This excerpt is taken from, "The Loss of the Space Shuttle Columbia: Portaging the Leadership Lessons with a Critical Thinking Model."[1] This demonstrates how to apply close reading to each paragraph. It should be noted that the authors are familiar with the Critical Thinking Model and have years of experience in the aerospace industry. This example is offered as a guide as you begin to critically read engineering material and mark-up what you read.

The *Columbia* Accident Investigation Board (CAIB) Report

The general facts surrounding the loss of the space shuttle *Columbia* on the morning of February 1, 2003, are well known. A piece of insulating foam broke away from the external fuel tank seconds after launch, puncturing the leading edge of the orbiter's left wing. The crew then spent fifteen days on orbit conducting a host of very successful science experiments, unaware that their spacecraft had been catastrophically damaged. On re-entry, hot gas tore through the interior structure of the wing, leading to wing failure, disintegration of the vehicle, and the death of the crew.

Unfortunately, the board's findings on organizational behavior have not been as broadly discussed. The technical story is fascinating; the CAIB's discussion of organizational behavior is heart-rending. The real meat lies here for those who lead or will lead technical organizations, because it's a tragic story of bright, devoted, hard-working professionals whose leaders allowed the team's thinking to stray adrift, killing seven of their friends and scattering an irreplaceable national asset across the Southwestern United States. We regard the CAIB report as required reading for all leaders in high technology enterprises not because of what they might learn about the threat of insulating foam to spacecraft, but rather the threat that uncritical thinking poses to even the nation's most successful, talented and hard-working teams. We'll briefly summarize the organizational piece for those unfamiliar with this second most disturbing facet of the *Columbia* mishap.

The CAIB's most severe criticism of NASA sprang from their observation of the strong similarity between the loss of *Columbia* and the loss of *Challenger*. Neither the loss of foam (*Columbia*), nor O-ring erosion (*Challenger*), were new issues; both had been observed on numerous prior flights. In both mishaps, technical team members raised grave concerns about the safety of the mission during the week prior to each orbiter's loss. In both events, leadership dismissed team member concerns, focused on keeping the schedule, and blithely inferred that past minor issues with O-rings/foam would remain minor. The "echoes of Challenger" led the CAIB to entitle an entire chapter, "History as Cause: *Columbia* and *Challenger*."14

The pages that follow are extracted directly from the CAIB Report, Chapter 6, "Decision Making at NASA." They summarize a very lengthy section 6.3, "Decision-Making During the Flight of STS-107," which detailed the substance of multiple meetings and extensive correspondence within and between program teams as decisions were made regarding the condition of *Columbia* during its final mission. The left column is verbatim from the report; our italicized remarks are to the right note, with vocabulary from Paul's model underlined.

We've chosen this section for emphasis because it describes the dysfunction of a specific team, involving small meetings and personal communications, rather than the report's broader treatment of the dysfunction of an entire agency or U.S. space policy. The team setting is more accessible to the undergraduate who can more readily imagine themselves in a team setting than executive management, and it is for that setting that we seek to first prepare them.

Summary: Mission Management Decision Making 15

Discovery and Initial Analysis of Debris Strike

In the course of examining film and video images of Columbia's ascent, the Intercenter Photo Working Group identified, on the day after launch, a large debris strike to the leading edge of Columbia's left wing. Alarmed at seeing so severe a hit so late in ascent, and at not having a clear view of damage the strike might have caused, Intercenter Photo Working Group members alerted senior Program managers by phone and sent a digitized clip of the strike to hundreds of NASA personnel via e-mail. These actions initiated a contingency plan that brought together an interdisciplinary group of experts from NASA, Boeing, and the United Space Alliance to analyze the strike. So concerned were Intercenter Photo Working Group personnel that on the day they discovered the debris strike, they tapped their Chair, Bob Page, to see through a request to image the left wing with Department of Defense assets in anticipation of analysts needing these images to better determine potential damage. By the Board's count, this would be the first of three requests to secure imagery of Columbia on-orbit during the 16-day mission.

Clear recognition of the need for better data.

Upon learning of the debris strike on Flight Day Two, the responsible system area manager from United Space Alliance and her NASA counterpart formed a team to analyze the debris strike in accordance with mission rules requiring the careful examination of any "out-of-family" event. Using film from the Intercenter Photo Working Group, Boeing systems integration analysts prepared a preliminary analysis that afternoon. (Initial estimates of debris size and speed, origin of debris, and point of impact would later prove remarkably accurate.)

Excellent initial inferences based upon scant preliminary data. "out-of-family" meant out of NASA's experience base.

As Flight Day Three and Four unfolded over the Martin Luther King Jr. holiday weekend, engineers began their analysis. One Boeing analyst used Crater, a mathematical prediction tool, to assess possible damage to the Thermal Protection System. Analysis predicted tile damage deeper than the actual tile depth, and penetration of the RCC coating at impact angles above 15 degrees. This suggested the potential for a burn-through during re-entry. Debris Assessment Team members judged that the actual damage would not be as severe as predicted because of the inherent conservatism in the Crater model and because, in the case of tile, Crater does not take into account the tile's stronger and more impact-resistant "densified" layer, and in the case of RCC, the lower density of foam would preclude penetration at impact angles under 21 degrees.

Gut-based judgment replaces engineering analysis. Inaccurate inference based on invalid logic, and unsubstantiated assumptions.

On Flight Day Five, impact assessment results for tile and RCC were presented at an informal meeting of the Debris Assessment Team, which was operating without direct Shuttle Program or Mission Management leadership. Mission Control's engineering support, the Mission Evaluation Room, provided no direction for team activities other than to request the team's results by January 24. As the problem was being worked,

Unchallenged working assumptions. Conspicuous lack of intellectual curiosity on the part of leadership.

Shuttle managers did not formally direct the actions of or consult with Debris Assessment Team leaders about the team's assumptions, uncertainties, progress,

Some team-members continued to recognize

or interim results, an unusual circumstance given that NASA managers are normally engaged in analyzing what they view as problems. At this meeting, participants agreed that an image of the area of the wing in question was essential to refine their analysis and reduce the uncertainties in their damage assessment.

the inadequacy of the data.

Each member supported the idea to seek imagery from an outside source. Due in part to a lack of guidance from the Mission Management Team or Mission Evaluation Room managers, the Debris Assessment Team chose an unconventional route for its request. Rather than working the request up the normal chain of command – through the Mission Evaluation Room to the Mission Management Team for action to Mission Control – team members nominated Rodney Rocha, the team's Co-Chair, to pursue the request through the Engineering Directorate at Johnson Space Center. As a result, even after the accident the Debris Assessment Team's request was viewed by Shuttle Program managers as a non-critical engineering desire rather than a critical operational need.

Insufficient clarity regarding the extent of team-member's discomfort with lack of imagery (data).

When the team learned that the Mission Management Team was not pursuing on-orbit imaging, members were concerned. What Debris Assessment Team members did not realize was the negative response from the Program was not necessarily a direct and final response to their official request. Rather, the "no" was in part a response to requests for imagery initiated by the Intercenter Photo Working Group at Kennedy on Flight Day 2 in anticipation of analysts' needs that had become by Flight Day 6 an actual engineering request by the Debris Assessment Team, made informally through Bob White to Lambert Austin, and formally through Rodney Rocha's e-mail to Paul Shack. Even after learning that the Shuttle Program was not going to provide the team with imagery, some members sought information on how to obtain it anyway.

Leadership canceled photo requests because:
a) inaccurate assumptions of the imaging capability,
b) inaccurate assumptions regarding value of photos
d) unwillingness to disrupt mission to inspect orbiter (confused purpose)16
e) inaccurate assumption that rescue was infeasible.17
These assumptions were accepted as fact.

Some perseverance displayed by those willing to circumvent bureaucratic obstacles.

Debris Assessment Team members believed that imaging of potentially damaged areas was necessary even after the January 24, Mission Management Team meeting, where they had reported their results. Why they did not directly approach Shuttle Program managers and share their concern and uncertainty, and why Shuttle Program managers claimed to be isolated from engineers, are points that the Board labored to understand. Several reasons for this communications failure relate to NASA's internal culture and the climate established by Shuttle Program management, which are discussed in more detail

Other parts of the report attribute this behavior to lack of intellectual courage on the part of team-members, and lack of empathy on the part of

in Chapters 7 and 8.

management.

A Flawed Analysis

An inexperienced team, using a mathematical tool that was not designed to assess an impact of this estimated size, performed the analysis of the potential effect of the debris impact. Crater was designed for "in-family" impact events and was intended for day-of launch analysis of debris impacts. It was not intended for large projectiles like those observed on STS-107. Crater initially predicted possible damage, but the Debris Assessment Team assumed, without theoretical or experimental validation, that because Crater is a conservative tool – that is, it predicts more damage than will actually occur – the debris would stop at the tile's densified layer, even though their experience did not involve debris strikes as large as STS-107's. Crater-like equations were also used as part of the analysis to assess potential impact damage to the wing leading edge RCC. Again, the tool was used for something other than that for which it was designed; again, it predicted possible penetration; and again, the Debris Assessment Team used engineering arguments and their experience to discount the results.

Inaccurate conclusions based on unjustified extrapolation of assumptions. The tool's severe predictions were dismissed not on the basis of logic, but on a history which showed that foam had never previously been a safety of flight issue.

As a result of a transition of responsibility for Crater analysis from the Boeing Huntington Beach facility to the Houston-based Boeing office, the team that conducted the Crater analyses had been formed fairly recently, and therefore could be considered less experienced when compared with the more senior Huntington Beach analysts. In fact, STS-107 was the first mission for which they were solely responsible for providing analysis with the Crater tool. Though post-accident interviews suggested that the training for the Houston Boeing analysts was of high quality and adequate in substance and duration, communications and theoretical understandings of the Crater model among the Houston-based team members had not yet developed to the standard of a more senior team. Due in part to contractual arrangements related to the transition, the Houston-based team did not take full advantage of the Huntington Beach engineers' experience.

A new support team failed to admit when they were over their heads (Intellectual humility).

At the January 24, Mission Management Team meeting at which the "no safety-offlight" conclusion was presented, there was little engineering discussion about the assumptions made, and how the results would differ if other assumptions were used.

Unchallenged assumptions. Lack of intellectual curiosity.

Engineering solutions presented to management should have included a quantifiable range of uncertainty and risk analysis. Those types of tools were readily available, routinely used, and would have helped management understand the risk involved in the decision. Management, in turn, should have demanded such information. The very absence of a clear and open discussion of uncertainties and assumptions in the analysis presented should have caused management to probe further.

Imprecise information. Inadequate intellectual perseverance and curiosity.

Shuttle Program Management's Low Level of Concern

While the debris strike was well outside the activities covered by normal mission flightrules, Mission Management Team members and Shuttle Program managers did not treat the debris strike as an issue that required operational action by Mission Control. Program managers, from Ron Dittemore to individual Mission Management Team members, had, over the course of the Space Shuttle Program, gradually become inured to External Tank foam losses and on a fundamental level did not believe foam striking the vehicle posed a critical threat to the Orbiter. In particular, Shuttle managers exhibited a belief that RCC panels are impervious to foam impacts. Even after seeing the video of Columbia's debris impact, learning estimates of the size and location of the strike, and noting that a foam strike with sufficient kinetic energy could cause Thermal Protection System damage, management's level of concern did not change.

Insufficient intellectual perseverance and curiosity.

The opinions of Shuttle Program managers and debris and photo analysts on the potential severity of the debris strike diverged early in the mission and continued to diverge as the mission progressed, making it increasingly difficult for the Debris Assessment Team to have their concerns heard by those in a decision-making capacity. In the face of Mission managers' low level of concern and desire to get on with the mission, Debris Assessment Team members had to prove unequivocally that a safety-of- flight issue existed before Shuttle Program management would move to obtain images of the left wing. The engineers found themselves in the unusual position of having to prove that the situation was unsafe – a reversal of the usual requirement to prove that a situation is safe.

Insufficient intellectual <u>fairness</u>.
<u>Confused purpose</u> (emphasis was justifying the safety of the next mission in lieu of recovering the current mission).

Other factors contributed to Mission management's ability to resist the Debris Assessment Team's concerns. A tile expert told managers during frequent consultations that strike damage was only a maintenance-level concern and that on-orbit imaging of potential wing damage was not necessary. Mission management welcomed this opinion and sought no others. This constant reinforcement of managers' pre-existing beliefs added another block to the wall between decision makers and concerned engineers.

Sociocentric blindness.
No <u>breadth</u> of inquiry.
No cultivation of dissenting <u>points of view.</u>

Another factor that enabled Mission management's detachment from the concerns of their own engineers is rooted in the culture of NASA itself. The Board observed an unofficial hierarchy among NASA programs and directorates that hindered the flow of communications. The effects of this unofficial hierarchy are seen in the attitude that members of the Debris Assessment Team held. Part of the reason they chose the institutional route for their imagery request was that without direction from the Mission Evaluation Room and Mission Management Team, they felt more comfortable with their own chain of command, which was outside the Shuttle Program. Further, when asked by investigators why they were not more vocal about their concerns, debris Assessment Team members opined that by raising contrary points of view about Shuttle mission safety, they would be singled out for possible ridicule by their peers and managers.

Insufficient intellectual <u>courage</u>.

A Lack of Clear Communication

Communication did not flow effectively up to or down from Program managers. As it became clear during the mission that managers were not as concerned as others about the danger of the foam strike, the ability of engineers to challenge those beliefs greatly diminished. Managers' tendency to accept opinions that agree with their own dams the flow of effective communications.

Sociocentric blindness. No cultivation of dissenting points of view.

After the accident, Program managers stated privately and publicly that if engineers had a safety concern, they were obligated to communicate their concerns to management. Managers did not seem to understand that as leaders they had a corresponding and perhaps greater obligation to create viable routes for the engineering community to express their views and receive information. This barrier to communications not only blocked the flow of information to managers, but it also prevented the downstream flow of information from managers to engineers, leaving Debris Assessment Team members no basis for understanding the reasoning behind Mission Management Team decisions.\

Deficient Intellectual Fairness/Empathy

The January 27 to January 31, phone and e-mail exchanges, primarily between NASA engineers at Langley and Johnson, illustrate another symptom of the "cultural fence" that impairs open communications between mission managers and working engineers. These exchanges and the reaction to them indicated that during the evaluation of a mission contingency, the Mission Management Team failed to disseminate information to all system and technology experts who could be consulted. Issues raised by two Langley and Johnson engineers led to the development of "what-if" landing scenarios of the potential outcome if the main landing gear door sustained damaged. This led to behind-the-scenes networking by these engineers to use NASA facilities to make simulation runs of a compromised landing configuration. These engineers – who understood their systems and related technology – saw the potential for a problem on landing and ran it down in case the unthinkable occurred. But their concerns never reached the managers on the Mission Management Team that had operational control over Columbia

Here's a team that showed perseverance, running their questions to ground by endrunning the bureaucracy. Their ad hoc study simulating landing with a blown tire showed the crew would survive, so they allayed their own concern.

A Lack of Effective Leadership

The Shuttle Program, the Mission Management Team, and through it the Mission Evaluation Room, were not actively directing the efforts of the Debris Assessment Team. These management teams were not engaged in scenario selection or discussions of assumptions and did not actively seek status, inputs, or even preliminary results from the individuals charged with analyzing the debris strike. They did not investigate the value of imagery, did not intervene to consult the more experienced Crater analysts at Boeing's Huntington Beach facility, did not probe the assumptions of the Debris Assessment Team's analysis, and did not consider actions to mitigate the effects of the damage on re-entry. Managers' claims that they didn't hear the engineers' concerns were due in part to their not asking or listening.

This is a catalog of what's already been said.

The Failure of Safety's Role

As will be discussed in Chapter 7, safety personnel were present but passive and did not serve as a channel for the voicing of concerns or dissenting views. Safety representatives attended meetings of the Debris Assessment Team, Mission Evaluation Room, and Mission Management Team, but were merely party to the analysis process and conclusions instead of an independent source of questions and challenges. Safety contractors in the Mission Evaluation Room

Deficient Intellectual Courage, Curiosity, and Perseverance.

were only marginally aware of the debris strike analysis. One contractor did question the Debris Assessment Team safety representative about the analysis and was told that it was adequate. No additional inquiries were made. The highest-ranking safety representative at NASA headquarters deferred to Program managers when asked for an opinion on imaging of Columbia. The safety manager he spoke to also failed to follow up.

Summary

Management decisions made during Columbia's final flight reflect missed opportunities, blocked or ineffective communications channels, flawed analysis, and ineffective leadership. Perhaps most striking is the fact that management – including Shuttle Program, Mission Management Team, Mission Evaluation Room, and Flight Director and Mission Control – displayed no interest in understanding a problem and its implications. Because managers failed to avail themselves of the wide range of expertise and opinion necessary to achieve the best answer to the debris strike question – "Was this a safety-of-flight concern?" –some Space Shuttle Program managers failed to fulfill the implicit contract to do whatever is possible to ensure the safety of the crew. In fact, their management techniques unknowingly imposed barriers that kept at bay both engineering concerns and dissenting views, and ultimately helped create "blind spots" that prevented them from seeing the danger the foam strike posed.

The most damning line in the report expresses dismay at the want of intellectual curiosity regarding implications [Emphasis added.]

The real tragedy- the Point of View of the crew and their families didn't intrude (Intellectual Empathy and Fairness). The focus on keeping the program schedule (a confused purpose) trumped ensuring the safety of the mission in progress.

Because this chapter has focused on key personnel who participated in STS-107 bipod foam debris strike decisions, it is tempting to conclude that replacing them will solve all NASA's problems. However, solving NASA's problems is not quite so easily achieved. Peoples' actions are influenced by the organizations in which they work, shaping their choices in directions that even they may not realize. The Board explores the organizational context of decision making more fully in Chapters 7 and 8.

Here the board hints at implications of their findings, yet to be discussed.

References

1. R. Niewoehner, C. Steidle, and E. Johnson, The Loss of the Space Shuttle Columbia: Portaging the Leadership Lessons with a Critical Thinking Model." Proceedings of American Society for Engineering Education Annual Conference, 2008.