge, MA: Blackwell Publishers, 1995), start to address how engineering and scientific work has changed.

[59] For a general overview of computing since World War II, see Paul E. Ceruzzi, *A History of Modern Computing*, 2nd ed. (Cambridge, MA: MIT Press, 2003). Paul E. Ceruzzi, *Beyond the Limits: Flight Enters the Computer Age* (Cambridge, MA: MIT Press, 1989), provides a good outline of the introduction of computers into aerospace, although the focus of the work is on-board computers rather than ground equipment or design tools. Gary Lee Downey, *The Machine in Me: An Anthropologist Sits among Computer Engineers* (New York: Routledge, 1998), and Louis L. Bucciarelli, *Designing Engineers, Inside Technology* (Cambridge, MA: MIT Press, 1994), both provide ethnographies of engineering that discuss the effects of the ubiquity of computers in the workplace.

[60] For a good overview of this topic, see Sergio Sismondo and Snait Gissis, "Practices of Modelling and Simulation," *Special Issue of Science in Context* 12 (1999). George E. Smith, "The Dangers of Cad," *Mechanical Engineering* (February 1986), gives an early warning of the dangers of increasingly closed simulation tools.

[61] Allen Richardson interview, by A. Brown, 15 February 2005.

tions, as was the Boeing engineer who did the *Columbia* analysis, could not know that the predictive powers of Crater were unknown outside a limited range of values. The piece of foam that fell from *Columbia*'s external tank was 640 times larger than Crater's valid range. The Crater model predicted that the foam strike would have broken entirely through the Thermal Protection System of the Shuttle and exposed the aluminum wing structure.[62] But because the engineers were aware that there were limitations to the tool, but not aware of how to correct or modify the model, they dismissed their results as too conservative and not predictive of a problem.

This example shows that the Boeing engineers were working in a mode of engineering where their relationships to the materials and objects that they build and study were profoundly mediated through a computer and profoundly dependent on the uncritical acceptance of the findings and assumptions of previous generations of engineers. In January 2003, Boeing engineers and NASA's Debris Assessment Team had no choice but to accept the results of their Crater analysis. Their reliance on a computer model, with the inherent lack of access to the mechanics of the model, let alone the assumptions and uncertainties underlying it, had profoundly affected their ability to make engineering judgments. A similar story can be told about the External Tank bolt catchers—their safety margin, flagged by the Board as dangerously low and a possible source of disaster, was computed using ancient data sets whose origins and limitations had been obscured by computerization.[63]

Engineering Education

There is a growing trend in the history of science to look towards pedagogy as a lens through which to understand how science and scientists come to be.[64] David Kaiser writes, "Scientists are not born, they are made. The ways in which this happens bears the marks of time and place."[65] This observation holds equally true for engineers. Engineering education has changed since Apollo 1. In the late 1960s, engineering schools started to move towards

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[62] CAIB, *Report*, pp. 144–145.

[63] Ibid., pp. 86–88.

[64] David Kaiser, *Pedagogy and the Practice of Science: Historical and Contemporary Perspectives* (Cambridge, MA: MIT Press, 2005), is a collection of essays examining science pedagogy over a variety of disciplines, places, and times. Andrew Warwick, *Masters of Theory: Cambridge and the Rise of Mathematical Physics* (Chicago: The University of Chicago Press, 2003), a study of mathematical training in 19th-century Cambridge and its relationship to 19th-century physics in Britain, is perhaps the most sustained development of the argument for the value of the study of pedagogy. Sharon Traweek, *Beamtimes and Lifetimes: The World of High Energy Physicists* (Cambridge, MA: Harvard University Press, 1988), examines contemporary Japanese physicists and identifies education as critical in the formation of a distinctively Japanese way of doing physics.

[65] Kaiser, *Pedagogy and the Practice of Science,* p. 1.

engineering science and away from engineering design as a model for the discipline.[66] Engineering students were required to take classes in physics, math, and chemistry to give them a thorough grounding in the physical sciences before going on to engineering classes. The ongoing effects of the National Defense Education Act of 1958 meant changes towards more easily teachable and assessable modes of learning as educators struggled to manage massive expansions in class sizes.[67] The combination of these two trends meant that for many freshmen and sophomores in the 1970s, engineering meant doing physics and math problem sets rather than sketching, building, and working with their hands.[68] This mode of learning fit well with the growing presence of computers in education, providing students with the mathematical tools needed to build and use their own software. As computers became ubiquitous, so engineering schools brought computing into engineering education.

These changes served to both render engineering more abstract and arcane, less connected to its objects of study, and to make it more automated. Both the *Challenger* and *Columbia* reports are critical of the relationships between NASA and its contractors, and particularly critical of the lack of engineering design and development capacity amongst some of the contractors.[69] Embodying engineering judgment in computer programs can devalue that judgment when embodied in engineers, leading to downgrading of the institutional value placed on engineers as employees. This leaves engineers and their skills more vulnerable to privatization and commodification and hence leads to the downgrading of the engineering design capacity of commercial organizations.

The new discipline of astronautics or astronautical engineering was also emerging over this period, intertwined with the development of NASA as an

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[66] Rosalind H. Williams, *Retooling: A Historian Confronts Technological Change* (Cambridge, MA: MIT Press, 2002), pp. 40–42.

[67] Barbara Barksdale Clowse, *Brainpower for the Cold War: The Sputnik Crisis and National Defense Education Act of 1958* (Westport, CT: Greenwood Press, 1981), examines the initial responses to the Sputnik crisis. David Kaiser, "Scientific Manpower, Cold War Requisitions, and the Production of American Physicists after World War II," *Historical Studies in the Physical and Biological Sciences* 33 (fall 2002), looks specifically at the relationship between Cold War geopolitics and changing styles of science and education during this period.

[68] Both Kathryn Henderson, *On Line and on Paper: Visual Representations, Visual Culture, and Computer Graphics in Design Engineering, Inside Technology* (Cambridge, MA: MIT Press, 1999), and Eugene S. Ferguson, *Engineering and the Mind's Eye* (Cambridge, MA: MIT Press, 1992), examine the changes in engineering brought about by changes in the ways in which students learn to interact with the material world. Ferguson discusses the loss of a visual intuitiveness amongst young engineers brought about by a move to a more analytic style of engineering in the 1960s and 1970s. Henderson looks at the ways in which engineering knowledge and practices are transformed when computer visualization tools are introduced into the workshop and drafting room.

[69] Presidential Commission on the Space Shuttle *Challenger* Accident, *Report to the President*, pp. 194–195; CAIB, *Report*, pp. 110–118.

organization.[70] The new discipline drew heavily on the principles of aeronautical engineering but taught students how to apply these principles in higher stress environments—at higher temperatures and pressures, with higher aerodynamic loads, in high-radiation environments, using finer tolerance manufacturing, and with larger and more complex vehicle systems. The new discipline of astronautical engineering had to learn how to manage problems with testing the massive vehicles it built. In many cases, it was physically impossible to adequately test astronautical hardware, and so new methods of producing knowledge about complex systems like computer modeling and simulation were developed. The Apollo 204 report illustrates the engineering challenges that accompanied the transition from designing and developing craft to operate within the atmosphere to craft designed to operate in the space environment. As the report makes clear, the levels of both precision and complexity needed to build a spacecraft grew dramatically, perhaps beyond the capacity of North American Aviation engineers to keep up. As astronautics developed, engineering scale, engineering knowledge, and engineering management changed.

The Systems Approach

Systems engineering as a philosophy emerged from the complex military defense projects of the 1950s. It can be best described as a "set of organizational structures and processes to rapidly produce a novel but dependable technological artifact within a predictable budget."[71] Systems engineering was one element in a long history of the application of scientific and engineering principles to complex commercial or organizational problems, a history that started with Taylorism and scientific management in the late 19th century.[72] Systems engineering involved the use of engineering ideas to organize large engineering projects—most profoundly, systems engineering defines project

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[70] W. Henry Lambright, *Powering Apollo: James E. Webb of NASA* (Baltimore: John Hopkins, 1995); W. Henry Lambright, Edwin A. Bock, and Inter-university Case Program, *Launching NASA's Sustaining University Program* (Syracuse, NY: Inter-university Case Program, 1969); Howard E. McCurdy, *Inside NASA: High Technology and Organizational Change in the U.S. Space Program* (Baltimore: Johns Hopkins, 1993).

[71] Stephen B. Johnson, *The Secret of Apollo: Systems Management in American and European Space Programs* (Baltimore: Johns Hopkins, 2002), p. 17.

[72] See James R. Beniger, *The Control Revolution: Technological and Economic Origins of the Information Society* (Cambridge, MA: Harvard University Press, 1986), and JoAnne Yates, *Control through Communication: The Rise of System in American Management* (Baltimore: Johns Hopkins, 1989), for a brief introduction to the literature on system and scientific management. Robert Kanigel, *The One Best Way: Frederick Winslow Taylor and the Enigma of Efficiency* (New York: Viking, 1997), and Hugh G. J. Aitken, *Scientific Management in Action: Taylorism at Watertown Arsenal, 1908–1915* (Princeton, NJ: Princeton University Press, 1985), both provide excellent introductions to Taylor and scientific management.

management as an engineering problem best solved by engineers and engineering practice. In this philosophy, management becomes a subset of engineering practice. The large SAGE (Semi-Automatic Ground Environment) air defense and Atlas missile projects trained a generation of engineers how to apply systems engineering ideas to complex research, development, and manufacturing projects.[73] Systems management experts from the Air Force and the aerospace industry were brought into NASA to manage the Apollo program as it grew in the 1960s.[74] The Apollo 204 accident marks the moment of transition into a full acceptance of systems engineering as the guiding philosophy of the space program, whereas throughout the early part of the 1960s, there was tension between the aircraft manufacturers and the missile-program-trained NASA engineering managers. Indeed, the most common historiographical interpretation of the larger significance of Apollo 204 is simply that—the fire forced NASA and its contractors to find new ways of managing the complexity of the Apollo program, and systems management was the new way.[75]

The manned spaceflight community within NASA made the transition from research and development to being primarily an operational organization in the 1980s and 1990s, as the focus of the U.S. manned spaceflight program moved from exploration to ready access to low-Earth orbit. Systems engineering as an overarching philosophy for the management of complexity was replaced with new approaches drawn from both the business and government worlds. This does not mean that the tools that collectively made up systems engineering—configuration control boards, integrated management

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[73] Agatha C. Hughes and Thomas Parke Hughes, *Systems, Experts, and Computers: The Systems Approach in Management and Engineering, World War II and After, Dibner Institute Studies in the History of Science and Technology* (Cambridge, MA: MIT Press, 2000); Thomas Parke Hughes, *Rescuing Prometheus*, 1st ed. (New York: Pantheon Books, 1998); and Kent C. Redmond and Thomas M. Smith, *From Whirlwind to Mitre: The R&D Story of the SAGE Air Defense Computer* (Cambridge, MA: MIT Press, 2000), all discuss the origins of systems management in the ballistic missile and air defense programs of the 1950s.

[74] Johnson's *The Secret of Apollo: Systems Management in American and European Space Programs* is by far the most comprehensive examination of the rise of systems management in the U.S. space program. See also Arnold S. Levine, *Managing NASA in the Apollo Era* (Washington, DC: NASA SP-4102, 1982); John M. Logsdon, *Managing the Moon Program: Lessons Learned from Project Apollo: Proceedings of an Oral History Workshop* (Washington, DC: NASA SP-4514, 1999).

[75] For examples of this type of interpretation, see Andrew Chaikin and Tom Hanks, *A Man on the Moon: The Voyages of the Apollo Astronauts* (New York: Penguin Books, 1998), chap. 1; Charles A. Murray and Catherine Bly Cox, *Apollo, the Race to the Moon* (New York: Simon & Schuster, 1989), chaps. 15–16; William E. Burrows, *This New Ocean: The Story of the Space Age*, 1st ed. (New York: Random House, 1998), pp. 406–415. Astronaut and flight controller biographies make a similar point. See, for example, Frank Borman and Robert J. Serling, *Countdown: An Autobiography*, 1st ed. (New York: W. Morrow, 1988), chap. 9; Michael Collins, *Carrying the Fire: An Astronaut's Journeys* (New York: Farrar, 1974), pp. 269–275; Christopher C. Kraft, *Flight: My Life in Mission Control* (New York: Dutton, 2001), pp. 269–278; Gene Kranz, *Failure Is Not an Option: Mission Control from Mercury to Apollo 13 and Beyond* (New York: Simon & Schuster, 2000), pp. 208–214.

systems, resident program offices at contractors—ceased to be used, but rather that the philosophy that a collection of these tools was the best way to manage a program was replaced by other ways of thinking.[76]

Total Quality Management, reengineering, and "faster, better, cheaper" took the place of systems engineering in the 1990s, part of a larger cultural trend in the United States that valorized the business approach to organization and emphasized the merits of private free-enterprise solutions to problems previously thought the realm of government.[77] The idea of using scientific and engineering principles to solve business and organizational challenges was replaced by the application of business and commercially derived management philosophy to an engineering organization.

Changes in engineering practice over the 1970s, 1980s, and 1990s meant that engineers in the manned space program were working in the increasingly mediated environment of computer-based engineering whilst working on technological systems that were becoming increasingly complex, difficult to test, and designed to operate at an increasingly high performance envelope. Margins for error grew ever smaller, whilst the computer-based tools being used to manage that margin grew increasingly less transparent. At the same time, the shared organizational philosophy of systems engineering was being abandoned by senior management in favor of more commercially oriented ideas, while engineers still used the tools of systems management.

FURTHER RESEARCH

There are several areas that call for further research in order to put together a picture of changes in engineering in the U.S. manned space program. The first area is studies of engineering in practice in the late 20th century. Although the genre of engineering ethnographies is growing, it is still small. Some of these studies examine the impact of computers in the engineering workplace, but none do so in the context of aeronautics or astronautics. Howard McCurdy's work on NASA culture provides an excellent base to work from but focuses on organizational change rather than engineering change from the 1970s onwards.[78] Furthermore, the field needs not just in-depth studies of engineering practice, but broad-scope surveys comparable to Sylvia Fries's *NASA Engineers in the Age of Apollo*.[79] We do not yet know

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[76] See CAIB, *Report*, pp. 105–110.

[77] Howard E. McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program* (Baltimore: Johns Hopkins, 2001).

[78] McCurdy, *Inside NASA: High Technology and Organizational Change in the U.S. Space Program*; McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program.*

[79] Sylvia Doughty Fries, *NASA Engineers and the Age of Apollo* (Washington, DC: NASA SP-4104, 1992).

enough about the educational and demographic characteristics of NASA engineers from the 1970s onwards.

There is a need for a body of literature on the recent institutional and cultural history of engineering comparable to the literature on the rise of the engineering profession in the later half of the 19th century. We know much about the ways in which engineers developed a clearly articulated professional identity, created a standardized curriculum and accreditation process, and made themselves middle-class in the late 19th century.[80] We know much about the engineering triumphs of the early 20th century and the involvement of engineers in the winning of World War II and the Cold War, both as producers of military technology but also as the creators of the consumer society.[81] But we know little about how engineers have responded to changing economic and cultural circumstances since the 1960s.

We need more nuanced histories of the NASA of the 1970s, 1980s, and 1990s. Reflecting the ongoing cultural legacy of the Apollo program, much of the literature on the U.S. manned spaceflight program focuses on the triumphs of the 1960s. Those histories that do attempt to cover the entire history of the program tend to fall into a declensionist mode of writing, discussing NASA's decline and fall from Apollo. A more nuanced understanding of the legacy of the Apollo program, including a more realistic assessment of the relative safety of Apollo and Shuttle missions, might serve to provide a new framework in which to understand the history of NASA over this period.

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80. For example, see Edwin T. Layton, *The Revolt of the Engineers: Social Responsibility and the American Engineering Profession* (Cleveland: Press of Case Western Reserve University, 1971); George S. Emmerson, *Engineering Education: A Social History* (New York: David & Charles; Crane, 1973); David F. Noble, *America by Design: Science, Technology, and the Rise of Corporate Capitalism*, 1st ed. (New York: Knopf, 1977); Brendan Patrick Foley, "Fighting Engineers: The U.S. Navy and Mechanical Engineering, 1840–1905" (Ph.D. thesis, MIT, June 2003).

81. See Thomas Parke Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970* (New York: Penguin Books, 1990); David A. Hounshell, *From the American System to Mass Production, 1800–1932: The Development of Manufacturing Technology in the United States* (Baltimore: Johns Hopkins, 1984); Terry S. Reynolds, *The Engineer in America: A Historical Anthology from Technology and Culture* (Chicago: University of Chicago Press, 1991).