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THE FUTURE OF NASA

HEARING

BEFORE THE

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION UNITED STATES SENATE

ONE HUNDRED EIGHTH CONGRESS

FIRST SESSION

OCTOBER 29, 2003

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ONE HUNDRED EIGHTH CONGRESS

FIRST SESSION

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THE FUTURE OF NASA

WEDNESDAY, OCTOBER 29, 2003

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
Washington, DC.

The Committee met, pursuant to notice, at 9:30 a.m., in room SR–253, Russell Senate Office Building, Hon. John McCain, Chairman of the Committee, presiding.

OPENING STATEMENT OF HON. JOHN McCAIN, U.S. SENATOR FROM ARIZONA

The CHAIRMAN. Good morning. Since the late fifties, NASA has worked to make exploration possible through its innovative technology and cutting edge research and scientific discoveries. NASA achievements have stretched the imagination, from putting men on the moon to developing technology that has allowed unprecedented access to the inner solar system. Discoveries have touched the lives of the public in many ways people aren't aware of, such as improving communications capabilities, monitoring weather patterns and enhancing national security and defense.

Although NASA has a history of notable achievements, it has also suffered heartbreaking failures, such as the tragic losses of the *Challenger* and *Columbia.* Since the grounding of the space shuttle after the *Columbia* accident, the construction of the international space station has come to a halt and NASA's capacity to conduct scientific research in space has been significantly diminished.

The *Columbia* accident in February forced us to revisit our assumptions that the safety culture at NASA, which was found so wanting after the *Challenger* disaster, had been corrected. In addition to revealing the institutional problems still endemic at NASA, the *Columbia* accident has caused us to examine their causes. A fundamental cause of the institutional problems identified by the Columbia Accident Investigation Board was NASA's lack of a clear and defining mission.

While we still feel the agony of defeat and of loss, where's the thrill of victory? The excitement that gripped China when it launched its first manned space vehicle a few weeks ago is missing in America. Do we want a space program that can once again capture and feed our imaginations? If we do want such a program, what does it entail and what are we willing and able to pay for it?

I hope that today we can begin examining some of the questions, including the future of human space flight and the next generation of space transportation technologies. More pressing, however, are the immediate problems confronting NASA. In the past week, media reports regarding concerns about the safety of the international space station has raised new doubts about NASA's commitment to reform and its ability to conduct safe and cost-effective space exploration.

While we examine what we want NASA to be and where we want mankind to go in the long-term, we also need to examine what NASA is doing in the shorter term. Some have questioned NASA's orbital space plane, OSP program. I share these concerns and am also concerned about NASA's use of limited competition for the OSP's development, which is estimated to cost over $15 billion.

I welcome Administrator O'Keefe and Admiral Gehman on the first panel to discuss their thoughts on NASA's future missions, goals, and strategies, as well as issues NASA should consider as it looks toward the future. The committee recognizes that both witnesses have prior commitments and will work to ensure that they can depart the hearing no later than 10:30, and that's why I would ask my colleagues to make their opening statements brief, and I want to thank both the Administrator and Admiral Gehman for appearing this morning. Senator Hollings?

[The prepared statement of Senator McCain follows:]

PREPARED STATEMENT OF HON. JOHN MCCAIN, U.S. SENATOR FROM ARIZONA

Since the late 1950s, NASA has worked to make America a leader in aeronautics and space exploration through its innovative technology, cutting edge research, and scientific discoveries. NASA's achievements have stretched the imagination from putting men on the moon to developing technology that has allowed unprecedented access to the inner solar system. Its discoveries have touched the lives of the American public in ways many aren't even aware of, such as by improving communication capabilities, monitoring weather patterns, and enhancing national security and defense.

Although NASA has a history of notable accomplishments, it has also suffered a number of disappointing, and at times, heart-breaking failures, such as the tragic losses of the *Challenger* and *Columbia.* Since the grounding of the Space Shuttle after the *Columbia* accident, the construction of the International Space Station has come to a halt, and NASA's capacity to conduct scientific research in space has been significantly diminished.

The *Columbia* accident in February forced us to revisit our assumptions that the safety culture at NASA, which was found so wanting after the *Challenger* disaster, had been corrected. In addition to revealing the institutional problems still endemic at NASA, the *Columbia* accident has caused us to examine their causes. A fundamental cause of the institutional problems identified by the Gehman Board was NASA's lack of a defining mission.

While we still feel the agony of defeat, and of loss, where is the thrill of victory? The excitement that gripped China when it launched its first manned space vehicle a couple of weeks ago is missing in America. Do we want a space program that can once again catalyze our interest and capture our imaginations? If we do want such a program, what does it entail, and are we willing and able to pay for it?

I hope that today we can begin examining some of these questions, including the future of human space flight and the next generation of space transportation technology.

More pressing, however, are the immediate problems confronting NASA. In the past week, media reports regarding concerns about the safety of the International Space Station have raised new concerns about NASA's commitment to reform and its ability to conduct safe and cost-effective space exploration.

While we examine what we want NASA to be and where we want mankind to go in the long term, we also need to examine what NASA is doing in the shorter term. Some, including the House Science Committee, have expressed concerns about NASA's Orbital Space Plane (OSP) program, which is estimated to require an initial investment of $15 billion. However, in a letter to NASA last week, the House Science Committee described this budget plan for the OSP program as "no longer credible." Putting aside the question of the merit of the OSP, in September, I sent a letter to NASA expressing my concerns about the limited competition that NASA has proposed for its development. I plan to discuss this and many other issues as well.

I welcome Administrator O'Keefe and Admiral Gehman on the first panel to discuss their thoughts on NASA's future missions, goals, and strategies, as well as issues NASA should consider as it looks toward the future. The committee recognizes that both witnesses have prior commitments, and we will work to ensure that they can depart the hearing no later than 10:30 a.m.

STATEMENT OF HON. ERNEST F. HOLLINGS, U.S. SENATOR FROM SOUTH CAROLINA

Senator HOLLINGS. Thank you, Mr. Chairman. The Columbia Accident Investigation Board found, and I quote, "The organizational causes of this accident are rooted in the space shuttle program's history and culture, including the lack of an agreed national vision for human space flight. The Board does believe that NASA and the Nation should give more attention to developing a new concept of operations for future activities, defining the range of activities the country intends to carry out in space that could provide more specificity than currently exists. Such a concept does not necessarily require full agreement on a future vision, but it should help identify the capabilities required and prevent the debate from focusing solely on the design of the next vehicle."

Admiral Gehman, I agree with that. I think that NASA needs the commission to institute a change of culture with respect to safety. To address this issue, I have introduced a commission bill, which gives the President the authority to appoint a top-level commission. I'm looking forward to having your suggestions as to any changes or criticism you have regarding this approach.

Mr. Chairman, there's a very interesting *Atlantic Monthly* article on the Space Shuttle *Columbia* disaster. I would ask consent that it be included in the record.

The CHAIRMAN. I read the article. It's very interesting. Without objection. Thank you, sir.

Senator HOLLINGS. Thank you.

[The prepared statement of Senator Hollings follows:]

PREPARED STATEMENT OF HON. ERNEST F. HOLLINGS, U.S. SENATOR FROM SOUTH CAROLINA

Today we will hear several grand visions of what the National Aeronautics and Space Administration can, and should, be. One of the highest tributes we can give the fallen heroes lost aboard the *Columbia* is to renew our commitment to space.

The question is this: how do we get there from here? The Columbia Accident Investigation Board, chaired by Admiral Gehman, gave us a roadmap for putting Space Shuttle safety on a more sound footing. However, many in the space community—and some on your own Board have expressed doubts about NASA's ability to reform itself.

Just last week, we learned from the Washington Post that two doctors had questioned the safety of sending the next mission to the Space Station. Instead of waiting until the agency could prove that the Station environment is safe, NASA launched saying "the Astronauts can come home if the Station is not safe." While the doctor's concerns were aired and steps were taken to satisfy them, it doesn't seem to me NASA has learned the lessons that Admiral Gehman was trying to teach.

All of this controversy contributes to a public cynicism about NASA and about space. There is no confidence in NASA's ability to execute its current program and no compelling plan for the agency's future that the American people can embrace. While NASA continues to stagger, China has sent its first astronaut into space.

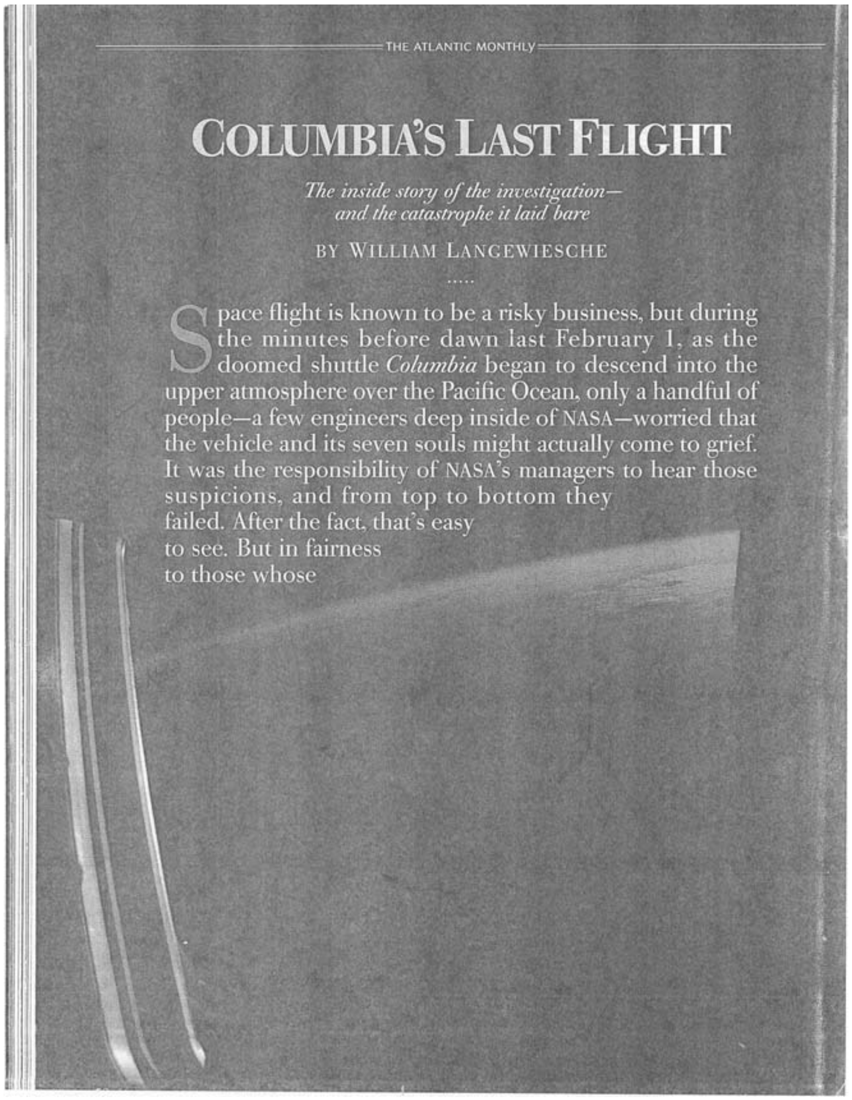
To solve these problems, I have proposed the creation of a National Space Commission. I have talked to the Administrator and the Vice President about my idea and have circulated the bill to members of this Committee.

In short, my bill would provide oversight in the short term to ensure that NASA returns safely to flight and reforms its safety culture. The Commission would then develop a new vision for the future of space that includes NASA's exploration agenda but also brings a broader National space agenda into focus.

Mr. Chairman, I hope that you and the other Members of the Committee can join me as a co-sponsor of the National Space Commission Act and that the Congress can act quickly on this legislation. The sooner we get started, the sooner we can move toward the next "giant leap for mankind."

[The news article referred to follows:]

The Atlantic Monthly, NOVEMBER, 2003—“COLUMBIA’S LAST FLIGHT”.



THE ATLANTIC MONTHLY

COLUMBIA’S LAST FLIGHT

The inside story of the investigation—and the catastrophe it laid bare

BY WILLIAM LANGEWIESCHE

Space flight is known to be a risky business, but during the minutes before dawn last February 1, as the doomed shuttle *Columbia* began to descend into the upper atmosphere over the Pacific Ocean, only a handful of people—a few engineers deep inside of NASA—worried that the vehicle and its seven souls might actually come to grief. It was the responsibility of NASA’s managers to hear those suspicions, and from top to bottom they failed. After the fact, that’s easy to see. But in fairness to those whose

Sunrise photographed by a crew member aboard the shuttle Columbia *on Flight Day 7 of the final mission* reputations have now been sacrificed, seventeen years and eighty-nine shuttle flights had passed since the *Challenger* explosion, and within the agency a new generation had risen that was smart, perhaps, but also unwise—confined by NASA's walls and routines, and vulnerable to the self-satisfaction that inevitably had set in.

Moreover, this mission was a yawn—a low-priority "science" flight forced onto NASA by Congress and postponed for two years because of a more pressing schedule of construction deliveries to the International Space Station. The truth is, it had finally been launched as much to clear the books as to add to human knowledge, and it had gone nowhere except into low Earth orbit, around the globe every ninety minutes for sixteen days, carrying the first Israeli astronaut, and performing a string of experiments, many of which, like the shuttle program itself, seemed to suffer from something of a make-work character—the examination of dust in the Middle East (by the Israeli, of course); the ever popular ozone study; experiments designed by schoolchildren in six countries to observe the effect of weightlessness on spiders, silkworms, and other creatures; an exercise in "astroculture" involving the extraction of essential oils from rose and rice flowers, which was said to hold promise for new perfumes; and so forth. No doubt some good science was done too—particularly pertaining to space flight itself—though none of it was so urgent that it could not have been performed later, under better circumstances, in the under-booked International Space Station. The astronauts aboard the shuttle were smart and accomplished people, and they were deeply committed to human space flight and exploration. They were also team players, by intense selection, and nothing if not wise to the game. From orbit one of them had radioed, "The science we're doing here is great, and it's fantastic. It's leading-edge." Others had dutifully reported that the planet seems beautiful, fragile, and borderless when seen from such altitudes, and they had expressed their hopes in English and Hebrew for world peace. It was Miracle Whip on Wonder Bread, standard NASA fare. On the ground so little attention was being paid that even the radars that could have been directed upward to track the *Columbia*'s re-entry into the atmosphere—from Vandenberg Air Force Base, or White Sands Missile Range—were sleeping. As a result, no radar record of the breakup exists—only of the metal rain that drifted down over East Texas, and eventually came into the view of air-traffic control.

From the speeding shuttle Rick Husband—Air Force test pilot, religious, family man, always wanted to be an astronaut—began to answer. He said, "Roger, ah," and was cut off on a word that began with "buh . . ." It was the *Columbia*'s last voice transmission.

Along the route, however, stood small numbers of shuttle enthusiasts, who had gotten up early with their video cameras and had arrayed themselves on hills or away from city lights to record the spectacle of what promised to be a beautiful display. The shuttle came into view, on track and on schedule, just after 5:53 Pacific time, crossing the California coast at about 15,000 mph in the superthin air 230,000 feet above the Russian River, northwest of San Francisco. It was first picked up on video by a Lockheed engineer in suburban Fairfield, who recorded a bright meteor passing almost directly overhead, not the shuttle itself but the sheath of hot gases around it, and the long, luminous tail of ionized air known as plasma. Only later, after the engineer heard about the accident on television, did he check his tape and realize that he had recorded what appeared to be two pieces coming off the *Columbia* in quick succession, like little flares in its wake. Those pieces were recorded by others as well, along with the third, fourth, and fifth "debris events" that are known to have occurred during the sixty seconds that it took the shuttle to cross California. From the top of Mount Hamilton, southeast of San Francisco, another engineer, the former president of the Peninsula Astronomical Society, caught all five events on tape but, again, did not realize it until afterward. He later said, "I'd seen four re-entries before this one. When we saw it, we did note that it was a little brighter and a little bit whiter in color than it normally is. It's normally a pink-magenta color. But you know, it wasn't so different that it really flagged us as something wrong. With the naked eye we didn't see the particles coming off."

One minute after the *Columbia* left California, as it neared southwestern Utah, the trouble was becoming more obvious to observers on the ground. There had been a bright flash earlier over Nevada, and now debris came off that was large enough to cause multiple secondary plasma trails. North of the Grand Canyon, in Saint George, Utah, a man and his grown son climbed onto a ridge above the county hospital, hoping for the sort of view they had seen several years before, of a fireball going by. It was a sight they remembered as "really neat." This time was different, though. The son, who was videotaping, started yelling, "Jesus, Dad, there's stuff falling off!" and the father saw it too, with his naked eyes.

The *Columbia* was flying on autopilot, as is usual, and though it continued to lay flares in its wake, the astronauts aboard remained blissfully unaware of the trouble they were in. They passed smoothly into dawn above the Arizona border, and sailed across the Navajo reservation and on over Albuquerque, before coming to the Texas Panhandle on a perfect descent profile, slowing through 13,400 mph at

210,000 feet five minutes after having crossed the California coastline. Nineteen seconds later, at 7:58:38 central time, they got the first sign of something being a little out of the ordinary: it was a cockpit indication of low tire pressures on the left main landing gear. This was not quite a trivial matter. A blown or deflated main tire would pose serious risks during the rollout after landing, including loss of lateral control and the possibility that the nose would slam down, conceivably leading to a catastrophic breakup on the ground. These scenarios were known, and had been simulated and debated in the inner world of NASA, leading some to believe that the best of the imperfect choices in such a case might be for the crew to bail out—an alternative available only below 30,000 feet and 220 mph of dynamic airspeed.

Nonetheless, for *Columbia*'s pilots it was reasonable to assume for the moment that the indication of low pressure was due to a problem with the sensors rather than with the tires themselves, and that the teams of Mission Control engineers at NASA's Johnson Space Center, in Houston, would be able to sort through the mass of automatically transmitted data—the so-called telemetry, which was far more complete than what was available in the cockpit—and to draw the correct conclusion. The reverse side of failures in a machine as complex as the shuttle is that most of them can be worked around, or turn out to be small. In other words, there was no reason for alarm. After a short delay the *Columbia*'s commander, Rick Husband, calmly radioed to Mission Control, "And, ah, Houston …" Sheathed in hot atmospheric gases, the shuttle was slowing through 13,100 mph at 205,000 feet.

Houston did not clearly hear the call.

With the scheduled touchdown now only about fifteen minutes ahead, it was a busy time at Mission Control. Weather reports were coming in from the landing site at the Kennedy Space Center, in Florida. Radar tracking of the shuttle, like the final accurate ground-based navigation, had not yet begun. Sitting at their specialized positions, and monitoring the numbers displayed on the consoles, a few of the flight controllers had begun to sense, just barely, that something was going seriously wrong. The worry was not quite coherent yet. One of the controllers later told me that it amounted to an inexplicable bad feeling in his gut. But it was undeniable nonetheless. For the previous few minutes, since about the time when the shuttle had passed from California to Nevada, Jeff Kling, an engineer who was working the mechanical-systems position known as MMACS (pronounced *Macs*), had witnessed a swarm of erratic indications and sensor failures. The pattern was disconcerting because of the lack of common circuitry that could easily explain the pattern of such failures—a single box that could be blamed.

Kling had been bantering good-naturedly on an intercom with one of his team, a technician sitting in one of the adjoining back rooms and monitoring the telemetry, when the technician noted a strange failure of temperature transducers on a hydraulic return line. The technician said, "We've had some hydraulic 'ducers go off-scale low."

Kling had seen the same indications. He said, "Well, I guess!"

The technician said, "What in the world?"

Kling said, "This is not funny. On the left side."

The technician confirmed, "On the left side …"

Now Kling got onto the main control-room intercom to the lead controller on duty, known as the flight director, a man named Leroy Cain. In the jargon-laced language of the control room Kling said, "Flight, Macs."

Cain said, "Go ahead, Macs."

"FYI, I've just lost four separate temperature transducers on the left side of the vehicle, hydraulic return temperatures. Two of them on system one, and one in each of systems two and three."

Cain said, "Four hyd return temps?"

Kling answered, "To the left outboard and left inboard elevon."

"Okay, is there anything common to them? DSC or MDM or anything? I mean, you're telling me you lost them all at exactly the same time?"

"No, not exactly. They were within probably four or five seconds of each other."

Cain struggled to assess the meaning. "Okay, where are those … where is that instrumentation located?"

Kling continued to hear from his back-room team. He said, "All four of them are located in the aft part of the left wing, right in front of the elevons … elevon *actuators*. And there is no commonality."

Cain repeated, "No commonality."

But all the failing instruments were in the left wing. The possible significance of this was not lost on Cain: during the launch a piece of solid foam had broken off from the shuttle's external fuel tank, and at high speed had smashed into the left wing; after minimal consideration the shuttle program managers (who stood above Mission Control in the NASA hierarchy) had dismissed the incident as essentially unthreatening. Like almost everyone else at NASA, Cain had taken the managers at their word—and he still did. Nonetheless, the strange cluster of left-wing failures was an ominous development. Kling had more-specific reasons for concern. In a wonkish, engineering way he had discussed with his team the telemetry they might observe if a hole allowed hot gases into the wing during re-entry, and had come up with a profile eerily close to what was happening now. Still, he maintained the expected detachment.

Cain continued to worry the problem. He asked for reassurance from his "guidance, navigation, and control" man, Mike Sarafin. "Everything look good to you, control and rates and everything is nominal, right?"

Sarafin said, "Control's been stable through the rolls that we've done so far, Flight. We have good trims. I don't see anything out of the ordinary."

Cain directed his attention back to Kling: "All other indications for your hydraulic systems indications are good?"

"They're all good. We've had good quantities all the way across."

Cain said, "And the other temps are normal?"

"The other temps are normal, yes, sir." He meant only those that the telemetry allowed him to see.

Cain said, "And when you say you lost these, are you saying they went to zero ..."

"All four of them are off-scale low."

"... or off-scale low?"

Kling said, "And they were all staggered. They were, like I said, within several seconds of each other."

Cain said, "Okay."

But it wasn't okay. Within seconds the *Columbia* had crossed into Texas and the left-tire-pressure indications were dropping, as observed also by the cockpit crew. Kling's informal model of catastrophe had predicted just such indications, whether from blown tires or wire breaks. The end was now coming very fast.

Kling said, "Flight, Macs."

Cain said, "Go."

"We just lost tire pressure on the left outboard and left inboard, both tires."

Cain said, "Copy."

At that moment, twenty-three seconds after 7:59 local time, the Mission Control consoles stopped receiving telemetry updates, for reasons unknown. The astronaut sitting beside Cain, and serving as the Mission Control communicator, radioed, "And *Columbia*, Houston, we see your tire-pressure messages, and we did not copy your last call."

At the same time, on the control-room intercom, Cain was talking again to Kling. He said, "Is it instrumentation, Macs? Gotta be."

Kling said, "Flight, Macs, those are also off-scale low."

From the speeding shuttle Rick Husband—Air Force test pilot, religious, good family man, always wanted to be an astronaut—began to answer the communicator. He said, "Roger, ah," and was cut off on a word that began with "buh ..."

It turned out to be the *Columbia*'s last voice transmission. Brief communication breaks, however, are not abnormal during re-entries, and this one raised no immediate concern in Houston.

People on the ground in Dallas suddenly knew more than the flight controllers in Houston. Four seconds after eight they saw a large piece leave the orbiter and fall away. The shuttle was starting to come apart. It continued intermittently to send telemetry, which though not immediately displayed at Mission Control was captured by NASA computers and later discovered; the story it told was that multiple systems were failing. In quick succession two additional chunks fell off.

Down in the control room Cain said, "And there's no commonality between all these tire-pressure instrumentations and the hydraulic return instrumentations?"

High in the sky near Dallas the *Columbia*'s main body began to break up. It crackled and boomed, and made a loud rumble.

Kling said, "No, sir, there's not. We've also lost the nose-gear down talkback, and right-main-gear down talkback."

"Nose-gear and right-main-gear down talkbacks?"

"Yes, sir."

At Fort Hood, Texas, two Dutch military pilots who were training in an Apache attack helicopter locked on to the breakup with their optics and videotaped three bright objects—the main rocket engines—flying eastward in formation, among other, smaller pieces and their contrails.

Referring to the loss of communications, one minute after the main-body breakup, Laura Hoppe, the flight controller responsible for the communications systems, said to Cain, "I didn't expect, uh, this bad of a hit on comm."

Cain asked another controller about a planned switchover to a ground-based radio ahead, "How far are we from UHF? Is that two-minute clock good?"

Kling, also, was hanging on to hope. He said, "Flight, Macs."

Cain said, "Macs?"

Kling said, "On the tire pressures, we did see them go erratic for a little bit before they went away, so I do believe it's instrumentation."

"Okay."

At about that time the debris began to hit the ground. It fell in thousands of pieces along a swath ten miles wide and 300 miles long, across East Texas and into Louisiana. There were many stories later. Some of the debris whistled down through the leaves of trees and smacked into a pond where a man was fishing. Another piece went right through a backyard trampoline, evoking a mother's lament: "Those damned kids ..." Still another piece hit the window of a moving car, startling the driver. The heaviest parts flew the farthest. An 800-pound piece of engine hit the ground in Fort Polk, Louisiana, doing 1,400 mph. A 600-pound piece landed nearby. Thousands of people began to call in, swamping the 911 dispatchers with reports of sonic booms and metal falling out of the sky. No one, however, was hit. This would be surprising were it not for the fact, so visible from above, that the world is still a sparsely populated place.

In Houston the controllers maintained discipline, and continued preparing for the landing, even as they received word that the Merritt Island radar, in Florida, which should by now have started tracking the inbound craft, was picking up only false targets. Shuttles arrive on time or they don't arrive at all. But, repeatedly, the communicator radioed, "*Columbia*, Houston, UHF comm check," as if he might still hear a reply. Then, at thirteen minutes past the hour, precisely when the *Columbia* should have been passing overhead the runway before circling down for a landing at the Kennedy Space Center, a phone call came in from an off-duty controller who had just seen a video broadcast by a Dallas television station of multiple contrails in the sky. When Cain heard the news, he paused, and then put the contingency plan into effect. To the ground-control officer he said, "GC, Flight."

"Flight, GC."

"Lock the doors."

"Copy."

The controllers were stunned, but lacked the time to contemplate the horror of what had just happened. Under Cain's direction they set about collecting numbers, writing notes, and closing out their logs, for the investigation that was certain to follow. The mood in the room was somber and focused. Only the most basic facts were known: the *Columbia* had broken up at 200,000 feet doing 12,738 mph, and the crew could not possibly have survived. Ron Dittemore, the shuttle program manager, would be talking to reporters later that day, and he needed numbers and information. At some point sandwiches were brought in and consumed. Like the priests who harvest faith at the bedsides of the dying, grief counselors showed up too, but they were not much used.

Cain insisted on control-room discipline. He said, "No phone calls off site outside of this room. Our discussions are on these loops—the recorded DVIS loops only. No data, no phone calls, no transmissions anywhere, into or out."

Later this was taken by some critics to be a typical NASA reaction—insular, furtive, overcontrolling. And it may indeed have reflected certain aspects of what had become of the agency's culture. But it was also, more simply, a rule-book procedure meant to stabilize and preserve the crucial last data. The room was being frozen as a crime scene might be. Somewhere inside NASA something had obviously gone very wrong—and it made sense to start looking for the evidence here and now.

Less than an hour later, at 10:00 A.M. eastern time, a retired four-star admiral named Hal Gehman met his brother at a lawyer's office in Williamsburg, Virginia. At the age of sixty, Gehman was a tall, slim, silver-haired man with an unlined face and soft eyes. Dressed in civilian clothes, standing straight but not stiffly so, he had an accessible, unassuming manner that contrasted with the rank and power he had achieved. After an inauspicious start as a mediocre engineering student in the Penn State Naval ROTC program ("Top four fifths of the class," he liked to say), he had skippered a patrol boat through the thick of the Vietnam War and gone on to become an experienced sea captain, the commander of a carrier battle group, vice-chief of the Navy, and finally NATO Atlantic commander and head of the U.S. Joint Forces Command. Upon his retirement, in 2000, from the sixth-ranked position in the U.S. military, he had given all that up with apparent ease. He had enjoyed a good career in the Navy, but he enjoyed his civilian life now too. He was a rare sort of man—startlingly intelligent beneath his guileless exterior, personally satisfied, and quite genuinely untroubled. He lived in Norfolk in a pleasant house that he had recently remodeled; he loved his wife, his grown children, his mother and father, and all his siblings. He had an old Volkswagen bug convertible, robin's-egg blue, that he had bought from another admiral. He had a modest thirty-four-foot sloop, which he enjoyed sailing in the Chesapeake, though its sails were worn out and he wanted to replace its icebox with a twelve-volt refrigeration unit. He was a patriot, of course, but not a reactionary. He called himself a fiscal conservative and a social moderate. His life as he described it was the product of convention. It was also the product of a strict personal code. He chose not to work with any company doing business with the Department of Defense. He liked power, but understood its limitations. He did not care to be famous or rich. He represented the American establishment at its best.

In the lawyer's office in Williamsburg his brother told him that the *Columbia* had been lost. Gehman had driven there with his radio off and so he had not heard. He asked a few questions, and absorbed the information without much reaction. He did not follow the space program and, like most Americans, had not been aware that a mission was under way. He spent an hour with the lawyer on routine family business. When he emerged, he saw that messages had been left on his cell phone, but because the coverage was poor, he could not retrieve them; only later, while driving home on the interstate, was he finally able to connect. To his surprise, among mundane messages he found an urgent request to call the deputy administrator of NASA, a man he had not heard of before, named Fred Gregory. Like a good American, Gehman made the call while speeding down the highway. Gregory, a former shuttle commander, said, "Have you heard the news?"

Gehman said, "Only secondhand."

Gregory filled him in on what little was known, and explained that part of NASA's contingency plan, instituted after the *Challenger* disaster of 1986, was the activation of a standing "interagency" investigation board. By original design the board consisted of seven high-ranking civilian and military officials who were pre-selected mechanically on the basis of job titles—the institutional slots that they filled. For the *Columbia*, the names were now known: the board would consist of three Air Force generals, John Barry, Kenneth Hess, and Duane Deal; a Navy admiral, Stephen Turcotte; a NASA research director, G. Scott Hubbard; and two senior civil-aviation officials, James Hallock and Steven Wallace. Though only two of these men knew much about NASA or the space shuttle, in various ways each of them was familiar with the complexities of large-scale, high-risk activities.

Most of them also had strong personalities. To be effective they would require even stronger management. Gregory said that it was NASA's administrator, Sean O'Keefe, who wanted Gehman to come in as chairman to lead the work. Gehman was not immune to the compliment, but he was cautious. He had met O'Keefe briefly years before, but did not know him. He wanted to make sure he wasn't being suckered into a NASA sideshow.

O'Keefe was an able member of Washington's revolving-door caste, a former congressional staffer and budget specialist—and a longtime protégé of Vice President Dick Cheney—who through the force of his competence and Republican connections had briefly landed the position of Secretary of the Navy in the early 1990s. He had suffered academic banishment through the Clinton era, but under the current administration had re-emerged as a deputy at the Office of Management and Budget, where he had been assigned to tackle the difficult problem of NASA's cost overruns and lack of delivery, particularly in the Space Station program. It is hard to know what he thought when he was handed the treacherous position of NASA administrator. Inside Washington, NASA's reputation had sunk so low that some of O'Keefe's former congressional colleagues snickered that Cheney was trying to kill his own man off. But O'Keefe was not a space crusader, as some earlier NASA administrators had been, and he was not about to pick up the fallen banners of the visionaries and try to lead the way forward; he was a tough, level-headed money man, grounded in the realities of Washington, D.C., and sent in on a mission to bring discipline to NASA's budget and performance before moving on. NASA's true believers called him a carpetbagger and resented the schedule pressures that he brought to bear, but in fairness he was a professional manager, and NASA needed one.

O'Keefe had been at NASA for just over a year when the *Columbia* self-destructed. He was in Florida standing at the landing site beside one of his deputies, a former shuttle commander named William Readdy. At 9:05 eastern time, ten minutes before the scheduled landing, Readdy got word that communications with the shuttle, which had been lost, had not been re-established; O'Keefe noticed that Readdy's face went blank. At 9:10 Readdy opened a book to check a time sequence. He said, "We should have heard the sonic booms by now. There's something really wrong." By 9:29 O'Keefe had activated the full-blown contingency plan. When word got to the White House, the executive staff ducked quickly into defensive positions: President Bush would grieve alongside the families and say the right things about carrying on, but rather than involving himself by appointing an independent presidential commission, as Ronald Reagan had in response to the *Challenger* accident, he would keep his distance by expressing faith in NASA's ability to find the cause. In other words, this baby was going to be dropped squarely onto O'Keefe's lap. The White House approved Gehman's appointment to lead what would essentially be NASA's investigation—but O'Keefe could expect little further communication. There was a chance that the President would not even want to receive the final report directly but would ask that it be deposited more discreetly in the White House in-box. He had problems bigger than space on his mind.

Nonetheless, that morning in his car Gehman realized that even with a lukewarm White House endorsement, the position that NASA was offering, if handled correctly, would allow for a significant inquiry into the accident. Gregory made it clear that Gehman would have the full support of NASA's engineers and technical resources in unraveling the physical mysteries of the accident—what actually had happened to the *Columbia* out there in its sheath of fire at 200,000 feet. Moreover, Gehman was confident that if the investigation had to go further, into *why* this accident had occurred, he had the experience necessary to sort through the human complexities of NASA and emerge with useful answers that might result in reform. This may have been overconfident of him, and to some extent utopian, but it was not entirely blind: he had been through big investigations before, most recently two years earlier, just after leaving the Navy, when he and a retired Army general named William Crouch had led an inquiry into the loss of seventeen sailors aboard the USS *Cole*, the destroyer that was attacked and nearly sunk by suicide terrorists in Yemen in October of 2000. Their report found fundamental errors in the functioning of the military command structure, and issued recommendations (largely classified) that are in effect today. The success of the *Cole* investigation was one of the arguments that Gregory used on him now. Gehman did not disagree, but he wanted to be very clear. He said, "I know you've got a piece of paper in front of you. Does it say that I'm not an aviator?"

Gregory said, "We don't need an aviator here. We need an investigator."

And so, driving down the highway to Norfolk, Gehman accepted the job. When he got home, he told his wife that he was a federal employee again and that there wouldn't be much sailing in the spring. That afternoon and evening, as the faxes and phone calls came in, he began to exercise

Attacks against the accident investigation began on the second day, and by midweek they showed no signs of easing. Congress in particular was thundering that Admiral Gehman was a captive investigator, and that his report would be a whitewash.

control of the process, if only in his own mind, concluding that the board's charter as originally written by NASA would have to be strengthened and expanded, and that its name should immediately be changed from the absurd International Space Station and Space Shuttle Mishap Interagency Investigations Board (the ISSSSMIIB) to the more workable *Columbia* Accident Investigation Board, or CAIB, which could be pronounced in one syllable, as *Cabe*.

NASA initially did not resist any of his suggestions. Gregory advised Gehman to head to Barksdale Air Force Base, in Shreveport, Louisiana, where the wreckage was being collected. As Gehman began to explore airline connections, word came that a NASA executive jet, a Gulfstream, would be dispatched to carry him, along with several other board members, directly to Barksdale. The jet arrived in Norfolk on Sunday afternoon, the day after the accident. One of the members already aboard was Steven Wallace, the head of accident investigations for the FAA. Wallace is a second-generation pilot, an athletic, tightly wound man with wide experience in government and a skeptical view of the powerful. He later told me that when Gehman got on the airplane, he was dressed in a business suit, and that, having introduced himself, he explained that they might run into the press, and if they did, he would handle things. This raised some questions about Gehman's motivations (and indeed Gehman turned out to enjoy the limelight), but as Wallace soon discovered, grandstanding was not what Gehman was about. As the Gulfstream proceeded toward Louisiana, Gehman rolled up his sleeves and, sitting at the table in the back of the airplane, began to ask for the thoughts and perspectives of the board members there—not about what might have happened to the *Columbia* but about how best to find out. It was the start of what would become an intense seven-month relationship. It was obvious that Gehman was truly listening to the ideas, and that he was capable of integrating them quickly and productively into his own thoughts. By the end of the flight even Wallace was growing impressed.

But Gehman was in some ways also naive, formed as he had been by investigative experience within the military, in which much of the work proceeds behind closed doors, and conflict of interest is not a big concern. The *Columbia* investigation, he discovered, was going to be a very different thing. Attacks against the CAIB began on the second day, and by midweek, as the board moved from Shreveport to Houston to set up shop, they showed no signs of easing. Congress in particular was thundering that Gehman was a captive investigator, that his report would be a whitewash, and that the White House should replace the CAIB with a *Challenger*-style presidential commission. This came as a surprise to Gehman, who had assumed that he could just go about his business but who now realized that he would have to accommodate these concerns if the final report was to have any credibility at all. Later he said to me, "I didn't go in thinking about it, but as I began to hear the *independence* thing—'You can't have a panel appointed by NASA investigating itself!'—I realized I'd better deal with Congress." He did this at first mainly by listening on the phone. "They told me what I had to do to build my credibility. I didn't invent it—they *told* me. They also said, 'We hate NASA. We don't trust them. Their culture is no good. And their cost accounting is no good.' And I said, 'Okay.'"

More than that, Gehman came to realize that it was the elected representatives in Congress—and neither O'Keefe nor NASA—who constituted the CAIB's real constituency, and that their concerns were legitimate. As a result of this, along with a growing understanding of the depth and complexity of the work at hand, he forced through a series of changes, establishing a congressional-liaison office, gaining an independent budget (ultimately of about $20 million), wresting the report from O'Keefe's control, rewriting the stated mission to include the finding of "root causes and circumstances," and hiring an additional five board members, all civilians of unimpeachable reputation: the retired Electric Boat boss Roger Tetrault, the former astronaut Sally Ride, the Nobel-laureate physicist Douglas Osheroff, the aerodynamicist and former Air Force Secretary Sheila Widnall, and the historian and space-policy expert John Logsdon. Afterward, the loudest criticism faded away. Still, Gehman's political judgment was not perfect. He allowed the new civilian members to be brought on through the NASA payroll (at prorated annual salaries of $134,000)—a strange lapse under the circumstances, and one that led to superficial accusations that the CAIB remained captive. *The Orlando Sentinel* ran a story about the lack of public access to the CAIB's interviews under the ambiguous headline "BOARD PAID TO ENSURE SECRECY." The idea evoked laughter among some of the investigators, who knew the inquiry's direction. But unnecessary damage was done.

Equally unnecessary was Gehman's habit of referring to O'Keefe as "Sean," a clubbish mannerism that led people to conclude, erroneously, that the two men were friends. In fact their relationship was strained, if polite. Gehman told me that he had never asked for the full story behind his selection on the morning of the accident—maybe because it would have been impossible to know the unvarnished truth. Certainly, though, O'Keefe had had little opportunity to contemplate his choice. By quick view Gehman was a steady hand and a good establishment man who could lend the gravitas of his four stars to this occasion; he was also, of course, one of the men behind the *Cole* investigation. O'Keefe later told me that he had read the *Cole* report during his stint as a professor, but that he remembered it best as the subject of a case study presented by one of his academic colleagues as an example of a narrowly focused investigation that, correctly, had not widened beyond its original mandate. This was true,

On the ground level, where the detailed analysis was being done, there was active resistance to the investigation at first, with some NASA engineers openly refusing to cooperate, or to allow access to technical documents. Gehman had to intervene.

but a poor predictor of Gehman as a man. His *Cole* investigation had not widened (for instance, into assigning individual blame) for the simple reason that other investigations, by the Navy and the FBI, were already covering that ground. Instead, Gehman and Crouch had gone deep, and relentlessly so. The result was a document that bluntly questioned current American dogma, identified arrogance in the command structure, and critiqued U.S. military assumptions about the terrorist threat. The tone was frank. For example, while expressing understanding of the diplomatic utility of labeling terrorists as "criminals," the report warned against buying into that language, or into the parallel idea that these terrorists were "cowards." When, later, I expressed my surprise at his freedom of expression, Gehman did not deny that people have recently been decried as traitors for less. But freedom of expression was clearly his habit: he spoke to me just as openly about the failures of his cherished Navy, of Congress, and increasingly of NASA.

When I mentioned this character trait to one of the new board members, Sheila Widnall, she laughed and said she'd seen it before inside the Pentagon, and that people just didn't understand the highest level of the U.S. military. These officers are indeed the establishment, she said, but they are so convinced of the greatness of the American construct that they will willingly tear at its components in the belief that its failures can be squarely addressed. Almost all of the current generation of senior leaders have also been through the soul-searching that followed the defeat in Vietnam.

O'Keefe had his own understanding of the establishment, and it was probably sophisticated, but he clearly did not anticipate Gehman's rebellion. By the end of the second week, as Gehman established an independent relationship with Congress and began to break through the boundaries initially drawn by NASA, it became clear that O'Keefe was losing control. He maintained a brave front of wanting a thorough inquiry, but it was said that privately he was angry. The tensions came to the surface toward the end of February, at about the same time that Gehman insisted, over O'Keefe's resistance, that the full report ultimately be made available to the public. The CAIB was expanding to a staff of about 120 people, many of them professional accident investigators and technical experts who could support the core board members. They were working seven days a week out of temporary office space in the sprawling wasteland of South Houston, just off the property of the Johnson Space Center. One morning several of the board members came in to see Gehman, and warned him that the CAIB was headed for a "shipwreck."

Gehman knew what they meant. In the days following the accident O'Keefe had established an internal Mishap Investigation Team, whose job was to work closely with the CAIB, essentially as staff, and whose members—bizarrely—included some of the decision-makers most closely involved with the *Columbia*'s final flight. The team was led by Linda Ham, a razor-sharp manager in the shuttle program, whose actions during the flight would eventually be singled out as an egregious example of NASA's failings. Gehman did not know that yet, but it dawned on him that Ham was in a position to filter the inbound NASA reports, and he remembered a recent three-hour briefing that she had run with an iron hand, allowing little room for spontaneous exploration. He realized that she and the others would have to leave the CAIB, and he wrote a careful letter to O'Keefe in Washington, requesting their immediate removal. It is a measure of the insularity at the Johnson Space Center that NASA did not gracefully acquiesce. Ham and another manager, Ralph Roe, in particular reacted badly. In Gehman's office, alternately in anger and tears, they refused to leave, accusing Gehman of impugning their integrity and asking him how they were supposed to explain their dismissal to others. Gehman suggested to them what Congress had insisted to him—that people simply cannot investigate themselves. Civics 101. Once stated, it seems like an obvious principle.

O'Keefe had a master's degree in public administration, but he disagreed. It was odd. He had not been with the agency long enough to be infected by its insularity, and as he later promised Congress, he was willing—no, *eager*—to identify and punish any of his NASA subordinates who could be held responsible for the accident. Nonetheless, he decided to defy Gehman, and he announced that his people would remain in place. It was an ill-considered move. Gehman simply went public with his letter, posting it on the CAIB Web site. Gehman understood that O'Keefe felt betrayed—"stabbed in the back" was the word going around—but NASA had left him no choice. O'Keefe surrendered. Ham and the others were reassigned, and the Mishap Investigation Team was disbanded, replaced by NASA staffers who had not been involved in the *Columbia*'s flight and would be more likely to cooperate with the CAIB's investigators. The board was never able to overcome completely the whiff of collusion that had accompanied its birth, but Gehman had won a significant fight, even if it meant that he and "Sean" would not be friends.

The space shuttle is the most audacious flying machine ever built, an engineering fantasy made real. Before each flight it stands vertically on the launch pad at the Kennedy Space Center, as the core component of a rocket assembly 184 feet tall. The shuttle itself, which is also known as the orbiter, is a winged vehicle roughly the size of a DC-9, with three main rocket engines in the tail, a large unpressurized cargo bay in the midsection, and a cramped two-level crew compartment in the nose. It is attached to a huge external tank containing liquid fuel for the three main engines. That tank in turn is attached to two solid-fuel rockets, known as boosters, which flank the assembly and bear its full weight on the launch pad. Just before the launch, the weight is about 4.5 million pounds, 90 percent of which is fuel. It is a dramatic time, ripe with anticipation; the shuttle vents vapors like a breathing thing; the ground crews pull away until finally no one is left; the air seems unusually quiet.

Typically there are seven astronauts aboard. Four of them sit in the cockpit, and three on the lower level, in the living quarters known as the mid-deck. Because of the shuttle's vertical position, their seats are effectively rotated backward 90 degrees, so they are sitting on their backs, feeling their own weight in a way that tends to emphasize gravity's pull. At the front of the cockpit, positioned closer to the instrument panel than is necessary for the typical astronaut's six-foot frame, the commander and the pilot can look straight ahead into space. They are highly trained. They know exactly what they are getting into. Sometimes they have waited years for this moment to arrive.

The launch window may be just a few minutes wide. It is ruled by orbital mechanics, and defined by the track and position of the destination—usually now the unfinished International Space Station. Six seconds before liftoff the three main engines are ignited and throttled up to 100 percent power, producing more than a million pounds of thrust. The shuttle responds with what is known as "the twang," swaying several feet in the direction of the external tank and then swaying back. This is felt in the cockpit. The noise inside is not very loud. If the computers show that the main engines are operating correctly, the solid rocket boosters ignite. The boosters are ferocious devices—the same sort of monsters that upon failure blew the *Challenger* apart. Each of them produces three million pounds of thrust. Once ignited, they cannot be shut off or throttled back. The shuttle lifts off. It accelerates fast enough to clear the launch tower doing about 100 mph, though it is so large that seen from the outside, it appears to be climbing slowly.

The flying is done entirely by autopilot unless something goes wrong. Within seconds the assembly rotates and aims on course, tilting slightly off the vertical and rolling so that the orbiter is inverted beneath the external tank. Although the vibrations are heavy enough to blur the instruments, the acceleration amounts to only about 2.5 Gs—a mild sensation of heaviness pressing the astronauts back into their seats. After about forty seconds the shuttle accelerates through Mach 1, 760 mph, at about 17,000 feet, climbing nearly straight up. Eighty seconds later, with the shuttle doing about 3,400 mph and approaching 150,000 feet, the crew can feel the thrust from the solid rocket boosters begin to tail off. Just afterward, with a bright flash and a loud explosion heard inside the orbiter, the rocket boosters separate from the main tank; they continue to travel upward on a ballistic path to 220,000 feet before falling back and parachuting into the sea. Now powered by the main engines alone, the ride turns smooth, and the forces settle down to about 1 G.

One pilot described the sensations to me on the simplest level. He said, "First it's like, 'Hey, this is a rough ride!' and then, 'Hey, I'm on an electric train!' and then, 'Hey, this train's starting to go pretty darned fast!'" Speed is the ultimate goal of the launch sequence. Having climbed steeply into ultra-thin air, the shuttle gently pitches over until it is flying nearly parallel to Earth, inverted under the external tank, and thrusting at full power. Six minutes after launch, at about 356,000 feet, the shuttle is doing around 9,200 mph, which is fast, but only about half the speed required to sustain an orbit. It therefore begins a shallow dive, during which it gains speed at the rate of 1,000 mph every twenty seconds—an acceleration so fast that it presses the shuttle against its 3 G limit, and the engines have to be briefly throttled back. At 10,300 mph the shuttle rolls to a head-up position. Passing through 15,000 mph, it begins to climb again, still accelerating at 3 Gs, until, seconds later, in the near vacuum of space, it achieves orbital velocity, or 17,500 mph. The plumes from the main engines wrap forward and dance across the cockpit windows, making light at night like that of Saint Elmo's fire. Only eight and a half minutes have passed since the launch. The main engines are extinguished, and the external tank is jettisoned. The shuttle is in orbit. After further maneuvering it assumes its standard attitude, flying inverted in relation to Earth and tail first as it proceeds around the globe.

For the astronauts aboard, the uphill flight would amount to little more than an interesting ride were it not for the possibility of failures. That possibility, however, is

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very real, and as a result the launch is a critical and complicated operation, demanding close teamwork, tight coordination with Mission Control, and above all extreme concentration—a quality often confused with coolness under fire. I was given a taste of this by an active shuttle commander named Michael Bloomfield, who had me strap in beside him in NASA's full-motion simulator in Houston, and take a realistic run from the launch pad into space. Bloomfield is a former Air Force test pilot who has flown three shuttle missions. He had been assigned to assist the CAIB, and had been watching the investigation with mixed emotions—hopeful that some effects might be positive, but concerned as well that the inquiry might veer into formalism without sufficiently taking into account the radical nature of space flight, or the basic truth that every layer of procedure and equipment comes at a cost, often unpredictable. Bloomfield called this the "risk versus risk" tradeoff, and made it real not by defending NASA against specific criticisms but by immersing me, a pilot myself, in the challenges of normal operations.

Much of what he showed me was of the what-if variety, the essence not only of simulator work but also of the crew's real-world thinking. For instance, during the launch, as the shuttle rockets upward on autopilot, the pilots and flight controllers pass through a succession of mental gates, related to various combinations of main-engine failures, at various altitudes and speeds. The options and resulting maneuvers are complicated, ranging from a quick return to the launch site, to a series of tight arrivals at select runways up the eastern seaboard, to transatlantic glides, and finally even an "abort into orbit"—an escape route used by a *Challenger* crew in 1985 after a single main-engine failure. Such failures allow little time to make the right decision. As Bloomfield and I climbed away from Earth, tilted onto our backs, he occasionally asked the operators to freeze the simulation so that he could unfold his thoughts to me. Though the choices were clear, the relative risks were rarely so obvious. It was a deep view into the most intense sort of flying.

After we arrived in space, we continued to talk. One of the gates for engine failure during the climb to the Space Station stands at Mach 21.8 (14,900 mph), the last point allowed for a "high energy" arrival into Gander, Newfoundland, and the start of the emergency transatlantic track for Shannon, Ireland. An abort at that point provides no easy solution. The problem with Gander is how to bleed off excess energy before the landing (Bloomfield called this "a take-all-your-brain-cells type of flying"), whereas the problem with Shannon is just the opposite—how to stretch the glide. Bloomfield told me that immediately before his last space flight, in the spring of 2002, his crew and a Mission Control team had gone through a full-dress simulation during which the orbiter had lost all three engines by Mach 21.7 (less than 100 mph from the decision speed). Confident in his ability to fly the more difficult Canadian arrival, Bloomfield, from the cockpit of the simulator, radioed, "We're going high-energy into Gander."

Mission Control answered, "Negative," and called for Shannon instead.

Bloomfield looked over at his right-seat pilot and said, "I think we oughta go to Gander. What do you think?"

"Yeah."

Bloomfield radioed back: "No, we think we oughta go to Gander."

Mission Control was emphatic. "*Negative*. We see you having enough energy to make Shannon."

As commander, Bloomfield had formal authority for the decision, but Mission Control, with its expert teams and wealth of data, was expressing a strong opinion, so he acquiesced. Acquiescence is standard in such cases, and usually it works out for the best. Bloomfield had enormous respect for the expertise and competence of Mission Control. He was also well aware of errors he had made in the past, despite superior advice or instructions from the flight controllers. This time, however, it turned out that two of the flight controllers had not communicated correctly with each other, and that the judgment of Mission Control therefore was wrong. Lacking the energy to reach Shannon, the simulator went into the ocean well short of the airport. The incident caused a disturbance inside the Johnson Space Center, particularly because of the long-standing struggle for the possession of data (and ultimately control) between the pilots in flight and the engineers at their consoles. Nevertheless, the two groups worked together, hammered out the problems, and the next day flew the same simulator profile successfully. But that was not the point of Bloomfield's story. Rather, it was that these calls are hard to make, and that mistakes—whether his or the controllers'—may become obvious only after it is too late.

For all its realism, the simulator cannot duplicate the gravity load of the climb, or the lack of it at the top. The transition to weightlessness is abrupt, and all the more dramatic because it occurs at the end of the 3 G acceleration: when the main engines cut off, the crew gets the impression of going over an edge and suddenly dropping into a free fall. That impression is completely accurate. In fact the term zero gravity (0 G), which is loosely used to describe the orbital environment, refers to physical acceleration, and does not mean that Earth's gravitational pull has somehow gone away. Far from it: the diminution of gravitational pull that comes with distance is small at these low-orbit altitudes (perhaps 200 miles above the surface), and the shuttle is indeed now falling—about like a stone dropped off a cliff. The fall does not, of course, diminish the shuttle's mass (if it bumps the Space Station, it does so with tremendous force), but it does make the vehicle and everything inside it very nearly weightless. The orbital part of the trick is that though the shuttle is dropping like a stone, it is also progressing across Earth's surface so fast (17,500 mph) that its path matches (roughly) the curvature of the globe. In other words, as it plummets toward the ground, the ground keeps getting out of its way. Like the orbits of all other satellites, and of the Space Station, and of the Moon as well, its flight is nothing but an unrestricted free fall around and around the world.

To help the astronauts adapt to weightlessness, the quarters are designed with a conventional floor-down orientation. This isn't quite so obvious as it might seem, since the shuttle flies inverted in orbit. "Down" therefore is toward outer space—and the view from the cockpit windows just happens to be of Earth sliding by from behind and overhead. The crews are encouraged to live and work with their heads "up" nonetheless. It is even recommended that they use the ladder while passing through the hatch between the two levels, and that they "descend" from the cockpit to the mid-deck feet first. Those sorts of cautions rarely prevail against the temptations of weightlessness. After Bloomfield's last flight one of his crew commented that they had all been swimming around "like eels in a can." Or like superhumans, as the case may be. It's true that there are frustrations: if you try to throw a switch without first anchoring your body, the switch will throw you. On the other hand, once you are anchored, you can shift multi-ton masses with your fingertips. You can also fly without wings, perform unlimited flips, or simply float for a while, resting in midair. Weightlessness is bad for the bones, but good for the soul. I asked Bloomfield how it had felt to experience gravity again. He said he remembered the first time, after coming to a stop on the runway in Florida, when he picked up a small plastic checklist in the cockpit and thought, "Man, this is so *heavy*!" He looked at me and said, "Gravity sucks."

And orbital flight clearly does not. The ride is smooth. When the cabin ventilation is turned off, as it must be once a day to exchange the carbon dioxide scrubbers, the silence is absolute. The smell inside the shuttle is distinctly metallic, unless someone has just come in from a spacewalk, after which the quarters are permeated for a while with "the smell of space," a pungent burned odor that some compare to that of seared meat, and that Bloomfield describes as closer to the smell of a torch on steel. The dominant sensation, other than weightlessness, is of the speed across the ground. Bloomfield said, "From California to New York in ten minutes, around the world once in ninety minutes—I mean, we're *moving*." He told me that he took to loitering in the cockpit at the end of the workdays, just for the view. By floating forward above the instrument panel and wrapping his legs around one of the pilot seats, he could position his face so close to the front windshield that the structure of the shuttle would seem to disappear.

The view from there was etched into his memory as a continuous loop. In brief, he said: It's night and you're coming up on California, with that clearly defined coastline, and you can see all the lights all the way from Tijuana to San Francisco, and then it's behind you, and you spot Las Vegas and its neon-lit Strip, which you barely have time to identify before you move across the Rockies, with their helter-skelter of towns, and then across the Plains, with its monotony of look-alike wheels and spokes of light, until you come to Chicago and its lakefront, from which point you can see past Detroit and Cleveland all the way to New York. These are big cities, you think. And because you grew up on a farm in Michigan, played football there in high school, and still know it like a home, you pick out Ann Arbor and Flint, and the place where I-75 joins U.S. Highway 23, and you get down to within a couple of miles of your house before zip, you're gone. Zip goes Cleveland, and zip New York, and then you're out over the Atlantic beyond Maine, looking back down the eastern seaboard all the way past Washington, D.C. Ten minutes later you come up on Europe, and you hardly have time to think that London is a sprawl, France is an orderly display, the Alps are the Rockies again, and Italy is indeed a boot. Over Sicily you peer down into Etna's crater, into the glow of molten rock on Earth's inside, and then you are crossing Africa, where the few lights you see are not yellow but orange, like open flames. Past the Equator and beyond Madagascar you come to a zone of gray between the blackness of the night and the brigh of the day. At the center of that zone is a narrow pink s. which is the atmospheric dawn as seen from above. Daylight is for the oceans—first the Indian and then the Pacific, which is very, very large. Atolls appear with coral reefs and turquoise lagoons, but mostly what you see is cloud and open water. Then the pink slice of sunset passes below, and the night, and soon afterward you come again to California, though at another point on the coast, because ninety minutes have passed since you were last here, and during that time the world has revolved beneath you.

Ultimately the shuttle must return to Earth and land. The problem then is what to do with the vast amount of physical energy that has been invested in it—almost all the calories once contained in the nearly four million pounds of rocket fuel that was used to shove the shuttle into orbit. Some of that energy now resides in the vehicle's altitude, but most resides in its speed. The re-entry is a descent to a landing, yes, but primarily it is a giant deceleration, during which atmospheric resistance is used to convert velocity into heat, and to slow the shuttle by roughly 17,000 mph, so that it finally passes overhead the runway in Florida at airline speeds, and circles down to touch the ground at a well tamed 224 mph or less. Once the shuttle is on the runway, the drag chute and brakes take care of the rest.

The re-entry is a one-way ride that cannot be stopped-once it has begun. The opening move occurs while the shuttle is still proceeding tail first and inverted, halfway around the world from the runway, high above the Indian Ocean. It is a simple thing, a brief burn by the twin orbital maneuvering rockets against the direction of flight, which slows the shuttle by perhaps 200 mph. That reduction is enough. The shuttle continues to free-fall as it has in orbit, but it now lacks the speed to match the curvature of Earth, so the ground no longer gets out of its way. By the time it reaches the start of the atmosphere, the "entry interface" at 400,000 feet, it has gently flipped itself around so that it is right-side up and pointed for Florida, but with its nose held 40 degrees higher than the angle of the descent path. The effect of this so-called angle of attack (which technically refers to the wings, not the nose) is to create drag, and to shield the shuttle's internal structures from the intense re-entry heat by cocking the vehicle up to greet the atmosphere with leading edges made of heat-resistant carbon-composite panels, and with 24,305 insulating surface tiles, each one unique, which are glued primarily to the vehicle's underside. To regulate the sink and drag (and to control the heating), the shuttle goes through a program of sweeping S-turns, banking as steeply as 80 degrees to one side and then the other, tilting its lift vector and digging into the atmosphere. The thinking is done by redundant computers, which use onboard inertial sensing systems to gauge the shuttle's position, altitude, descent rate, and speed. The flying is done by autopilot. The cockpit crews and mission controllers play the role of observers, albeit extremely interested ones who are ready to intervene should something go wrong. In a basic sense, therefore, the re-entry is a mirror image of the launch and climb, decompressed to forty-five minutes instead of eight, but with the added complication that it will finish with the need for a landing.

Bloomfield took me through it in simulation, the two of us sitting in the cockpit to watch while an experienced flight crew and full Mission Control team brought the shuttle in from the de-orbit burn to the touchdown, dealing with a complexity of cascading system failures. Of course, in reality the automation usually performs faultlessly, and the shuttle proceeds to Florida right on track, and down the center of the desired descent profile. Bloomfield expressed surprise at how well the magic had worked on his own flights. Because he had launched on high-inclination orbits to the Russian station Mir and the International Space Station, he had not flown a *Columbia*-style re-entry over the United States, but had descended across Central America instead. He said, "You look down over Central America, and you're so low that you can see the forests! You think, 'There's no *way* we're going to make it to Florida!' Then you cross the west coast of Florida, and you look inside, and you're still doing Mach 5, and you think, 'There's no *way* we're going to slow in time!'" But you do. Mach 5 is 3,500 mph. At that point the shuttle is at 117,000 feet, about 140 miles out. At Mach 2.5, or 1,650 mph, it is at 81,000 feet, about sixty miles out. At that point the crew activates the head-up displays, which project see-through flight guidance into the field of vision through the windshield. When the shuttle slows below the speed of sound, it shudders as the shock waves shift. By tradition if not necessity, the commander then takes over from the autopilot, and flies the rest of the arrival manually, using the control stick.

Bloomfield invited me to fly some simulated arrivals myself, and prompted me while I staggered around for a few landings—overhead the Kennedy Space Center at 30,000 feet with the runway and the coastal estuaries in sight below, banking left into a tight, plunging energy-management turn, rolling out onto final approach at 11,000 feet, following an extraordinarily steep, 18-degree glide slope at 345 mph, speed brakes on, pitching up through a "pre-flare" at 2,000 feet to flatten the descent, landing gear out at 300 feet, touching down on the main wheels with some skips and bumps, then drag chute out, nose gear gently down, and brakes on. My efforts were crude, and greatly assisted by Bloomfield, but they gave me an impression of the shuttle as a solid, beautifully balanced flying machine that in thick air, at the end, is responsive and not difficult to handle—if everything goes just right. Bloomfield agreed. Moreover, years have passed in which everything did go just right—leaving the pilots to work on the finesse of their touchdowns, whether they were two knots fast, or 100 feet long. Bloomfield said, "When you come back and you land, the engineers will pull out their charts and they'll say things like 'The boundary layer tripped on the left wing before the right one. Did you feel anything?' And the answer is always 'Well … no. It was an incredibly smooth ride all the way down.'" But then, on the morning of February 1, something went really wrong—something too radical for simulation, that offered the pilots no chance to fly—and the *Columbia* lay scattered for 300 miles across the ground.

The foam did it. That much was suspected from the start, and all the evidence converged on it as the CAIB's investigation proceeded through the months that followed. The foam was dense and dry; it was the brownish-orange coating applied to the outside of the shuttle's large external tank to insulate the extreme cold of the rocket fuels inside from the warmth and moisture of the air. Eighty-two seconds after liftoff, as the *Columbia* was accelerating through 1,500 mph, a piece of that foam—about nineteen inches long by eleven inches wide, weighing about 1.7 pounds—broke off from the external tank and collided with the left wing at about 545 mph. Cameras near the launch site recorded the event—though the images when viewed the following day provided insufficient detail to know the exact impact point, or the consequences. The CAIB's investigation ultimately found that a gaping hole about ten inches across had been punched into the wing's leading edge, and that sixteen days later the hole allowed the hot gases of the re-entry to penetrate the wing and consume it from the inside. Through enormous effort this would be discovered and verified beyond doubt. It was important nonetheless to explore the alternatives. In an effort closely supervised by the CAIB, groups of NASA engineers created several thousand flow charts, one for each scenario that could conceivably have led to the re-entry breakup. The thinking was rigorous. For a scenario to be "closed," meaning set aside, absolute proof had to be found (usually physical or mathematical) that this particular explanation did not apply: there was no cockpit fire, no flight-control malfunction, no act of terrorism or sabotage that had taken the shuttle down. Unexpected vulnerabilities were found during this process, and even after the investigation was formally concluded, in late August, more than a hundred scenarios remained technically open, because they could not positively be closed. For lack of evidence to the contrary, for instance, neither bird strikes nor micrometeorite impacts could be completely ruled out.

But for all their willingness to explore less likely alternatives, many of NASA's managers remained stubbornly closed-minded on the subject of foam. From the earliest telemetric data it was known that intense heat inside the left wing had destroyed the *Columbia*, and that such heat could have gotten there only through a hole. The connection between the hole and the foam strike was loosely circumstantial at first, but it required serious consideration nonetheless. NASA balked at going down that road. Its reasons were not rational and scientific but, rather, complex and cultural, and they turned out to be closely related to the errors that had led to the accident in the first place: simply put, it had become a matter of faith within NASA that foam strikes—which were a known problem—could not cause mortal damage to the shuttle. Sean O'Keefe, who was badly advised by his NASA lieutenants, made unwise public statements deriding the "foamologists"; and even Ron Dittemore, NASA's technically expert shuttle program manager, joined in with categorical denials.

At the CAIB, Gehman, who was not unsympathetic to NASA, watched these reactions with growing skepticism and a sense of déjà vu. Over his years in the Navy, and as a result of the *Cole* inquiry, he had become something of a student of large organizations under stress. To me he said, "It has been scorched into my mind that bureaucracies will do anything to defend themselves. It's not evil—it's just a natural reaction of bureaucracies, and since NASA is a bureaucracy, I expect the same out of them. As we go through the investigation, I've been looking for signs where the system is trying to defend itself." Of those signs the most obvious was this display of blind faith by an organization dependent on its engineering cool; NASA, in its absolute certainty, was unintentionally signaling the very problem that it had. Gehman had seen such certainty proved wrong too many times, and he told me that he was not about to get "rolled by the system," as he had been rolled before. He said, "Now when I hear NASA telling me things like '*Gotta* be true!' or 'We *know* this to be true!' all my alarm bells go off … Without hurting anybody's feelings, or squashing people's egos, we're having to say, 'We're sorry, but we're not *accepting* that answer.'"

That was the form that the physical investigation took on, with hundreds of NASA engineers and technicians doing most of the detailed work, and the CAIB watching closely—and increasingly stepping in. Despite what Gehman said, it was inevitable that feelings got hurt and egos squashed—and indeed that serious damage to people's lives and careers was inflicted. At the NASA facilities dedicated to shuttle operations (Alabama for rockets, Florida for launch and landing, Texas for management and mission control) the CAIB investigators were seen as invaders of sorts, unwelcome strangers arriving to pass judgment on people's good-faith efforts. On the ground level, where the detailed analysis was being done, there was active resistance at first, with some NASA engineers openly refusing to cooperate, or to allow access to records and technical documents that had not been pre-approved for release. Gehman had to intervene. One of the toughest and most experienced of the CAIB investigators later told me he had a gut sense that NASA continued to hide relevant information, and that it does so to this day. But cooperation between the two groups gradually improved as friendships were made, and the intellectual challenges posed by the inquiry began to predominate over fears about what had happened or what might follow. As so often occurs, it was on an informal basis that information flowed best, and that much of the truth was discovered.

Board member Steven Wallace described the investigation not as a linear path but as a picture that gradually filled in. Or as a jigsaw puzzle. The search for debris began the first day, and soon swelled to include more than 25,000 people, at a cost of well over $300 million. NASA received 1,459 debris reports, including some from nearly every state in the union, and also from Canada, Jamaica, and the Bahamas. Discounting the geographic extremes, there was still a lot to follow up on. Though the amateur videos showed pieces separating from the shuttle along the entire

For all their willingness to explore less likely alternatives, many of NASA's managers were stubbornly closed-minded on the subject of foam. NASA balked at going down that road. The reasons were not rational and scientific but, rather, complex and cultural.

path over the United States, and though search parties backtracked all the way to the Pacific coast in the hope of finding evidence of the breakup's triggering mechanism, the westernmost piece found on the ground was a left-wing tile that landed near a town called Littlefield, in the Texas Panhandle. Not surprisingly, the bulk of the wreckage lay under the main breakup, from south of Dallas eastward across the rugged, snake-infested brushland of East Texas and into Louisiana; and that is where most of the search took place. The best work was done on foot, by tough and dedicated crews who walked in tight lines across several thousand square miles. Their effort became something of a close sampling of the American landscape, turning up all sorts of odds and ends, including a few apparent murder victims, plenty of junked cars, and the occasional clandestine meth lab. More to the point, it also turned up crew remains and more than 84,000 pieces of the *Columbia*, which, at 84,900 pounds, accounted for 38 percent of the vehicle's dry weight. Certain pieces that had splashed into the murky waters of lakes and reservoirs were never found. It was presumed that most if not all the remaining pieces had been vaporized by the heat of re-entry, either before or after the breakup.

Some of the shuttle's contents survived intact. For instance, a vacuum cleaner still worked, as did some computers and printers and a Medtronic Tono-Pen, used to measure ocular pressure. A group of worms from one of the science experiments not only survived but continued to multiply. Most of the debris, however, was a twisted mess. The recovered pieces were meticulously plotted and tagged, and transported to a hangar at the Kennedy Space Center, where the wing remnants were laid out in correct position on the floor, and what had been found of the left wing's reinforced carbon-carbon (RCC) leading edge was reconstructed in a transparent Plexiglas mold—though with large gaps where pieces were missing. The hangar was a quiet, poignant, intensely focused place, with many of the same NASA technicians who had prepared the *Columbia* for flight now involved in the sad task of handling its ruins. The assembly and analysis went on through the spring. One of the principal CAIB agents there was an affable Air Force pilot named Patrick Goodman, an experienced accident investigator who had made both friends and enemies at NASA for the directness of his approach. When I first met him, outside the hangar on a typically warm and sunny Florida day, he explained some of the details that I had just seen on the inside—heat-eroded tiles, burned skin and structure, and aluminum slag that had emerged in molten form from inside the left wing, and had been deposited onto the aft rocket pods. The evidence was complicated because it resulted from combinations of heat, physical forces, and wildly varying airflows that had occurred before, during, and after the main-body breakup, but for Goodman it was beginning to read like a map. He had faith. He said, "We know what we have on the ground. It's the truth. The debris is the truth, if we can only figure out what it's saying. It's not a theoretical model. It exists." Equally important was the debris that did not exist, most significantly large parts of the left wing, including the lower part of a section of the RCC leading edge, a point known as Panel Eight, which was approximately where the launch cameras showed that the foam had hit. Goodman said, "We look at what we don't have. What we do have. What's *on* what we have. We start from there, and try to work backwards up the timeline, always trying to see the previous significant event." He called this "looking uphill." It was like a movie run in reverse, with the found pieces springing off the ground and flying upward to a point of reassembly above Dallas, and then the *Columbia*, looking nearly whole, flying tail-first toward California, picking up the Littlefield tile as it goes, and then higher again, through entry interface over the Pacific, through orbits flown in reverse, inverted but nose first, and then back down toward Earth, picking up the external tank and the solid rocket boosters during the descent, and settling tail-first with rockets roaring, until just before a vertical touchdown a spray of pulverized foam appears below, pulls together at the left-wing leading edge, and rises to lodge itself firmly on the side of the external tank.

The foam did it.

There was plenty of other evidence, too. After the accident the Air Force dug up routine radar surveillance tapes that upon close inspection showed a small object floating alongside the *Columbia* on the second day of its mission. The object slowly drifted away and disappeared from view. Subsequent testing of radar profiles and ballistic coefficients for a multitude of objects found a match for only one—a fragment of RCC panel of at least 140 square inches. The match never quite passed muster as proof, but investigators presumed that the object was a piece of the leading edge, that it had been shoved into the inside of the wing by the impact of the foam, and that during maneuvering in orbit it had floated free. The picture by now was rapidly filling in.

But the best evidence was numerical. It so happened that because the *Columbia* was the first of the operational shuttles, it was equipped with hundreds of additional engineering sensors that fed into an onboard data-collection

Some of the *Columbia*'s contents survived intact. A vacuum cleaner still worked, as did some computers and a Medtronic Tono-Pen. A group of worms from one of the science experiments not only survived but continued to multiply.

device, a box known as a modular auxiliary data system, or MADS recorder, that was normally used for postflight analysis of the vehicle's performance. During the initial debris search this box was not found, but such was its potential importance that after careful calculation of its likely ballistic path, another search was mounted, and on March 19 it was discovered—lying in full view on ground that had been gone over before. The really surprising thing was its condition. Though the recorder was not designed to be crash-proof, and used Mylar tape that was vulnerable to heat, it had survived the breakup and fall completely intact, as had the data that it contained, the most interesting of which pertained to heat rises and sequential sensor failures inside the left wing. When combined with the telemetric data that already existed, and with calculations of the size and location of the sort of hole that might have been punched through the leading edge by the foam, the new data allowed for a good fit with computational models of the theoretical airflow and heat propagation inside the left wing, and it steered the investigation to an inevitable conclusion that the breach must have been in the RCC at Panel Eight.

By early summer the picture was clear. Though strictly speaking the case was circumstantial, the evidence against the foam was so persuasive that there remained no reasonable doubt about the physical cause of the accident. As a result, Gehman gave serious consideration to NASA's request to call off a planned test of the launch incident, during which a piece of foam would be carefully fired at a fully rigged RCC Panel Eight. NASA's argument against the test had some merit: the leading-edge panels (forty-four per shuttle) are custom-made, $700,000 components, each one different from the others, and the testing would require the use of the last spare Panel Eight in the entire fleet. NASA said that it couldn't afford the waste, and Gehman was inclined to agree, precisely because he felt that breaking the panel would prove nothing that hadn't already been amply

Fires started by fallen debris, Athens, Texas

proved. By a twist of fate it was the sole NASA member of the CAIB, the quiet, cerebral, earnestly scientific Scott Hubbard, who insisted that the test proceed. Hubbard was one of the original seven board members. At the time of the accident he had just become the director of NASA's Ames Research Center, in California. Months later now, in the wake of Gehman's rebellion, and with the CAIB aggressively moving beyond the physical causes and into the organizational ones, he found himself in the tricky position of collaborating with a group that many of his own people at NASA saw as the enemy. Hubbard, however, had an almost childlike belief in doing the right thing, and having been given this unfortunate job, he was determined to see it through correctly. Owing to the closeness of his ties to NASA, he understood an aspect of the situation that others might have overlooked: despite overwhelming evidence to the contrary, many people at NASA continued stubbornly to believe that the foam strike on launch could *not* have caused the *Columbia*'s destruction. Hubbard argued that if NASA was to have any chance of self-reform, these people would have to be confronted with reality, not in abstraction but in the most tangible way possible. Gehman found the argument convincing, and so the foam shot proceeded.

The work was done in San Antonio, using a compressed-nitrogen gun with a thirty-five-foot barrel, normally used to fire dead chickens—real and artificial—against aircraft structures in bird-strike certification tests. NASA approached the test kicking and screaming all the way, insisting, for instance, that the shot be used primarily to validate an earlier debris-strike model (the so-called Crater model of strikes against the underside tiles) that had been used for decision-making during the flight, and was now known to be irrelevant. Indeed, it was because of NASA obstructionism—and specifically the illogical insistence by some of the NASA rocket engineers that the chunk of foam that had hit the wing was significantly smaller (and therefore lighter) than the video and film record showed it to be—that the CAIB and Scott Hubbard finally took direct control of the testing. There was in fact a series of foam shots, increasingly realistic according to the evolving analysis of the actual strike, that raised the stakes from a glancing blow against the underside tiles to steeper-angle hits directly against leading-edge panels. The second to last shot was a 22-degree hit against the bottom of Panel Six: it produced some cracks and other damage deemed too small to explain the shuttle's loss. Afterward there was some smugness at NASA, and even Sean O'Keefe, who again was badly advised, weighed in on the matter, belittling the damage. But the shot against Panel Six was not yet the real thing. That was saved for the precious Panel Eight, in a test that was painstakingly designed to duplicate (conservatively) the actual impact against the *Columbia*'s left wing, assuming a rotational "clocking angle" 30 degrees off vertical for the piece of foam. Among the engineers who gathered to watch were many of those still living in denial. The gun fired, and the foam hit the panel at a 25-degree relative angle at about 500 mph. Immediately afterward an audible gasp went through the crowd. The foam had knocked a hole in the RCC large enough to allow people to put their heads through. Hubbard told me that some of the NASA people were close to tears. Gehman had stayed away in order to avoid the appearance of gloating. He could not keep the satisfaction out of his voice, however, when later he said to me, "Their whole house of cards came falling down."

NASA's house was by then what this investigation was really all about. The CAIB discovered that on the morning of January 17, the day after the launch, the low-level engineers at the Kennedy Space Center whose job was to review the launch videos and film were immediately concerned by the size and speed of the foam that had struck the shuttle. As expected of them, they compiled the imagery and disseminated it by e-mail to various shuttle engineers and managers—most significantly those in charge of the shuttle program at the Johnson Space Center. Realizing that their blurred or otherwise inadequate pictures showed nothing of the damage that might have been inflicted, and anticipating the need for such information by others, the engineers at Kennedy then went outside normal channels and on their own initiative approached the Department of Defense with a request that secret military satellites or ground-based high-resolution cameras be used to photograph the shuttle in orbit. After a delay of several days for the back-channel request to get through, the Air Force proved glad to oblige, and made the first moves to honor the request. Such images would probably have shown a large hole in the left wing—but they were never taken.

JEFF MITCHELL/REUTERS NEW MEDIA INC./CORBIS

When news of the foam strike arrived in Houston, it did not seem to be crucially important. Though foam was not supposed to shed from the external tank, and the shuttle was not designed to withstand its impacts, falling foam had plagued the shuttle from the start, and indeed had caused damage on most missions. The falling foam was usually popcorn sized, too small to cause more than superficial dents in the thermal protection tiles. The CAIB, however, discovered a history of more-serious cases. For example, in 1988 the shuttle *Atlantis* took a heavy hit, seen by the launch cameras eighty-five seconds into the climb, nearly the same point at which the *Columbia* strike occurred. On the second day of the *Atlantis* flight Houston asked the crew to inspect the vehicle's underside with a video camera on a robotic arm (which the *Columbia* did not have). The commander, Robert "Hoot" Gibson, told the CAIB that the belly looked as if it had been blasted with shotgun fire. The *Atlantis* returned safely anyway, but afterward was found to have lost an entire tile, exposing its bare metal belly to the re-entry heat. It was lucky that the damage had happened in a place where a heavy aluminum plate covered the skin, Gibson said, because otherwise the belly might have been burned through.

Nonetheless, over the years foam strikes had come to be seen within NASA as an "in-family" problem, so familiar that even the most serious episodes seemed unthreatening and mundane. Douglas Osheroff, a normally good-humored Stanford physicist and Nobel laureate who joined the CAIB late, went around for months in a state of incredulity and dismay at what he was learning about NASA's operational logic. He told me that the shuttle managers acted as if they thought the frequency of the foam strikes had somehow reduced the danger that the impacts posed. His point was not that the managers really believed this but that after more than a hundred successful flights they had come blithely to accept the risk. He said, "The excitement that only exists when there is danger was kind of gone—even though the danger was not gone." And frankly, organizational and bureaucratic concerns weighed more heavily on the managers' minds. The most pressing of those concerns were the new performance goals imposed by Sean O'Keefe, and a tight sequence of flights leading up to a drop-dead date of February 19, 2004, for the completion of the International Space Station's "core." O'Keefe had made it clear that meeting this deadline was a test, and that the very future of NASA's human space-flight program was on the line.

Falling foam had plagued the shuttle from the start, and indeed had caused damage on most missions. In 1988 the *Atlantis* took a heavy hit. Its commander told the CAIB that the shuttle's belly looked as if it had been blasted with shotgun fire.

From Osheroff's scientific perspective, deadlines based on completion of the International Space Station were inherently absurd. To me he said, "And what would the next goal be after that? Maybe we should bring our pets up there! 'I wonder how a Saint Bernard urinates in zero gravity!' NASA sold the International Space Station to Congress as a great science center—but most scientists just don't agree with that. We're thirty years from being able to go to Mars. Meanwhile, the only reason to have man in space is to study man in space. You can do that stuff—okay—and there are also some biology experiments that are kind of fun. I think we *are* learning things. But I would question any statement that you can come up with better drugs in orbit than you can on the ground, or that sort of thing. The truth is, the International Space Station has become a huge liability for NASA"—expensive to build, expensive to fly, expensive to resupply. "Now members of Congress are talking about letting its orbit decay—just letting it fall into the ocean. And it does turn out that orbital decay is a very good thing, because it means that near space is a self-cleaning place. I mean, garbage does not stay up there forever."

In other words, completion of the Space Station could provide a measure of NASA's performance only in the most immediate and superficial manner, and it was therefore an inherently poor reason for shuttle managers to be ignoring the foam strikes and proceeding at full speed. It was here that you could see the limitations of leadership without vision, and the consequences of putting an executive like O'Keefe in charge of an organization that needed more than mere discipline. This, however, was hardly an argument that the managers could use, or even in private allow themselves to articulate. If the Space Station was unimportant—and perhaps even a mistake—then one had to question the reason for the shuttle's existence in the first place. Like O'Keefe and the astronauts and NASA itself, the managers were trapped by a circular space policy thirty years in the making, and they had no choice but to strive to meet the timelines directly ahead. As a result, after the most recent *Atlantis* launch, in October of 2002, during which a chunk of foam from a particularly troublesome part of the external tank, known as the "bipod ramp," had dented one of the solid rocket boosters, shuttle managers formally decided during the post-flight review not to classify the incident as an "in-flight anomaly." This was the first time that a serious bipod-ramp incident had escaped such a classification. The decision allowed the following two launches to proceed on schedule. The second of those launches was the *Columbia*'s, on January 16.

The videos of the foam strike reached Houston the next day, January 17. They made it clear that again the offending material had come from the area of the bipod ramp, that this time the foam was larger than ever before, that the impact had occurred later in the climb (meaning at higher speed), and that the wing had been hit, though exactly where was not clear. The astronauts were happily in orbit now, and had apparently not felt the impact, or been able to distinguish it from the heavy vibrations of the solid rocket boosters. In other words, they were unaware of any trouble. Responsibility for disposing of the incident lay with engineers on the ground, and specifically with the Mission Management Team, or MMT, whose purpose was to make decisions about the problems and unscripted events that inevitably arose during any flight. The MMT was a high-level group. In the Houston hierarchy it operated above the flight controllers in the Mission Control room, and just below the shuttle program manager, Ron Dittemore. Dittemore was traveling at the time, and has since retired. The MMT meetings were chaired by his protégé, the once rising Linda Ham, who has come to embody NASA's arrogance and insularity in many observers' minds. Ham is the same hard-charging manager who, with a colleague, later had to be forcefully separated from the CAIB's investigation. Within the strangely neutered engineering world of the Johnson Space Center, she was an intimidating figure, a youngish, attractive woman given to wearing revealing clothes, yet also known for a tough and domineering management style. Among the lower ranks she had a reputation for brooking no nonsense and being a little hard to talk to. She was not smooth. She was a woman struggling upward in a man's world. She was said to have a difficult personality.

As the head of the MMT, Ham responded to news of the foam strike as if it were just another item to be efficiently handled and then checked off the list: a water leak in the science lab, a radio communication failure, a foam strike on the left wing, okay, no safety-of-flight issues here—right? What's next? There was a trace of vanity in the way she ran her shows. She seemed to revel in her own briskness, in her knowledge of the shuttle systems, in her use of acronyms and the strange, stilted syntax of aerospace engineers. She was decisive, and very sure of her sense for what was important and what was not. Her style got the best of her on day six of the mission, January 21, when at a recorded MMT meeting she spoke just a few words too many, much to her later regret.

It was at the end of a report given by a mid-ranking engineer named Don McCormack, who summarized the progress of an ad hoc engineering group, called the Debris Assessment Team, that had been formed at a still lower level to analyze the foam strike. The analysis was being done primarily by Boeing engineers, who had dusted off the soon to be notorious Crater model, primarily to predict damage to the underwing tile. McCormack reported that little was yet resolved, that the quality of the Crater as a predictor was being judged against the known damage on earlier flights, and that some work was being done to explore the options should the analysis conclude that the *Columbia* had been badly wounded. After a brief exchange Ham cut him short, saying, "And I'm really ... I don't think there is much we can do, so it's not really a factor during the flight, since there is not much we can do about it." She was making assumptions, of course, and they were later proved to be completely wrong, but primarily she was just being efficient, and moving the meeting along. After the accident, when the transcript and audiotapes emerged, those words were taken out of context, and used to portray Ham as a villainous and almost inhumanly callous person, which she certainly was not. In fact, she was married to an astronaut, and was as concerned as anyone about the safety of the shuttle crews. This was a dangerous business, and she knew it all too well. But like her boss, Ron Dittemore, with whom she discussed the *Columbia* foam strike several times, she was so immersed in the closed world of shuttle management that she simply did not elevate the event—this "in-family" thing—to the level of concerns requiring action. She was intellectually arrogant, perhaps, and as a manager she failed abysmally. But neither she nor the others of her rank had the slightest suspicion that the *Columbia* might actually go down.

The frustration is that some people on lower levels were actively worried about that possibility, and they understood clearly that not enough was known about the effects of the foam strike on the wing, but they expressed their concerns mostly to one another, and for good reason, because on the few occasions when they tried to alert the decision-makers, NASA's management system overwhelmed them and allowed none of them to be heard. The question now, of course, is why.

The CAIB's search for answers began long before the technical details were resolved, and it ultimately involved hundreds of interviews and 50,000 pages of transcripts. The manner in which those interviews were conducted became a contentious issue, and it was arguably Gehman's biggest mistake. As a military man, advised by military men on the board, he decided to conduct the interviews according to a military model of safety probes, in which individual fault is not formally assigned, and the interviews themselves are "privileged," meaning forever sealed off from public view. It was understood that identities and deeds would *not* be protected from view, only individual testimonies to the CAIB, but serious critics cried foul nonetheless, and pointed out correctly that Gehman was using loopholes to escape sunshine laws that otherwise would have applied. Gehman believed that treating the testimony as privileged was necessary to encourage witnesses to talk, and to get to the bottom of the story, but the long-term effect of the investigation will be diminished as a result (for instance, by lack of access to the raw material by outside analysts), and there was widespread consensus among the experienced (largely civilian) investigators actually conducting the interviews that the promise of privacy was having little effect on what people were willing to say. These were not criminals they were talking to, or careful lawyers. For the most part they were sincere engineering types who were concerned about what had gone wrong, and would have been willing even without privacy to speak their minds. The truth, in other words, would have come out even in the brightest of sunshine.

The story that emerged was a sad and unnecessary one, involving arrogance, insularity, and bad luck allowed to run unchecked. On the seventh day of the flight, January 22, just as the Air Force began to move on the Kennedy engineers' back-channel request for photographs, Linda Ham heard to her surprise that this approach (which according to front-channel procedures would have required her approval) had been made. She immediately telephoned other high-level managers in Houston to see if any of them wanted to issue a formal "requirement" for imagery, and when they informed her that they did not, rather than exploring the question with the Kennedy engineers she simply terminated their request with the Department of Defense. This appears to have been a purely bureaucratic reaction. A NASA liaison officer then e-mailed an apology to Air Force personnel, assuring them that the shuttle was in "excellent shape," and explaining that a foam strike was "something that has happened before and is not considered to be a major problem." The officer continued, "The one problem that this has identified is the need for some additional coordination within NASA to assure that when a request is made it is done through the official channels." Months later one of the CAIB investigators who had followed this trail was still seething with anger at what had occurred. He said, "Because the problem was not identified in the traditional way—'Houston, we have a problem!'—well, then, 'Houston, we *don't* have a problem!' Because *Houston* didn't *identify* the problem."

But another part of Houston was doing just that. Unbeknownst to Ham and the shuttle management, the low-level engineers of the Debris Assessment Team had concluded that the launch films were not clear enough to indicate where the foam had hit, and particularly whether it had hit the underside tile or a leading-edge RCC panel. Rather than trying to run their calculations in the blind, they had decided that they should do the simple thing and have someone take a look for damage. They had already e-mailed one query to the engineering department, about the possibility of getting the astronauts themselves to take a short spacewalk and inspect the wing. It later turned out that this would have been safe and easy to do. That e-mail, however, was never answered. This time the Debris Assessment engineers decided on a still simpler solution—to ask the Department of Defense to take some high-resolution pictures. Ignorant of the fact that the Kennedy group had already made such a request, and that it had just been peevishly canceled, they sent out two requests of their own, directed, appropriately, to Ron Dittemore and Linda Ham, but through channels that were a little off-center, and happened to fail. Those channels were ones they had used in their regular work as engineers, outside the formal shuttle-management structure. By unfortunate circumstance, the request that came closest to getting through was intercepted by a mid-level employee (the assistant to an intended recipient, who was on vacation) who responded by informing the Debris Assessment engineers, more or less correctly, that Linda Ham had decided against Air Force imagery.

The confusion was now total, yet also nearly invisible—and within the suppressive culture of the human spaceflight program, it had very little chance of making itself known. At the top of the tangle, neither Ron Dittemore nor Linda Ham ever learned that the Debris Assessment Team wanted pictures; at the bottom, the Debris Assessment engineers heard the "no" without suspecting that it was not an answer to their request. They were told to go back to the Crater model and numerical analysis, and as earnest, hard-working engineers (hardly rebels, these), they dutifully complied, all the while regretting the blind assumptions that they would have to make. Given the obvious potential for a catastrophe, one might expect that they would have gone directly to Linda Ham, on foot if necessary, to make the argument in person for a spacewalk or high-resolution photos. However, such were the constraints within the Johnson Space Center that they never dared. They later said that had they made a fuss about the shuttle, they might have been singled out for ridicule. They feared for their standing, and their careers.

Low-level engineers in Houston e-mailed a query to superiors about the possibility of getting the astronauts to take a spacewalk and inspect the wing. It turned out that this would have been safe and easy to do. That e-mail, however, was never answered.

The CAIB investigator who asked the engineers what conclusion they had drawn at the time from management's refusal later said to me, "They all thought, 'Well, none of us have a security clearance high enough to view any of this imagery.' They talked about this openly among themselves, and they figured one of three things:

"'One: The "no" means that management's already got photos, and the damage isn't too bad. They can't show us the photos, because we don't have the security clearance, and they can't *tell* us they have the photos, or *tell* us the damage isn't bad, because that tells us how accurate the photos are—and we don't have the security clearance. But wait a minute, if that's the case, then what're we doing here? Why are we doing the analysis? So no, that can't be right.

"'Okay, then, two: They already took the photos, and the damage is so severe that there's no hope for recovery. Well ... that can't be right either, because in that case, why are we doing the analysis?

"'Okay, then, three: They took the photos. They can't tell us they took the photos, and the photos don't give us clear definition. So we need to do the analysis. That's gotta be it!'"

What the Debris Assessment engineers could not imagine is that no photos had been taken, or ever would be—and essentially for lack of curiosity by NASA's imperious, self-convinced managers. What those managers in turn could not imagine was that people in their own house might really be concerned. The communication gap had nothing to do with security clearances, and it was complete.

Gehman explained the underlying realities to me. He said, "They claim that the culture in Houston is a 'badgeless society,' meaning it doesn't matter what you have on your badge—you're concerned about shuttle safety together. Well, that's all nice, but the truth is that it *does* matter what badge you're wearing. Look, if you really do have an organization that has free communication and open doors and all that kind of stuff, it takes a special kind of management to make it work. And we just don't see that management here. Oh, they *say* all the right things. 'We have open doors and e-mails, and anybody who sees a problem can raise his hand, blow a whistle, and stop the whole process.' But then when you look at how it really works, it's an incestuous, hierarchical system, with invisible rankings and a very strict informal chain of command. They all know that. So even though they've got all the trappings of communication, you don't actually *find* communication. It's very complex. But if a person brings an issue up, what caste he's in makes all the difference. Now, again, NASA will deny this, but if you talk to people, if you really listen to people, all the time you hear 'Well, I was afraid to speak up.' Boy, it comes across loud and clear. You listen to the meetings: 'Anybody got anything to say?' There are thirty people in the room, and *slam!* There's nothing. We have plenty of witness statements saying, 'If I had spoken up, it would have been at the cost of my job.' And if you're in the engineering department, you're a nobody."

One of the CAIB investigators told me that he asked Linda Ham, "As a manager, how do you seek out dissenting opinions?"

According to him, she answered, "Well, when I hear about them ..."

He interrupted. "Linda, by their very nature you may not hear about them."

"Well, when somebody comes forward and tells me about them."

"But Linda, what techniques do you use to *get* them?"

He told me she had no answer.

This was certainly not the sort of risk-versus-risk decision-making that Michael Bloomfield had in mind when he described the thinking behind his own shuttle flights.

At 7:00 A.M. on the ninth day, January 24, which was one week before the *Columbia*'s scheduled re-entry, the engineers from the Debris Assessment Team formally presented the results of their numerical analysis to Linda Ham's intermediary, Don McCormack. The room was so crowded with concerned observers that some people stood in the hall, peering in. The fundamental purpose of the meeting would have been better served had the engineers been able to project a photograph of a damaged wing onto the screen, but, tragically, that was not to be. Instead they projected a typically crude PowerPoint summary, based on the results from the Crater model, with which they attempted to explain a nuanced position: first, that if the tile had been damaged, it had probably endured well enough to allow the *Columbia* to come home; and second, that for lack of information they had needed to make assumptions to reach that conclusion, and that troubling unknowns therefore limited the meaning of the results. The latter message seems to have been lost. Indeed, this particular PowerPoint presentation became a case study for Edward Tufte, the brilliant communications specialist from Yale, who in a subsequent booklet, *The Cognitive Style of PowerPoint*, tore into it for its dampening effect on clear expression and thought. The CAIB later joined in, describing the widespread use of PowerPoint within NASA as one of the obstacles to internal communication, and criticizing the Debris Assessment presentation for mechanically underplaying the uncertainties that remained.

Had the uncertainties been more strongly expressed as the *central* factor in question, the need to inspect the wing by spacewalk or photograph might have become obvious even to the shuttle managers. Still, the Mission Management Team seemed unprepared to hear nuance. Fixated on potential tile damage as the relevant question, assuming without good evidence that the RCC panels were strong enough to withstand a foam strike, subtly skewing the

Linda Ham, known for a tough and domineering management style, came to embody NASA's arrogance and insularity. She responded to news of the foam strike as if it were just another item to be efficiently handled and then checked off the list.

discussion away from catastrophic burn-through and toward the potential effects on turnaround times on the ground and how that might affect the all-important launch schedule, the shuttle managers were convinced that they had the situation as they defined it firmly under control.

At a regularly scheduled MMT meeting later that morning McCormack summarized the PowerPoint presentation for Linda Ham. He said, "The analysis is not complete. There is one case yet that they wish to run, but kind of just jumping to the conclusion of all that, they do show that [there is], obviously, a potential for significant tile damage here, but thermal analysis does not indicate that there is potential for a burn-through. I mean, there could be localized heating damage. There is ... obviously there is a lot of uncertainty in all this in terms of the size of the debris and where it hit and the angle of incidence."

Ham answered, "No burn-through means no catastrophic damage. And the localized heating damage would mean a tile replacement?"

"Right, it would mean possible impacts to turnaround repairs and that sort of thing, but we do not see any kind of safety-of-flight issue here yet in anything that we've looked at."

This was all too accurate in itself. Ham said, "And no safety of flight, no issue for this mission, nothing that we're going to do different. There may be a turnaround [delay]."

McCormack said, "Right. It could potentially [have] hit the RCC ... We don't see any issue if it hit the RCC ..."

The discussion returned to the tiles. Ham consulted with a tile specialist named Calvin Schomburg, who for days had been energetically making a case independent of the Debris Assessment analysis that a damaged tile would endure re-entry—and thereby adding, unintentionally, to the distractions and false assumptions of the management team. After a brief exchange Ham cut off further discussion with a quick summary for some people participating in the meeting by conference call, who were having trouble hearing the speakerphone. She said, "So, no safety-of-flight kind of issue. It's more of a turnaround issue similar to what we've had on other flights. That's it? All right, any questions on that?"

And there were not.

For reasons unexplained, when the official minutes of the meeting were written up and distributed (having been signed off on by Ham), all mention of the foam strike was omitted. This was days before the *Columbia*'s re-entry, and seems to indicate sheer lack of attention to this subject, rather than any sort of cover-up.

The truth is that Linda Ham was as much a victim of NASA as were *Columbia*'s astronauts, who were still doing their science experiments then, and free-falling in splendor around the planet. Her predicament had roots that went way back, nearly to the time of Ham's birth, and it involved not only the culture of the human space-flight program but also the White House, Congress, and NASA leadership over the past thirty years. Gehman understood this fully, and as the investigation drew to a close, he vowed to avoid merely going after the people who had been standing close to the accident when it occurred. The person standing closest was, of course, Linda Ham, and she will bear a burden for her mismanagement. But by the time spring turned to summer, and the CAIB moved its operation from Houston to Washington, D.C., Gehman had taken to saying, "Complex systems fail in complex ways," and he was determined that the CAIB's report would document the full range of NASA's mistakes. It did, and in clean, frank prose, using linked sentences and no PowerPoint displays.

As the report was released, on August 26, Mars came closer to Earth than it had in 60,000 years. Gehman told me that he continued to believe in the importance of America's human space-flight effort, and even of the return of the shuttle to flight—at least until a replacement with a clearer mission can be built and put into service. It was a quiet day in Washington, with Congress in recess and the President on vacation. Aides were coming from Capitol Hill to pick up several hundred copies of the report and begin planning hearings for the fall. The White House was receiving the report too, though keeping a cautious distance, as had been expected; it was said that the President might read an executive summary. Down in Houston, board members were handing copies to the astronauts, the managers, and the families of the dead.

Gehman was dressed in a suit, as he had been at the start of all this, seven months before. It was up to him now to drive over to NASA headquarters, in the southwest corner of the city, and deliver the report personally to Sean O'Keefe. I went along for the ride, as did the board member Sheila Widnall, who was there to lend Gehman some moral support. The car was driven by a Navy officer in whites. At no point since the accident had anyone at NASA stepped forward to accept personal responsibility for contributing to this accident—not Linda Ham, not Ron Dittemore, and certainly not Sean O'Keefe. However, the report in Gehman's hands (248 pages, full color, well bound) made responsibility very clear. This was not going to be a social visit. Indeed, it turned out to be extraordinarily tense. Gehman and Widnall strode up the carpeted hallways in a phalanx of anxious, dark-suited NASA staffers, who swung open the doors in advance and followed close on their heels. O'Keefe's office suite was practically imperial in its expense and splendor. High officials stood in small, nervous groups, murmuring. After a short delay O'Keefe appeared—a tall, balding, gray-haired man with stooped shoulders. He shook hands and ushered Gehman and Widnall into the privacy of his inner office. Ten minutes later they emerged. There was a short ceremony for NASA cameras, during which O'Keefe thanked Gehman for his important contribution, and then it was time to leave. As we drove away, I asked Gehman how it had been in there with O'Keefe.

He said "Stiff. Very stiff."

We talked about the future. The report had made a series of recommendations for getting the shuttle back into flight, and beyond that for beginning NASA's long and necessary process of reform. I knew that Gehman, along with much of the board, had volunteered to Congress to return in a year, to peer in deeply again, and to try to judge if progress had been made. I asked him how genuine he thought such progress could be, and he managed somehow to express hope, though skeptically.

By January 23, the *Columbia*'s eighth day in orbit, the crew had solved a couple of minor system problems, and after a half day off, during which no doubt some of the astronauts took the opportunity for some global sightseeing, they were proceeding on schedule with their laboratory duties, and were in good spirits and health. They had been told nothing of the foam strike. Down in Houston, the flight controllers at Mission Control were aware of it, and they knew that the previous day Linda Ham had canceled the request for Air Force photographs. Confident that the issue would be satisfactorily resolved by the shuttle managers, they decided nonetheless to inform the flight crew by e-mail—if only because certain reporters at the Florida launch site had heard of it, and might ask questions at an upcoming press conference, a Public Affairs Office, or PAO, event. The e-mail was written by one of the lead flight controllers, in the standard, overly upbeat style. It was addressed to the pilots, Rick Husband and William McCool.

Under the subject line "INFO: Possible PAO Event Question," it read,

> Rick and Willie,
>
> You guys are doing a fantastic job staying on the timeline and accomplishing great science. Keep up the good work and let us know if there is anything that we can do better from an MCC/POCC standpoint.
>
> There is one item that I would like to make you aware of for the upcoming PAO event ... This item is not even worth mentioning other than wanting to make sure that you are not surprised by it in a question from a reporter.

The e-mail then briefly explained what the launch pictures had shown—a hit from the bipod-ramp foam. A video clip was attached. The e-mail concluded,

> Experts have reviewed the high speed photography and there is no concern for RCC or tile damage. We have seen this same phenomenon on several other flights and there is absolutely no concern for entry. That is all for now. It's a pleasure working with you every day.

The e-mail's content honestly reflected what was believed on the ground, though in a repackaged and highly simplified form. There was no mention of the inadequate quality of the pictures, of the large size of the foam, of the ongoing analysis, or of Linda Ham's decision against Air Force imagery. This was typical for Mission Control communications, a small example of a long-standing pattern of something like information-hoarding that was instinctive and a matter as much of style as of intent: the astronauts had been told of the strike, but almost as if they were children who didn't need to be involved in the grown-up conversation. Two days later, when Rick Husband answered the e-mail, he wrote, "Thanks a million!" and "Thanks for the great work!" and after making a little joke, that "Main Wing" could sound like a Chinese name, he signed off with an e-mail smile—:). He made no mention of the foam strike at all. And with that, as we now know, the crew's last chance for survival faded away.

Linda Ham was wrong. Had the hole in the leading edge been seen, actions could have been taken to try to save the astronauts' lives. The first would have been simply to buy some time. Assuming a starting point on the fifth day of the flight, NASA engineers subsequently calculated that by requiring the crew to rest and sleep, the mission could have been extended to a full month, to February 15. During that time the *Atlantis*, which was already being prepared for a scheduled March 1 launch, could have been processed more quickly by ground crews working around the clock, and made ready to go by February 10. If all had proceeded perfectly, there would have been a five-day window in which to blast off, join up with the *Columbia*, and transfer the stranded astronauts one by one to safety, by means of tethered spacewalks. Such a rescue would not have been easy, and it would have involved the possibility of another fatal foam strike and the loss of two shuttles instead of one; but in the risk-versus-risk world of space flight, veterans like Mike Bloomfield would immediately have volunteered, and NASA would have bet the farm.

The fallback would have been a desperate measure—a jury-rigged repair performed by the *Columbia* astronauts themselves. It would have required two spacewalkers to fill the hole with a combination of heavy tools and metal scraps scavenged from the crew compartment, and to supplement that mass with an ice bag shaped to the wing's leading edge. In theory, if much of the payload had been jettisoned, and luck was with the crew, such a repair might perhaps have endured a modified re-entry and allowed the astronauts to bail out at the standard 30,000 feet. The engineers

By the time it got to Texas, the *Columbia* had already proved itself a heroic flying machine, having endured for so long at hypersonic speeds with little left of the midsection of its left wing, and the plume of hot gas still in there, alive, eating it away.

Columbia astronauts on the flight deck during re-entry

who came up with this plan realized that in reality it would have been extremely dangerous, and might well have led to a high-speed burn-through and the loss of the crew. But anything would have been better than attempting a normal re-entry as it was actually flown.

The blessing, if one can be found, is that the astronauts remained unaware until nearly the end. A home video shot on board and found in the wreckage documented the relaxed mood in the cockpit as the shuttle descended through the entry interface at 400,000 feet, at 7:44:09 Houston time, northwest of Hawaii. The astronauts were drinking water in anticipation of gravity's redistributive effect on their bodies. The *Columbia* was flying at the standard 40-degree nose-up angle, with its wings level, and still doing nearly 17,000 mph; outside, though the air was ultra-thin and dynamic pressures were very low, the aerodynamic surfaces were beginning to move in conjunction with the array of control jets, which were doing the main work of maintaining the shuttle's attitude, and would throughout the re-entry. The astronauts commented like sightseers as sheets of fiery plasma began to pass by the windows.

The pilot, McCool, said, "Do you see it over my shoulder now, Laurel?"

Sitting behind him, the mission specialist Laurel Clark said, "I was filming. It doesn't show up nearly as much as the back."

McCool said to the Israeli payload specialist, Ilan Ramon, "It's going pretty good now. Ilan, it's really neat—it's a bright orange-yellow out over the nose, all around the nose."

The commander, Husband, said, "Wait until you start seeing the swirl patterns out your left or right windows."

McCool said, "Wow."

Husband said, "Looks like a blast furnace."

A few seconds later they began to feel gravity. Husband said, "Let's see here ... look at that."

McCool answered, "Yup, we're getting some Gs." As if it

NASA TV/GETTY IMAGES

were unusual, he said, "I let go of the card, and it falls." Their instruments showed that they were experiencing one hundredth of a G. McCool looked out the window again. He said, "This is amazing. It's really getting, uh, fairly bright out there."

Husband said, "Yup. Yeah, you definitely don't want to be outside now."

The flight engineer, Kalpana Chawla, answered sardonically, "What—like we did before?" The crew laughed.

Outside, the situation was worse than they imagined. Normally, as a shuttle streaks through the upper atmosphere it heats the air immediately around it to temperatures as high as 10,000°, but largely because of the boundary layer—a sort of air cushion created by the leading edges—the actual surface temperatures are significantly lower, generally around 3,000°, which the vehicle is designed to withstand, if barely. The hole in the *Columbia*'s leading edge, however, had locally undermined the boundary layer, and was now letting in a plume of superheated air that was cutting through insulation and working its way toward the inner recesses of the left wing. It is estimated that the plume may have been as hot as 8,000° near the RCC breach. The aluminum support structures inside the wing had a melting point of 1,200°, and they began to burn and give way.

The details of the left wing's failure are complex and technical, but the essentials are not difficult to understand. The wing was attacked by a snaking plume of hot gas, and eaten up from the inside. The consumption began when the shuttle was over the Pacific, and it grew worse over the United States. It included wire bundles leading from the sensors, which caused the data going into the MADS recorder and the telemetry going to Houston to fail in ways that only later made sense. At some point the plume blew right through the top of the left wing, and began to throw molten metal from the insides all over the aft rocket pods. At some point it burned its way into the left main gear well, but it did not explode the tires.

As drag increased on the left wing, the autopilot and combined flight-control systems at first easily compensated for the resulting tendency to roll and yaw to the left. By external appearance, therefore, the shuttle was doing its normal thing, banking first to the right and then to the left for the scheduled energy-management turns, and tracking perfectly down the descent profile for Florida. The speeds were good, the altitudes were good, and all systems were functioning correctly. From within the cockpit the ride appeared to be right.

By the time it got to Texas the *Columbia* had already proved itself a heroic flying machine, having endured for so long at hypersonic speeds with little left of the midsection inside its left wing, and the plume of hot gas still in there, alive, and eating it away. By now, however, the flight-control systems were nearing their limits. The breakup was associated with that. At 7:59:15 Mission Control noticed the sudden loss of tire pressure on the left gear as the damage rapidly progressed. This was followed by Houston's call "And *Columbia*, Houston, we see your tire-pressure messages, and we did not copy your last call," and at 7:59:32 by *Columbia*'s final transmission, "Roger, ah, buh ..."

The *Columbia* was traveling at 12,738 mph, at 200,000 feet, and the dynamic pressures were building, with the wings "feeling" the air at about 170 mph. Now, suddenly, the bottom surface of the left wing began to cave upward into the interior void of melted and burned-through bracing and structure. As the curvature of the wing changed, the lift increased, causing the *Columbia* to want to roll violently to the right; at the same time, because of an increase in asymmetrical drag, it yawed violently to the left. The control systems went to their limits to maintain order, and all four right yaw jets on the tail fired simultaneously, but to no avail. At 8:00:19 the *Columbia* rolled over the top and went out of control.

The gyrations it followed were complex combinations of roll, yaw, and pitch, and looked something like an oscillating flat spin. They seem to have resulted in the vehicle's flying backwards. At one point the autopilot appears to have been switched off and then switched on again, as if Husband, an experienced test pilot, was trying to sort things out. The breakup lasted more than a minute. Not surprisingly, the left wing separated first. Afterward the tail, the right wing, and the main body came apart in what investigators later called a controlled sequence "right down the track." As had happened with the *Challenger* in 1986, the crew cabin broke off intact. It assumed a stable flying position, apparently nose high, and later disintegrated like a falling star across the East Texas sky.

William Langewiesche is a national correspondent for The Atlantic *and a former professional pilot. His* Atlantic *cover story "The Crash of EgyptAir 990" won the 2002 National Magazine Award for Reporting. His most recent books include* Inside the Sky *(1998) and* American Ground: Unbuilding the World Trade Center *(2002).*

The CHAIRMAN. Senator Brownback and Senator Nelson, I ask you to be brief because of the time constraints.

STATEMENT OF HON. SAM BROWNBACK, U.S. SENATOR FROM KANSAS

Senator BROWNBACK. I will. Thank you for the hearing. I just want to make one note on it. I've had a number of meetings with Mr. O'Keefe and I appreciate it. I think you've done a good job. I think the issue of manned spaceflight now cries out for a national vision. Let us step back and fully address the questions surrounding the orbital space plane, and hold it up until we establish a national vision of where we want to go in manned space flight and how we're going to do it. That's what I'm going to be pressing for in a commission or by other means. Thank you, Mr. Chairman.

The CHAIRMAN. Senator Nelson?

STATEMENT OF HON. BILL NELSON, U.S. SENATOR FROM FLORIDA

Senator NELSON. Mr. Chairman, this is an important hearing because it's on the future of NASA, which means it's on the future of the hopes and dreams of a lot of Americans that this be a successful program. As I have shared privately with the Administrator, the future of NASA is that the Administrator cannot be the only one that leads the program. The leadership's got to emanate from the White House. I've shared this privately with the Vice President. The Vice President or the President have to encapsulate the dreams of Americans by putting it in to the space program and giving that leadership.

I would add that space flight can't be done on the cheap. We can't continue to go through what we've done over the past decade and a half. If we're going to have a space program, we're going to have to give the resources, and it's my hope that in my lifetime that we will see an international crew from planet Earth go to the planet Mars. That can be phased in over a 25-year period, but we've got to start the work now, we've got to start the planning, and that, of course, will captivate the imagination of the American people once we begin that venture. Thank you.

The CHAIRMAN. Thank you very much. Senator Nelson refers to a meeting that we had with the Vice President and we were very gratified to see that he has taken a personal role in trying to help us sort out these priorities and funding for the future along with Administrator O'Keefe. I welcome both witnesses. Mr. O'Keefe, welcome, please proceed.

STATEMENT OF HON. SEAN O'KEEFE, ADMINISTRATOR, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mr. O'KEEFE. Thank you, Mr. Chairman. I appreciate the time and thank you very much for the invitation to speak on this very, very important question. If I would, sir, I'd like to submit for the record the prepared statement and quickly summarize a couple of points with a few charts I think all members have before you.

First, the strategic plan that we developed, consistent with the President's budget proposal that was advanced on February 3, is a historic document in the sense that it is concise as it focuses on a very limited number of mission objectives that we're after, which I'll quickly touch on. Second, it is concise in the sense that it is readable, in sharp contrast to strategic plans which appear to more resemble Brookland telephone book-sized documents. This one is short, it's written in a language that most of us can comprehend, and it is put together in a way that concisely lays out what the vision and mission objectives are.

And the principal mission objectives to fulfill that vision are to understand and protect the home planet. All the Earth sensing and climate change-related kind of research activities we have underway are examples of that, as well as our continued aeronautics focus in that direction. To explore the universe in search for life is a continued effort as manifested in so many different programs that we're exploring to expand our capacity, developing the capability to go beyond low Earth orbit and examine any destination that may in turn be informed by the scientific inquiry. We aim to inspire the next generation of explorers. This is an element of our history that at its founding was a focus on education and how it in turn can motivate individuals to consider at a very early age, in grammar school as well as in early high school, the objectives of math, science, engineering, and technical-related fields. That's our contribution to that and one that's been heightened and re-emphasized as a consequence of the focus of the strategic plan.

The stepping-stone approach that can be taken to this is to look specifically at our immediate capacity within low Earth orbit as part of exploring the universe and searching for life to develop our own understanding of this planet, as well as our capacity to develop the capabilities to go beyond low Earth orbit. Then, looking beyond to accessible planetary services, the outer planets and beyond, is the technology we seek to develop to achieve those kinds of objectives. And then to be informed, again, by the science that may come forward in the years ahead as well as the exploration objectives we may be after for the purposes of accomplishing any of those destinations and opportunities for discovery.

We've narrowed the strategic building block of investments that we're making down very specifically in this budget. This strategic plan to very clearly focus on three primary areas of need and have been intractable limitations that we've had for the entire time we've engaged in any space exploration endeavor. The primary areas power generation or propulsion capabilities, the capability of human beings to endure and survive the experience of space travel, and the capacity to assure communications, all three of which are focused very specifically in the way that we have evolved the program to the current Fiscal Year 2004 request pending before Congress.

Summarized in the power generation and propulsion capabilities as Project Prometheus, we plan to develop the capability to at least accomplish the task of any outer planetary destination to do multiple on-orbit passes as opposed to the singular fly by approach that we've been restricted to for the past 40 years. In addition to that, develop the capability to improve the speed of space travel and communication capability by a factor of at least two to three, which would therefore cut down the amount of time necessary to arrive at any destination.

The Human Research Initiative is a specific response to the human capabilities and endurance focus that is a specific set of budget initiatives that have been presented as part of the strategic plan to establish the capacity for human endurance beyond the experience that we have attained on the international space station or on space shuttle flights in recent years. And to understand what those consequences are to human physiology to permit any exploration beyond low Earth orbit.

Finally, on optical communications, the basic objective is to assure that we have assured communications in a condition like this to be informed based on immediate events. As it stands now, our capacity for communications transmission, while good, is slower than what it needs to be to support any exploration objective beyond low Earth orbit.

So those are the three areas, from a technology standpoint as well as human endurance capacity, that we have sought to emphasize specifically toward any future exploration opportunity in the years ahead.

Also, the science questions that drive these particular set of destinations may evolve from the fundamental questions of how the solar system evolved, how do humans adapt in space, what is Earth's sustainability and habitability conditions that we need to really be mindful of in terms of our own human behavior that affects our climate condition, and is there life beyond the planet of origin. Indeed, it is a quest that our Space Science Associate Administrator, Ed Weiler, refers to as the attempt to sweep the last crumb of the plate of human arrogance. The notion that somehow we are all there is in this universe is a rather far reach, and so therefore understanding how we go about developing this debate as well as informing it by information and analysis is part of our science question pursuit.

The pursuits are to look at the history of major solar system events, the effects of deep space on physiology, as a consequence of it, and the impact of human and natural events on the earth that seeks to answer: what are we doing to change physically our material condition here on this planet? NASA will also look at the origins of life in this solar system as an immediate confined effort, but also to expand it well beyond to the universe as a consequence of our gaining information that we've achieved from not only the Hubble telescope but also from the soon-to-be operational infrared space telescope.

The activities are planetary sample analysis to look at what the absolute age is of our own solar system, as well as an understanding of how we evolved during the course of this time, measurement of responses to radiation, and indeed, I'm sure we'll discuss that a bit today given the present conditions of a solar event that has and will continue to have an effect on our own habitation here on Earth, the detection of any number of different conditions that need to be informed to assess the capability to survive in any space environment.

The potential destinations to accomplish these science objectives may be in low Earth orbit certainly at this present condition, asteroids, the moon, Mars, beyond the Van Allen belts, libration points, as well as the range of other capabilities or destinations that we can conceive. But they all hinge on our capacity to develop, generate power and power propulsion capabilities to get there and to do it in a way that can sustain that kind of environment for any period of time and safely return, to develop the capability for humans to endure and survive the experience, and to assure those communication capabilities.

Those are the focused primary objectives that we see in this program before you: the development of the strategic plan and this interagency cooperation process that each of you have referred to in your opening statements. These are the kind of linchpins we're continuing to look to in developing a longer-term vision. We do agree that this will in turn require a national kind of focus for that objective that will be turning on the prospect and the capability to conquer these three primary issues that need to be better informed in order to explore any vision or mission objectives that would extend us beyond our present condition.

Again, Mr. Chairman, I thank you for the opportunity to appear. I appreciate it.

[The prepared statement of Mr. O'Keefe follows:]

PREPARED STATEMENT OF SEAN O'KEEFE, ADMINISTRATOR, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mr. Chairman and Members of the Committee, I appreciate the opportunity to appear before the Committee today to discuss NASA's vision for the future of space exploration. As the NASA team works hard to return the Space Shuttle to flight and to resume assembly of the International Space Station, it is important that we not lose sight of where the Nation's space exploration efforts are headed over the long-term. History shows that space exploration endeavors span multiple decades. The decisions that led to the development of the Space Shuttle were made 30 years ago in the early 1970s. Similarly, the decision to initiate the Space Station program was made almost 20 years ago in the mid-1980s. We can expect that decisions made today will guide where and how we venture into the cosmos for decades to come.

That is why I so strongly welcome the opportunity to elaborate on NASA's Strategic Plan for future space research and exploration. While meeting the challenges of today, it is critically important that we not lose sight of the opportunities of tomorrow.

As members of the Committee know, we recently solicited input from Members of the Committee and continue to welcome your ideas. As the exploration vision is developed, the priority, timing, and specifics of some existing programs may change. We will continue to work with Members of this Committee to ensure that the programs pursued are directly aligned with the vision.

In February 2003, NASA released the Agency's new Strategic Plan. This important document is the product of extensive senior leadership debate within NASA. It codifies NASA's Vision of improving life here, extending life to there, and finding life beyond which we hope to achieve by advancing our Mission goals of understanding and protecting our home planet, exploring the Universe and searching for life, and inspiring the next generation of explorers. The Strategic Plan sets the framework by which decisions on future NASA activities will be made, lays out a long-term blueprint for future space exploration, and describes the goals that the NASA team is committed to achieving for the American people.

NASA released our Strategic Plan months before the law required, because the Agency is serious about our Vision and Mission and linking our budget priorities to the goals identified in the Strategic Plan. Early release of the Strategic Plan also ensured it was available during Congressional consideration of NASA's FY 2004 budget.

NASA's Vision

The NASA Strategic Plan begins with the NASA Vision. Instead of compiling a list of everything NASA does, the Agency made a conscious decision to develop a short, concise, and compelling vision statement. Thirteen simple, but powerful, words comprise the NASA Vision. It includes only the most compelling reasons why the Nation invests in aeronautics and space research and articulates how NASA will contribute to America's legacy for future generations.

To improve life here

The first part of NASA's Vision, "To improve life here," encompasses the terrestrial and tangible benefits of NASA research. NASA aeronautics research develops technologies that make air travel safer and more efficient with fewer environmental impacts. NASA's Earth Science research informs decisions on global change by taking advantage of the unique vantage point of space to help scientists develop a comprehensive understanding of the complex interactions between Earth's atmosphere, lands and oceans. The demands of NASA space missions drive technological innovation across a range of industrial and national security sectors. Through space research, scientists are developing new medical devices and approaches to the fight against deadly diseases. These and many other benefits represent the tangible return from investments in NASA research. With NASA's vision achieved, future engineers will look back at the Agency's work and credit America with solving some of the most pressing transportation, environmental, and technological problems of our time.

To extend life to there

The second part of NASA's Vision, "To extend life to there," inherits and expands on the great American tradition of pioneering exploration. As President Bush has so eloquently stated, "This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart." Since the epic voyage of Lewis and Clark, America has shaped the future by pioneering the frontier. From John Glenn's historic flight in 1961 to the twin rovers currently on their way to Mars, NASA has become the modern-day expression of this tradition. NASA pushes the bounds of human experience and delivers new vistas for human activity. In doing so, NASA ensures American leadership on the frontier and into the future, inspires the American public and the world, and motivates the next generation of scientists and engineers. With our vision achieved, future explorers will look back at NASA's work and credit America with pioneering our solar system's frontier.

To find life beyond

The third part of NASA's Vision, "To find life beyond," seeks answers to questions asked by philosophers, theologians, and scientists since the time of the ancient Greeks. What is our place in the universe? It is the part of our vision has undergone the most change in recent years. A little over a decade ago, there was practically no evidence from our science missions and telescopes that habitable worlds existed beyond Earth. Our cosmos appeared to be a beautiful, but desolate, universe. Much has changed over the past decade. Science missions have found evidence for water, a key ingredient of life, on the planet Mars and some moons of Jupiter. Telescopes have found evidence of over 100 planets circling stars beyond our solar system. Scientists have found life thriving in environments on Earth that were previously thought to be barren. Taken together, these lines of investigation indicate that we may be on the verge of finding life beyond Earth within our lifetime or the lifetime of our children. It would be a profound discovery, a watershed event in human history. As President Bush has stated, "We are that part of creation that seeks to understand all creation." With our vision achieved, future researchers will look back at NASA's work and credit America with the greatest scientific discoveries in human history.

NASA's Space Exploration Strategy

The NASA Strategic Plan fundamentally changes our approach to space exploration. We achieved the marvel of the Moon landing, an incredible accomplishment that has shaped much of NASA today, driven by a great external imperative, the Cold War. That imperative drove our Nation to focus on sending humans to a single destination, the Moon, within a fixed timeframe, a decade. Although a great achievement in human history, the Apollo effort was not sustained. If we are to achieve our vision and send human explorers into the solar system, we must have a more flexible and sustainable strategy.

Scientific inquiry and discovery will guide where and how often we go. We hope to go when new capabilities allow us to do so in a sustainable fashion, so that we can return to that destination when needed and move deeper into our solar system in the future. We will use human and robotic teams to explore as we move out into the solar system.

This strategy provides the framework from which decisions about where, when, and how the next steps in human space exploration will be made.

Human and Robotic Teams

A fundamental element of NASA's space exploration strategy is the use of human and robotic teams to advance our exploration objectives. History shows that space exploration can only be comprehensively performed when robots and humans are used together. Each brings unique capabilities. Robots go where it is still too dangerous for astronauts to go, or perform repeatable or predictable tasks for which astronauts are not necessary. This was the role of the robotic Ranger and Surveyor missions to the Moon that preceded the Apollo astronauts. Astronauts, however, bring the incredibly adaptive tool of the human mind to the frontier. Astronauts provide an ability to reason, learn, plan, react, and manipulate in ways that robots cannot. This has been the role of the astronaut missions supporting the Hubble Space Telescope. Similar relationships between humans and robots can be found in deep-sea exploration today and in the history of the Russian space program.

As the Mars Pathfinder mission showed, the growth of the Internet and high-bandwidth communications offer new means for involving the public directly in the experience of exploration. But only astronauts can translate the adventure of exploration for those back on Earth and provide the human element that puts images from other worlds into full context.

Stepping Stones

The second element of NASA's space exploration strategy is our plan to use stepping stones to reach ever outward in our solar system. This acknowledges that there are many desirable destinations for future human and robotic space exploration and many different pathways between these destinations. Stepping stones include both destinations that are likely to be the focus of intense research and investigation, as well as destinations that provide a convenient testing ground for new exploration approaches and capabilities.

Research over the past decade has identified three destinations that appear to be key to the NASA Vision of finding life beyond. These three destinations will likely be the major research focus of future space exploration. They include:

- The planet Mars, once thought to be a dry and barren planet, is now believed to harbor significant quantities of water ice beneath its surface. Evidence from recent science missions indicates that liquid water may have flowed on the surface of Mars in the distant past and may occasionally erupt onto its surface today. Where there is liquid water, there is the possibility that life may have developed—or even still exists. Through the rest of this decade, NASA will be sending seven spacecraft to Mars, including four landings and three rovers. The first two rovers, the twin rovers Spirit and Opportunity, will arrive at Mars next January.
- The moons of Jupiter, including Europa, Ganymede and Callisto, were once thought to be worlds locked in ice. Evidence from our highly successful and recently completed Galileo mission indicates that these worlds likely harbor planet-wide oceans underneath their icy surfaces. Again, where there is liquid water, there is the possibility that life may have developed. We are planning a breakthrough mission, called the Jupiter Icy Moons Orbiter (JIMO), which will undertake an in-depth, three-year investigation of these worlds early next decade, map out their oceans, and understand their potential for life.
- Planets beyond our solar system, include over 100 that have been discovered to date. We plan to launch two space-based telescopes this decade that will likely identify hundreds, and possibly thousands, of additional planets circling other stars. Most will be very large planets not suitable for life, but there is the possibility that we may begin to identify planets that are closer in size to our own Earth. Eventually, we may want to erect highly capable space telescopes at locations above low-Earth orbit, called "libration points," to characterize and image these Earth-sized planets.

Depending on what our robotic and telescopic trailblazers find at these destinations over the next decade-and-a-half, we will be in a position to know where to send much more capable human and robotic teams to undertake extensive research in the years that follow.

Building Blocks

The third element of NASA's space exploration strategy is the use of "building blocks." This acknowledges two key facts. First, a handful of enabling capabilities are necessary to conduct in-depth exploration of our solar system and beyond. Second, it is desirable to develop these capabilities in a flexible way so they can be used to support missions to more than one destination. There are many necessary building blocks for sustainable exploration, including reliable and affordable launch, intelligent robotics, high-bandwidth communications, lightweight materials, and modular and reusable components. But three building blocks that we will likely need for future human exploration are:

- *Crew Transport*—Reliable, safe, and affordable transport of astronauts from Earth's surface to destinations in space is a critical component of any future human exploration effort. We are working to determine the best way to replace the Space Shuttle for crew transport to and from the International Space Station, as well as provide key building blocks for transporting crews farther into our solar system.
- *Crew Health*—To safely sustain human operations for long periods of time beyond low-Earth orbit, we will need to know how to protect astronauts from the dangers of space flight and ensure they remain productive in various space environments. This research is already being carried out on the International Space Station, which provides the database from which medical countermeasures to the effects of low-gravity can be developed. Other research being carried out on the ground, including radiation research and life support systems research, is also critical to overcoming the limitations of the human body for exploration deep into our solar system.
- *High Energy Power and Propulsion*—New capabilities are necessary to overcome the constraints of mass, energy and time that limit our current exploration missions. Today's robotic probes often operate their instruments on the same power as a light bulb and are highly constrained in when, how often, and how quickly they can visit planets and moons. The lifetimes of robotic rovers are limited to months by their power systems. If we are ever to send humans deep into our solar system, we will need more power and improved propulsion systems. Project Prometheus, a new NASA program started last year, is developing power and propulsion capabilities that will greatly enhance current robotic missions, enable new classes of robotic missions, and provide a key building block to enhance future human missions.

Eyes On the Future

In closing, I would like to paint a picture in words of where the space exploration strategy laid out in the NASA Vision and Strategic Plan will take us in the future.

Imagine a time in the not too distant future.

The world, from scientists to schoolchildren, is continually abuzz with excitement over discoveries and achievements made throughout the solar system by teams of human and robotic explorers. Robots roll, crawl, fly, and wriggle into every nook and cranny on the planet Mars, going where astronauts cannot, in the search for ancient and present life. Astronaut scientists at Martian outposts direct this robotic search and analyze specimens, reasoning in ways robots cannot, to understand the history of life on our sister planet.

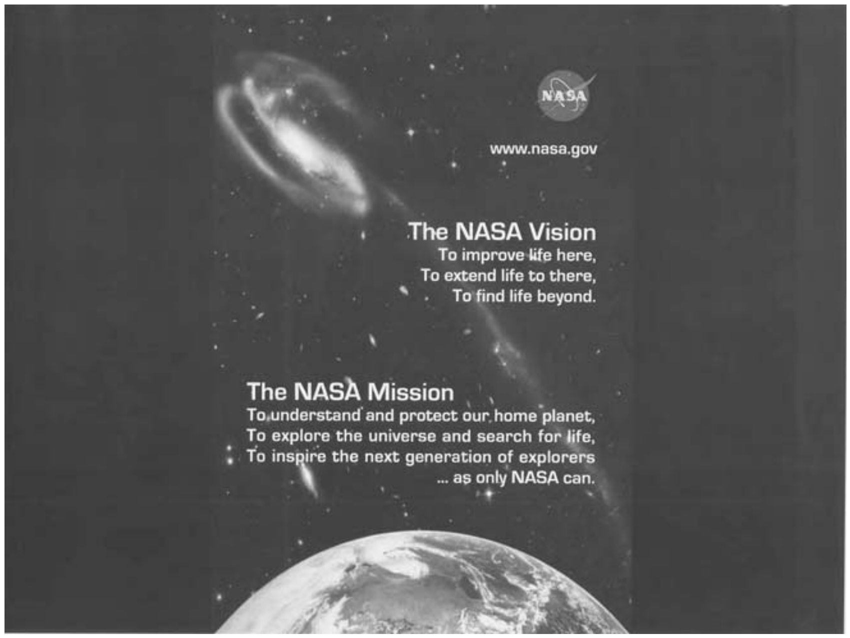
Closer to home, astronaut engineers troubleshoot construction problems as robots assemble and maintain constellations of space-based observatories in Earth's neighborhood. These observatories provide breathtaking images of continents and oceans on Earth-like planets around other stars and unprecedented precision in understanding and predicting the global cycles of our home planet.

At the edges of our solar system, robotic divers plunge the watery depths of Jupiter's moons, mapping dark oceans and illuminating their potential inhabitants. Streaming video is sent back to Earth from these and other locations, allowing researchers and the public to experience the exploration of new worlds firsthand.

The space systems necessary to enable this vision, such as enhanced power and propulsion, intelligent robotics, high-bandwidth communications, lightweight materials, and modular and reusable components, have driven cutting-edge research in key sectors such as information technology and nanotechnology. Private industry and government employ these tools to benefit the economy, homeland security, and national security. The peaceful application of American technology is credited with opening the solar system frontier for humanity, and the United States has gone down in history as the Nation that made the biggest scientific discovery of all time, life beyond Earth.

This is the future of space exploration if we faithfully implement the vision and strategy laid out in the NASA Strategic Plan. I sincerely appreciate the forum that the Committee provided today to highlight the NASA Vision and Strategic Plan, and I look forward to the opportunity to respond to your questions.

ATTACHMENT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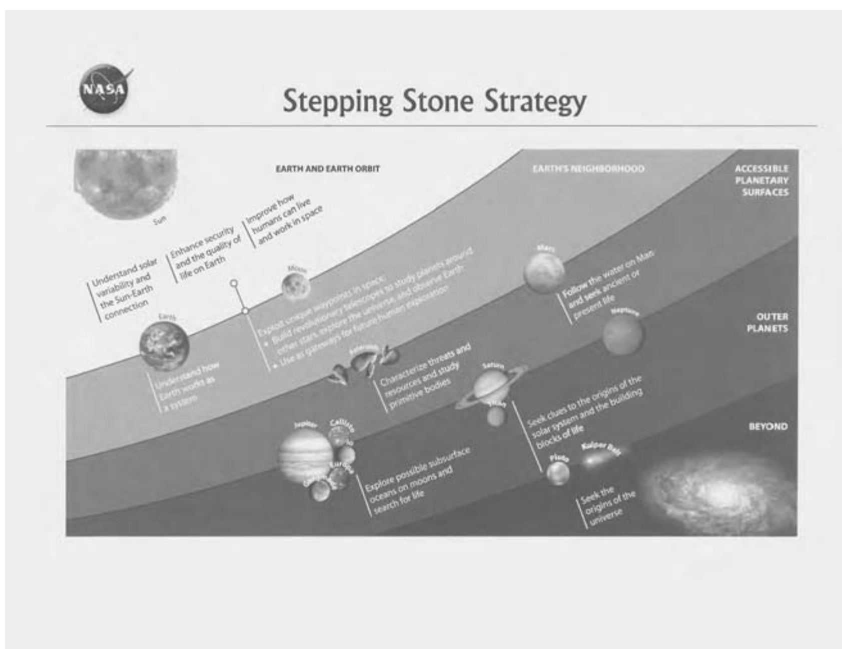
To improve life here,
To extend life to there,
To find life beyond.
The NASA Mission
To understand and protect our home planet,
To explore the universe and search for life,
To inspire the next generation of explorers
... as only NASA can.


Stepping Stone Strategy
EARTH AND EARTH ORBIT
EARTH'S NEIGHBORHOOD
ACCESSIBLE PLANETARY SURFACES
OUTER PLANETS
BEYOND
Sun
Understand solar variability and the Sun-Earth connection
Enhance security and the quality of life on Earth
Improve how humans can live and work in space
Earth
Understand how Earth works as a system
Exploit unique waypoints in space:
• Build revolutionary telescopes to study planets around other stars, explore the universe, and observe Earth
• Use as gateways for future human exploration
Characterize threats and resources and study primitive bodies
Mars
Follow the water on Mars and seek ancient or present life
Saturn
Titan
Seek clues to the origins of the solar system and the building blocks of life
Jupiter
Callisto
Explore possible subsurface oceans on moons and search for life
Pluto
Kuiper Belt
Seek the origins of the universe

Strategic Building Block Investments:
High-Leverage, Broadly Enabling Capabilities

Technological Barriers

Power: Providing ample power for propulsion and science

Transportation: Providing safe, reliable and economical transportation to and from space and throughout the solar system

Human Capabilities: Understanding and overcoming human limitations in space

Communications: Providing efficient data transfer across the solar system

FY 2003 Request

Nuclear Systems Initiative
- Greatly increased power for space science and exploration

Integrated Space Transportation Plan
- Orbital Space Plane
- Extended Shuttle Operations
- Next Generation Launch Systems

In-Space Propulsion Program
- Efficient Solar System Transportation

Space Station Restructuring
- Research Priority Focused
- Management Reforms
- Sound Financial Base

Bioastronautics Program
- Roadmap to address human limitations

FY 2004 Request

Project Prometheus
- Nuclear power and propulsion for revolutionary science and orbital capabilities
- First mission to Jupiter's Moons

Human Research Initiative
- Accelerate research to expand capabilities
- Enable 100-plus day missions beyond low-Earth orbit

Optical Communications
- Vastly improve communication to transform science capability
- First demonstration from Mars

Science Drivers Determine Destinations
(Selected Examples)

	Science Questions	Pursuits	Activities	Destinations
How did we get here?	• How did the Solar System evolve? 	• History of major Solar System events	• Planetary sample analysis: absolute age determination "calibrating the clocks"	• Asteroids • Moon • Mars • Venus
	• How do humans adapt to space? 	• Effects of deep space on cells	• Measurement of genomic responses to radiation	• Beyond Van Allen belts
Where are we going?	• What is Earth's sustainability and habitability? 	• Impact of human and natural events upon Earth	• Measurement of Earth's vital signs "taking the pulse"	• Earth orbits • Libration points
Are we alone?	• Is there Life beyond the planet of origin? 	• Origin of life in the Solar System • Origin of life in the Universe	• Detection of bio-markers and hospitable environments	• Cometary nuclei • Europa • Libration points • Mars • Titan

The CHAIRMAN. Thank you very much. Admiral Gehman, welcome back.

STATEMENT OF ADMIRAL HAROLD GEHMAN, USN (RET.), CHAIRMAN, COLUMBIA ACCIDENT INVESTIGATION BOARD

Admiral GEHMAN. Thank you very much, Mr. Chairman. Senator Hollings, thank you for quoting from our report. That's the same passage I chose to open my remarks with. I won't repeat it except to say that the board stands by those remarks. The institutional causes of this accident were just as serious as the foam, in our opinion.

When we wrote this great big 248-page report, which we are very proud of, we had three goals in mind. The first one was to determine whether or not the shuttle itself is safe or could be made safe, and we made 15 recommendations that are return-to-flight type of recommendations to make the shuttle itself safe.

The second goal we had in mind was to cause NASA to change the way it does business because we don't like their engineering and safety practices. We wrote in the report and I quote, "that the shuttle program in its present organizational arrangement is essentially unsafe in the long term."

The third goal we had in mind was to cause a national debate to cover two topics. One is what we call a lack of an agreed national vision of what it is the United States wants to do in space; second, the great disappointment that the board found, particularly those of us that don't follow NASA very closely, that here we are in 2003 and we do not have a replacement vehicle for the shuttle even on the drawing board, much less in production, and we are years and many years away from a replacement vehicle. So driving a debate to answer those two things is one of our goals.

I think this hearing is very important to get that debate started and get some energy into it and I'm delighted to appear and offer whatever help I can. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you very much, Admiral, and again, welcome back. I'm not sure you're as glad to be back as we are to have you back. We thank you.

Administrator O'Keefe, the *Washington Post* yesterday reported that Congressman Sherwood Boehlert, Chairman of the House Science Committee, asked you to suspend the orbital space plane program. The Post reported that Congressman Boehlert stated that, "Until the Nation develops a shared vision to guide such projects, public support for the Nation's civilian space program will inevitably founder." What's your response to Congressman Boehlert's statements?

Mr. O'KEEFE. Yes, sir, we are preparing that now as a matter of fact. It will go over today and I'd be happy to send a copy here to this Committee. The approach we've taken is to respond to requests and entreaties that we examine what it would take in order to accelerate the development of a crew transfer vehicle. What we've been engaged in with absolutely no commitments at present is the development of all the requirements necessary to support what a crew transfer vehicle would look like, and we have begun developing the requests for the proposal. That won't even be issued under the present plan until early December, late November at the earliest, and there's no contract envisioned to be awarded even under this accelerated approach until August of next year.

So in deference to the concerns that the House Science Committee has raised in terms of us getting ahead of the headlights, if you will, and awarding contracts prior to the concurrence of Congress in this approach we have developed, we are pursuing that which is consistent with what's included in the President's budget for Fiscal Year 2004 with the alternative of looking at what an accelerated approach would take. But that would not be operational until next summer at the earliest. So as a consequence, we concur in Chairman Boehlert's concern that we not be ahead of that and are not planning to do so. We are making preparation for that outcome should that be desired.

The CHAIRMAN. Admiral Gehman, the CIAB report states, "It does believe that NASA and the Nation should give more attention to developing a new concept of operation for future activities, defining the range of activities the country intends to carry out in space that could provide more specificity than currently exists." It states further the "Concept of operations should help identify the capabilities required and prevent the debate from focusing solely on the design of the next vehicle."

Would you expand a little bit on this concept of operations and the role that Congress should play in its development. By the way, I notice that the appropriators don't seem to be as concerned as many of us since they added $81 million in pork for NASA on the appropriations bill. Go ahead, Admiral.

Admiral GEHMAN. Mr. Chairman, the board is in its deliberation as to how long the service life of the space shuttle as we know it now should be. The board decided to take a look at the status of the shuttle replacement, and we were trying to determine whether or not the shuttle could be made to last 5 years, 15 years, 20 years. We wanted to know, what's the United States' plan to replace the shuttle and how long does it have to last?

We were somewhat surprised to find that the United States doesn't have a replacement for the shuttle. So we scratched our heads and we did a little research and decided to look at the previous programs, X–33 programs, X–34 programs, and other programs, and found that $1 billion had been spent here and $1 billion had been spent there. The program lasted 2 years or 3 years and then was stopped. We found some common reasons for all of this start-stop, start-stop, which was that the institutions, including NASA, Congress, the White House and the contractors, and I don't want to point blame at any one entity, tried to design the vehicle before they decided what they want the vehicle to do.

It seemed that every time an engineer or a scientist came forward and said getting out of Earth's orbit and getting back into the atmosphere is very, very difficult and very dangerous to do. Going to Mars is easier than getting in and out of the Earth's atmosphere, and if we could just get out of the Earth's atmosphere and back in again safely that would be a giant engineering step. Yet when somebody comes forward with such a modest goal, it costs a lot of money, and the program doesn't fly.

So we felt that it was very important for there to be an agreement on what you want to do and then let the design of the vehicle follow from an agreed mission. And I'll admit that we were biased, because we examined the shuttle in the *Columbia* accident right down to the millimeter, and we became convinced that strapping human beings on top of several million pounds of high explosives and then launching them to defeat the laws of gravity and to get up to 17,500 miles an hour and then trying to dissipate all that energy to come back into the Earth's atmosphere again is very, very dangerous and always will be dangerous, and we're not very good at it.

We suggested that we try and agree on what we want the vehicle to do, while trying to limit our appetite and then go out and design the vehicle, and that was our approach. I hope that answers your question.

The CHAIRMAN. It does. It also has to be something that Americans can be excited about and be committed to. I'm afraid that's been lacking recently in NASA's agenda, but——

Mr. O'KEEFE. Mr. Chairman, can I quickly comment?

The CHAIRMAN.—time is short but go ahead.

Mr. O'KEEFE. Just very quickly. I concur exactly in Admiral Gehman's assessment of the history as well as what led us to this with one further addition. Every previous attempt appears to have counted on either a suspension of the laws of physics or a miracle, an invention to be developed during the course of its activity in order to achieve the objectives it looked to.

What we're trying to do with the orbital space plane and a crew transfer vehicle, precisely what the board report has recommended, which is to separate the crew from the cargo, develop a capability that is based on known technologies that presses the edge of what that technology can do in order to provide a crew transfer system back and forth.

So I think Admiral Gehman is dead on-point in terms of his assessment of what have caused the prior stops in this case, but your point, Mr. Chairman, is also exactly right on. It's got to be something that's going to excite the imagination and be based on necessary technology leaps that do not require or imply that a suspension of the law of physics is required in order to achieve it. It can't be done.

The CHAIRMAN. Senator Hollings. Thank you.

Senator HOLLINGS. Well, Admiral Gehman, it really depends on the President's appetite. Senators go in one direction, House Members go in another, experts suggest this, other experts suggest that. If I were the President, I'd take Admiral Gehman and several members from your commission that's been working all year long now and have been debating and everything else, plus perhaps some others of national talent and package them together and say, go to it now and finalize the Gehman commission report with a vision and a plan and a program. Do you think a Presidential commission is the proper approach, a good approach?

Admiral GEHMAN. Yes, sir. I'm not an expert in Washington dynamics here, but clearly

Senator HOLLINGS. You're the only one making sense. Go ahead.

Admiral GEHMAN. I support anything which will activate the debate and also put the debate in some kind of order, which a commission would do. There may be other ways too, but yes, sir, I would support anything that would cause the branches of the Government plus the scientists and engineers to be forced together to come up with an answer.

Senator HOLLINGS. Right. Now with respect to Mr. O'Keefe, you seem to be long on vision of space but short on the safety of space. You come up and perform and you take me and I'm following you and everything's happy and then I pick up the newspaper and you don't seem to know what's going on. Who knows what's going on over there at NASA? Who's responsible? In other words, you didn't know anything about *Columbia* until it happened. That's correct. Apparently, you didn't know anything about the safety going, sending these astronauts back up to the state station until it just about happened and you had members signing off down below and everything else, saying the air and the water quality were unsafe, they wouldn't give clearance and everything else and you let it go, and when asked, you answered, well, if they're running out of air, tell them to come on home.

Now, that's what I saw. Now, that bothers me that nobody seems to be in charge of safety. Who is over there in NASA?

Mr. O'KEEFE. Thank you, Senator. That's a very important line of inquiry and I appreciate you raising the question. I am responsible. I am accountable for this agency. In contrast to the press reports, I assure you I knew exactly what was occurring leading up to the flight readiness review for Expedition 8. There were two scientists, two technical folks in the medical operations division that were concerned about environmental monitoring and the caliber of that equipment and its sustainability over time, not its present condition, as well as the quality of the exercise equipment that is necessary in order to keep the physiological standing of the astronauts up to standard.

They raised concerns to their superior, who is essentially the chief medical officer at the Johnson Space Center, who in turn heard those issues, decided that safety of flight considerations were a problem, and raised that at the flight readiness review and brought them in to attest to that point. I understood there to be a persistent concern thereafter on the part of these two medical operations folks, so I therefore asked that there be a reconvening before the Expedition 8 flight occurred to make sure that all those issues were vetted again. Their expressions of comfort were that there was adequate samples coming back on the Expedition 7 flight, which just arrived the night before last, in which there was a specific set of samples that we can now test and monitor to assure the crew's safety and condition.

I spoke to the international space station crew members on Monday as well, and as a consequence of this issue we have the samples back, we're going to analyze them, but there is no safety of flight considerations that the crew feels is necessary. So, notwithstanding the press accounts on this, I assure you, sir, I'm aware of it, worked through it, took extra means to assure that we'd run the question to ground before the flight took off. I went to Moscow myself then flew to Kazakhstan, witnessed that flight, spoke to the astronauts involved, and assured that all of the factors had been run to ground.

So all that considered, the last gasp in this case is that if everything else were a problem, yes, indeed, they could return and leave the international space station. But nothing at the present time would suggest there is any safety of flight considerations. I have met with the two folks who had those initial concerns when I went to the Johnson Space Center last Friday. This an exercise of due diligence I view as part of my responsibility. I am following through on that, sir.

Senator HOLLINGS. Admiral Gehman, what's your comment? Are the safety systems there adequate?

Admiral GEHMAN. Senator, I don't have personal knowledge of the safety systems; I don't have personal knowledge of this particular incident. I'm just relaying to you what was in our report, which is that it seemed that in the shuttle program, remember we only looked at the shuttle program, we didn't look at all of NASA, the motto of proving that it's safe had been changed to prove that it's unsafe. Here is a situation in which, if you had the motto that said prove it's safe, you would have a hard time doing that if your monitors weren't working and your test equipment wasn't working.

Now the question is, whether NASA has fallen back into the unhealthy attitude, which we accused the shuttle program of doing, of having to prove that it's unsafe to get anything done. My understanding of this situation is that did not happen. In other words, people raised concerns, they didn't have to prove it was unsafe, which is what happened to the picture takers and the engineers in the case of the shuttle, so it sounds like they're listening.

But, once again, if you took as a rule in space flight that you had to prove it's safe and your monitors aren't working and your test equipment's not working, then it looks to me like you're headed toward thin ice.

Mr. O'KEEFE. If I could add just one quick point. Admiral Gehman is exactly right. We have turned that cube and required that we prove that it's safe. The concern raised by the two folks within the medical operations community was that it is safe right now, but over time we can't attest to the possibility safety that may degrade. The decision—the risk return judgment, or risk management judgment—was made in terms of what remedial action we have to take in order to assure if there are failures our ability to monitor that condition.

I think the theme that Admiral Gehman has talked about is exactly right. We have tried to change this to a point of open communications. We want to hear every point of view, and frankly I'd be nervous if there were not issues raised. If everyone was of unanimous view, we'd want to go out and seek a minority position in order to make sure we weren't talking ourselves into something.

Senator HOLLINGS. Well, Mr. Administrator, how is it that Internet had to inform you of the safety concern?

Mr. O'KEEFE. No, sir, I was informed by the flight readiness review reports that occurred on or about the second of October, if I remember correctly, that those issues had been raised. What I got through the Internet was a continuing indication that all the way up to 3 or 4 days before the flight that there were still lingering issues that had not been fully resolved or were not vetted properly. So rather than leave that confusion, I asked that there be a reconvening of that whole discussion before the flight occurred, so that everyone involved, every single interested party, expressed those concerns again and be sure that we have the analysis on the table to prove that it's safe.

I think the point Admiral Gehman makes is exactly on as to the approach we took to this. In the end, the risk judgment was made that on the present condition this is a future concern that we have to continue to monitor. We have to prepare the capability to replace equipment on future logistics flights that are going to the international space station. But at the present time those concerns were enjoined, they were vetted, they were argued, and in turn analyzed in terms of how we respond to them. The comfort level was high before that flight ever occurred, and indeed that's what happened.

The CHAIRMAN. Senator Hutchison? Senator Brownback?

Senator HUTCHISON. Is that the right order? Are you sure? Well, let me just ask you, Mr. O'Keefe recently I met with Buzz Aldrin and I know that you are familiar with his concerns that NASA is abandoning the heavy-lift capabilities and looking at the orbital space plane to take people to the shuttle or to the station. My question is, will the orbital space plane have the ability to take equipment and will it be able to take what is necessary to do major repairs to the space station in the future, or are his concerns warranted?

Mr. O'KEEFE. Yes, thank you, Senator. The very clear direction that we've taken with the orbital space plane is consistent with the *Columbia* Accident Investigation Board's report, which is to separate the crew from the cargo, and as a consequence, this is a crew transfer vehicle, or envisioned as such. The continuing effort that we're going to work with here is to answer how you then provide the cargo capacity, whether you do it by a number of commercial options, and whether you develop a cargo lift capacity. The arrival now of the ATV system, which the European space agency will be delivering in September of next year, now supplements very dramatically what we have in terms of logistics and cargo capacity on the progress vehicles by a factor of about three.

As a result, the cargo support for the international space station will be well covered once the shuttle returns, and ATV arrives. Right now, we're really restricted to the progress vehicles, which are unmanned in capability. But no, the orbital space plane, as envisioned and based on the requirements, is consistent with the board's recommendation that we separate the crew from the cargo, and I think the issues that are raised by others as well is, what is going to provide for that cargo capacity? And we need to address that question as well and I think we're down the road toward meeting that particular concern too.

Senator HUTCHISON. So you're looking at some kind of an unmanned vehicle that would take cargo?

Mr. O'KEEFE. Yes.

Senator HUTCHISON. And you believe that would provide any kind of repair equipment capability needed for the space station, and it isn't going to be left up there damaged and not have a capacity to be fixed?

Mr. O'KEEFE. Yes. Part of what we're doing in our return to flight efforts now is to develop the on-board repair capacity that could be lifted by shuttle, brought to the international space station, and stored aboard international space station for exactly those eventualities, as well as on shuttle or any other vehicle that would be required. So that's part of what the first couple of flights after we return to flight will really be demonstrating is our capacity to do it, and fortunately, a lot of the options we're looking at today are dramatically reduced in terms of weight requirements, space requirements, all that, and some of the solutions are really pretty straightforward that should not be a show-stopper in terms of mass or requirements for stowage.

Senator HUTCHISON. Can you give us any ballpark estimate of when our next space shuttle would go up?

Mr. O'KEEFE. Well, based on the return to flight plan that we have been proceeding with, if all the options are selected and are implemented, I think we have to be really driven by the milestone objectives of complying with 15 recommendations specifically, and all 29 recommendations contained in the report as well. If those milestone objectives are hit and we are able to do this on the pace that we think based on today's option set, it is conceivable. We could be looking at late summer, early fall as a prospect. That said, we're going to be driven by the milestones and when we are fit to fly that's when we're going to engage in it, not before. The calendar's not going to drive this.

Senator HUTCHISON. Let me just ask you a bigger picture question. I know since the accident there has been a lot of give and take about the future of NASA and I would just ask, number one, do you still consider the space station a core mission for NASA? Let me stop there and ask my second question.

Mr. O'KEEFE. Well, consistent with the strategies that we talked about a little bit at the opening statement, the space station's greatest utility at this point is to have us gain a clear understanding of what the human endurance, the physiology requirements are for any space exploration objectives. We're learning a lot as a capacity of a continuous presence in space, now pushing almost 3 years. Next year will be the third continuous year of human presence in space.

Beyond that, the science that we can yield from the research that's performed aboard the station is justified as well. Yes indeed, it is a core requirement that we view as necessary to inform the human endurance approaches that we need for any exploration objectives beyond low Earth orbit, and to understand, I think, the science yield that is yet to come that is really quite promising in that regard. We view it as an important requirement.

Senator HUTCHISON. Last question. Do you envision a big announcement about the reinvigoration of the commitment to NASA at some point in our future? Because we've all known that you're studying, that there are commissions, there are ongoing efforts at the White House to determine what we ought to be doing. Do you envision an announcement about what NASA's future is?

Mr. O'KEEFE. In our discussions that several members of the Committee participated in with the Vice President, I think the understanding clearly is that there is an interagency process underway in which we are looking at various options for the vision objectives as well as the strategic modification to this basic plan we have presented. To the extend that the President decides on those options, that would be attendant with whatever manner in which he would see appropriate to release that. Certainly we remain hopeful that that is achievable. We're doing our best to support that outcome, but that is entirely his choice, and I would not want to foreclose or preclude his options in that regard.

The CHAIRMAN. Senator Nelson?

Senator NELSON. Mr. Chairman, to continue the line of discussion earlier, I take it that in your plan for an orbital space plane to take the crew to and from the space station, assumes an unmanned vehicle for cargo. What are your plans to make the space shuttle unmanned as a vehicle to carry cargo and when would that occur?

Mr. O'KEEFE. Yes, sir. That is an option, that is one approach that could be examined, an autonomous capacity on shuttle is one of the means that could be examined for a cargo lift capacity. It's got an impressive capability for that purpose. But again, consistent with the comments I think Admiral Gehman offered earlier, there is no replacement of shuttle per se, because the notion that somehow there would be a crew capability and a cargo capacity embodied in the same asset is part of the reason that drove the board, I believe correctly, to say separate the crew from the cargo.

So this is one option, one approach that could be used. There are others that are under examination and certainly there are a lot of commercial alternatives that have been proposed and certainly advanced to several members here as well as others, and so which approach would be taken in that case we're hoping to converge on here pretty quickly, but that is one option.

Senator NELSON. You know, Admiral, there's an interesting parallel in your report to 17 years ago to the Rogers commission report, because the space shuttle had been developed to be the space transportation system. That's why it was called STS, and it was to do everything to and from space. As a result of the destruction of *Challenger,* the Rogers commission said, what you ought to do is separate out those cargos that can go that you don't need the human in the loop, and save the space shuttle for those particular missions.

Now, 17 years later we've got another iteration as a result of your commission. You're actually saying, let's develop a new vehicle that is much safer to go to and from for humans and put your more difficult kind of cargo payloads on something that is not quite as reliable. So in that regard I guess we better get upon the matter of developing the space plane. It looks like the House of Representatives is beginning to give you some heartburn, Mr. Administrator, so we better have a couple of prayer sessions to see what we can do, because as the Admiral has said, in the meantime we're going to have to fly the space shuttle and humans are going to have to be on it, and we've got to make it as safe as possible. But there's a long lead time and we've got to develop these new technologies.

Mr. O'KEEFE. Yes, sir. Well, as for the heartburn I keep Rolaids handy all the time as well as Advil, so it's a daily condition. There's not a problem in that regard. But it is I think a situation where the concerns addressed by the House in this case are legitimate in that we not get in front of the headlights beyond what the administration has proposed. And that's exactly what we're pursuing right now. We're not committing the administration or the Congress ourselves beyond the scope of what is contained in the budget today.

That said, we are exploring the option to accelerate, and to the extent that that would be pursued there would be ample opportunity to review. That question would be incorporated as part of the President's proposal, as part of 2005 as well as the Congress' consideration of such a move well before any contract award in that case, so I think we can work our way through this, but we are trying to prepare ourselves as a matter of due diligence to make that option possible rather than something that we begin with with a clean sheet of paper were that chosen as an approach.

Senator NELSON. Let me ask you another question about the future of NASA, which is the subject of this hearing. I don't see a direct objective for human exploration and you've already stated that that's a decision that would be made by the President. So do you need a directive, a direct directive from the President for us to state our goal?

Mr. O'KEEFE. Well, the stepping stone chart, strategy that was laid out as the second one, would envision the prospect of human exploration beyond low Earth orbit, but the emphasis in the strategy, I think, is to really emphasize the question of let's develop a technology and capacity to make that kind of vision, that kind of dream a reality. And in two we develop the power generation and propulsion capabilities, do so, beat the human endurance challenges that we believe are persistent as well as to assure communications, we are not in the mode or position to do anything more than establish that as a goal or a dream, and so therefore to permit that to happen, this is going at it from the direction of technology development, no question.

Senator NELSON. Well, how do you go about getting that directive out of the White House?

Mr. O'KEEFE. Again, I think process that is underway at present with the interagency effort that, again, you were party to the effort with the Vice President's solicitation of views and approaches on how we could proceed with that, they are being taken very, very seriously and that is being vetted and I'm optimistic that we'll see clarity in that regard at whatever period of time the President so chooses.

Senator NELSON. Mr. Chairman, may I just ask one question on the last statement? As you develop your technologies for exploration beyond low Earth orbit, what are the human limitations that you see beyond low Earth orbit and what are you doing to address those?

Mr. O'KEEFE. Yes, sir. Among the many, the three that really impress me as being particularly profound that we really need to get some resolution to, the first is a dramatic reduction in muscle mass, that typically on the course of a 6-month expedition on the international space station, even with the exercise equipment and the various physiological regimes that we've developed for that, it is not atypical to see about a 30, 25 to 30 percent muscle mass loss in that span of time.

Same is true of bone mass. It is as high as about a 10 percent bone mass loss as well. And so as a consequence, with those two alone, while it is regenerative, and it takes about the span of time that it takes during the course of the mission back on Earth for that comparable period of 6 months to be regenerated, it nonetheless is a very rapid degenerative capacity or circumstance that occurs.

The second major variable is the very odd and not understandable from the scientific community's view they're really seeing this as a conundrum while you see a degradation in one sense, you also see a rapid acceleration of cell growth in other area. So trying to understand what this phenomenon, what it's created, why in this particular microgravity condition that's the case is a real severe question that we need to have resolution to.

And the third one is the radiation effect. In low Earth orbit right now, the equivalency of radiation exposure is not dramatically higher than what we would see in lots of other Earth-bound kind of conditions. Beyond 600 miles and up in the Van Allen belt it's a factor of three greater. So surviving that experience without having the bulk and mass of radiation shielding, using material, is something that really is a challenge, because otherwise that requires more propulsion, more power generation, more mass and capability and volume to support something like that. All three of those

The CHAIRMAN. Mr. O'Keefe, I promised to get you out at 10:30 and we have two more questioners. I'd appreciate it if you——

Mr. O'KEEFE. This is the last statement. All three of those are part of the human endurance initiative and human research initiative that's contained in the Fiscal Year 2004 budget proposal to deal with all three of those areas. I apologize, Mr. Chairman.

The CHAIRMAN. Thank you. Senator Brownback and then Senator Sununu.

Senator BROWNBACK. Thank you very much, Mr. Chairman. And Administrator, Admiral, thank you for being here. I've got a chart that I want to put up and make a point with it and ask first, Admiral, you about this, because I think you alluded to it in some of your comments. We've had five starts and stops within the last number of years costing what I've totaled up about $5 billion for various types of replacements for space shuttle.

It's part of my concern right now with going forward with the orbital space plane when we're not exactly sure what all of this is going to be about that we would have the similar sort of thing, we would start, we'd spend a couple billion dollars and not have the vision or zest to move this on forward.

I would ask you, and then I want to ask Mr. O'Keefe, if I could, as well, how can we go about establishing this national vision that will have sufficient buy-in by the public, and zest, that it would keep us from doing a sixth one of these and spending a few billion dollars to do that.

Admiral GEHMAN. Well, Senator, I know that Senator Hollings has proposed a National Space Commission, probably to get at some of these issues. I would offer—and this is in response, also, to a comment that Senator McCain made earlier, and your comment, about the zest—my board studied the Space Shuttle program at Columbia, all the way back to the Nixon years in which they designed the Shuttle, in order to understand how we got to where we are today. And in the course of that study, we became convinced how difficult it is to get into and out of low-Earth orbit. It is extraordinarily dangerous and very difficult to do. And, unfortunately, I think that one of the missions and goals of however we achieve this national consensus is going to have be to convince the American taxpayers and the Congress of the United States, that, whereas it's not very jazzy and not very exciting just to get into and out of low-Earth orbit, we have to do it, and we have to do it more safely than 49 out of 50 times. That's not good enough.

Ten years from now, I anticipate us going into and out of low-Earth orbit every month or every week. So we have to have some way of doing it reliably and safely and inexpensively.

No matter what your vision is for human spaceflight, whether it's Mars or the L2 or the Moon or whatever it is, it starts in low-Earth orbit. It doesn't start on the surface of the Earth. We have no possible way to harness enough energy to large objects all the way to Mars from the surface of the Earth. It'll start from low-Earth orbit.

So we really do need to perfect getting into and out of low-Earth orbit reliably. And in our report, we went and looked at these things, and they essentially failed for two reasons. One was, as Mr. O'Keefe has said several times, they depended upon some kind of a giant technological leap to happen during the course of the program—those giant technological leaps don't happen like that; they are developed by robust research development programs—or the Congress of the United States got disenchanted when they started to go overrun, to cost more, they were behind schedule, and they were costing billions, and finally OBM—either the White House, OBM, or the Congress said, "cease and desist." Well, unfortunately, that's the nature of what we're doing here.

So my answer is, based on our study of how we got to where we are today in the Shuttle Program, and of those the three things is, we need some leadership to say just getting into and out of low-Earth orbit is a goal worthy of itself, without killing a lot of people. And that's hard to argue, because it isn't very jazzy.

Senator BROWNBACK. Let me ask you, Mr. O'Keefe, because I've have sensed your frustration for some period of time on this discussion of vision, as, "Yes, it's great, but how do we get there," we've got to get the Project Prometheus that you're working on, a greater power generation, you've got to get into low-Earth space orbit. As a policymaker, I look at issues that I try to take to the public, and I say you've got to have the vision, and you're saying you've got to have the technology to do the vision. How can we marry those up so that we don't get these unsustainable types of projects?

And we've seen, also, visions articulated that we haven't fulfilled. "Let's go to Mars," and it sounded great, and we didn't do it. But, I mean, there's got to be a thread and some learning that we can take from all of these things, because I don't think you don't get there without a vision. Without a vision, the people do perish on the way. But we also have to have it tied to that technology and a national buy-in that sustains it.

Your thoughts on how we can tie the vision and the technological ability?

Administrator O'KEEFE. Oh, I think you've put your finger right to it, Senator. This is the source of the frustration. And it really has to be done in tandem.

The call for a national debate or a national commission, or whatever, in and of itself, is laudable. No question. But it has to have some focus, some agenda, some specific approach to it that says, let's look at how you develop a consensus for, not only the vision, but the means to get there. Because, you're right, during the course of our history, of recent history, the last couple of decades, we've done all kinds of effort to look at establishing very, very lofty goals, and never attaining it because the technology wasn't developed to achieve it; or we have focused extensively on a number of those failed programs, which all required an invention to happen. They were dependent upon some suspension of the law of physics, or something, in order to make them possible.

So the approach that we're right on the verge of, and I think we're really converging nicely, is, not only an approach that we've advocated of develop a technology based on what you know you can achieve, and with a lot of push that you have to stretch the edge of in order to make it really perform to its maximum extent, and to develop the means to articulate a vision, which several Members have all discussed here, as requiring of national focus, and then asking, potentially, as both you and Senator Hollings have proposed, the notion of a commission to look at that specific agenda, look at that specific focus, and validate it, modify it, amend it, do whatever's appropriate in order to achieve that goal. That could be substantial progress that has defied us for the last three decades, and that would be an incredible achievement if we could do that. I think we're very much on the verge of doing just that.

Senator BROWNBACK. Thank you.

Senator Sununu?

STATEMENT OF HON. JOHN E. SUNUNU, U.S. SENATOR FROM NEW HAMPSHIRE

Senator SUNUNU. Administrator, in your opinion, who is ultimately responsible for setting that vision? Is it our responsibility to enact legislation stating what the vision should be? Is it your responsibility or NASA's responsibility to move forward and articulate a vision that sort of we buy into and then appropriate funds for? Is it the President's responsibility to say, I'm the chief executive, here is the vision that we shall have for NASA, or is something that we need to or we're best deferring to a third party, a commission, if you will? Who's ultimately responsible for that?

Mr. O'KEEFE. Thank you, Senator. I am a traditionalist in this regard. I'm very much of the school that it is the administration, the executive's responsibility to propose and for Congress to dispose in those manners. And in this particular case what we're working on very, very diligently is an interagency effort to provide the best advice we can to frame this debate for the President's consideration, and whatever he chooses is then the point of debate, and I think a commission could help potentially frame the nature of that discussion thereafter.

If you hand in an agenda, it ends up differently than I think what we saw a decade ago, in which everyone was handed a clean sheet of paper to go off and dream something up, and I think the profound comment that came from that was, everyone agrees that there should be a vision and no two people can agree on what it ought to be. This is an attempt where we really have to set that agenda, and I think the President is, certainly dispositionally, prepared to engage in that regard.

Senator SUNUNU. In taking on that challenge as Administrator, you have a strategic plan here for 2003 is there anything in here that you would argue represents that kind of long-term vision? If so, are there things you can point to in the strategic plan that, for those reasons, are somewhat at odds with the current budgetary path? In other words, if you're articulating a new vision and it's not necessarily in the 2003 budget resolution that covers the next 3 or 4 years, what in here fits that description of a leading vision?

Mr. O'KEEFE. I appreciate that. The strategic plan is just that. It is a strategy to achieve the capacity and the capability to aspire to any of those objectives, any of those positions taken. It is the baseline from which we're starting our discussion, debate as the interagency team, and indeed, as part of what is in the President's budget right now is the minimums of what's required in terms of a baseline approach for power generation, propulsion, human endurance, and communications requirements to upgrade to achieve any of those objectives. The vision or the ultimate objective is what, I think, we're working at now as part of the interagency process to serve up to the President for his consideration.

Senator SUNUNU. There was some discussion of the process that was used to deal with the questions raised about safety of flight recently, and I think you described pretty clearly the path that you followed in gathering information, convening an additional meeting to deal with safety of flight questions. Is there anything that you described in that process that is different or new as a result of the findings of Admiral Gehman's commission?

Mr. O'KEEFE. Absolutely. I think we've been profoundly affected by not only the accident but also the very astute observations of the board on what caused it. It was hardware and material failures, but it was also human failures, and many of those human failures turned on our capacity to communicate. So, if anything, I think with this last example leading up to the Expedition 8 launch demonstrates for the flight readiness review, when it's all examined, is an extensive overabundance of coverage of communications for folks to really be in a position where they're free to raise the concerns and issues, and again, I would be alarmed if there were no concerns raised, and indeed would go seeking minority views of this.

The fact that there was, I think, a continual effort all the way up, and leading to the launch had there been lingering concerns I was there in Kazakhstan and would not have permitted that to occur. So the fact that we're all resolved by that point and at least everyone understood what the circumstances were is a very, very hard lesson learned from the communications message that emerged from the accident investigation board's report.

Senator SUNUNU. One final question following up on the point that Senator Brownback made about the series of programs that haven't fulfilled expectations or haven't been technologically feasible—$5 billion is a lot of money even in Washington. In the strategic plan there was some discussion, a nice photograph of the Scram jet, the X–43. What's the status of that? You suggested that there's no money being put into specific product development. You're doing some planning for an RFP if one is appropriate, but what is the status of the Scram jet and does that more appropriately belong on this list as well?

Mr. O'KEEFE. Not necessarily, no. X–43 is proceeding apace, it is part of a cooperative effort of an agreement that we have in place with the Defense Department for their national aerospace initiative that they're pursuing to develop hypersonic capacities, and this begins that long trek in that direction. It is severable and divorced from the question of whether you need a crew transfer vehicle, that's not the intention. But if we are ever to achieve the capacity for a horizontal launch as opposed to a vertical launch system that uses expendable launch vehicles, we've got to begin this process and do it in a way like the X–43 and the Scram jet in developing a hypersonic capacity over time that would make that feasible, but that's not something on the immediate horizon, I don't envision it ever being in a condition of cancellation. I think it's more the one bite at a time approach that has been more characteristic of NASA's history in trying to develop each of those incremental pieces of the technology to get to some objective, and that's what that's after and we're doing it in concert with the Defense Department.

Senator SUNUNU. Thank you.

The CHAIRMAN. I would ask your indulgence for Senator Hollings to ask one additional question.

Senator HOLLINGS. Mr. O'Keefe, this committee has on its plate 17 dead astronauts, including three in Apollo 1, preventable, seven in the Challenger, preventable, and apparently seven preventable in the *Columbia.* Let me read this one statement appearing in this article, if we've got it in the record: "Assuming a starting point on the fifth day of the flight, NASA engineers subsequently calculated that by requiring the crew to rest and sleep, the mission could have been extended to a full month to February the 15th. During that time, the Atlantis, which was already being prepared for a scheduled March 1 launch, could have been processed and made ready to go by February 10. If all had proceeded perfectly, there would have been a 5-day window in which to blast off, join up with the *Columbia,* and transfer the stranded astronauts one by one to safety by means of a tethered space walk." Do you agree?

Mr. O'KEEFE. Yes, sir. It's a very high-risk maneuver, but it's one we certainly would have attempted had there been an indication at that time.

Senator HOLLINGS. So the lessons of the taking the pictures and everything else like that, we could have saved them, and otherwise all you got to do is always have a back-up safety shuttle. You can start a shuttle flight tomorrow. The foam can knock out the side again, and to prevent burning up on re-entry you could have that Atlantis or second shuttle up and save those astronauts. Isn't that right?

Mr. O'KEEFE. Well, sir, that is one approach and it's one that is a very high-risk maneuver.

Senator HOLLINGS. Is something wrong with that?

Mr. O'KEEFE. It's a very high-risk maneuver. But if, by gosh, you're trying to save lives.

Yes, sir, I agree. We would have attempted it. There is just no question in my mind we would have tried had we been aware of that.

Senator HOLLINGS. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you both for your indulgence. Thank you for being here with us today and I can not assure you that this is your last assurance.

Admiral GEHMAN. Thank you, Mr. Chairman.

Mr. O'KEEFE. Thank you, Mr. Chairman.

The CHAIRMAN. Our next panel is Dr. Wesley Huntress, Director of Geophysical Laboratory, the Carnegie Institute; Dr. Robert Zubrin is the President of the Mars Society; Dr. David Woods, Professor, Institute for Ergonomics at Ohio State University; and Mr. Richard Tumlinson, Co-Founder of the Space Frontier Foundation. Welcome to our witnesses, and Dr. Huntress, as soon as you're prepared we'll begin with you, sir, and thank the witnesses for being here, and pull the microphone a little bit closer to you. Thank you.

STATEMENT OF DR. WESLEY T. HUNTRESS, JR., DIRECTOR, GEOPHYSICAL LABORATORY, CARNEGIE INSTITUTION OF WASHINGTON

Dr. HUNTRESS. Mr. Chairman, thank you very much. I'm very grateful for the opportunity to testify before you here today on my view of the future of this planet's human space flight program. Mr. Chairman, I believe that the American public wants an adventurous space program to exciting destinations in the solar system but they're not getting it. We're stuck in low-Earth orbit when the challenge is to move outward to those exotic places in the solar system where we've been given tantalizing glimpses from our robotic exploration program. The shuttle and the space station are the legacy of a long-past era, in which the space program was a weapon in the cold war. The Apollo program was not primarily the exploration or science program we were all fond of remembering, it was really a demonstration of power and national will intended to win over the hearts and minds around the world and to demoralize the Soviet Union.

Exploration is not what motivated Kennedy to open the public purse. Beating the Russians did. *Apollo* accomplished that and the Nation moved on to other priorities, which did not include what space enthusiasts and much of the public thought would happen, lunar bases and on to Mars. Nowadays, the imperatives for space exploration are very different. Three decades of wishful thinking and building space ambitions on inadequate funding has led us into a blind alley. The space station is not the transportation node for missions beyond Earth's orbit that it was supposed to be. Instead, it's become an Earth orbital dead-end, and the space shuttle is not the low-cost, low-risk, operational space transportation system that it was supposed to be, and we're burdened with a history and a legacy that can not be easily or quickly undone.

The legacy of the *Columbia* accident should be to create a new pathway and a new sense of purpose for human space flight, and if space explorers are to risk their lives it should be for extraordinary reasons such as exploration of the moon, Mars, asteroids, construction, and servicing of space telescopes. The whole point of leaving home is to go somewhere, not to endlessly circle the block. The problem is not human space flight, the problem is this kind of human space flight.

I believe that among all the destinations that are within our reach in the next 50 years, such as the moon, libration points in near-Earth space, near-Earth asteroids, and Mars, that Mars is the ultimate destination we should pursue in the new century. Mars is the most scientifically rewarding destination and the one place that can galvanize human interest like no other. It's the logical destination for humans in the next decades of our new century. Mars is the most Earth-like of all of the planets in our solar system, it may have had life early in its history, it might possibly harbor microbial life below its surface today, and 1 day in the future it may become a new home for humankind. It has fascinated humans for centuries and it's within our reach.

In pursuing these destinations, the human space flight program needs to be set on a new path that leads to a future that the public has been expecting for decades, a path that takes humans beyond Earth orbit to compelling new destinations in the solar system. We need a national vision that sets destinations for human exploration and systematically pursues its fulfillment with both robotic and human space flight, and the Nation needs a commitment from the administration and Congress for a manifest destiny for American in space.

I'm leading a study by the International Academy of Astronautics that recommends the nature adopt a long-term policy for its space program along the following lines. First, to set a goal for human space flight to establish a permanent presence in the solar system and specifically to establish a human outpost on Mars by the middle of the century. Second, to devise a progressive step-by-step approach for achieving this goal, one that does not require an Apollo-like spending curve. Third, this progressive approach should include intermediate destinations, such as the libration points, moon, near-Earth asteroids, to provide the stepping stones to Mars where useful exploration goals can be carried out. Fourth, space exploration is intrinsically global and should involve cooperation with other space-faring nations.

To enable such a vision, NASA's Earth to orbit transportation and on-orbit infrastructure would have to be reinvented. The current space shuttle and international space station are not on this critical path other than for conducting research on human physiology in space. First, we need to carry out America's obligations to its international partners for an orderly completion of the ISS. The goals of the ISS should be limited and refocused to those specific purposes required to enable human exploration beyond Earth orbit.

Second, retire the shuttle after flying only those missions necessary to complete the ISS. The shuttle is extremely expensive, dated, operationally fragile, and risky for its crews. Third, reinvent our method of access to Earth orbit. Human transport to and from space and within space should be separated from cargo transport. New, simpler, lower-risk, lower-cost Earth to orbit transportation systems for both humans and cargo should be devised that support human requirements for exploration beyond Earth orbit. Fourth, develop an architecture for this highway to deep space, leading to human outposts on Mars by 2050, engage all space-faring nations in developing such a plan, utilizing the best that each nation has to offer, and the U.S. should take the lead. And sixth, to continue the use of robotic missions for scientific research and to prepare for human flights.

None of this will happen if we go on as we are. Thank you for your attention.

[The prepared statement of Dr. Huntress follows:]

PREPARED STATEMENT OF DR. WESLEY T. HUNTRESS, JR., DIRECTOR, GEOPHYSICAL LABORATORY, CARNEGIE INSTITUTION OF WASHINGTON

Mr. Chairman and Members of the Committee:

I am grateful for the opportunity to testify before you today on my view of the future of this planet's human space flight program. The public wants an adventurous space program, a Mission From Planet Earth to new exciting destinations in the solar system and beyond. The public wants to know where we are going, how we are going to get there and wants to go along for the ride even if only virtually. America has the right stuff, but today's human space flight program isn't giving the public what it wants.

Old Legacies

The challenge for NASA is to throw off the yoke of the Apollo program legacy and to move outward beyond Earth to exotic places in the solar system, those places where we have been given tantalizing glimpses from our robotic exploration program. The Shuttle and Space Station are the legacy of a long-past era in which the space program was a weapon in the Cold War. The Apollo program was not primarily the science or exploration program we are all fond of remembering, it was a demonstration of power and national will intended to win over hearts and minds around the world and to demoralize the Soviet Union. Exploration is not what motivated Kennedy to open the public purse. Beating the Russians did. It worked. Apollo accomplished what was intended and the Nation moved on to other priorities, which did not include what space enthusiasts and much of the public thought would happen—lunar bases and on to Mars.

The Space Shuttle and International Space Station (ISS) are the products of NASA attempting over the decades to preserve the Apollo era of human space flight already passed by. These are complex, expensive projects that produce enormous strain on NASA's budget and corresponding stress on the heroic people who work so hard to preserve the enterprise. The current human space flight program is barely affordable with what NASA is appropriated. The Apollo era is gone, the imperatives for space exploration are very different now than they were in the 1960s, and three decades of wishful thinking and building space ambitions on an inadequate funding basis has led the Nation into a blind alley. The ISS is not the expected transportation node for missions beyond Earth orbit that it was supposed to be; it has become an Earth-orbital end unto itself. And the Space Shuttle is not the low-cost, low-risk operational space transportation system that it was supposed to be.

The legacy of the *Columbia* accident should be to create a new pathway and sense of purpose for human spaceflight. We should provide a more robust transportation system for our astronauts and a more rewarding program of exploration for these heroes. They should be assured of a reliable, safe system for transporting them a distance no farther than the distance between New York and Washington. And if space explorers are to risk their lives it should be for extraordinarily challenging reasons—such as exploration of the Moon, Mars, and asteroids, and for construction and servicing space telescopes—not for making 90 minute trips around the Earth. *The whole point of leaving home is to go somewhere, not to endlessly circle the block.*

Just as for Apollo, the Shuttle and ISS were developed for political imperatives; not so much for space exploration but to keep humans flying and to serve a foreign policy agenda. The Shuttle and ISS have not proven to be the next steps to human deep space exploration as advertised, instead they have become an impediment—serving only to maintain a human presence in near-Earth space until society finally decides to undertake missions to destinations beyond Earth orbit. Immediately after the *Columbia* accident, Charles Krauthammer, a noted columnist put it far better than my scientist training allows:

"We slip the bonds of Earth not to spend 20 years in orbit studying zero-G nausea, but to set foot on new worlds, learn their mysteries, establish our presence . . . After millennia of dreaming of flight, the human race went from a standing start at Kitty Hawk [almost exactly 100 years ago] to the moon in 66 years. And yet in the next 34 years, we've gone nowhere . . . For now, we need to keep the shuttle going because we have no other way to get into space. And we'll need to support the space station for a few years, because we have no other program in place . . . If we are going to risk that first 150 miles of terrible stress on body and machine to get into space, then let's do it to get to the next million miles—to cruise the beauty and vacuum of interplanetary space to new worlds . . . the problem is not manned flight. The problem is this kind of manned flight, shuttling up and down at great risk and to little end."

New Options

We have reached a point now where we reflect fondly on a time past when America shined brilliantly in human space exploration, but can only lament our retreat while others climb a path we pioneered and abandoned. We can shine again. We are a wealthy and capable nation. We have the resources. The required technology is at hand or just around the corner of development. These are not the issues. The issue is national will. Space exploration has become a part of our culture. The public believes that flying in space is part of who we are as a nation. "Space exploration is an element of our national being" [Harrison Schmidt, former astronaut and former Senator from New Mexico]. Our robotic explorers generate enormous interest when they fly and land on other planets. But the public expectation is that these robotic missions are a prelude to sending humans.

What the public wants is clarity of purpose. A Space Station advertised as "the next logical step" without filling in the blank "to what" doesn't do it. There is a growing chorus of leaders inside and outside of government concerned that NASA's post-*Columbia*-investigation posture is business as usual. The consensus of many is that a coherent vision for human spaceflight over the next several decades is required, one that has a clear sense of purpose and destination. According to Neil Lane, former NSF Director and Presidential Science Advisor, "Unless we can get a clear, stated mission, we should step back and not risk further lives."

Sooner or later we must have a clear destination for human spaceflight or it will not survive, and America will be much the poorer for it. And a new option doesn't have to be funded like Apollo, it can proceed at a steady pace. The country needs the challenge of grander exploration to justify the risk, lift our sights, fuel human dreams, and advance human discovery and knowledge. *We need to go somewhere!*

There are organizations outside NASA and the U.S. Government that are addressing this issue. The International Academy of Astronautics is conducting a study entitled "The Next Steps in Exploring Deep Space". Its purpose is to provide a logical and systematic roadmap for the long-term scientific exploration of the solar system beyond Earth orbit with a goal to land humans on Mars sometime in the next 50 years. The study will be completed this coming spring and envisions the establishment of a permanent human presence in space using an evolutionary approach to the development of space transportation infrastructure utilizing well-defined intermediate destinations as stepping stones to Mars.

In addition, a workshop this past spring run by three organizations—The Planetary Society (TPS), the American Astronautical Society (AAS) and the Association of Space Explorers (ASE)—has made recommendations for near-term actions to solve our post-*Columbia* problems in human transportation to Earth orbit. My testimony draws heavily on the results from this joint workshop and from the IAA study. The workshop statement and a short briefing on the interim results of the IAA study are attached.

The Exploration Imperative

Beginning in 1952, a series of symposiums on space travel were held at New York City's Hayden Planetarium that attracted the greatest visionaries of the day, including Werner von Braun, Willey Ley, and the space artist Chesley Bonestel. That vision of our future was subsequently captured in a series of illustrated articles for Collier's Magazine, launching a national dream of space exploration. As a nation of people who make dreams happen, and who explore to provide for a better life, we didn't do too badly with making that mid-Century dream of space travel come true. But after the Apollo missions the dream to move on was put on hold. So why should we revive that dream to explore space in this new 21st Century? For the same reasons that we explored and developed air travel in the 20th Century. Because it challenges us! At the beginning of the 20th Century in America the great public adventures were exploration of the polar regions of Earth and powered flight through the air. A century later, millions of humans travel in comfort through the air to destinations around the planet. No one in 1900 could have dreamed it possible to fly in comfort from New York to Paris in just over six hours.

And so it will be in the 21st Century. At the beginning of this century we know how to travel in space, but are only just on its edge. We fly into space on dangerous, unwieldy, bolted-together hunks of thin metal and bulky propellant, spinning around our own planet in a fragile metal can strung together with cables and trusses. In one of history's major anomalies, we even flew men to the Moon and back 30 years ago, but are unable to do it now. By the end of the 21st Century, space travel will be as commonplace as air travel is at the end of the 20th. We just can't predict the details right now, just as the Wright Brothers could never have imagined a Boeing 747 in 1903.

Exploration and the drive to discover and understand are qualities that have allowed the humans to survive and become the dominant species on the planet. Human beings strive to know and understand what surrounds them. By exploring the unknown, humans gain security and dispel fear of the unknown, of what is beyond. This survival mechanism is encoded in our genes. Just as human civilization uses the challenge of exploration to hone scientific and technological skills for survival, and exploits the adventure to provide hope for the future, human populations also have a need for heroes to provide inspiration. This is particularly important for our youth, who need to be provided with a positive vision for their future. Every generation has had its heroes. Today, the astronaut is a hero figure because astronauts carry out adventurous work that achieves exciting goals, personifying the kind of life that our youth would like to lead. Space exploration presents a positive image of the future and inspires our youth towards achievement.

The Science Imperative

In the 1960s, the space program was popular in the U.S. because the public knew precisely what the goal was, how the game was played and followed every play. Today, the public's innate acceptance of the abstract notion of exploration as a human imperative does not necessarily extend to their checkbook without clear articulation of goals and benefits. Today the public benefit can be expressed as a clear set of goals because science and technology has progressed to the point where it can dare attempt answer some of the most burning questions that human beings have been asking since they started gazing upward at the sky. Questions such as 'Where do we come from?' and 'What will happen to us in the future?' and 'Are we alone in the Universe?' These very fundamental human questions can be recast as scientific challenges—goals to be achieved in the course of exploring space. And from these scientific goals, plans can be formulated for both robotic and human explorers including the destinations and the exploration objectives of each.

Where did we come from? This is a question that approaches the contemplation of existence. Even so, astronomers can address the question by determining how the Universe began and evolved, and learning how galaxies, stars and planets formed, and searching for Earth-like planets around other stars. The answers require large and complex space telescope systems made possible by human construction and servicing in space.

What will happen to us in the future? Every human wonders about the future. One form of this question asks if there is any threat to us from space, especially from earth-crossing asteroids. The answer will come from surveys of the earth-crossing asteroid population in space and space missions that determine their composition and structure. Another form of this question asks what future humans have in traveling to and living on other planets. Is our species destined to populate space? Ultimately I believe the answer is yes, and the information will come from exploring space and utilizing the resources we can find in the most promising places in space such as Mars.

Are we alone in the Universe? Every human being wants to know the answer to this question. We are compelled to find its answer. Some find comfort in the notion that we should be alone; others are fearful of the potential for other life "out there". Most scientists see the possibilities and are overwhelmed by the notion that the universe might be teeming with life; at least microbial life and perhaps even intelligent forms. We will find the answer by searching for life in the most promising places in the solar system such as Mars, and by looking for signs of life on planets outside the solar system with space telescopes.

Destinations

The IAA study starts with these public questions and defines the scientific objectives required to answer them. The scientific objectives in turn determine what kind of exploration is required at which destinations in the solar system. Four destinations for human exploration result from this exercise: the Sun-Earth Lagrangian point L2, the Moon, Near-Earth Asteroids, and Mars.

Mars, the most distant and most challenging of these destinations, is also the most scientifically rewarding and the one place that can galvanize human interest like no other. It is the logical destination for humans in the next decades of our new century. Mars is the most Earth-like of all the other planets in our solar system. It may have had life in its early history, it might possibly harbor microbial life below its surface today, and one day in the distant future it may become a new home for human kind. It has fascinated humans for centuries and it is within our reach.

A brief description of the scientific and exploration utility of the four identified human destinations are described below, arranged in order of energetic difficulty for a systematic, progressive approach to exploration beyond Earth orbit.

Sun-Earth Lagrangian Point L2 (SEL2) is a point about 1 million miles from the dark side of the Earth opposite the Sun that is the site of choice for future space astronomical telescopes that will search for and image Earth-like planets around other stars. These telescopes will of necessity be large, complex systems requiring servicing by astronauts in a manner similar to the Hubble Space Telescope. SEL2 is easy to get to, with round trip times on the order of 2–3 weeks and could serve as the initial step in developing a deep space transportation capability.

The Moon is a scientifically rewarding destination where we can obtain information on the probability for impact of asteroids on the Earth, on the history of the Sun and its effect on the Earth's environment, and perhaps on the earliest history of the Earth itself. The proximity of the Moon makes it attractive as a potential proving ground for surface systems, habitats and other technologies, possibly including the use of lunar resources, but it is not necessarily on the critical path to Mars exploration.

Near-Earth Objects travel in orbits between the Earth and Mars and represent both a potential resource in space and a potential impact hazard to Earth. Robotic missions to these objects will be necessary to assess these potentials. The jury is out on whether human missions would be necessary for these purposes, but there is no doubt that a one-year human mission to a Near-Earth Object would serve as an excellent intermediate step before any mission to Mars. An NEO human mission would provide a lower-risk test flight of the systems necessary to reach Mars.

Mars is the ultimate destination for humans in the first half of this century. It is on this most Earth-like planet that humans can establish a permanent presence—utilizing resources the planet has to offer from its atmosphere, soil and subsurface ice and water. The scientific goals will be to understand the similarities and differences between Earth and Mars, particularly the history of water and its distribution on Mars, the geological and climatological histories of Mars and a search for evidence of past or present life. The question of possible life on another world is probably the largest driver for humans in space and particularly for Mars exploration.

Our ultimate ability to reach these destinations requires that architectures developed today for transportation from the Earth's surface to orbit have a top-level requirement to consider the future needs for space transportation to deep space. Otherwise, it is likely that a solution will be derived that is useless for the next step beyond Earth orbit.

The Architecture

The IAA study proposes an architecture for enabling this vision. *Mars is the goal,* but intermediate destinations are identified that comprise a progressive approach to this long-term objective. The approach is *science-based* to address key questions of public interest. These science goals provide the context for destinations, capabilities and technology investments. It is a *stepping-stone approach* in which there is a logical progression to successively more difficult destinations. This approach requires *incremental investments* to maintain progress, rather than huge new budgets, and destinations can be adjusted to manage cost and risk. Major new *technology developments* early in the program are avoided to reduce cost. Solar electric and nuclear electric propulsion, which are already under development, along with improved chemical propulsion can meet early transportation needs. *Cargo and crew are separated* to minimize crew risk and flight time. Cargo, supplies, and exploration equipment travel slower on more efficient electric propulsion systems in advance of the crew, who use faster but less efficient chemical propulsion systems.

The IAA study proposes development first of a chemically propelled Deep Space Transportation Vehicle (DSTV) initially capable of carrying astronauts from low-Earth orbit to SEL2. The DSTV would be equally capable of carrying astronauts to lunar orbit if it is decided that lunar missions are an important step toward Mars. Later this vehicle could be upgraded for the much longer trips to NEOs and Mars. A separate electrically propelled Deep Space Cargo Vehicle (DSCV) would be developed to carry equipment and supplies to these same destinations.

The IAA study does not address Earth-to-orbit infrastructure requirements. This has been done by the TPS/AAS/ASE workshop that recommends the retirement of the Shuttle after the ISS has been completed. Both the IAA study and the TPS/AAS/ASE workshop recognize the potential of utilizing non-US launch systems to carry crew and cargo to low Earth orbit. In addition, new vehicles for Earth to orbit transportation, separating crew from cargo, would be developed that take into account crew and cargo Earth-to-orbit lift requirements for further exploration beyond Earth orbit.

The Space Station is not on the critical path in the IAA transportation architecture. Its high inclination orbit creates a severe penalty for Station-launched missions to the Moon and planets. However, the Space Station is required in order to study the effects of space travel on humans and to develop the technologies required for human support during long-term space flight.

Robots and Humans

So how do we implement such a plan, do we use human or robotic missions? The answer has always been: both. The robotic and human space exploration enterprises have co-existed and cooperated during the space program's entire history. The relevant question is whether any potential investigation requires using human explorers, with their associated cost. The argument often used to dismiss humans is that technology will produce a machine with sufficient intelligence and dexterity to render a human unnecessary. The time to develop such a machine, however, may be either unpredictable or too long to meet a reasonable schedule. No matter how clever or useful the robots we make, they will always be tools for enhancing human capabilities.

There is a role for both robots and humans. The strategy is to use robotic means for reconnaissance and scientific exploration to the full extent that robots can accomplish the desired goals. At the point when human explorers are sent, robotic missions can be used to establish local infrastructure before the arrival of humans. This is implemented using robotic outposts, which are later occupied and utilized by the human explorers. During human occupation, robots provide required support services and become sensory extensions and tools for human explorers.

In any case, science cost effectiveness is not a good exclusive metric for assessing human vs. robotic modes for scientific exploration because the decision to proceed with human exploration will not be made on scientific grounds alone. Human exploration of space is motivated by societal factors other than science. Nonetheless, when a decision is made to continue human exploration beyond Earth orbit, it will provide a tremendous opportunity for scientist-explorers and science should be a motivating force in defining human space exploration goals.

A space exploration enterprise that satisfies the public requires humans in space. In the minds of the public, robotic exploration is an extension of the human experience and a prelude to human exploration itself. Robotic exploration is the method of choice for reconnaissance and scientific investigation to the extent that robots can accomplish the desired goals. However, only human explorers will ultimately to fulfill the public's sense of destiny in space.

The Bottom Line

The human spaceflight program needs to be set on a new path that leads to a future that the public has been expecting for decades—a path that takes humans beyond Earth orbit to new, important destinations in the solar system.

We need a national vision that sets a destination for human exploration and systematically pursues its fulfillment with both robotic and human spaceflight.

Drawing heavily on the IAA study, I believe this vision should involve:

1. The goal of establishing a permanent human presence in the solar system with the stated objective to establish human presence on Mars by the middle of this Century.
2. Recognition that exploration beyond Earth orbit is intrinsically global, and should involve cooperation with other space-faring nations.

3. A progressive, step-by-step approach for human exploration beyond Earth orbit that does not require an Apollo-like spending curve. Any requirements for increased spending can then be made incrementally on an annual basis.
4. A set of exciting and rewarding destinations in this step-by-step approach to Mars including the Sun-Earth Lagrangian Point L2, the Moon and Near-Earth Asteroids.
5. Re-invention of our Earth-to-orbit transportation and on-orbit infrastructure to support the goals for exploration beyond Earth orbit. The current Space Shuttle and International Space Station are not on that critical path other than research on human physiology in space.
6. Development of new in-space systems for transporting humans and cargo from low Earth orbit to deep space destinations. No large technological breakthroughs are necessary.
7. Continued use of robotic missions for scientific research and preparation for future human flights. Robotic precursor missions will be required to reduce the risk for human explorers and to provide on-site support for humans. Human explorers will be required for intensive field exploration and for in-space servicing of complex systems.

Drawing heavily from the TPS/AAS/ASE workshop, some near-term actions to enable this policy (specifically number 5 above) are:

1. The Shuttle should be retired after flying only those missions necessary to complete the International Space Station in favor of a simpler, safer and less costly system for transporting humans to and from Earth orbit.
2. Human transport to and from space, and within space, should be separated from related cargo transport. New Earth-to-orbit transportation systems for humans and cargo should be designed and built, but not until the requirements for human exploration beyond Earth orbit are understood and can be accommodated.
3. The U.S. should carry out its obligations to its international partners to complete the International Space Station. The goals of the ISS should be refocused to those specific purposes required to enable human exploration beyond Earth orbit.

None of this will happen if we go on as we are. The national will to carry out a new option for space exploration already exists in the people of the United States. The nation has the necessary wealth. It is only a matter of leadership by the Administration and Congress. The architecture advocated here does not require an immediate large increase in the NASA budget. It does require a commitment to the resources required as the space program gradually and systematically increases in scale and scope, but not so much in any one year as would be required for an Apollo-like initiative.

We need a commitment from the Administration and Congress to a manifest destiny for America in space.

STEPPING INTO THE FUTURE

A Workshop in Memory of the ***Columbia*** *7*

On April 29–30, 2003, The Planetary Society, the Association of Space Explorers, and the American Astronautical Society held a workshop at the George Washington University's Space Policy Institute about the future of human space transportation. The following conclusions have been endorsed by The Planetary Society and the American Astronautical Society and by a number of astronauts present at the workshop. ASE did not take a formal position on the conclusions.

Conclusions

Human space exploration is a great and unifying enterprise of planet Earth. The loss of *Columbia* reminds us that astronauts are the emissaries of humankind as part of our civilization's aspirations for great achievements and new discoveries. The United States' commitment to human exploration reflects humankind's movement outward from Earth, to become eventually a multi-planet species. We do this to understand and cope with the limits of Earth, its finite resources and indeed its finite lifetime, and to satisfy the innate desire of people to advance civilization and understand their place in the universe. We do this not just for our own country, but also for all our planet's citizens. Furthermore, the space enterprise provides a unique means of building national intellectual, technical and personal capabilities. It is a commitment to a positive future.

The Planetary Society, the Association of Space Explorers-USA, and the American Astronautical Society convened a group of experts at a workshop, in memory of the *Columbia* space shuttle crew, to assess launch vehicle requirements to meet the needs of human space exploration beyond Earth orbit. Our conclusions from this assessment are:

The Imperative

- There are strong societal imperatives for exploring space. The natural curiosity to explore new frontiers coupled with an instinctive desire to preserve the future of humankind motivates our continued exploration of space. Space exploration will provide new knowledge and resources for a more prosperous and secure future.
- There are fundamental questions concerning our cosmic origin, our future and whether or not we are alone in the universe. Science in pursuit of these questions can provide a credible goal-oriented strategy for an evolutionary approach to exploring deep space destinations with both robots and humans.
- The exploration of deep space by humans will be energized by the goals of individual nations woven into an international enterprise and infused with a sense of human destiny in space.

The Destinations

- The most important scientific destinations for human explorers are the Moon, Mars, Near-Earth Objects and the Sun-Earth Lagrangian point L2 [1] (for astronomical observatories).
- Mars is the ultimate destination for human explorers in the foreseeable future. Consequently the robotic Mars exploration program should progress beyond sample return to robotic outposts in preparation for human presence.

A Strategy

- By adopting a phased approach to human exploration beyond Earth orbit, we can develop a cost-effective program that is exciting, scientifically rewarding and for which the risks can be measured and managed.
- The initial stages of a robust human exploration architecture can proceed using existing and currently planned propulsion technologies.
- We see no essential role for continuing flight of the shuttle orbiter beyond its immediate goal of completing construction of the International Space Station and early transport of crewmembers to and from the Station. As soon as an alternate mode of human transport into and from low Earth orbit (LEO) is available, which should be accomplished as soon as possible, the shuttle orbiter should be retired.
- Crew and cargo should be transported separately to increase flexibility, reduce cost and reduce risk associated with human space exploration.
- The underutilized fleet of existing expendable launch vehicles should play a major role in the next stages of human space exploration, as well as in human and cargo transportation into LEO.
- Increased investment in on-orbit operations and in-space propulsion technologies is required.

International Cooperation

- Exploration beyond Earth orbit is an intrinsically global enterprise. It is unlikely that any nation acting alone will commit the necessary resources for a major human exploration mission initiative beyond Earth orbit.
- International partnerships provide tangible benefits for human space exploration. These include broadening public and political support, sharing of the cost and risk, adding resiliency and enriching the scientific and technological content.
- To this end all space faring nations should strengthen mechanisms for exchanging information on human exploration activities and plans, increase international participation in robotic exploration missions, and explore mechanisms for sharing critical roles among partners.

[1] Lagrangian points (L1–L5) are points in space where the gravitational forces from the two most nearby influential gravitational masses (in this case the Sun and Earth) are in equilibrium.

ATTACHMENT

NEXT STEPS IN DEEP SPACE

IAA

Next Steps in Exploring Deep Space

A Cosmic Study by the International Academy of Astronautics
- A vision for the future and a description of what *could* be done
- Not a strategic plan or a product of any national space agency
- Human space exploration as a global enterprise

A logical and systematic roadmap
- To establish a permanent human presence in space
- For conducting scientific exploration of the solar system and the Universe
- With a goal to land humans on Mars sometime in the next 50 years
- Evolutionary architecture emphasizing intermediate destinations of scientific and programmatic value: *Stepping stones to Mars*

A work in progress
- Final report to be submitted in early 2004
- All ideas and contributions are welcomed

NEXT STEPS IN DEEP SPACE

IAA

The Imperatives: Why Explore Deep Space?

To Discover - the exploration imperative

- Expand the frontiers of human experience
- Fulfill the basic human need to always move forward
- Inspire, educate, and engage our youth and the public

To Understand - the scientific imperative

- Knowledge and understanding of what surrounds us in space
- Answers to fundamental questions of our origins and destiny
- Advance and sustain human learning and technological progress

To Unify - the political imperative

- Toward a global endeavor without national boundaries
- Toward mutual achievement and security through challenging enterprise
- Toward human utilization of the solar system

NEXT STEPS IN DEEP SPACE

IAA

Ages-old human questions lead to scientific challenges

Where do we come from?

- Determine how the universe of stars and planets began and evolved
- Determine the origin and evolution of Earth and its biosphere

What will happen to us in the future?

- Determine the nature of the space environment and cosmic hazards to Earth
- Determine the potential for human permanent presence in space

Are we alone in the universe?

- Determine if there is or ever has been other life in the Solar System
- Determine if there are life-bearing planets around other stars

How do we meet these challenges?

- Conduct a systematic, scientific exploration of the Solar System
- Conduct astronomical observations of the Universe beyond

NEXT STEPS IN DEEP SPACE

IAA

From Science Objectives to Exploration Objectives

Science objectives lead to the following exploration objectives…

- Conduct astronomical investigations using large space observatories
- Conduct scientific exploration of the Moon, Mars and (later) Europa
- Conduct a scientific survey of a diverse suite of Near Earth Objects

…at four destinations which can be reached by humans in the next 50 years

- Sun-Earth Libration Point L2, the Moon, NEO's, and Mars

…which can lead to a permanent human presence in space

- Robotic exploration leads to a human outpost at L2
- Capabilities grow to encompass visits to NEO's and the Moon
- Human exploration of Mars can be achieved by the middle of this century

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NEXT STEPS IN DEEP SPACE

IAA

Destination: Sun-Earth L2

A constellation of space telescopes

- Survey the Universe across the spectrum and to the beginning of time
- Observe the process of planetary system formation in the galaxy
- Search for terrestrial-like planets around other stars
- Search for evidence of life in the spectrum of extra-solar planets

Exploration architecture

- Initial step: A "Deep Space Shuttle" providing access from LEO
- Human outpost for assembly and maintenance of observatories
- Preparation for later interplanetary voyages
- Trade study: Humans at L2 vs. other locations (with robotic transfer of telescopes)

NEXT STEPS IN DEEP SPACE

IAA

Destination: Moon

Lunar outposts for exploration on the Moon

- Search for evidence of the origin of the Earth-Moon system
- Determine the history of asteroid and comet impacts on Earth
- Obtain evidence of the Sun's history and its effects on Earth through time
- Search for samples from the earliest episodes in the history of the Earth
- Determine the form, amount, and origin of lunar ice

Exploration architecture

- A proving ground for development of surface systems, habitats, and technologies
- Deep Space Shuttle provides the necessary transportation capability
- Possible use of lunar resources to enhance access to other destinations
- The Moon may not be in the "critical path" to Mars

NEXT STEPS IN DEEP SPACE

IAA

Destination: Near-Earth Objects

Field exploration of asteroids

- Survey the diversity and composition of NEO's
- Determine the bulk properties and internal structures of NEO's
- Determine utility of NEO's as potential resources for materials in space and how we might mitigate future Earth impacts

Exploration architecture

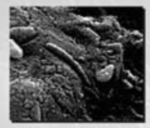
- An intermediate deep space destination to test a human Mars expedition
- Cargo (via SEP) and crew travel separately from L2 or other gateway, to minimize crew flight time
- High degree of commonality with L2 infrastructure

NEXT STEPS IN DEEP SPACE
IAA

Destination: Mars

Outposts on Mars - robots and humans working together

- Determine the geological and climatological histories of the Mars
- Determine the history of water and its distribution and form on Mars
- Search for evidence of past and current life on Mars
- Establish a permanent human presence on Mars - the most Earth-like planet



Exploration architecture

- Cargo travels separately via SEP or NEP, crew rendezvous at or near Mars
- All exploration equipment and habitats arrive before crew for risk reduction
- Phobos/Deimos a possible first destination in Martian system to reduce incremental investment; high commonality with NEO infrastructure

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NEXT STEPS IN DEEP SPACE
IAA

Guiding Principles of the Architecture

Mars is the goal

- Intermediate destinations and local architectures are established with this ultimate goal in mind

Science-driven

- Address key questions of broad scientific and public interest
- Science goals and objectives provide context for destinations, capabilities, and technology investments

Stepping-stone approach

- Logical progression to successively more difficult destinations
- Minimize incremental investments to maintain progress; adjust destinations if necessary to help manage cost and risk

Utilize existing or planned capabilities

- Avoid requiring major new technology developments early in the program
- Solar electric and nuclear electric propulsion, along with improved chemical propulsion, can meet early transportation needs

Separate cargo and crew

- Minimize crew flight time by using minimum-mass transfer vehicles
- Cargo, supplies, and exploration equipment travel in advance of crew using highly efficient electric propulsion

The CHAIRMAN. Thank you. Dr. Zubrin.

STATEMENT OF DR. ROBERT ZUBRIN, PRESIDENT, MARS SOCIETY

Dr. ZUBRIN. Thank you. Mr. Chairman, Members of the Committee, thank you for inviting me here to testify today. Why is NASA stuck in low-Earth orbit? To answer this question, you need to take a look at the two fundamental ways that NASA has operated in its history, which breaks down basically into two different periods. There's the period from 1961 to 1973, which therefore may be fairly called the Apollo period, and the 30 years since, which can be called the shuttle era or called well, there it is.

In the *Apollo* method of operation, the way things work are as follows. The Nation's political leadership sets a focus goal for the human space flight program. NASA develops a plan on how to achieve that goal. Vehicles are designed to implement that plan. Those vehicles are built and the plan is flown.

In the shuttle era mode, what happens instead? In this mode, technologies and hardware elements are developed in accord with the wishes of various technical communities. These projects are then justified by arguments that they might prove useful later at some time in the future when grand projects are attempted. So, in other words, contrasting these approaches, what you see is that the *Apollo* mode is destination-driven, the shuttle mode is constituency-driven, driven by the constituencies within the various NASA centers, aerospace, major corporations, and elsewhere.

If you want to understand it even more clearly, consider an analogy. Imagine two couples, two young couples, both want to build their own house. Couple number one has an idea of the kind of house they want, so they hire an architect to design that house. They then acquire building parts to build out that design and they build the house. Couple number two polls their neighbors on what house parts they might have for sale, buy those that are most convincingly marketed, acquire a random set of house parts, which they pile up in their back yard, and then when their relatives come by and ask them why do you have all this junk in your back yard, they say, well, it's to build a house. They say, really, show me the design, so they hire an architect to design a house that includes all these parts.

Now such a house design obviously becomes incredibly complex and can never be built, but that's not the point. The plan provides a convincing rationale justifying the purchases. That's the shuttle mode. That's what we've got to break from.

The problem with NASA's lack of current achievement is not money. If you look at the average NASA budget, if you take NASA's total budget from 1961 to 1973, translate it into current dollars, average it out over the 12 years, it's $17 billion a year. NASA's current budget is only 10 percent less than that. The problem is lack of focus, it's lack of a goal.

What should the goal be? As Dr. Huntress has said, it should be humans to Mars. Mars is where the science is, Mars is where the challenge is and Mars is where the future is. However, it shouldn't be humans to Mars in 50 years, it should be humans to Mars in 10. This is possible. Despite whatever statements people have made about problems, real or imagined, the fact remains that we are much better prepared today to send humans to Mars than we were to send men to the moon in 1961 when Kennedy started the moon program and we were there 8 years later.

We can do this. We do not need gigantic nuclear electric spaceships to send people to Mars. That is pork, it's nonsense. We can go to Mars with chemical propulsion, you can get to Mars in 6 months with chemical propulsion. You can overcome all the problems of weightlessness by not going in zero gravity, you can spin up the spacecraft, you have artificial gravity, you don't get these bone and muscle problems. We don't need to spend 30 years on orbit watching astronauts' musculature degrade in 0 G to verify that it degrades in 0 G. We can avoid it through engineering solutions.

The way you get humans to Mars without complex futuristic mega-spacecraft is this. You do it in two launches of a Saturn 5-class booster, which you can create by either re-engineering the Saturn 5 or converting the shuttle, lose the orbiter, replace it with an upper stage interfering, you have a Saturn 5-class capability that can lift 120 tons to Earth orbit or throw 40 to 50 tons to either the moon or Mars.

Then you do the mission in two launches. The first launch you send to Mars an unmanned Earth-return vehicle, nobody in it, it flies out to Mars on fuel too. It takes 8 months to get there, minimum energy trajectory, you land it on Mars, you run a pump. You suck in the Martian air, which is carbon dioxide, you react the carbon dioxide with a small amount of hydrogen that you bring from Earth, produces a large supply of methane oxygen rocket propellant. Now you have a fully fueled Earth-return vehicle sitting waiting for you on the surface of Mars. This is 19th century chemical engineering.

Then once that is done you launch the crew to Mars. Because the return ride is waiting on Mars, you don't need to fly to Mars in that gigantic Battlestar Galactica spaceship. You fly to Mars in a basic habitation module like a big tuna can with a life support system in it. You fly out to Mars, take 6 months to get there, you land near the Earth-return vehicle, use the hab as your house on Mars, as your lab on Mars for a year and a half, and you get a launch window back to Earth. You get in the Earth-return vehicle, you fly home. You leave the hab behind on Mars so each time you do this you add another hab to the base. Before you know it we've begun the beginning of the first human settlement on a new world. There is nothing in there that's beyond our capability.

That's a short explanation. If you want a longer one, there's a whole book on it, which I'd be happy to give to every member of this Committee, that explains the plan in depth. Now, how do we make this happen now? You've got to get NASA back on the Apollo mode of thinking. How do you do that? Reject their requests to fund things. Do not fund the orbital space plane for $17 billion. It's a thing that is not integrated into any plan. It will not take you anywhere.

Instead, what you should do this year is fund them $60 million to fund two $30 million 6-month studies, one by NASA JSC, one by an interagency task force led by somebody from the non-NASA space community, two competing teams, each commissioned to develop a plan to get humans to Mars in 10 years with a cost cap of say $30 billion for all the development, $3 billion for the recurring mission, have them report back with their plans, present it to a blue ribbon commission headed by somebody like Admiral Gehman or whomever to judge the plans for feasibility, cost, technical merit, exploratory punch, choose the better plan, choose the better team, and fund that plan.

It is within your power to make this happen. It is within your power to give the American people a space program that is actually going somewhere, and I ask that you do so. Thank you for your attention.

[The prepared statement of Dr. Zubrin follows:]

PREPARED STATEMENT OF DR. ROBERT ZUBRIN, PRESIDENT, MARS SOCIETY

Senator McCain, members of the Commerce Committee, I would like to thank you for inviting me to testify here today on the future of the U.S. space program. Since many of you may be unfamiliar with me, I hope you will forgive me if I take a few seconds to establish my credentials. I am an engineer with a Masters degree in Aeronautics and Astronautics, a doctorate in Nuclear Engineering, and fifteen years aerospace industry experience. I currently lead my own company, Pioneer Astronautics, which has five NASA and military R&D contracts at this time. I am the author or co-author of over 100 papers, three patents, and five books related to the field, and am the head of an international non-profit organization known as the Mars Society which has built and run a human Mars exploration operations research station on Devon Island, 900 miles from the North Pole.

My remarks today will address four areas. First, I will discuss why NASA is failing, and what fundamental change in method of operation needs to be undertaken if the space agency is to be made effective again, and in particular, explain why an overarching goal must be adopted if that is to occur. Second, I will explain what that goal should be. Third, I will present a plan for a pioneering space program that would allow NASA fulfill its promise and achieve that goal within ten years. Finally, I will make specific recommendations as to what Congress and the Executive branch need to do this year in order to put the space program on the right track.

1. Why is NASA Failing?

In the recent *Columbia* hearings, numerous members of congress continually decried the fact that the U.S. space program is "stuck in Low Earth Orbit." This is certainly a serious problem. If it is to be addressed adequately, however, America's political leadership needs to reexamine NASA's fundamental mode of operation.

Over the course of its history, NASA has employed two distinct modes of operation. The first, prevailed during the period from 1961–1973, and may therefore be called the Apollo Mode. The second, prevailing since 1974, may usefully be called the Shuttle Era Mode, or Shuttle Mode, for short.

In the Apollo Mode, business is conducted as follows. First, a destination for human spaceflight is chosen. Then a plan is developed to achieve this objective. Following this, technologies and designs are developed to implement *that* plan. These designs are then built, after which the mission is flown.

The Shuttle Mode operates entirely differently. In this mode, technologies and hardware elements are developed in accord with the wishes of various technical communities. These projects are then justified by arguments that they might prove useful at some time in the future when grand flight projects are initiated.

Contrasting these two approaches, we see that the Apollo Mode is *destination driven,* while the Shuttle Mode pretends to be technology driven, but is actually *constituency driven.* In the Apollo Mode, technology development is done for mission directed *reasons.* In the Shuttle Mode, projects are undertaken on behalf of various internal and external technical community pressure groups and then defended using *rationales.* In the Apollo Mode, the space agency's efforts are *focused and directed.* In the Shuttle Mode, NASA's efforts are *random and entropic.*

Imagine two couples, each planning to build their own house. The first couple decides what kind of house they want, hires an architect to design it in detail, then acquires the appropriative materials to build it. That is the Apollo Mode. The second couple polls their neighbors each month for different spare house-parts they would like to sell, and buys them all, hoping to eventually accumulate enough stuff to build a house. When their relatives inquire as to why they are accumulating so much junk, they hire an architect to compose a house design that employs all the knick-knacks they have purchased. The house is never built, but an adequate excuse is generated to justify each purchase, thereby avoiding embarrassment. That is the Shuttle Mode.

In today's dollars, NASA average budget from 1961–1973 was about $17 billion per year. This is only 10 percent more than NASA's current budget. To assess the comparative productivity of the Apollo Mode with the Shuttle Mode, it is therefore useful to compare NASA's accomplishments between 1961–1973 and 1990–2003, as the space agency's total expenditures over these two periods were equal.

Between 1961 and 1973, NASA flew the Mercury, Gemini, Apollo, Skylab, Ranger, Surveyor, and Mariner missions, and did all the development for the Pioneer, Viking, and Voyager missions as well. In addition, the space agency developed hydrogen oxygen rocket engines, multi-staged heavy-lift launch vehicles, nuclear rocket engines, space nuclear reactors, radioisotope power generators, spacesuits, in-space life support systems, orbital rendezvous techniques, soft landing rocket technologies, interplanetary navigation technology, deep space data transmission techniques, reentry technology, and more. In addition, such valuable institutional infrastructure as the Cape Canaveral launch complex, the Deep Space tracking network, Johnson Space Center, and JPL were all created in more or less their current form.

In contrast, during the period from 1990–2003, NASA flew about three score Shuttle missions allowing it to launch and repair the Hubble Space Telescope and partially build a space station. About half a dozen interplanetary probes were launched (compared to over 30 lunar and planetary probes between 1961–73). Despite innumerable "technology development" programs, no new technologies of any significance were actually developed, and no major space program operational infrastructure was created.

Comparing these two records, it is difficult to avoid the conclusion that that NASA's productivity in *both* missions accomplished *and* technology development during its Apollo Mode was at least ten times greater than under the current Shuttle Mode.

The Shuttle Mode is the expenditure of large sums of money without direction by strategic purpose. That is why it is hopelessly inefficient. But the blame for this waste cannot be placed on NASA leaders alone, some of whom have attempted to rectify the situation. Rather, the political class must also accept major responsibility.

Consider the following. During the same week in September that House members were roasting Administrator O'Keefe for his unfortunate advocacy of a destination-free NASA, a Senate committee issued a report saying that a top priority for the space agency was to develop a replacement Space Shuttle system. Did any of the Senators who supported this report explain why? Why do we need another Shuttle system? To keep doing what we are doing now? But is that what we actually want to do?

Congress and the Executive branch need to get together and open a discussion as to what the Nation actually wants to accomplish in space. Hearings should be held, and the options for a strategic objective examined in public. Is our primary aim to keep sending astronauts on joyrides in low Earth orbit? In that case, a second generation Shuttle might be worth building. But if we want to send humans to the Moon or Mars, we need make that decision, and then design and build a hardware set that is appropriate to actually accomplish *those* goals.

Advocates of the Shuttle Mode claim that by avoiding the selection of a destination they are developing the technologies that will allow us to go anywhere, anytime. That just isn't true. The Shuttle Mode will never get us anywhere at all. The Apollo Mode got us to the Moon, and it can get us back, or take us to Mars. But leadership is required.

In the beginning, there was the Word.

2. What Should our Goal Be?

In order to accomplish anything in space we need to set a goal. What should that goal be? In my view, the answer is straightforward: Humans to Mars within a decade.

Why Mars? Because of all the planetary destinations currently within reach, Mars offers the most, both scientifically, socially, and in terms of what it portends for the human future.

In scientific terms, Mars is critical, because it is the Rosetta Stone for letting us understand the position of life in the universe. Images of Mars taken from orbit show that the planet had liquid water flowing on its surface for a period of a billion years during its early history, a duration five times as long as it took life to appear on Earth after there was liquid water here. So if the theory is correct that life is a naturally phenomenon, emergent from chemical complexification wherever there is liquid water, a temperate climate, sufficient minerals, and time, then life should have appeared on Mars. If we can go to Mars, and find fossils of past life on its surface, we will have good reason to believe that we are not alone in the universe. If we send human explorers, who can erect drilling rigs which can reach ground water where Martian life may yet persist, we will be able to examine it, and by so doing determine whether life as we know it on Earth is the pattern for all life everywhere, or alternatively, whether we are simply one esoteric example of a far vaster and more interesting tapestry. These things are worth finding out.

In terms of its social value, Mars is the bracing positive challenge that our society needs. Nations, like people, thrive on challenge and decay without it. The challenge of a humans-to-Mars program would also be an invitation to adventure to every youth in the country, sending out the powerful clarion call: "Learn your science and you can become part of pioneering a new world." There will be over 100 million kids in our Nation's schools over the next ten years. If a Mars program were to inspire just an extra one percent of them to scientific educations, the net result would be 1 million more scientists, engineers, inventors, medical researchers and doctors, making technological innovations that create new industries, finding new medical cures, strengthening national defense, and generally increasing national income to an extent that utterly dwarfs the expenditures of the Mars program.

But the most important reason to go to Mars is the doorway it opens for the future. Uniquely among the extraterrestrial bodies of the inner solar system, Mars is endowed with all the resources needed to support not only life but the development of a technological civilization. In contrast to the comparative desert of the Earth's Moon, Mars possesses oceans of water frozen into its soil as permafrost, as well as vast quantities of carbon, nitrogen, hydrogen, and oxygen, all in forms readily accessible to those clever enough to use them. These four elements are the basic stuff not only of food and water, but of plastics, wood, paper, clothing, and most importantly, rocket fuel.

In addition, Mars has experienced the same sorts of volcanic and hydrologic processes that produced a multitude of mineral ores on Earth. Virtually every element of significant interest to industry is known to exist on the Red Planet. While no liquid water exists on the surface, below ground is a different matter, and there is every reason to believe that geothermal heat sources could be maintaining hot liquid reservoirs beneath the Martian surface today. Such hydrothermal reservoirs may be refuges in which survivors of ancient Martian life continue to persist; they would also represent oases providing abundant water supplies and geothermal power to future human settlers. With its 24-hour day-night cycle and an atmosphere thick enough to shield its surface against solar flares, Mars is the only extraterrestrial planet that will readily allow large scale greenhouses lit by natural sunlight. Mars can be settled. For our generation and many that will follow, Mars is the New World. In establishing our first foothold on Mars, we will begin humanity's career as a multi-planet species.

Mars is where the science is, Mars is where the challenge is, and Mars is where the future is. That's why Mars must be our goal.

3. How Do We Get There?

Humans to Mars may seem like a wildly bold goal to proclaim in the wake of disaster, yet such a program is entirely achievable. From the technological point of view, we're ready. Despite the greater distance to Mars, we are much better prepared today to send humans to Mars than we were to launch humans to the Moon in 1961 when John F. Kennedy challenged the Nation to achieve that goal—and we were there eight years later. Given the will, we could have our first teams on Mars within a decade.

The key to success come from rejecting the policy of continued stagnation represented by senile Shuttle Mode thinking, and returning to the destination-driven Apollo Mode method of planned operation that allowed the space agency to perform so brilliantly during its youth. In addition, we must take a lesson from our own pioneer past and from adopt a "travel light and live off the land" mission strategy similar to that which has well-served terrestrial explorers for centuries.

The plan to explore the Red Planet in this way is known as Mars Direct. Here's how it could be accomplished

At an early launch opportunity, for example 2009, a single heavy lift booster with a capability equal to that of the Saturn V used during the Apollo program is launched off Cape Canaveral and uses its upper stage to throw a 40-tonne unmanned payload onto a trajectory to Mars. (Such a booster could be readily created by converting the Shuttle launch stack, deleting the Orbiter and replacing it with a payload fairing containing a hydrogen/oxygen rocket stage.) Arriving at Mars eight months later, the spacecraft uses friction between its aeroshield and Mars' atmosphere to brake itself into orbit around the planet, and then lands with the help of a parachute. This payload is the Earth Return Vehicle (ERV). It flies out to Mars with its two methane/oxygen driven rocket propulsion stages unfueled. It also carries six tonnes of liquid hydrogen cargo, a 100 kilowatt nuclear reactor mounted in the back of a methane/oxygen driven light truck, a small set of compressors and automated chemical processing unit, and a few small scientific rovers.

As soon as the craft lands successfully, the truck is telerobotically driven a few hundred meters away from the site, and the reactor deployed to provide power to the compressors and chemical processing unit. The hydrogen brought from Earth can be quickly reacted with the Martian atmosphere, which is 95 percent carbon dioxide gas (CO_2), to produce methane and water, thus eliminating the need for long-term storage of cryogenic hydrogen on the planet's surface. The methane so produced is liquefied and stored, while the water is electrolyzed to produce oxygen, which is stored, and hydrogen, which is recycled through the methanator. Ultimately, these two reactions (methanation and water electrolysis) produce 24 tonnes of methane and 48 tonnes of oxygen. Since this is not enough oxygen to burn the methane at its optimal mixture ratio, an additional 36 tonnes of oxygen is produced via direct dissociation of Martian CO_2. The entire process takes ten months, at the conclusion of which a total of 108 tonnes of methane/oxygen bipropellant will have been generated. This represents a leverage of 18:1 of Martian propellant produced compared to the hydrogen brought from Earth needed to create it. Ninety-six tonnes of the bipropellant will be used to fuel the ERV, while 12 tonnes are available to support the use of high powered, chemically fueled long range ground vehicles. Large additional stockpiles of oxygen can also be produced, both for breathing and for turning into water by combination with hydrogen brought from Earth. Since water is 89 percent oxygen (by weight), and since the larger part of most foodstuffs is water, this greatly reduces the amount of life support consumables that need to be hauled from Earth.

The propellant production having been successfully completed, in 2011 two more boosters lift off the Cape and throw their 40-tonne payloads towards Mars. One of the payloads is an unmanned fuel-factory/ERV just like the one launched in 2009, the other is a habitation module carrying a crew of four, a mixture of whole food and dehydrated provisions sufficient for three years, and a pressurized methane/oxygen powered ground rover. On the way out to Mars, artificial gravity can be provided to the crew by extending a tether between the habitat and the burnt out booster upper stage, and spinning the assembly.

Upon arrival, the manned craft drops the tether, aerobrakes, and lands at the 2009 landing site where a fully fueled ERV and fully characterized and beaconed landing site await it. With the help of such navigational aids, the crew should be able to land right on the spot; but if the landing is off course by tens or even hundreds of kilometers, the crew can still achieve the surface rendezvous by driving over in their rover. If they are off by thousands of kilometers, the second ERV provides a backup.

However, assuming the crew lands and rendezvous as planned at site number one, the second ERV will land several hundred kilometers away to start making propellant for the 2013 mission, which in turn will fly out with an additional ERV to open up Mars landing site number three. Thus, every other year two heavy lift boosters are launched, one to land a crew, and the other to prepare a site for the next mission, for an average launch rate of just one booster per year to pursue a continuing program of Mars exploration. Since in a normal year we can launch about six Shuttle stacks, this would only represent about 16 percent of the U.S. launch capability, and would clearly be affordable. In effect, this "live off the land" approach removes the manned Mars mission from the realm of mega-spacecraft fantasy and reduces it in practice as a task of comparable difficulty to that faced in launching the Apollo missions to the Moon.

Fig. 1 The Mars Direct plan. First an unfueled Earth Return Vehicle (ERV, right) is delivered to Mars where it manufactures its propellant from the Martian atmosphere. The crew then flies to Mars in the tuna-can-shaped hab module, which also provides living quarters, lab, and workshop for a 1.5 year Mars stay. (Artwork courtesy of Robert Murray, Pioneer Astronautics.)

The crew will stay on the surface for 1.5 years, taking advantage of the mobility afforded by the high powered chemically driven ground vehicles to accomplish a great deal of surface exploration. With a 12 tonne surface fuel stockpile, they have the capability for over 24,000 kilometers worth of traverse before they leave, giving them the kind of mobility necessary to conduct a serious search for evidence of past or present life on Mars—an investigation key to revealing whether life is a phenomenon unique to Earth or general throughout the universe. Since no-one has been left in orbit, the entire crew will have available to them the natural gravity and protection against cosmic rays and solar radiation afforded by the Martian environment, and thus there will not be the strong driver for a quick return to Earth that plagues alternative Mars mission plans based upon orbiting mother-ships with small landing parties. At the conclusion of their stay, the crew returns to Earth in a direct flight from the Martian surface in the ERV. As the series of missions progresses, a string of small bases is left behind on the Martian surface, opening up broad stretches of territory to human cognizance.

In essence, by taking advantage of the most obvious local resource available on Mars—its atmosphere—the plan allows us to accomplish a manned Mars mission with what amounts to a lunar-class transportation system. By eliminating any requirement to introduce a new order of technology and complexity of operations beyond those needed for lunar transportation to accomplish piloted Mars missions, the plan can reduce costs by an order of magnitude and advance the schedule for the human exploration of Mars by a generation. Indeed, since a lunar-class transportation system is adequate to reach Mars using this plan, it is rational to consider a milestone mission, perhaps five years into the program, where a subset of the Mars flight hardware is exercised to send astronauts to the Moon.

Exploring Mars requires no miraculous new technologies, no orbiting spaceports, and no gigantic interplanetary space cruisers We don't need to spend the next thirty years with a space program mired in impotence, spending large sums of money and taking occasional casualties while the same missions to nowhere are flown over and over again and professional technologists dawdle endlessly in their sand boxes without producing any new flight hardware. We simply need to choose our destination, and with the same combination of vision, practical thinking, and passionate resolve that served us so well during Apollo, do what is required to get there.

We can establish our first small outpost on Mars within a decade. We and not some future generation can have the eternal honor of being the first pioneers of this new world for humanity. All that's needed is present day technology, some 19th century industrial chemistry, a solid dose of common sense, and a little bit of moxie.

4. What Congress Needs to Do Now

The U.S. civilian space program is presently in a crisis. It is now apparent that the Shuttle Orbiter cannot be used much longer as a system for transporting crews to Earth orbit. The *Columbia* disaster has made it clear that the antiquated Orbiters are becoming increasingly unsafe. Moreover, even if the Orbiter could be flown safely, it is clear that using a launch vehicle with a takeoff thrust matching that of a Saturn V to transport half a dozen people to the Space Station makes about as much sense as using an aircraft carrier to tow water skiers. The Shuttle was designed as a self-launching space station. Absent a permanent space station on-orbit, such a vehicle had some justification. But with the establishment of the ISS, the rationale for using a flying Winnebago as a space taxi is no longer sustainable.

NASA has already begun to respond to this reality by starting the Orbital Space Plane (OSP) program, which will move the human taxi-to-orbit function from the Shuttle to a small capsule or mini-orbiter that can be launched on top of an Atlas or Delta. If constrained to the objective of producing a simple reliable capsule instead of a complex mini shuttle, such a program could make a great deal of sense. A simple capsule will be much safer than a more complex system, will have a much lower development cost, and can be made available for flight much sooner, thereby cutting short the risks and costs associated with prolonged Shuttle operations. Launched aloft a medium lift expendable launch vehicle, it could assume the Shuttle's crew transfer function at less than 1/5th the cost.

As rational as such an approach might be, however, it poses a direct threat to the jobs of hundreds of thousands of people associated with the existing Shuttle program, and to the bottom line of several major and many minor aerospace companies. For this reason, some people have been lobbying for making the OSP a complex mini shuttle program that would take many years to complete, and cost, at most recent estimate, some $17 billion.

This is the wrong approach, and is emblematic of the pathology associated with what we have termed NASA's Shuttle Mode of operation. The raid upon the treasury it involves would sap funding for any other space initiatives, and the delay it would entail in Shuttle replacement would expose our astronauts to serious unnecessary risk. Furthermore, despite patently false claims to the contrary, the wing-and-landing gear ballasted mini-Shuttle is wildly suboptimal for use in any missions beyond low Earth orbit.

As presently constituted, Congress should not fund this program. Making a gold-plated mini-shuttle the centerpiece of NASA's development efforts for the next ten years would prevent any human exploration operations for a generation, at the end of which we would be no better prepared to commence piloted planetary exploration than we are today. In fact, we would be worse off, since by simply downsizing from the Orbiter to the OSP mini-Shuttle as a means of transporting humans to orbit at lower recurring cost, we would end up discarding the ten-billion dollar asset represented by the STS launch stack. This would be a disaster, since in the context of a well-planned human exploration initiative, the STS stack would almost certainly be converted into a heavy lift vehicle, rather than scrapped. Such would be the consequences of adopting the piecemeal, reactive approach to dealing with the Shuttle/OSP problem.

Rather than appropriate $17 billion for an OSP program that will not take us anywhere, Congress should appropriate $60 million to fund *two* six-month $30 million studies to develop end-to-end plans for human exploration of Mars. One of these $30 million studies should be conducted at NASA Johnson Space Center. The other $30 million should go to fund a *competing* interagency team led by someone from one of the non-NASA government space agencies. Each of these teams should be charged with the task of developing a complete space architecture and mission plan that enables humans to Mars within ten years of program start, with lunar missions enabled by a modified subset of the Mars mission hardware. Constraints should be placed on the plans such as a total development cost limit of $30 billion or less, with a recurring Mars mission cost no greater than $3 billion.

Upon completion of the study, each of the plans should be submitted to a blue-ribbon panel appointed by Congress for evaluation on merit of cost, technical feasibility, and exploration capability. Based on that assessment, the team deemed superior should be selected to lead the human exploration program, and the hardware elements required to implement its plan should be funded and built in accordance with a multi-year schedule laid down in the plan, and then flown.

Once again, Congress should not fund the construction of *things.* It should fund the implementation of a *plan.*

Directing funding in this focused way does not preclude engaging in exploratory research. What it does mean, however, is that the technologies chosen for research and development are those necessary to enable or enhance the plan, rather than those needed to maintain or enhance the funding of established research and development constituencies.

The recommendation to fund two competing program design teams may seem surprising to some. However the experience of the past several decades has made it clear that, absent the spur of competition, efficient plans will not be generated. The nation does not need a Mars program plan that is bloated with funding for a plethora of unnecessary technology and infrastructure developments. Yet the incentive of as bureaucracy is to use the Mars mission as a kind of Christmas tree upon which to hang various desired technology programs as ornaments. This is the problem that caused NASA to respond to the elder president Bush's call for a Space Exploration Initiative with a hopelessly bloated and overpriced plan in 1989, and is the root pathology that drove the generation of a hyper-complex gargantuan space program design by the NASA Headquarters NExT group during the more recent period.

Mark Twain once said that nothing so focuses the mind as the knowledge that you are going to be shot in the morning. Only the certain knowledge that the cost increases associated with insertion of unnecessary elements in the mission plan threatens the complete loss of programmatic control will force either NASA or an alternative government organization to put parochial interests aside and design the best and most streamlined program possible.

5. Conclusion

Senator McCain, distinguished members of the Commerce Committee. Humanity today stands at the brink of a liberating development which will be remembered far into future ages, when nearly all the other events of our time are long forgotten. That development is the initiation of the human career as a spacefaring species.

The Earth is not the only world. There are numerous other planetary objects in our own solar system, millions in nearby interstellar space, and hundreds of billions in the galaxy at large. The challenges involved in reaching and settling these new worlds are large, but not beyond humanity's ultimate capacity. Were we to become spacefarers, we will open up a prospect for a human future that is vast in time and space, and rich in experience and potential to an extent that exceeds the imagination of anyone alive today. When we open the space frontier, we will open the door to the creation of innumerable new branches of human civilization, replete with new languages, new cultures, new literatures, new forms of social organization, new knowledge, technological contributions, and epic histories that will add immeasurably to the human story.

We were once a small collection of tribes living in the east African rift valley. Had we stayed in our native habitat, that is all we would be today. Instead, we ventured forth, took on the challenges of the inhospitable ice age environments to the north, and then elsewhere, and in consequence, transformed ourselves into a global civilization. When we go into space, the expansion of our possibilities will be equally dramatic. As a result, the human experience a few thousand years from now will be as rich in comparison to ours, as our global society is in comparison to tribal culture of the Kenyan rift valley at the time of our species' origin.

Therefore, I believe that we here today sitting in this historic chamber are gathered not at the end of history, but at the beginning of history. That our Nation shall be remembered not so much for the great deeds our predecessors have already done, but for the still greater accomplishments they have prepared us, and those who will follow us, to do. Let us therefore embrace our role as humanity's vanguard, as pioneers of the future. Let us honor the true American tradition by continuing it, and bravely take on the untamed space frontier to open new worlds for our posterity, as our courageous predecessors did for us.

Ladies and gentlemen of the Senate, I ask that you embrace the challenge of Mars, and act forcefully to put NASA on a track that will deliver real results. The American people want and deserve a space program that is actually going somewhere. For that to occur, it needs be given a goal, from that goal a produce a plan, and from that plan, action. It is within your power to make this happen. It is within your power to initiate a program of exploration that will lead in time to the greatest flowering of human potential, knowledge, progress, and freedom that history has ever known. I ask that you do so.

Thank you for your attention.

The CHAIRMAN. I'll look forward to reading your book, Doctor. Thank you for your enthusiastic testimony. Dr. Woods.

STATEMENT OF DAVID WOODS, PROFESSOR, INSTITUTE FOR ERGONOMICS, THE OHIO STATE UNIVERSITY

Dr. WOODS. Senator McCain and Members of the Committee, I want to thank you for investing your time and energy on the future of NASA. As a specialist on risky decisionmaking, I've spent my career investigating failures and improving safety in complex settings, including nuclear power, health care, and aerospace, including studies of how mission control handles anomalies.

To look forward and envision NASA as a high-reliability organization, to shift topics a little bit from the future missions, we first need to look back with clarity unobscured by hindsight bias. Admiral Gehman, as he's pointed out this morning already, found that the hole in the wing was not produced simply by debris, but by holes in organizational decisionmaking. The factors that produced the holes in decisionmaking are not unique to NASA, but are generic vulnerabilities we've seen before in other tragedies and we unfortunately are likely to see again.

The board's investigation shows how NASA failed to balance safety risks with intense production pressure. As a result, this accident matches a classic pattern, a drift toward failure as defenses erode in the face of production pressure. The paradox of production and safety conflicts is that safety investments are most important when least affordable by schedule. The NASA of the future will recognize when the side effects of production pressure increase safety risks and will be able to add investments to safety.

Another general pattern revealed in *Columbia* is an organization that takes past success as a reason for confidence instead of constantly monitoring for new emerging risks. NASA could not see the holes in its own decision-making process. The NASA of the future will have a safety organization that questions NASA's own model, the risks it faces, and the counter-measures it deploys. Such a reassessment will help NASA find places where it has underestimated the potential for trouble.

A third general pattern is a fragmented problem-solving process where no one could see the big picture, combined with breakdowns at the boundaries of organizational units. People were making decisions about what did or not pose a risk on very shaky technical data and without meaningful cross checks, but even more critically, no one noticed how their decisions rested on such shaky grounds, and no one noted the cross checks were missing.

The NASA of the future will have a safety organization with the technical expertise and authority to enhance coordination across the normal chain of command. A final pattern in *Columbia* is a failure to revise assessments as new evidence accumulates. Research has consistently shown that revising assessments is quite difficult and usually requires a new way of looking at previous facts. We provide this fresh view through interactions across diverse groups with diverse knowledge and tools.

The NASA of the future will have a safety organization that provides a fresh view on risk to help NASA see its own blind spots. How will this future for NASA come about. A new safety organization and culture can arise based on the principles of the emerging field of resilience engineering. Resilience engineering is build on the insights from the above patterns that we found in too many tragedies, and is concerned with assessing organizational risk, that is, the risk that the holes in organizational decisionmaking will produce an unrecognized drift toward failure boundaries. Resilience engineering also depends on having techniques, resources, and authority to make extra targeted investments in areas that can rebalance safety and production when they conflict.

A traditional dilemma for safety organizations is the problem of cold water and an empty gun. Safety organizations raise questions which stop progress on production goals. We just saw that in the discussion on ISS. That's the cold water. Yet, when line organizations ask for help on how to address the concerns, safety organizations may be unprepared to contribute the empty gun. As a result, in the long run the safety organization will fail in its mission.

To avoid this pitfall and to achieve the vision, there are several actions that Congress can consider. First, create a new safety leadership team in NASA, well versed in organizational decisionmaking, systems approaches to safety, and human factors in complex systems. Second, provide the resources and authority to achieve what I call the three "I"s of an effective safety organization. That is, to provide an independent voice that will challenge the conventional assumptions within management. Second, constructive involvement in targeted everyday decision-making so they have a finger on the pulse of what goes on, and actively generate information about weaknesses and how the organization is actually operating.

To accomplish these three "I's"; independence, involvement, and information, Congress needs to provide funding directly and independent from NASA headquarters. Similarly, the safety leadership team needs to be chosen and accountable to designees of Congress, not directly to the NASA chain of command. For the safety organization to able to monitor what goes on and to be a constructive contributor, it needs to control a set of resources with its own authority to decide how to invest those resources to help line organizations.

In conclusion, unfortunately it sometimes takes tragedies such as *Columbia* to create windows of opportunity for rapid learning and improvement. It is our responsibility to those who sacrificed so much to seize the opportunity to lead change. Congress can energize the creation of an independent, involved, and informed safety organization using principles of resilience engineering so that the NASA of the future will be able to create foresight about the changing patterns of risk before failure and harm occurs.

[The prepared statement of Dr. Woods follows:]

PREPARED STATEMENT OF DAVID WOODS, PROFESSOR, INSTITUTE FOR ERGONOMICS, THE OHIO STATE UNIVERSITY

CREATING FORESIGHT: HOW RESILIENCE ENGINEERING CAN TRANSFORM NASA'S APPROACH TO RISKY DECISION MAKING

Introduction

To look forward and envision NASA as a high reliability organization, we need first to look back with clarity unobscured by hindsight bias. Admiral Gehman and the Columbia Accident Investigation Board (CAIB) found the hole in the wing was produced not simply by debris, but by holes in organizational decision making. The factors that produced the holes in decision making are not unique to today's NASA or limited to the Shuttle program, but are generic vulnerabilities that have contributed to other failures and tragedies across other complex industrial settings.

For 24 years my research has examined the intersection of human decision making, computers, and high risk complex situations from nuclear power emergencies to highly automated cockpits to medical decision making, and specifically has included studies of how space mission operation centers handle anomalies.

CAIB's investigation shows how NASA failed to balance safety risks with intense production pressure. As a result, this accident matches a classic pattern—a drift toward failure as defenses erode in the face of production pressure. When this pattern is combined with a fragmented problem solving process that is missing cross checks and unable to see the big picture, the result is an organization that cannot see its own blind spots about risks. Further, NASA was unable to revise its assessment of the risks it faced and the effectiveness of its countermeasures against those risks as new evidence accumulated. What makes safety/production tradeoffs so insidious is that evidence of risks become invisible to people working hard to produce under pressure so that safety margins erodes over time.

As an organizational accident *Columbia* shows the need for organizations to monitor their own practices and decision processes to detect when they are beginning to drift toward safety boundaries. The critical role for the safety group within the organization is to monitor the organization itself—to measure organizational risk—the risk that the organization is operating nearer to safety boundaries than it realizes.

In studying tragedies such as *Columbia,* we have also found that failure creates windows for rapid learning and improvement in organizations. Seizing the opportunity to learn is the responsibility leaders owe to the people and families whose sacrifice and suffering was required to make the holes in the organization's decision making visible to all. NASA and Congress now have the opportunity to transform the culture and operation of all of NASA (Shuttle, ISS, and space science missions), and by example transform other high risk organizations.

The target is to help organizations maintain high safety despite production pressure. This is the topic of the newly emerging field of *Resilience Engineering* which uses the insights from research on failures in complex systems, including organizational contributors to risk, and the factors that affect human performance to provide practical systems engineering tools to manage risk proactively.

NASA can use the emerging techniques of Resilience Engineering to balance the competing demands for very high safety with real time pressures for efficiency and production. By following the recommendations of the CAIB to thoroughly re-design its safety organization and provide for an independent technical authority, NASA can provide a model for high reliability organizational decision making.

The Trouble with Hindsight

The past seems incredible, the future implausible.[1]

Hindsight bias is a psychological effect that leads people to misinterpret the conclusions of accident investigations.[2] Often the first question people ask about the decision making leading up to an accident such as *Columbia* is, "why did NASA continue flying the Shuttle with a known problem . . .?" (The known problem refers

[1] Woods, D.D. and Cook, R.I. (2002). Nine Steps to Move Forward from Error. *Cognition, Technology, and Work,* 4(2): 137–144.

[2] The hindsight bias is a well reproduced research finding relevant to accident analysis and reactions to failure. Knowledge of outcome biases our judgment about the processes that led up to that outcome.

In the typical study, two groups of judges are asked to evaluate the performance of an individual or team. Both groups are shown the same behavior; the only difference is that one group of judges are told the episode ended in a poor outcome; while other groups of judges are told that the outcome was successful or neutral. Judges in the group told of the negative outcome consistently assess the performance of humans in the story as being flawed in contrast with the group told that the outcome was successful. Surprisingly, this hindsight bias is present even if the judges are told beforehand that the outcome knowledge may influence their judgment.

Hindsight is not foresight. After an accident, we know all of the critical information and knowledge needed to understand what happened. But that knowledge is not available to the participants before the fact. In looking back we tend to oversimplify the situation the actual practitioners faced, and this tends to block our ability to see the deeper story behind the label human error.

to the dangers of debris striking and damaging the Shuttle wing during takeoff which the CAIB identified as the physical cause of the accident.)

As soon as the question is posed in this way, it is easy to be trapped into oversimplifying the situation and the uncertainties involved before the outcome is known.[3] After-the-fact "the past seems incredible," hence NASA managers sound irrational or negligent in their approach to obvious risks. However, before any accident has occurred and while the organization is under pressure to meet schedule or increase efficiency, potential warning flags are overlooked or re-interpreted since the potential "future looks implausible." For example, the signs of Shuttle tile damage became an issue of orbiter turn around time and not a flight risk.

Because it is difficult to disregard "20/20 hindsight", it is easy to play the classic blame game, define a "bad" organization as the culprit, and stop. When this occurs, the same difficulties that led to the *Columbia* accident will go unrecognized in other programs and in other organizations.

The CAIB worked hard to overcome hindsight bias and uncover the breakdown in organizational decision making that led to the accident. All organizations can misbalance safety risks with pressure for efficiency. It is difficult to sacrifice today's real production goals to consider uncertain evidence of possible future risks. The heart of the difficulty is that it is most critical to invest resources to follow up on potential safety risks when the organization is least able to afford the diversion of resources due to pressure for efficiency or throughput.

Five General Patterns Present in Columbia

The CAIB report identifies a variety of contributors to the accident. These factors have been seen before in other accidents.[4] Focusing on the general patterns present in this particular accident helps guide the process of envisioning the future of NASA as a high reliability organization.

Classic patterns also seen in other accidents and research results include:

- Drift toward failure as defenses erode in the face of production pressure.
- An organization that takes past success as a reason for confidence instead of investing in anticipating the changing potential for failure.
- Fragmented problem solving process that clouds the big picture.
- Failure to revise assessments as new evidence accumulates.
- Breakdowns at the boundaries of organizational units that impedes communication and coordination.

1. The basic classic pattern in this accident is—Drift toward failure as defenses erode in the face of production pressure.

My colleague, Erik Hollnagel in 2002, captured the heart of the *Columbia* accident when he commented on other accidents:

> If anything is unreasonable, it is the requirement to be both efficient and thorough at the same time—or rather to be thorough when with hindsight it was wrong to be efficient.

Hindsight bias, by oversimplifying the situation people face before outcome is known, often hides tradeoffs between multiple goals. The analysis in the CAIB report provides the general context of a tighter squeeze on production goals creating strong incentives to downplay schedule disruptions. With shrinking time/resources available, safety margins were likewise shrinking in ways which the organization couldn't see.

Goal tradeoffs often proceed gradually as pressure leads to a narrowing focus on some goals while obscuring the tradeoff with other goals. This process usually happens when acute goals like production/efficiency take precedence over chronic goals like safety. If uncertain "warning" signs always lead to sacrifices on schedule and efficiency, how can any organization operate within reasonable parameters or meet stakeholder demands?

The paradox of production/safety conflicts is: safety investments are most important when least affordable. It is precisely at points of intensifying production pressure that extra investments for managing safety risks are most critical.

The NASA of the future will need a means to recognize when the side effects of production pressure may be increasing safety risks and under those circumstances develop a means to add investments to safety issues at the very time when the organization is most squeezed on resources and time.

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[3] See S. Dekker's The Field Guide to Human Error Investigations. Ashgate, 2002.

[4] Hollnagel, E. (1993). *Human Reliability Analysis: Context and Control.* London: Academic Press.

2. Another general pattern identified in Columbia is that an organization takes past success as a reason for confidence instead of digging deeper to see underlying risks.

One component in the drift process is the interpretation of past "success". The absence of failure is taken as positive indication that hazards are not present or that countermeasures are effective. An organization usually is unable to change its model of *itself* unless and until overwhelming evidence accumulates that demands revising the model. This is a guarantee that the organization will tend to learn late, that is, revise its model of risk only after serious events occur. An effective safety organization assumes its model of risks and countermeasures is fragile and seeks out evidence to revise and update this model.[5] To seek out such information means the organization is willing to expose its blemishes.

During the drift toward failure leading to the *Columbia* accident a mis-assessment took hold that resisted revision (that is, the mis-assessment that foam strikes pose only a maintenance and not a risk to orbiter safety). It is not simply that the assessment was wrong, but the inability to re-evaluate the assessment and re-examine evidence about risks that is troubling.

The missed opportunities to revise and update the organization's model of the riskiness of foam events seem to be consistent with what I have found in other cases of failure of foresight. I have described this discounting of evidence as "distancing through differencing" whereby those reviewing new evidence or incidents focus on differences, real and imagined, between the place, people, organization and circumstances where an incident happens and their own context. By focusing on the differences, people see no lessons for their own operation and practices or only narrow well bounded responses.

Ominously, this *distancing through differencing* that occurred throughout the build up to the final *Columbia* mission can be repeated in the future as organizations and groups look at the analysis and lessons from this accident and the CAIB report. Others in the future can easily look at the CAIB conclusions and deny their relevance to their situation by emphasizing differences (*e.g.,* my technical topic is different, my managers are different, we are more dedicated and careful about safety, we have already addressed that specific deficiency).

One general principle to promote organizational learning in NASA is—Do not discard other events because they appear on the surface to be dissimilar. Rather, every event, no matter how dissimilar on the surface, contains information about underlying general patterns that help create foresight about potential risks before failure or harm occurs.

The NASA of the future will have a safety organization that question NASA's own model of the risks it faces and the countermeasures deployed. Such review and reassessment will help NASA find places where it has underestimated the potential for trouble and revise its approach to create safety.

3. Another general pattern identified in Columbia is a fragmented problem solving process that clouds the big picture.

During *Columbia* there was a fragmented view of what was known about the strike and its potential implications. There was no place or person who had a complete and coherent view of the analysis of the foam strike event including the gaps and uncertainties in the data or analysis to that point. It is striking that people used what looked like technical analyses to justify previously reached conclusions, instead of using technical analyses *to test tentative hypotheses* (*e.g.,* CAIB report, p. 126 1st column).

People were making decisions about what did or did not pose a risk on very shaky or absent technical data and analysis, and critically, *they couldn't see their decisions rested on shaky grounds* (*e.g.,* the memos on p. 141, 142 of he CAIB report illustrate the shallow, off hand assessments posing for and substituting for careful analysis).

The breakdown or absence of cross-checks is also striking. Cross checks on the rationale for decisions is a critical part of good organizational decision making. Yet no cross checks were in place to detect, question or challenge the specific flaws in the rationale, and *no one noted that cross-checks were missing.*

There are examples of organizations that avoid this fragmentation problem. Ironically, one of them is teamwork in NASA's own Mission Control which has a successful record of analyzing and handling anomalies.[6] In particular, the Flight Direc-

[5] Rochlin, G. I. (1999). Safe operation as a social construct. *Ergonomics, 42* (11), 1549–1560.

[6] For example, see: E.S. Patterson, J.C. Watts-Perotti, D.D. Woods. Voice Loops as Coordination Aids in Space Shuttle Mission Control. *Computer Supported Cooperative Work,* 8, 353—371, 1999. J.C. Watts, D.D. Woods, E.S. Patterson. Functionally Distributed Coordination during Anomaly Response in Space Shuttle Mission Control. Proceedings of Human Interaction with

tor and his or her team practice identifying and handling anomalies through simulated situations. Note that shrinking budgets lead to pressure to reduce training investments (the amount of practice, the quality of the simulated situations, and the number or breadth of people who go through the simulations sessions can all decline).

The fragmentation of problem solving also illustrates Karl Weick's point[7] about how important it is that high reliability organizations exhibit a "deference to expertise", "reluctance to simplify interpretations", and "preoccupation with potential for failure" none of which were in operation in NASA's organizational decision making leading up to and during *Columbia*.

The NASA of the future will have a safety organization that ensures that adequate technical grounds are established and used in organizational decision making.

To accomplish this for NASA, the safety organization will need to define the kinds of anomalies to be practiced as well as who should participates in those simulation training sessions. The value of such training depends critically on designing a diverse set of anomalous scenarios with detailed attention to how they unfold. By monitoring performance in these simulated training cases, the safety personnel are able assess the quality of organizational decision making.

4. The fourth pattern in Columbia is a Failure to revise assessments as new evidence accumulates.

I first studied this pattern in nuclear power emergencies 20 plus years ago.[8] What was interesting in the data then was how difficult it is to revise a mis-assessment or to revise a once plausible assessment as new evidence comes in. This finding has been reinforced in subsequent studies in different settings.

The crux is to notice the information that changes past models of risk and calls into question the effectiveness of previous risk reduction actions, without having to wait for complete clear cut evidence. If revision only occurs when evidence is overwhelming, there is a grave risk of an organization acting too risky and finding out only from near misses, serious incidents, or even actual harm. Instead, the practice of revising assessments of risks needs to be an ongoing process. In this process of continuing re-evaluation, the working assumption is that risks are changing or evidence of risks has been missed.

Research consistently shows that revising assessments successfully requires a new way of looking at previous facts. We provide this *"fresh"* view:

(a) by bringing in people new to the situation

(b) through interactions across diverse groups with diverse knowledge and tools,

(c) through new visualizations which capture the big picture and re-organize data into different perspectives.

One constructive action is to develop the collaborative inter-changes that generate fresh points of view or that produce challenges to basic assumptions. This cross checking process is an important part of how NASA mission control responds to anomalies. One can also capture and display indicators of safety margin to help people see when circumstances or organizational decisions are pushing the system closer to the edge of the safety envelope.

What is so disappointing about NASA's organizational decision making is that the correct diagnosis of production/safety tradeoffs and useful recommendations for organizational change were noted in 2000. The Mars Climate Orbiter report of March 13, 2000 clearly depicts how the pressure for production and to be 'better' on several dimensions led to management accepting riskier and riskier decisions. This report recommended many organizational changes similar to the CAIB. A slow and weak response to the previous independent board report was a missed opportunity to improve organizational decision making in NASA.

The NASA of the future will have a safety organization that provides "fresh" views on risks to help NASA see its own blind spots and question its conventional assumptions about safety risks.

Complex Systems, IEEE Computer Society Press, Los Alamitos, CA, 1996. Patterson, E.S., and Woods, D.D. (2001). Shift changes, updates, and the on-call model in space shuttle mission control. *Computer Supported Cooperative Work,* 10(3–4), 317–346.

[7] Weick, K. E., Sutcliffe, K. M. and Obstfeld, D. (1999). Organizing for High Reliability: Processes of Collective Mindfulness. *Research in Organizational Behavior,* Volume 21, pp. 81–123.

[8] D.D. Woods, J. O'Brien, and L.F. Hanes. Human factors challenges in process control: The case of nuclear power plants. In G. Salvendy, editor, *Handbook of Human Factors/Ergonomics,* Wiley, New York, 1987.

5. Finally, the Columbia accident brings to the fore another pattern: *Breakdowns at the boundaries of organizational units.*

The CAIB notes how a kind of catch 22 was operating in which the people charged to analyze the anomaly were unable to generate any definitive traction and in which the management was trapped in a stance shaped by production pressure that views such events as turn around issues. This effect of an *"anomaly in limbo"* seems to emerge only at boundaries of different organizations that do not have mechanisms for constructive interplay. It is here that we see the operation of the generalization that in risky judgments we have to defer to those with technical expertise (and the necessity to set up a problem solving process that engages those practiced at recognizing anomalies in the event).

This pattern points to the need for mechanisms that create effective overlap across different organizational units and to avoid simply staying inside the chain of command mentality (though such overlap can be seen as inefficient when the organization is under severe cost pressure).

The NASA of the future will have a safety organization with the technical expertise and authority to enhance coordination across the normal chain of command.

Resilience Engineering

Resilience Engineering is built on insights derived from the above five patterns. Resilience Engineering is concerned with assessing organizational risk, that is the risk that holes in organizational decision making will produce unrecognized drift toward failure boundaries.[9]

While assessing technical hazards is one kind of input into Resilience Engineering, the goal is to monitor organizational decision making. For example, Resilience Engineering would monitor evidence that effective cross checks are well-integrated when risky decisions are made or would serve as a check on how well the organization is practicing the handling of simulated anomalies (what kind of anomalies, who is involved in making decisions).

Other dimensions of organizational risk include the commitment of the management to balance the acute pressures of production with the chronic pressures of protection. Their willingness to invest in safety and to allocate resources to safety improvement in a timely, proactive manner, despite pressures on production and efficiency, are key factors in ensuring a resilient organization.

The degree to which the reporting of safety concerns and problems is truly open and encouraged provides another significant source of resilience within the organization. Assessing the organization's response to incidents indicates if there is a learning culture or a culture of denial. Other dimensions include:

Preparedness/Anticipation: is the organization proactive in picking up on evidence of developing problems versus only reacting after problems become significant?

Opacity/Observability—does the organization monitors safety boundaries and recognize how close it is to 'the edge' in terms of degraded defenses and barriers? To what extent is information about safety concerns widely distributed throughout the organization at all levels versus closely held by a few individuals?

Flexibility/Stiffness—how does the organization adapt to change, disruptions, and opportunities?

Revise/Fixated—how does the organization update its model of vulnerabilities and the effectiveness of countermeasures over time?

[9] For initial background on the emergence of resilience engineering see Rasmussen, J. Risk Management, Adaptation, and Design for Safety. In B. Brehmer and N.-E. Sahlin (Eds.) Future Risks and Risk Management. Kluwer Academic, Dordrecht, 1994. Rasmussen, J. (1997). Risk Management in a Dynamic Society: A Modelling Problem. *Safety Science,* 27, 183–213. Reason, J. (2001). Assessing the Resilience of Health Care Systems to the Risk of Patient Mishaps. Carthy, J., de Leval, M. R. and Reason, J. T. (2001). Institutional Resilience in Healthcare Systems. Quality in Health Care, 10: 29–32. Weick, K. E. and Sutcliffe, K. M. (2001). Managing the unexpected: assuring high performance in an age of complexity. San Francisco: Jossey-Bass. Cook, R. I., Render, M. L. and Woods, D.D. (2000). Gaps in the continuity of care and progress on patient safety. *British Medical Journal,* 320, 791–794, March 18, 2000. Woods, D. D. and Shattuck, L. G. (2000). Distance supervision—local action given the potential for surprise *Cognition, Technology and Work,* 2, 86–96. Leveson, N. G. (in press). A New Accident Model for Engineering Safer Systems. *Safety Science.* Roberts, K.H., Desai, V., and Madsen, P. (in press) Work Life and Resilience in High Reliability Organizations. In E. Kossek and S. Lambert (Eds.) Work and Life Integration Mahwah: NJ: Erlbaum.

The NASA of the future will create a new safety organization and culture that is skilled at the three basics of Resilience Engineering:

(1) detecting signs of increasing organizational risk, especially when production pressures are intense or increasing;

(2) having the resources and authority to make extra investments in safety at precisely these times when it appears least affordable;

(3) having a means to recognize when and where to make targeted investments to control rising signs of organizational risk and re-balance the safety and production tradeoff.

These mechanisms will produce an organization that creates foresight about changing risks before failures occur.

Redesigning NASA for Safety: An Independent, Involved, and Informed Safety Organization

One traditional dilemma for safety organizations is the problem of "cold water and an empty gun." Safety organizations raise questions which stop progress on production goals—the "cold water." Yet when line organizations ask for help on how to address the safety concerns, while being responsive to production issues, the safety organization has little to contribute—the "empty gun." As a result, the safety organization fails to better balance the safety/production tradeoff in the long run. In the short run following a failure, the safety organization is emboldened to raise safety issues, but in the longer run the memory of the previous failure fades, production pressures dominate, and the drift processes operate unchecked (as has happened in NASA before *Columbia* and appears to be happening again with respect to ISS).

Re-shuffling personnel and re-tuning the existing safety organization does not meet the spirit of the CAIB recommendations. First, a new leadership team well versed in organizational decision making, systems approaches to safety, and human factors in complex systems needs to be assembled and empowered.

Second, the key target for the new safety organization is to monitor and balance the tradeoff of production pressure and risk. To do this the leadership team needs to implement a program for managing organizational risk—detecting emerging 'holes' in organizational decision making—based on advancing the techniques of Resilience Engineering.

Third, the new safety organization needs the resources and authority to achieve the three "I's" of an effective safety organization (independence, involvement, information):

provide an *independent* voice that challenges conventional assumptions within NASA management,

constructive *involvement* in targeted but everyday organizational decision making (for example, ownership of technical standards, waiver granting, readiness reviews, and anomaly definition).

actively generate *information* about how the organization is actually operating, especially to be able to gather accurate information about weaknesses in the organization.

Safety organizations must achieve independence enough to question the normal organizational decision making. At best the relationship between the safety organization and NASA senior management will be one of *constructive tension.* Inevitably, there will be periods where senior management tries to dominate the safety organization. Congress needs to provide the safety organization the tools to resist these predictable episodes by providing funding directly and independent from NASA headquarters. Similarly, to achieve independence, the safety leadership team needs to be chosen and accountable to designees of Congress, not directly to the NASA administrator or NASA headquarters.

Safety organizations must be involved in enough everyday organizational activities to have a finger on the pulse of the organization and to be seen as a constructive part of how NASA balances safety and production goals. This means the new safety organization needs to control a set of resources and the authority to decide how to invest these resources to help line organizations provide high safety while accommodating production goals. For example, the safety organization could decide to invest and develop new anomaly response training programs when it detects holes in organizational decision making processes.

In general, safety organizations risk becoming information limited as they can be shunted aside from real organizational decisions, kept at a distance from the actual work processes, and kept busy tabulating irrelevant counts when their activities are seen as a threat by line management (for example, the 'cold water' problem). Independent, involved and informed—these three properties of an effective safety organization are closely connected and mutually reinforcing.

Conclusion

The future NASA will balance the goals of both high productivity and ultra-high safety given the uncertainty of changing risks and certainty of continued pressure for efficient and high performance. To carry out this dynamic balancing act requires a new safety organization designed and empowered to be independent, involved and informed. The safety organization will use the tools of Resilience Engineering to monitor for "holes" in organizational decision making and to detect when the organization is moving closer to failure boundaries than it is aware. Together these processes will *create foresight* about the changing patterns of risk before failure and harm occurs.

Unfortunately, it sometimes takes tragedies such as *Columbia* to create windows of opportunity for rapid learning and improvement. It is our responsibility to seize the opportunity created at such cost to lead change. Congress can energize the creation of an independent, involved and informed safety organization in NASA. The NASA of the future can become the model of an organization that escapes the trap of production pressure eroding safety margins.

The CHAIRMAN. Thank you. Mr. Tumlinson, welcome.

STATEMENT OF RICK TUMLINSON, FOUNDER, SPACE FRONTIER FOUNDATION

Mr. TUMLINSON. Good afternoon, Senator McCain, Members of the Committee. Before I start I want to plant a thought in your mind. The next American to enter space will do so within a year. They will not be a government employee and they will not be flying on a government vehicle. Just think about that.

I'm honored to be given this chance to discuss our future in space and I'm honored and pleased

The CHAIRMAN. Who will it be, Mr. Tumlinson?

Mr. TUMLINSON. I'll get to that as we move along, building the suspense there, sir.

The CHAIRMAN. Thank you.

Mr. TUMLINSON. I'm honored to be given the chance to discuss the future of America's agenda in space and I congratulate you for reaching outside the usual circle of suspects. Over the years I've been known to give NASA a bit of a hard time for failing to open space to the American people, but to be frank, they've really never been given that job. In fact, as ironic as it is for such a frontier nation as our own, it's not now, nor has it ever been, the policy of the United States to open space to human settlement, and without such a powerful vision to develop, to organize itself around, and steer toward, other interests have taken the wheel, turning what was once the greatest tool for exploration ever seen in human history into a jobs program and a corporate cash cow. Worse, it's squandered the position of the symbol of American spirit and as an inspiration to new generations here and around the world.

So what do we do to change this sad state of affairs? First, we must agree that the development and permanent human habitation of space is the goal of the human space flight program, for if it is not then I must agree with the scientists, who say that this is a waste of time. Cancel the program, send the astronauts home, let them get jobs with airlines. Personally, I don't want to see that happen. We're America, we're a nation of pioneers, and we must recognize the reason we send people into space is to send people into space to live, to work, and to expand the human domain.

If America can recognize this truth we can make it the drive of our space agenda. Then the way forward becomes very clear. We will begin to see the Earth as the center of an expanding bubble of life. So far that bubble has been expanded to the moon. The inside of that bubble is what I call the near frontier. It's a place where our government explorers have done their job. The closer we get to the Earth the more sense it makes for the settlers and shopkeepers to take over in the form of commercial enterprises.

From the moon outwards extends the far frontier, where private investment offers little hope of return, but the investment of our society in the form of tax dollars does. It's returned in the form of science, knowledge, and the understanding of what is next as the bubble expands. We must get NASA as our modern day Lewis and Clarks out of the near frontier of low-Earth orbit and back to the job of exploring, and that means sending them to the far frontier of the moon and Mars.

At the same time, we must mobilize the incredible power and imagination of the American private sector that has made this Nation great, to take on the operational tasks that it does best in the near frontier. In other words, NASA should get out of what should be the business of driving trucks and building housing in a place where their work is done. Such things are done far more efficiently in our culture by the private sector.

For example, NASA long ago pioneered the concept of earth to space transportation. Now it must hand this function to others. In fact, the private sector is already moving into this new market and doing so quickly. Contrast NASA's plans for a $10 billion orbital space plane with the innovative $30 million suborbital rocket ship now under constructed by famed aircraft builder Burt Rutan and the half-dozen or so other rocket ships in the suborbital realm that are being built by what I call the alternative space firms, we're the alt. space firms.

Sure, orbital spacecraft design is far more complex than suborbital, but $10 billion more complex? Imagine what the Rutans and these other elements of the alt space community could do in a competitive transportation marketplace for just a fraction of the orbital space plane's budget. Obviously, given these new set of players in the field, I believe we should end the orbital space plane project and the shuttle programs now. The government should offer prizes and multiple NASA and DOD launch contracts to any U.S. firms that can demonstrate safe and reliable orbital transportation at the lowest cost. Plus, we should create a nurturing regulatory environment for these innovative projects.

NASA can then concentrate on the challenge of space-to-space transportation and the surface habitations it will need to return to the moon and go on to Mars as it rediscovers its role as an exploration agency. Now, if these things are done, within a decade we could see a thriving community of hotels, science, industrial, and government facilities orbiting the Earth like a string of pearls. Our first space town, Alpha Town, could be created.

Meanwhile, NASA astronauts will train for Mars missions at NASA's planetary surface training base on the South Pole of the moon, spending their free time at the nearby lunar Hilton, also home to astronomers working on giant far-side observatories as they look for signs of life on the other world, selenologists studying the moon's surface for hints to the history of the Earth, helium-3 and platinum miners back from surveying new mining sites, and the usual guest lists of poets, artists, and the few people there just for the view of Earth outside of their window.

This all is a tiny hint of what is possible if we do the things we need to do now. We must decide to go outwards, this time to stay. We must create a new partnership between the Government and the private sector, the people, as we've done in the computer and Internet worlds, and trust the people to do what they do best for the benefit of both. And someone of vision must stand up, declare the frontier open for business, and tell NASA which way to go. As I know, the great people of that organization can do it if their orders are clear.

Opening the frontier of space will give our children choices, as Kennedy said, by providing new opportunities and turn the future before them from an ever-narrowing wedge of declining possibilities in an ever-more depleted and controlled world to a wide-open vista of hope. Space offers us vast new resources to supply our civilization, from the unlimited energy available in space to asteroids made up of more gold and platinum than the human race has used in its entire history. It will create unimaginable new wealth and an economy that is endlessly expanding as space itself.

Given the new spaces and places out there, our children will have the chance to grow democracy and freedom into new forms and continue this great experiment our ancestors began when they came to this world not so long ago. For me, that is a dream worth having, and for me that is a worthy goal for America. Thank you.

[The prepared statement of Mr. Tumlinson follows:]

PREPARED STATEMENT OF RICK TUMLINSON, FOUNDER, SPACE FRONTIER FOUNDATION

Rick Tumlinson—Biographical Information—October 2003

Rick N. Tumlinson—Born to a long time Texas family whose pioneering credits include co founding the Texas Rangers and fighting in the Alamo, Rick Tumlinson is a well-known firebrand and evangelist for the space frontier. He is the son of an Air Force Sergeant and his English wife, and was educated primarily in England and Texas. A regular contributor to the space industry paper "Space News" Tumlinson's writings and quotes have appeared in the *New York Times, Wall Street Journal, Los Angeles Times, Miami Herald, Reader's Digest* and dozens of other publications. He has appeared on such national television programs as *ABC's World News Tonight, the CBS Morning Show, and Politically Incorrect.* Internationally he has appeared on TV sets from Russia to China's CCTV and the BBC and been quoted in a wide range of journals, from the Economist to China's People's Daily.

Tumlinson worked for noted scientist Gerard K. O'Neill at the Space Studies Institute, produced the animated videos used to gain funding for the Air Force's DC–X rocket project and created the first ever paid political announcement for space. He was the first space consultant for the Sci Fi channel and played a major role in raising funding the International Space University. He helped pass the Space Settlement Act of 1988, testified before the National Commission on Space, was a founding trustee of the X-Prize and has been a lead witness in three congressional hearings on NASA in the 1990s. Rick is Executive Director and co-Founder of the Foundation for the International Non-Governmental Development of Space (FINDS),a multi-million dollar foundation which funds breakthrough projects and activities such as Helium 3 research, laser launch studies, and asteroid processing projects, The organization provided $1OOk in seed money for the Mars Society, operated the Cheap Access to Space Prize and supported such projects as The WATCH asteroid search program. FINDS was also the primary funding source and co sponsored a very successful series of Senate Space Roundtables in conjunction with the Space Frontier Foundation and the lobby Pro-Space over the last few years.

Mr. Tumlinson co-founded the firm LunaCorp, which produced the first ever TV commercial shot on the International Space Station for Radio Shack. He led the team which turned the Mir Space Station into the world's first commercial space facility, co founded the space firm MirCorp, signed up Dennis Tito, the world's first "citizen explorer," and has assisted in numerous other such projects.

Recently, Rick has appeared as an expert guest on the "CBS Evening News with Dan Rather," CNBC's "Open Exchange" and was quoted in the *Washington Post, LA Times,* and the *Orlando Sentinel,* regarding the Space Shuttle *Columbia* disaster. He appears often as a space commentator on CNN and is working on his first book. "Manifesto for the Space Frontier."

In his spare time Rick collects vintage tin space toys and robots from the 1950s, is into four-wheel drive off-roading, raising tropical fish and riding his motorcycle.

SPACE FRONTIER FOUNDATION

Background

Who We Are

The Space Frontier Foundation is an organization of space activists, scientists and engineers, media and political professionals, entrepreneurs, and citizens from all backgrounds, beliefs and nations. Our central and driving goal is the large-scale permanent settlement of space as soon as possible, using the resources we find there, and the imaginations we bring to the task.

We believe all people have the "right stuff' and that everyone will benefit from opening the space frontier. Given the fragility of our planet we also believe that it is vital that we not only preserve the biosphere of earth using the resources of space, but that we expand that biosphere, taking life to worlds now dead. If successful, we see our future as exciting and full of possibility.

We reject the ideas that the world's greatest moments are in its past, that the advancement of our technological civilization must mean the decline of our ecosystem, and we are determined to transform the image held by many that the future will be worse than the present.

We believe that free people, free markets and free enterprise will become unstoppable forces in the irreversible settlement of this new frontier, and that our world is on the verge of a truly historic breakthrough—access to space for all.

To make that happen, we are engaged in the transformation of space from a government-owned bureaucratic program-into a new partnership between the public and private sectors-that will lead to a dynamic and inclusive frontier open to all people.

This all means we are about opening space for you and your children, and doing it now! So get involved!

The Business of the Foundation:

Foundationers inspire!

Foundation speakers present a future that excites inspires and includes citizens from all nations, and through awards, briefings, gatherings and presentations our ideas are driving the portrayal of space into new directions.

Foundationers Are Active!

We work on policy issues at the national and international level, interacting with those who make the decisions. We speak to the media, challenging their old assumptions about space and the future, and using our access to let the world know what is possible on the frontier, and needs to be done today to get us there. We teach, letting the children of our world know they have a better tomorrow in store, and using the vastness of our universe to bring them together as we all reach for the dream of a tomorrow that is full of choices and hope.

Foundationers Make Things Happen!

- Remember the Lunar Prospector that found signs of water on the Moon? Foundationers helped start that project.
- Recall the breakthrough flights of the little rocket called the DC–X? Foundationers helped get it off the ground.
- Who were the people who made the Mir the world's first commercial space station? Foundationers put up their sweat and cash and took a stand.

- Who shot the first TV commercial on the space station? Foundationers worked with the space station partners and put Radio Shack in space.
- Who signed up Dennis Tito to fly and fought for his right to go into space? Foundationers did the deal and helped clear the path for his incredible adventure.
- Who are the people building many of the new and innovative vehicles to fly people like you and I into space? Foundationers are building new re-usable rocketships right now.
- Who threw the world's first global space party known as Yuri's Night? Foundationers put the "rock" into rocket and reached out to a new generation.

Our members are encouraged to take actions that help to open the Frontier in their private lives jobs and businesses. Dozens of our members have formed companies and organizations that further our goals in different ways. From other nonprofits to rocket companies to space services and travel groups to publishing and Internet firms, they are getting the word out and making space happen!

Events and Projects of the Foundation

Space Enterprise Symposiums—In space, nobody stays until somebody pays. That means we either create profitable enterprises or remain dependent on the government and taxpayer largesse. In our SES events we bring space entrepreneurs and real financiers and investors together, to educate both on the economic promise and peril of this new frontier.

Return to the Moon Conference—

Yuri's Night—

Roundtables—

Conference—As a manifestation of our "All of the above" philosophy, the Space Frontier Conference (SFC) is the center-piece event in the Foundation's annual calendar. It brings together entrepreneurs, scientists, engineers, entertainment leaders, government representative and private citizens to talk about, present, share and debate the latest and greatest ideas and activities affecting space.

The WATCH

Permission to Dream

Vision to Reality Award

Vision of the Tomorrow Award

Chained Rocket Award

Return to the Moon Symposium—One of the most important ways we can accelerate the exploration and settlement of the Solar System is to Return to the Moon to establish a permanent government and commercial base. Held each year in Houston on the day humans first stepped on the Moon, the RTM Symposium is the world's premiere gathering of experts, entrepreneurs, astronauts and activists working to make this happen.

Senate Space Roundtables—The Foundation keeps a strong presence in Washington D.C. . . From the asteroid threat to commercializing the space station and space solar power, our Space Roundtables provide an important forum to educate lawmakers and staffers about issues facing the space frontier movement.

Yuri's Night—Each April this global space party puts the "Rock" back into "Rocketship". Aimed at the under 30 set, Yuri's night celebrates the historic flight of Yuri Gagarin that opened the era of humans in space, bringing a new generation into the fight for the frontier.

The WATCH—The WATCH program is focused on leveraging and focusing the attention of astronomers and the media on the threat and promise we face from near Earth objects such as asteroids and comets. To date the WATCH has funded discovery and tracking programs, and supported important NEO educational outreach events and meetings.

Permission to Dream—PTD uses space to deliver a message of hope, unity and involvement to youth around the world. To date PTD has supported the placement of donated telescopes and lessons in countries as diverse as Chile, Iran, Zimbabwe, Russia and India, and is developing classroom projects and hands on space educational outreach in Los Angeles and other U.S. cities.

Awards—The Foundation uses various awards to move our agenda ahead and reward those who help create and realize our vision of an open Space Frontier. Our Vision to Reality Award goes to those projects and firms who make things happen in space, and our Vision of the Future Award is given to the film or media project that best inspires and educates people about the possibilities offered by the Frontier.

"The Space Frontier Foundation is pound for pound the most effective space group in the world."

TESTIMONY OF RICK TUMLINSON, FOUNDER, SPACE FRONTIER FOUNDATION

Why space?

"We choose to go to the Moon. We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too. . ."

Standing in Houston, Texas in the early 1960s, a young and vibrant President named John F. Kennedy looked skyward and offered a new and hopeful future to his generation. In the middle of a Cold War, in the heart of a time when the threat of total annihilation loomed over the heads of everyone, he dared to challenge those listening to take on a higher goal. Rather than succumb to the darkness, he held out light, and rather than cast what was in reality a technological face off into the mix of that shadow war, he held it aloft, a beacon to all who could hear and understand what he meant. At just the time when it seemed there was no choice but the continuation of a pointless global wrestling match which at any moment could result in the end for all, he spoke of choices.

Choices

Today we must ask ourselves again. What kind of tomorrow do we want to give to our kids? The choice is ours. You might say we have three possible futures we can give them—less, the same and more.

Our first possible choice, and the one lots of folks sometimes seem to believe is inevitable, is the worst. It's what might happen if we keep on rolling along and do nothing about conserving our natural resources or accessing new. The characterization we see in popular culture and films such as the Matrix, the Terminator series, and other dark dystopian images. It is an apocalyptic vision, the result of a time when all the world's cultures rush to create consumer societies such as those in Europe, Japan and the USA. Eventually our excesses exceed our limits and we end up with a polluted and stripped world whose environment collapses, bringing down whole societies, leading to war, famine, the end of global culture, and the dawn of a new dark age.

Our second choice is to attempt to sustain the human race on this one world through rationing of resources—at the cost of personal freedom—as we anesthetize ourselves with virtual realities and sensory distortions. . . Under the heavy hand of global Big Brother, our lives, actions, and even our very thoughts will be monitored and controlled. Imagination and innovation will be seen as threats to order and safety. Risk will be avoided at all cost. Perhaps we will eventually become so physically and intellectually passive that we finally load ourselves into banks of virtual electronic realities and pass the eons in a bliss of pretend adventures and paradises uncounted, until some global catastrophe such as an asteroid strike sends us into oblivion.

Or there's the third choice, opening the High Frontier of space and breaking out into the galaxy. Celebrating the spirit of exploration and individuality, we begin to truly explore and open the space around us to human settlement. Turning debates between free enterprise technologists and protectors of the Earth on their heads, we unleash the power of human imagination to create ways to harvest the resources of space, not only saving this precious planet, but also blazing a path to the stars. This is a tomorrow where life is exciting, new possibilities open up each day, and humanity spreads outwards, as the harbinger of life to worlds now dead. This future is characterized by new ideas and cultures spreading everywhere, the entire human race engaged in spreading life to the stars and a future that is ever expanding and hopeful.

Opening the space frontier will also change what it means to be an American. The effect of the space frontier on America will be profound. Our pioneering past will at last have a direct link to our future. Our heritage will be connected with our tomorrow in a visible and exciting way. The paths blazed by Daniel Boone, Davy Crockett and Lewis and Clark will continue onward and upward across the stars. The spirit of family will be resurrected as the frontier ethics of hard work and familial support are reinforced through the simple need to survive and prosper in a hostile environment. Our relationship to the rest of the world will change, as we throw open the doors to a better tomorrow for all, and as we always do, offer to hold those doors open for all and everyone to follow. Opening the frontier will change what it means to be a human being. We will become a multi-planet species, assuring our survival, and that of the life forms for which we are responsible. And a child living in such times will know why they are alive, and be able to see an unending and ever opening panorama of possibility stretching out before them

A Human Need

The simplicity of the needs which are fulfilled by opening this frontier is what makes it all so compelling and at once so elusive. We always want to make things seem more practical. In conversations and talk we speak of the need for "down to Earth" answers to such questions as those the frontier poses. But the real needs are often much more spiritual, much more about the core issues of life, and those of us who speak of the frontier often do ourselves a disservice by trying to dress down our Vision. We want to answer engineers and accountants with numbers, politicians with political reasons, environmentalists with new fixes for the seemingly intractable challenges we face in resource utilization and pollution.

The reasons we must open the frontier are as varied as the people who want to see it opened. And almost all of the reasons are good ones, although some, to me begin to rise above the rest. But in the end, most either enable or lead to a few basic and very core rationales.

We must open the frontier to expand this grand experiment called freedom, because without an arena to feed and nurture the ideals of liberty, individual choice and the right to do and be whatever you want they may well perish from the Earth. We must open the frontier because without an edge to our packed culture of individuals, nurturing and then bringing in new ideas and giving release to bad ones, the center comes apart. We must open the frontier to find and create new wealth for humanity, because everyone in the world deserves the chance to have the same fine house, fine cars, and good life you can potentially have, and this planet alone simply cannot provide support that, unless you give up yours (and someone, sometime will try and make you do so). We open the frontier to help save the planet we love from the ravages caused by our ever growing numbers and our hunger for new forms of energy, materials and products. Finally, and most importantly, we must open the frontier as humans to survive as a species and to protect our precious biosphere from destruction by the forces of the universe or ourselves by making it redundant.

As you can see, there are "Big" reasons, such as species survival and the need to provide new choices to future generations. For example, to those who must look into the eyes of a child who carries their immortality, we must open the frontier because our children deserve a future of more and better, not the drab and boring and potentially scary place we hold before them now. As Kennedy was pointing out, we must offer them more choices, not fewer.

Yet, many of the real reasons we reach outwards aren't easily quantifiable, often boiling down to the examination of history, the faith we have in what is possible in any new arena of human endeavour, and in fact, down to a deep, almost mystical belief that this is the "right" thing to do. And then, just below the surface of all of these lies something that is simply genetic-the drive for any species to expand its domain.

I believe that the human species is pioneering creature, that for us to be at our best we must always be pushing out from the center into new realms, that we must always be expanding outwards or we turn on ourselves. I believe it is the destiny of the human race to open the Frontier of space, and that if we do not we shall be doomed to the long slow spiraling decay of stagnation. Our move into space must be irreversible before this occurs, or society will turn inwards and our destiny in the stars will be forgotten for decades, if not centuries.

These aren't all the reasons, but they should give you the flavor of what this important movement is all about, for as you can see, they touch on the central issues of our time, of all times.

How are we doing in relation to these goals?

We aren't.

As driving, important and exciting as the possibilities offered by the frontier are, we aren't trying to open it. We are wandering around and around in circles at the edge of this new ocean, going nowhere and doing nothing of importance. It's no mystery why our space efforts are in trouble. As currently structured the U.S. national space program not only cannot open space, but has no intention of ever doing so!

It is not now, nor has it ever been the policy of the United States to open the space frontier to human settlement and development.

Any belief amongst those in the space community that opening the space frontier to wide spread participation, development and settlement is national policy is self delusion. A delusion well fed by those promoting projects originated by our space agency and its totally dependent contractors, who's rhetoric is often sprinkled with references to the space frontier and the inevitability of its settlement. Using loaded terms, such as "the next logical step," the public has been repeatedly sold lavish and expensive projects. The goal we are supposedly "stepping" towards is illustrated by beautiful propaganda art and simulations portraying the great and glorious frontier on which we are supposedly putting our multi-billion dollar down payment. Yet the projects and programs promoted actually have no connection to the opening of a frontier in a historical sense and there is no "logical" progression from today's program to an open frontier in space. Such "future fluff" is actually verbal and visual candy, cynically used to excite and titillate those whose support is needed for constant budget battles in Congress.

Even if one does not buy the idea that space is a frontier for human settlement, the current human space program is a failure. It will perhaps surprise you to hear me say this, but if NASA's charter in space is purely to expand our scientific understanding of the universe, then we should cancel our human space flight program right now. If the question is phrased that way, I find myself agreeing with a large portion of the scientific community who say it is neither the most effective nor cost efficient way of doing this type of work. Cancel it now and spend the money on probes and robotic spacecraft.

But for me that is not the reason to have a human space program. It is all those I listed above. The expansion of the human species beyond planet Earth. The creation of a better future with more choices for our children. The opening of a new and endless frontier. Unfortunately when judged by these criteria as well, the current U.S. space program is a failure.

If the job of NASA's human space flight program is to support the exploration of space in terms of the pure quest for knowledge *and* to prepare the way for others to follow as we expand the human domain, then they have failed. In other words, if the agency's job is to explore and survey the unknown "lands" of space for both scientific and economic benefit in the same way that James Cook explored the then unknown world of the Pacific for his nation, or the way Lewis & Clark explored the west for ours, they have not succeeded. And if the agency is to be judged on how well it has trail blazed, opened new paths and created a route to the frontier for the rest of America to travel, it has been an utter, expensive and embarrassing disaster.

The Space Frontier Principles

To date our national human space flight program has been elitist, exclusive and a dead end. It has never included the people for whom it was allegedly created, and who foot the bills. Our space leaders to date have also ignored at their own peril several essential truths. And, although the propaganda and imagery they put forth as they seek more and more taxpayer funds may seem to indicate otherwise, most people would be shocked to learn, it is NOT their intention to open space to human settlement. Our space programs are just that programs—they are not part of any larger cohesive or visionary agenda. These programs are a hodge-podge of activities that just happen to use space to achieve their short-term goals. Composed of projects with no long term unifying agenda there is no over arching and transformational goal, and no plan to blaze a path the rest of us can follow into space. The low level goals they do have include technology development, military domination, enhancing national pride, indirectly inspiring education, supporting terrestrial industries, and at times advancing science. Nowhere is it written in their operational guiding documents or principles that space is a place to be pioneered or opened to permanent human habitation.

Foundationers see space as a place, as the next frontier for humans to explore, utilize and settle as their home. This to us is the real goal of any national or international human space flight agenda, and we are working to make it the goal of our activities in space, both public and private. *Although it may seem academic, this difference is key, and completely changes the type of space activities we undertake, how we spend our money and what investments we make.*

We also believe that the ideals of free enterprise based democracy should be extended into space. Democracies consist of free peoples bound together by the belief that the people have primacy over the state, and that individuals should have the power to create new wealth unimpeded by that state. The settlement of the American western frontier was a result of the application (often by default) of these core concepts.

Extended and applied to space, they add up to what I call the Space Frontier Principles. I believe that unless these ideas underlie our future space plans they are doomed to failure. After all, space is a frontier then we should treat it as one, including our government space policy leaders.

- Without low cost, reliable and regular access to space there can be no Frontier.
- Space is a Frontier, not a Program
- If space is a frontier then the government should treat it as one.
- In free societies opportunities are exploited by individuals or groups in the form of companies and private institutions.
- Frontiers are not opened by governments for the people—but by the people—supported by or in spite of their government. Put another way, our Federal space program must be designed to help the American people open the frontier. It *must not* attempt to open the frontier for us.
- A Frontier based space agenda must focus on creating technologies and infrastructure that are long term in nature, re-usable, build a foundation for those who follow, are low cost to build and operate, and supportable over time by the wealth they create.

I believe that unless these ideas underlie our future space plans they are doomed to failure.

The Near Frontier and the Far Frontier

We have the wrong people doing the wrong job in the wrong place for the wrong reasons. To understand what I mean, we need to have a new way of looking at space. One that can create a context for our discussion. To help with this I developed a map of space that can be used to see where we are in the opening of the frontier, and who in our culture should be doing what, and where.

The way I see it, the Earth is the center of an expanding bubble of human activity and life. As we have lifted ourselves off of the planet, that bubble has grown outwards with our human presence. First Gagarin and the Mercury astronauts moved the edge of that bubble to LEO, and then Apollo pushed it even further. Now its edge sits at the Moon. This area of space I call the Near Frontier.

The Near Frontier

The Near Frontier is comprised of the Earth, and the surprisingly large number of comets and asteroids that either

inhabit or pass regularly through our neighborhood. It is the next step outward for our species, the next zone for expanded human activity. This area is unique in all the Solar System, since the costs of accessing it are far lower than other areas, and much time has been spent exploring its potential. I believe that NASA's Lewis and Clark's have done their job here in the neighborhood of Earth.

In the Near Frontier the presumption is that the first stages of exploration are complete. One might say that Lewis and Clark have surveyed this region. And now it is time for the rest of the Nation to take over. The Near Frontier should be handed over to universities and private firms to explore and develop for human use. The billions of dollars now spent on constructing massively expensive, non-focused and expendable government housing and developing and operating incredibly inefficient elitist transportation systems to support them is a complete waste of taxpayer funds.

The Near Frontier is the wrong place for the Federal government to focus its energy and funding. Rather, it is a place that is not only primed for the private sector to develop but is already seeing its first potentially successful private operations, and rather than being a drain on the national treasury, it is ready to become a prosperous zone of human activity and a generator of wealth for our Nation.

To encourage this, our government should end its inappropriate operational activities in this area and hand it off to the people by creating a climate that incubates, enables and encourages private sector activities of all sorts.

The Far Frontier

Beyond the Moon lies the Far Frontier. This is the place yet to feel the touch of humanity, and it includes Mars, the rest of the Solar System and the entire Universe. This area is beyond the reach of commercial entities and projects based on private investment. But, like pure scientific research, the Far Frontier does qualify as a place where long term cultural investment makes sense, both for its own sake, and as the next place to be developed and opened to human activity, where appropriate. This is where the pooled resources of the people can be used to support exploration in the quest for knowledge and as a precursor to the following wave of civilization. Such support can come in the form of taxes, academia or the dues collected by a membership society such as the terrestrial National Geographic Society. This is where NASA and the space agencies of Earth should aim themselves now their job is essentially done in the Near Frontier.

But first they must pry themselves from the useless activities they now cling to in low Earth orbit. If they do so they can give society a new domain to explore and open to humanity. The entire rest of the universe is their reward for getting out of the way in the Near Frontier. Thus the Far Frontier is where we must set the sights of our national space program. It is beyond the known and out into the new and untouched horizons that we need our 21st century Lewis and Clarks and Cooks to go. It is on these unexplored worlds and places that we should focus the eyes of science. Our corps of highly skilled government astronauts should not be driving trucks from Earth to buildings in the sky. Instead they should be climbing over the hills of Mars and telling an anxious world what they have found, or combing the skies for evidence that we are not alone in this vast universe.

ISS and AlphaTown

If we are to develop a true space economy, not only must transportation costs be brought down, but the entire mental framework of our past "mission orientation" must change. In the past our forays into space have each had an endpoint and each was intended to achieve some near term goal, often without being used as a stepping stone to the next. We have traded the success of short term stunts and triumphs for sustainability, making it more important to get up there at any cost, than to be able to operate in space cheaply and efficiently. The frontier mindset rejects this thinking. We go into space to stay, and whatever we do there today is meant to become a "foundation" upon which others can build. Just as in space transportation, we reject the idea of "use it once and throw it away" that was the hallmark of our dead end space efforts in the past and continues to this day, as NASA and its partners in the international Space Station begin plans to de-orbit the massive facility a few years from now, even as they are still building it.

Based on the Frontier concept, and staying true to our pioneer beliefs, we reject these plans and will fight to see the ISS retained in space as a nexus for future activities, even if it must be flown into a storage orbit and mothballed. We believe in using what we have at hand to leverage the opening of the frontier, be it the discarded parts of the old Cold War space program, or the shiny new government works programs orbiting overhead today.

It is ideas that change actions, and mindsets, once created take a long time to change. The Cold War space program was a win at any cost activity, and led to a mindset that short-term success can come at the expense of long term sustainability. Goals, no matter how arbitrary or non-realistic, were to be achieved by throwing large amounts of money at them, so long as progress could be shown—no matter how dubious. As government centric, it also engendered a mentality that to sustain legislative support, the importance of the government effort must be highlighted and take precedence over any commercial or other efforts to achieve the same goals. In fact, government managers came to see other efforts to create space facilities as threats to their own program, and in many cases sabotaged or in other ways worked to undermine private efforts. After all, how would a government bureaucrat, having spent years lobbying for billions to build their space station, be able to defend those expenditures in the light of a commercial facility operating more cheaply, and producing better results just down the orbital street?

Thus the challenge is to create a new way of thinking in the minds of those currently dominating the space field, and also those who might wish to join in space activities in the future. Rather than seeing commercial efforts as threats to their turf and jobs security, the Foundation has been working to show how new partnerships can be created in space that parallel those on Earth. For example, here on Earth government activities are often used to catalyze commercial offshoots, and Federal investments in technology often lead to private sector economic drivers. From highways funded by taxpayer dollars to forts on ancient frontiers that became the seeds of cities, we see the government and private sectors as complimentary to each other, not competitors.

In 1995 the Foundation started a campaign called "Alpha Town" to create an image and conceptual framework in people's minds that related to how our culture and communities work here on Earth. One goal is to transform the International Space Station (ISS) from a multi-billion-dollar public-works project, into the kernel of the first human town in space. The Foundation is working to promote policies and activities that will turn ISS into the catalyst at the center of a true LEO community. "AlphaTown" encompasses projects that are policy oriented as well as technological.

A Space Station Authority

The Foundation believes the right management in charge of the space station is critical to making it an outpost for all humanity rather than stagnating as a government lab and public works project. Although built and operated today by government for government, we believe that if the station is to achieve its full potential and truly become "the next logical step" to opening the frontier, it must begin to serve a much broader constituency, including the private sector. We believe a civic/private authority would function as a landlord for the entire space station, and act as a catalyst for new activities and growth, while streamlining operations and lowering costs for all. Much like a terrestrial port authority, its goal would be the economic and scientific success of the station.

ET

The U.S. space shuttle's giant external tanks are one example of an extremely valuable artificial space resource that now goes to waste. At present, with each successful flight of a shuttle, an empty tank with mass greater than the full payload of the shuttle itself is brought to 99 percent of orbital speed and then discarded to bum up in the atmosphere. Over a 10-year period about 10,000 tons of that tankage will be brought almost to orbit and then discarded, with a value on orbit of about $35 billion. The ET project is determined to stop this waste and begin to have this valuable resource stockpiled in orbit.

Mir

In keeping with our frontier philosophy, the Space Frontier Foundation began in the mid-nineties to take a stand in favor of keeping the Russian space station Mir from being destroyed. Our Keep Mir Alive campaign stood in direct opposition to those who wanted to "bulldoze" the facility to clear the way for the new ISS. Yet, to Foundationers the Mir, as old and aged as it was represented yet another "place" in space, and perhaps not as shiny as the new facility, could still be used as a lever for future space activities by those with imagination.

Foundation members led the team that eventually leased the Mir, converting it for a few months into the world's first commercial space station. Although we lost the battle to save the facility, this action showed human activities in space weren't exclusive to governments, and that individuals and non-government groups could take on big, human oriented projects in space—a historic first that eventually led to the flight of California businessman Dennis Tito a year later.

Space Hotels

With the flight of Dennis Tito into space, the door opened for a new industry to arise on the frontier. As we have seen he was not the last, but the first of this new type of visitor to space. Given the difficulties presented by his stay on the currently government operated space station; some are advocating and developing plans for separate commercial space hotel facilities. Even if ISS were to become a commercially operated facility, it would still be mainly a research and technology oriented facility, and not truly suitable for "casual" visitors or those simply wanting to experience space for periods of time. After all, a laboratory and a hotel are different things, and serve different roles. There are many proposals for building orbiting hotels and tourist facilities on orbit, a potentially huge market. From re-cycled spacecraft and external tanks to new facilities, perhaps based on inflatable technology, these new "buildings" and facilities will increase the size and economic potential of Alpha Town, creating new destinations and locations for development.

The Moon

The Moon lies on the edge of the Near and Far Frontiers. It represents a transition zone between the area that can be best developed and whose over all activity base should begin to be led primarily by the private sector, and the Far Frontier, where business plans don't yet make sense, infrastructure is non-existent and travel times and mission costs preclude most private concerns from operating. As we reach the Moon, although we find there are businesses in the embryonic stages who have realistic plans and even funding for Lunar projects, we are just on the edge of the "giggle zone" of private finance. Yet, our feet have literally been upon it several times. For the Moon, the time has come to move from being a totally unknown entity, to one that, although it still needs major exploration, can begin to fit into plans for development and utilization.

If we are successful there will be facilities on the Moon, such as hotels, mining, science and training facilities such as I discuss below, and over time some will choose to live there perhaps. But, given the difficulties of differences in gravity, day/night cycles etc. . . it may not ever become a thriving space metropolis with a breeding population of humans (whose children might well be forever bound to the lightly gravity world and unable to return to Earth. . .) By the way, I do not recognize the spurious Moon vs. Mars debate. They are different places, and we have different ends in mind for them. To Foundationers they are complimentary, not competitive.

Planetary Exploration Training Base

Most serious participants in the space community realize that as NASA sheds the burden of trying to operate the ISS and begins to look at sending humans to Mars, they will need a place to go to train, to develop infrastructure and transportation systems and "get their feet wet" (or dusty in this case). The moon is the perfect place for this exercise. LEO to Lunar transfer vehicles, lunar orbit to surface vehicles, habitats, life support, energy systems, all can be developed and tried out on the Moon before we risk human lives on a one way trip to Mars. I believe that a Planetary Exploration Training Base should be a high priority on the Moon. Potential Mars explorers need to be trained somewhere with high radiation, extreme temperatures, and temperature differentials, lots of dust and dirt, where, if they tear their space suits or damage their equipment, they can die. We need to know what happens to a space suit when it is worn in such an environment every day for weeks at a time before a Mars explorer can trust her life to it, and that can't be done on Earth.

There are many large scale Lunar based science projects which demand a strong and ongoing infrastructure that could be commercially provided. One exciting idea is the construction of a new Lunar far side observatory, made up of dozens of small telescopes that scientists say could combine their power to see objects as small as continents, on planets circling other suns. In this case the NASA might well help form a team of co-operating universities and observatories. This team could then contract out the construction and operation of this project to companies which would specialize in economic lunar surface operations.

NASA and the space agencies can build training facilities for future Mars and planetary surface exploration and operations, scientists can build far side observatories shielded from the light and radio noise of Earth, others can study the Lunar crust for hints as to the formation of the universe itself. At the same time, the private sector can develop and supply housing based on its learning curve in LEO as it takes over ISS and builds new commercial space stations. Such industries can provide economic leverage and support for the agency's activities, saving the government millions. For example, a private firm might build a luxury hotel facility for those who might want to fly under a lunar dome on their own human powered wings, or relax in the low gee for a few weeks while contemplating the blue marble of Earth on the horizon. Meanwhile, also renting rooms in the hotel are those specialists listed above, and space agency teams, perhaps managing a group of astronauts in a nearby crater as they develop a simulated Mars surface base and test their systems.

All of this then helps argue for a strong and robust interplanetary transportation system. Again, the interests of the two cultures coincide. The commercial firms will need low cost and regular transport to and from the Moon, and cannot afford to fund the development of transportation infrastructure. The governments need such systems for any future human exploration of the solar system and/or Mars settlements, if future exploration of Mars is not to be a dead end set of stunts. The government can support the technology development and help build the highway, much as they do on Earth, and the private sector can build and operate the "trucks" over time, also as they do on Earth. And everyone wins.

NEOs

Contrary to the view that space is empty, our Solar System is filled with millions and millions of small objects. Those that approach the Earth or are easy to reach in terms of energy are called NEOs or Near Earth Objects. There are several types of objects in the area referred to as NEO Space, some orbiting in relatively the same place, such as the small clusters we find at various stable points, which are caused by the interacting gravity of the Earth, Moon, Sun and other planets. But most follow long looping elliptical orbits, crossing the orbits of the Earth and Moon in a predictable manner. And yes, somewhere out there the younger sibling of the dinosaur killer is hurtling towards the Earth at thousand of mile per hour. When it hits, be it tomorrow, next week, or in a hundred thousand years, our party will be over.

What to Do Now?

I believe that the space aware (us) have a duty to point out such threats as those posed by NEO's, after all, the potential destruction of our home world is a great argument for getting our eggs out of this one basket. By the same token, and why we should care about such things as sky searches and asteroid shield plans is that it makes little sense to try and expand the human race into space if we are going to be wiped out by some careening solar iceberg while getting our act together.

Valiant sweaty Bruce Willis's saving the Earth and spectacular "we all gonna die!" scenarios aside, the promise of the resources such rockpiles might contain that excites us from a frontier perspective, and it is here where we focus our attentions. Many believe that long term, such resources are integral to the human break out into space.

The threat from asteroids and comets is often the focus of the media, highlighting the need for a much expanded search for these objects, which could wipe out life as we know it. But the same rocks which could kill us can help us live better lives due to the resources they contain. Many of these objects are literally floating gold mines, continuing amounts of gold, platinum and other precious metals that would stagger the imagination. They also offer us the chance move environmentally destructive mining operations from the living Earth to the dead emptiness of space.

The search itself, with its broad societal implications, is the proper domain for the government to provide support. As with the Moon, NASA should support early exploration now and later, transitional missions, with large com mercial participation in the form of partnerships or outright purchases of data. But eventually, it is the private sector that should lead the actual exploration, characterization, sampling and utilization of these important resources. I would like to see the Federal government offering prizes for the location of potential threats and acting as a clearing house for NEO information.

It could also offer to buy data from those who can mount missions to NEOs privately, thus saving tax dollars and catalyzing a potential new industry. The government has an important role in updating laws regarding ownership of such data, and of course the thorny issue of mining and ownership rights must all be clarified before anyone seriously tries to stake a claim on one of these floating goldmines.

Mars

I and the Foundation have always been for the exploration of Mars, particularly as a prelude to permanent settlement of Mars and the rest of the solar system. But we are against dead-end stunt type missions to Mars that do not provide stepping stones to possible future settlement.

However, although we may support the concept, as mentioned above, the idea of settlement was and is still not our national goal in space. In the past NASA's planned paper missions to the Red Planet have simply presented it as a place to perform the Apollo Program Mark II. For government planners, flags and footsteps are the goal for Mars, as they were for the Moon. In fact, all of the official plans so far introduced for sending humans to Mars fall under the category of stunt. Somehow, the lessons of the past failed to reach the ears of this group, and they do not understand that we simply cannot afford another let down like that we have seen since the end of the Apollo era.

To advocates of human settlement "Das Mars Project" used to represent all that was bad about our government space program; centralized in the traditional government/aerospace cabal, stunt oriented, elitist, vastly overpriced and with no long term growth plan for growth from first missions to settlements. Unfortunately, thanks to the NASA attitude that all space is theirs, this entire debate is based on confusion between the roles of government and the private sector. What both sides have missed is what I have laid out in the Near Frontier/Far Frontier paradigm. The government is never going to succeed in developing space businesses, and those planning space businesses are not going to propose going to Mars in a business plan.

The Settlement of Mars

We must greatly expand and accelerate the exploration of Mars, particularly as it enables the settlement of Mars and the rest of the solar system. Money's saved from space station shuttle and center operations should be used to fund the development and demonstration of pioneering technologies that will enable the exploration and settlement of Mars. And yes, humans should go to Mars, as humans should go everywhere that it makes technical, economic, scientific, environmental sense to go. That's what an open frontier means.

The drive to open Mars to human settlement will fire the imaginations of our youth in a way that the more routine operational aspects of settling the Near Frontier will not. It is a symbol that will have a positive effect on all space activities, if it is part of the agenda I have outlined here. It will be seen as a national endorsement of space as a frontier, and it will be the most visible aspect of the government's role in the new space partnership I suggest. In frank political terms, human exploration of Mars also provides the carrot needed to pull NASA's management, human space flight centers, the astronaut corps and its cheerleaders away from the Near Frontier.

If NASA needs public support, it need not fly members of the Senate in space. The camera shot from the helmet of the first woman to peer down the vast depths of the Valles Marinaris canyon will be enough by far.

Defining the Roles is the Key to Mars

The key to making Mars a real frontier is to understand the separate and very different roles the government and the private sector must play to make it so. 'These roles are not only differentiated by the area or location, but by the activities themselves. Just as on Earth we see the government's role in this new field of human activity as one of catalyst, cheerleader, guarantor of safety and lawful behavior. Right now, and until Earth's governments either begin to divest and hand over Near Earth space and we see the development of low cost space transportation, there simply is no money to even begin talking about large scale plans for Martian exploration, let alone settlement. However, if the Nation adopts the Near Frontier/ Far Frontier model, NASA can release its grip on the Earth-Moon system by privatizing and commercializing all operational activities such as the station and space transportation systems and move its focus to the exploration of the Far Frontier. If structured correctly, government could prime the pump for the creation of leading edge technologies to aid in that quest, and be a good customer for the private sector to provide the bulk of needed services for such a program. If this happens, enormous resources would then become available to begin the quest, IF the taxpayers can then be persuaded to do so.

Continuity and economic viability must be designed into any exploration program from day one. Remember Lewis and Clark. Just as Jefferson's mandate was not just to explore but also to survey the Louisiana Purchase, so to on Mars we must explore for both science and development. The Reagan appointed 1986 National Commission on Space report did recognize the need for permanence to be built in to any Mars planning, but it too was based on a massive infrastructure and in-space transportation build up, and would not allow any permanent development to occur on the Red planet for decades.

The Space Exploration Initiative presented during the Bush administration not only didn't build on the permanence idea presented by NCOS, it retreated to the old flags and footsteps approach to space exploration. With its unspoken mandate to rationalize then current NASA projects such as the space station, it called for the station to be used as a port of departure. For their money, the taxpayers would get to watch three to six people plant a flag, and once again leave our spoor behind in the Martian dust with no plan or promise of anything of substance coming from the adventure. Needless to say, it was DOA in Congress.

Even the smallest humans to Mars missions will require a substantial investment and to spread out that investment across an entire culture is not a bad idea. I believe in democracy, and if the taxpayers can be persuaded and the goal remains the first permanent human settlements on the Red Planet, we support the concept—as long as all aspects of the project utilize commercially provided data and support systems to the maximum extent possible. Any agenda that includes the Moon and Mars should be designed to create infrastructure that will support long term access and transportation to and from those worlds, and be carried out in a way that leverages one off of the other and all off of the activities of the commercial sector—as well as the taxpayer funded specific missions and programs along the way.

The Right to Own New Land in Space

Finally, for all of these new areas in both the Near Frontier and Far Frontier (including the Moon, Mars and the NEOs) to become the great sources of wealth and possibility they can be, we need to begin putting in place the rights of those who explore and develop such new "lands" in space to own them. Throughout history, it has been the ability to gain and hold land which has driven them forth, and given them the will to carve new human domains out of wilderness. Space is no different. If people are going to invest their wealth and lives in opening the frontier, they should have the right to pass what they have done down to the next generations. When the time is right, the U.S. should stand up and recognize that in space, the same rights to own property exist as on Earth.

Earth to LEO

The primary goal for the Nation in this decade must be achieving cheap access to space. Because if you can't get there regularly and cheaply to develop, test and manufacture your product you can't make a profit. If there is no profit, there will be no frontier.

Unfortunately, costs about the same today to put a human in space on the government shuttle as it did 30 years ago thanks to the incestuous, self-preserving and self-feeding institution that our shuttle program has become. And according to NASA the new OSP program will not help that situation and may make it worse, while costing us billions of dollars we need not spend.

The development of cheap, reliable and regular transportation to and from space is THE key requirement for opening the space frontier. Once again, there are strong mutual interests between the private and public sectors to be satisfied, once again, there is a chance for a partnership, and once again there is the chance to create new industries and jobs. And unfortunately, once again we are faced with a government controlled monopoly—this time operating the only human capable space transportation system in the United States.

It is time for change. NASA and the U.S. Government need to get out of the trucking and passenger carrying business as represented by the shuttle and OSP programs, and back to supporting exploration and scientific progress. NASA and its parasitic contractors must no longer be allowed to manage the designing, building and operation of what are essentially glorified government space trucks/vans. Can you imagine if the government had done the same thing with an airline? It is as if the FAA owned our single national air carrier. With no real competition it would never get cheaper, better or more efficient . . . and no one would be able to afford to fly on it. That's the socialist monopoly we have in space flight. It has not improved safety or access and wasted billions of tax dollars. And with the announced plans for the Orbital Space Plane (or what some call the Orbital Stupid Plane) our Nation will be pouring even more billions into a giant step backwards when it comes to access to space.

In contrast to this dinosaurian penchant for repeatedly getting stuck in quickly evaporating swamps of old ideas, a new lean, mean set of alternative space firms are out there building truly innovative systems for carrying paying passengers and payloads on sub-orbital flights for what may turn out to be less than a hundred thousand dollars a flight. Unencumbered by traditions, bureaucracies and structures designed to siphon tax dollars rather than realize profits, these firms are where innovations and new ideas can be born and tested on the anvil of the market system. But they face enormous challenges on the road to success. Often self-funded and working close to the economic edge they have waited and watched as our government hasn't done the job and are now going to open space their way—if they survive. These little mammals are doing their best to dodge the smothering feet of government regulations and paranoia and hold out hope for a whole new path into space, but they need help to survive. And if they are truly to contribute to our national space efforts they need the current system changed dramatically to acknowledge them, to support rather than hinder them, and to let them in.

Rise of the Alt. Space Firms

Several years ago in writings and talks I pointed out that I thought the new so called "robber barons" of space would come from the computer world. I saw these people as pre filtered for technological savvy, comfortable with new and innovative ideas, definitely out of the box thinkers, and raised on the space program, science fiction literature, and media such as Star Trek, B–5 and Star Wars. Oh, and also—although I was saying this before the dot-com melt down—they have lots of money in a culture where they will feel the need to do something great and important. In other words they would want to give something back. Well, some of them made it through the rough times in their own industry, and have done as we hoped, and jumped into the space field.

I call these new players Alternative Space Companies, or to put it into techno speak, the Alt.Space movement. They do have the money and the dreams, and yes, in their hearts they want to see the human species expand into space, of this I am sure. Or as Paypal founder and rocket builder Elon Musk said in meeting in his living room recently, our job is to "Back-up the Biosphere."

The first shots of this revolution were fired when telecom millionaires Walt Anderson and Chirenjeev Kathuria joined with the Jeff Manber (former Executive Director of the Space Business Roundtables) myself and other Foundationers to go to Moscow and found *MirCorp,* with the goal of transforming the old Russian Mir into the world's first commercial space station (which led to Dennis Tito and others flying aboard the ISS). Shortly afterwards, the *X-Prize* was founded. (Which directly influenced Rutan to finance and build his spaceship.) These activities began to fire up the imaginations of private citizens, who had thought themselves shut out of the space game. Within a couple of years, several new firms had been founded by those wanting to leverage off of the potential for flying what I call "citizen explorers" into space.

Within the last few months we have recently seen the first ripples that will be caused by the new Alt.Space "barons" and their own rocketship projects, in the form of Scott Bezos of Amazon.com's *Blue Horizons,* Elon Musk's *Space X,* and John Carmack (owner of Id Software created the hugely popular video games "Quake" and "Doom") who owns *Armadillo Aerospace.* The recent highly publicized roll out of famed aircraft builder Burt Rutan's test vehicle, which was apparently financed by a major software firm's founder gave the world its first Alt.Space poster child, yet there are also many other firms working in this field.

Serious, business oriented, successful survivors of a tough industry, with big dreams and deep pockets these sole source funded projects join with other not so new players in the field with funded firms like Bob Bigelow (sole owner of Budget Suites of America) whose *Bigelow Aerospace* is building a prototype space hotel, Charlie Chaffer's *Celestis and Team Encounter* whose Solar Sail Project just contracted with NASA to collect data on its voyage out of the solar system, and *Constellation Services Incorporated,* whose cargo containers promise to reduce cost tore supply ISS at this critical time. Others, like Dennis Wingo's *SpaceCorp.,* Walt Anderson's *Orbital Recovery,* John Powell's *JP Aerospace, Pioneer Aerospace, and X-Cor Aerospace* complete a mix that is wide and deep in its potential to profoundly change the space transportation habitation and services field.

These are real firms, and are poised to transform space access and operations as we know it—if they get the right breaks, and the support of the Nation they call home.

According to some experts, $1 in market potential offered to the private sector will produce $10 in the type of technological and operational breakthroughs we might get from the current government -centric approach we have today. Some put the ratio even higher. If Burt Rutan can build a re-usable sub-orbital space ship system for under $40 million, what can he and the other alternative firms out there do for let's say the $10 billion we are about to waste on OSP? (The equivalent of 3 or 4 shuttle flights.) Rather than waste that money on yet another specific-use dead end program, let's offer that money to the private sector to carry humans and cargo to and from space and get $100–200 billion of innovation and common sense. A few billion dollars a year market for separate payload and passenger flights to and from ISS and to fulfill other NASA and DOD needs would produce a huge change in our Nation's space access capabilities. Imagine, rather than one or two inside firms working on cost-plus contracts to fulfill single use needs they helped develop in the first place, we could have a dozen space delivery and transportation firms. NASA and DOD would no longer fund multi-million dollar studies, multi-billion dollar development programs or prop up aging technologies, but would simply pay on delivery when their payloads were delivered . . . just like the rest of America and most of the world does on Earth. These new commercially oriented space trains, trucks, buses and taxis would carry not only government payloads, but also compete to carry commercial passengers and payloads to what could become a rapidly expanding human frontier in space.

To get there we must make radical changes, not just operationally, but most importantly, mentally, and in the structure and management of our current system. To that end I offer a ten point plan to tum our space agenda around. This plan will assure the maximum science and commercial activity in space, while creating an expanding wedge of human activities that will lead to a prosperous and growing human frontier in space. (It will also save the tax payers a huge chunk of change!}

- NASA should immediately be ordered to begin planning the retirement of the shuttles, and all human oriented shuttle and Earth to low Earth orbit (LEO} vehicle development offices, centers, programs and studies should be canceled as soon as possible.
- Congress should kill such projects as the Orbital Space Plane and its current space capsule program immediately and transfer the $10 billion it was about to waste to a set of new activities to open LEO to the people and new industries that should by right follow our 30 years of Federal exploration of this area. To do this, while also seeding the agency's return to real exploration beyond the Near Frontier, the following things should be implemented ASAP:
- The agency should be mandated to begin creating new procedures that will allow it to sign multiple payload and passenger delivery contracts at some date certain in the future, just as it does today when it uses FedEx, UPS or American Airlines to move its valuable cargo and employees around on Earth.
- At least $1 billion of former OSP/capsule related funds should be transferred to the Alternative Access to Space program immediately to begin the re-education of agency managers away from exclusionary cost-plus contracting methods and start implementation of commercial LEO freight delivery.

- A set of National Space Prizes (NSP} should be created.-To incentivize the development of the vehicles needed to serve the former shuttle/OSP/capsule market and to assure multiple players and real competition down the road, several billion dollars of the saved OSP/capsule/shuttle money should be used to fund four/five prizes for the first teams to fly four people (or relative mass) safely to and from LEO at the lowest demonstrated cost, with the shortest turn around period. (Perhaps funded using a portion of current OSP/capsule development money, as a means of helping.)
- To provide an ongoing market for the NSP winners, all Federal entities needing access to LEO should be mandated to use their current multi-billion dollar budgets (such as that about to be wasted on shuttle flights) to buy their rides using roughly the same criteria as the NSP. They must begin creating new procedures that will allow them to sign multiple payload and passenger delivery contracts at some date certain in the future, just as they do when using Fed-Ex, UPS or American Airlines to move valuable cargo and employees around on Earth.
- To further assist their new partners in the national space effort, all Federal space transportation regulations should be streamlined to allow the maximum freedom of development for the alternative space firms. This includes giving them the same regulatory over-rides now given to government systems such as government space launches, the space shuttles and the airline industry.
- As this space revolution is implemented, near term access to ISS should be purchased from the Russians, using Soyuz, Progress and other very capable vehicles.
- NASA and the Department of Defense should implement a series of X programs in cooperation with the private sector based on the old NACA model of enhancing commercial and military capabilities. And this effort must not be allowed to morph into development programs for government vehicles. Potential areas of research might involve thermal protection systems (TPS), and robust (airline-like) engine development projects.
- We should mothball or give our very capable Russian friends managerial leadership of the current high inclination space station and use the remaining elements still on the ground to build a lower inclination, more commercially accessible station.
- In either case, the ISS management structure on both should be changed to an Airport/Seaport Authority model, not a scientific institute, which will be too narrow in focus, expertise and bias. A Space Station Authority can do a much better job at creating a safe, efficient and productive environment for all users, commercial and scientific. This I SSA will be encouraged to lower station costs in all areas of operations, and not just allow, but encourage access to the station and its airlocks by the widest range of commercial space transporters and suppliers.
- All NASA vehicle and habitat development activity should be re-focused from Earth to LEO operations to in space missions aimed at the Far Frontier, such as a permanent Return to the Moon and the long term exploration and opening of the Martian frontier.

Heavy Lift

If massive heavy lift is needed for such things as supporting a permanent human return to the Moon or a humans-to Mars initiative, we have two choices. The first is to utilize the existing shuttle infrastructure investment in people, hardware and facilities. The current external tank and solid rocket stacks could be used as the basis of an automated re-usable cargo ship (near term this could easily be the existing space shuttles, as they apparently can be flown remotely) or grown into a very heavy lift vehicle. If this path is chosen, I would encourage the use of the external tanks that it would be carrying into orbit as part of any planned orbital infrastructure.

However, if I am to stay true to the idea that NASA should get completely out of the Earth to LEO transportation business-and that our goal is to grow a strong space transportation industry for all sorts of payloads-my answer in the area of heavy lift is a bit different. As I have been educated over time by my peers in the field on this issue, my preference has become more pure in relation to this cause. I believe the best way to get heavy lift to support a return to the Moon and a human mission to Mars is to have NASA stay out of it entirely and buy the rides in this area as well. Rather than a massive new NASA vehicle development project, the agency and its contractors should instead focus on the development and construction of the habitats and transportation systems it will need on and between those two worlds, and stay out of the Earth to LEO transportation arena entirely.

There already exists capability in the U.S. Delta class and Russian Progress vehicles to loft many tons of payloads to LEO and Lunar orbit. Using the new and exciting concept of on-orbit assembly or in-space construction that the agency has been allegedly learning by building ISS, these components can be assembled into any size needed for either project. Although not available on the scale of a potential automated shuttle derived cargo vehicle, if one considers the development and operational costs of such a brand new system versus the eventual freight bill of a competitively bid delivery to space contract using modified current day systems or those in development already in the private sector, the taxpayers could save millions. Meanwhile, such an approach would continue to fuel, rather than compete with the space transportation industry.

The time is now.

It is time for America to step up and face the future.

Time for the United States to push into a new frontier of technology and leadership.

It is time for the White House and Congress to give the people of this Nation a new and positive tomorrow. It is time to show the world that America doesn't just drop bombs, but can build dreams.

Let's be frank. NASA as currently constituted cannot do the things I have outlined. It is bloated, self preservation oriented, and is spending it's time wasting billions of our tax dollars re-inventing the wheel and re-reinventing the wheel and so on. . .without knowing why it even needs a wheel, and where it wants to go once it has a vehicle. The agency and its encrustation of existing contractors need to be totally re-vamped. This can be done by Congress and the White House via enacting new policies and changes over time, or by giving the agency a tough clear and hard to achieve goal, which may well force the needed changes. After all, as Kennedy said "we don't do these things because they are easy, but because they are hard!"

Some call for the agency to be shut down, and I admit there are times I feel the same way. The private sector is already beginning its own space program, and the agency, especially its human space flight component, may soon be redundant. One former shuttle astronaut pointed out recently that the next American to ride into space on an American spaceship will be a civilian riding in a private rocket! Think about it! The contrast between the Alt. Space firms approach to space and NASA's reveals a true split in the genetic line of the evolution of human space flight. Those who lead our Nation can ignore this reality, try to stomp it to death, or embrace it, nurture it and leverage off of it for the greater good and glory of all Americans.

The Frontier is Open and On to Mars!

It is time for dramatic action. . .or the future will pass into the hands of others. . .

The Congress and White House should unite behind a declaration that the Near Frontier is open for business, and the Nation is going to explore and open the Far Frontier of the Moon and Mars. . .this time to stay! No hesitation, no endless timescales, no wimping out for the greatest nation on Earth. We must do this hard and fast and do it now, and on a very tight and challenging time scale. (Don't tell me we can't do it quickly and well, this is the same nation that went from a standing start to the Moon in under ten years forty years ago!)

As President Kennedy recognized in the middle of the darkest days of the Cold War, there is no perfect time to do something bold and beautiful. Or perhaps, such times as then and now are exactly the right time to take a stand for what is great and honorable in humanity. If such incredible boldness can be summoned in such a time, then it can be summoned now. And we need it now more than ever. America needs a shining light. The world needs a shining light. Space can be the place where that light can hang for all to see. And now is exactly when such choices must be called out by those of vision.

Within my lifetime I want to be able to cast my eyes upwards and see a string of pearls in the night above the Earth as the first orbital community of Alpha Town celebrates its first quarter century, while glittering lights shimmer at the South Pole of the Moon. . .as the first Lunar city celebrates its first decade. And shooting like a star across the night, the glow of nuclear motors in the night above, as the first regular space liners begin their service to and from Mars. . .where a whole new branch of humanity is being born beneath the amber skies of a new world they call Home.

The CHAIRMAN. Thank you very much, Mr. Tumlinson. We have a vote on and so I'd like to ask very briefly Dr. Huntress, Dr. Woods and Mr. Tumlinson, do you agree with Dr. Zubrin's assertion that we shouldn't fund the orbital space plane?

Dr. HUNTRESS. I agree with Bob that we should be going to Mars, that we should have an alternate vision of where we're going in space, and I think we ought to consider carefully what system we use to send our humans to Earth orbit, and they need to be low-cost and low-risk and I'm not sure

The CHAIRMAN. Dr. Huntress, should we fund the orbital space plane?

Dr. HUNTRESS. No.

The CHAIRMAN. Dr. Woods?

Dr. WOODS. My expertise is on the safety organization and NASA and how to improve that.

The CHAIRMAN. Mr. Tumlinson?

Mr. TUMLINSON. Obviously cancel it right away, get the free market in there.

The CHAIRMAN. Dr. Huntress and Dr. Zubrin and Dr. Woods, Mr. Tumlinson, very quickly, what's the implications of China's launch?

Dr. HUNTRESS. That we have a new potential international partner for the enterprise of going back into space.

The CHAIRMAN. Partner or competitor?

Dr. HUNTRESS. They can be both. Partners often are competitors as well.

The CHAIRMAN. Overall, good or bad?

Dr. HUNTRESS. Good.

The CHAIRMAN. Dr. Zubrin?

Dr. ZUBRIN. I think it's good because we need a kick in the butt and it's a message that, you know, the tortoise can catch the hare and we better wake up and start moving again. This is America's time right now, this is our time on the world stage, and we have a chance to do something very historic, shaping future human history in terms of leading the settlement of the solar system. I think that it should be Americans that do that because I think that the former civilization we have should be the starting point for humanity as it branches out further into space and worlds to Mars, worlds beyond. So I think it's a wake-up call. I'm glad we have it but I don't want to lose.

The CHAIRMAN. Mr. Tumlinson?

Mr. TUMLINSON. You're talking to a guy here who's got the tank of Tiananmen on his wall at home. I would also ask you how many items you have in your office that were made in China that began as American projects or American ideas. And then I would say I agree with Bob, I want a free enterprise democracy to lead our way into space. I told that to China TV just last week and the People's Daily and a little confused by that one, but I would also say that I think we have a choice here. Do we answer their socialist space program with our socialist space program or do we answer their socialist space program with the power of free enterprise?

The CHAIRMAN. Good point. Dr. Zubrin, just in closing, we're going to launch a little vehicle that's going to land on one of the poles of Mars and it's going to dig into the ground to see if there's water there. Do you believe they're going to find it, and number two is, what's the implication?

Dr. ZUBRIN. Well, they'll certainly find water on the poles of Mars, we know there's water. What they're looking for are traces of past life. The implications of whether or not there ever was life on Mars are absolutely profound. We know Mars is a suspect for life. There's water erosion features all over the surface of Mars, and in fact some of these things were created by recent outflows that came out of the side of craters and things, which means there's liquid water underground on Mars now and there was liquid water on the surface of Mars for a much longer period of time than it took life to appear on the surface of the Earth after there was liquid water here.

So if the theory is correct that life is a naturally emerging phenomenon from chemistry wherever you have an aqueous environment and sufficient periods of time, life should have appeared on Mars. And if life did appear on the surface of Mars, there's a very good chance it's still underground on Mars. Now, if we can establish that, if that's true, then it means life is a generally phenomenon of the universe. If it's not true, it means we're alone. Either way it's of immense philosophical importance, it's of much greater scientific significance than anything having to do with lunar geology, for example

The CHAIRMAN. And this discovery could spark enormous, enormous interest, it seems to me, in Mars, yes, no?

Dr. ZUBRIN. I think it could, yes, and it should.

The CHAIRMAN. Senator Brownback is going to come back with additional questions. I don't know if Senator Nelson will be able to or not, but as an amateur, if we can get this out to the American people I don't know how many Americans know that this project is about to go——

Senator NELSON. Mr. Chairman, this would be the spark that will take us to Mars.

Dr. ZUBRIN. Let me just make a comment. Whenever I talk to a public audience I'm not talking about space industry people, I'm talking about just regular folks that I present to at some length with a plan of how we can send humans to Mars, the primary question I get from American people is, why aren't we doing this? There's a big sense of disappointment almost verging on a sense of betrayal. Looking at Washington, they say, this is the sort of thing this country ought to be doing, this is the sort of thing that NASA ought to be doing, and this is the sort of path that our political leadership should lead us on.

The CHAIRMAN. Obviously you agree, Mr. Tumlinson.

Mr. TUMLINSON. I agree.

The CHAIRMAN. You agree with Dr. Huntress?

Mr. TUMLINSON. Yes.

The CHAIRMAN. Dr. Woods, from a safety standpoint?

Dr. WOODS. Absolutely.

The CHAIRMAN. We got to go vote and Senator Brownback will be back.

Senator NELSON. Mr. Chairman, you can't do it and I can't do it. It's going to take the President of the United States making a declaration that that's what the vision of this country is.

The CHAIRMAN. I've thought about that on occasion. Wait just a minute until Senator Brownback comes back.

[Recess.]

Senator BROWNBACK. If we could have the panelists retake their seats, I would appreciate that, so that we could have a discussion and move forward. Sorry about the vote that took place in the middle of the discussion. Thank you all for being willing to stay here. I thought, during your presentations and quick questioning with the Chairman, this is just too rich of a panel to let pass, and so I appreciate your willingness to let us go vote so we could come back and can have a discussion.

Dr. Zubrin, I was very taken by your comments and the way you put this forward in a fairly straightforward technological manner, that we could go to Mars now. You've put this forward, I'm sure, previously. What have the people, either the contractors or the people at NASA, said in response to your pretty direct, straightforward way of how we could get to Mars?

Dr. ZUBRIN. Well, what happened was this. The plan that I was describing to you is known as the Mars Direct Plan, and it was developed at the Martin Company by a team of engineers, led by me—I was at the Martin Company in the early 90s—in response to the excessively complex and costly Space Exploration Initiative 90-day report that was causing Congress to reject the Space Exploration Initiative of 1989–90 time frame.

Senator BROWNBACK. The Mars mission then?

Dr. ZUBRIN. The previous President George Bush called for humans——

Senator BROWNBACK. Right.

Dr. ZUBRIN. OK. And NASA came up with this incredible 30-year plan to build giant orbiting space stations to build giant orbiting spaceships to get to Mars in 30 years, and the cost estimate ran into several hundred billion dollars, and Congress said, "We're outta here." OK? So at the Martin Company, a number of us engineers convinced management that a alternative plan had to be developed that was more practical if there was to be any program, and they gave us a green light, and we did, and then we went and presented at various NASA centers.

Now, the plan——

Senator BROWNBACK. What was the cost of your plan that you came up with?

Dr. ZUBRIN. The cost estimates at that time ranged in the neighborhood of $30 billion for development, and then recurring mission costs on the order of $2 to $3 billion after you had the hardware set.

Now, we presented it to NASA originally in 1990, at various NASA centers. It became immediately controversial. A lot of people in NASA supported it; some opposed it, especially people associated with the Space Station Program, who felt we were dejustifying their program, because we didn't make use of the Space Station.

However, it got around, and eventually I was invited to brief Michael Griffin, who was the associate administrator for exploration that came in around 1991 or so, and he became a supporter of the plan. He briefed Golden, who became supportive in vaguer terms.

They had me go back to JSC, telling everybody to listen. So they listened, and then they came up with their own version of the plan, which was somewhat modified. It was expanded. They went——

Senator BROWNBACK. Who came up with this?

Dr. ZURBIN. Johnson Space Center, the human exploration team there, which, at that time, was led by people like Mike Duke, Dave Weaver, John Connolly.

Anyway—I could give you some more names—Carl Mandel—anyway, these folks, they said, "Look, we like your principles. OK? No on-orbit assembly direct launch to Mars, use of Martian resources starting on the very first mission, long-duration stays on Mars starting on the very first mission, which helps the plan, it actually lowers propulsion requirements to do it that way. OK? But we've got to design it ourselves to see that the numbers work."

Now, they went, and they designed an expanded version of the plan. It had a larger crew. They had a crew of six. I had recommended a crew of four. They had bigger vehicles. They had more equipment. But it was—and they needed three heavy-lift launch permission, instead of my two. So I called their plan the Semi-Direct Plan. But, be that as it may, they then went and did a cost estimate. And this was the same group that had costed out the 90-day report at $400 billion. They costed out their expanded version of Mars Direct at $55 billion.

Senator BROWNBACK. Is that publicly available?

Dr. ZURBIN. You could probably——

Senator BROWNBACK. That proposal?

Dr. ZURBIN.—you could probably get it. Some of these guys are gone. But, for instance, John Connolly, of Johnson Space Center, is still there. And they did write up this report. They called it a Design Reference Mission. Carl Mandel is no longer at JSC, but I think he's at the Governor's office or something, in Texas. I'm sure these people can dig up these reports.

Senator BROWNBACK. But, I mean, did they file a report that would be publicly such that I could access that report?

Dr. ZURBIN. I believe there was a report written by the Government Printing Office.

Now, the fact is that by the time they came out with this, there was a new Administration which was not favorable to human Mars exploration, and it was kind of like, you know, "Put it on the back shelf and don't, you know, make a big deal about this, you know, because we're not doing this." OK?

But I think the report's available. I believe the Government Printing Office did do a printing of what they called their Design Reference Mission, and I think you can get it.

Senator BROWNBACK. Why not go to the Moon again, in testing your model and design of what you're talking about, I mean, on a much closer-in scale to—or does that model not work?

Dr. ZURBIN. OK. If you do Mars in the way that I have recommended, you can use a subset of the hardware to also do the Moon. And in that context, it is rational, as a milestone exercise within the mission plan, to do a mission to the Moon perhaps 6 years into the program, on your way to Mars. Just as in Apollo, before we actually landed the astronauts on the Moon, we flew the

Apollo hardware in Earth orbit and then in lunar orbit before we actually committed it to a lunar landing.

But you don't want to design a separate lunar program. You don't want to go to the Moon with the idea of, "We're going to the Moon, and, trust us, this hardware will probably be handy when you want to go to Mars."

So you design for Mars, and you design the hardware, set in a modular way, that a subset of it can also do the Moon. And then, in that context, you can do the Moon, and the Moon can be done as an ancillary part of the Mars program and even give you an early milestone within the program. So I think that's a good way to proceed. But you don't want to just make a Moon program as a thing in itself.

Senator BROWNBACK. Dr. Huntress, there's a lot of vision capacity in going back to the Moon. There's a great vision capacity in going to Mars. I think a number of people technologically feel like it's too difficult to go to Mars today, or too expensive, given the earlier attempt, or that this is a vision that a President previously had tried, and it didn't sustain itself. The vision of going to the Moon sustained itself amongst the American public, and so woe be to a Member of Congress that would vote against monies to go to the Moon, when the public was really sold on this concept. Could we present that and sell that to the public, to go back to the Moon?

Dr. HUNTRESS. I think it would be more difficult to sell going back to the Moon to the public than going to Mars. There's going to be a "been there, done that" sort of a thing, and what are we going to do that's new.

Senator BROWNBACK. Well——

Dr. HUNTRESS. You could——

Senator BROWNBACK.—let me ask you this—answer your own question, then. What would we learn, going back to the Moon, that's new, that's useful, scientifically?

Dr. HUNTRESS. There are some scientifically useful things that we could learn from the Moon. We can sort through the layers of the Moon to learn about the history of asteroid fluxes on the Earth. The Moon is a witness plate that preserves its record of asteroid impacts. So we could understand the impact flux on our planet much better by doing that. We could also do something very similar, looking at implanted solar wind that would tell us about the history of the Sun and how the Sun has helped, or not, to create a habitable planet for us. We can learn about the Earth-Moon history, how this twin planet system developed. Those are geological kinds of explorations. We could use the back side of the Moon for radio telescopes, because it's in radio silence on the other side of the Earth.

So there are good scientific reasons that you—to go back to the Moon. But science is not why we send human beings into the Solar System. Science benefits. We can do scientific exploration. But the reason we send humans instead of robots is because of sociological reasons, it's because that's what we want to do, because we want humans to explore, and society regards our robotic program as a prelude, in fact, to sending human beings.

Senator BROWNBACK. Mr. Tumlinson, I've met with a number of individuals that have talked along the lines of what you have, that we need to get more of the commercial sector involved in this. Matter of fact—and they have talked for various reasons, but they have talked about the engine that that is in this country, and always has been, of a great engine.

But one of them was saying, in particular, that our vision that we could and should step toward now would be the dominance of Earth-Moon orbit, the dominance of this region that the Earth and the Moon inhabit, and dominate it for exploration and research and sociological. But also for commercial, strategic, and military purposes. What do you think of that as a national vision, the dominance of Earth-Moon orbit, for those various component reasons?

Mr. TUMLINSON. Well, I go back to my near-frontier/far-frontier model there, and I, frankly, believe that the dominant forces between the Earth and the Moon, especially as we get close to LEO, should now become more and more the private-sector domination of that area. Were seeing lots of uses that are occurring. We're seeing the development of these transportation system, these suborbital, what some people call, space tourism vehicles, those types of things, into that area.

I think when we start looking at the expansion of our society, literally the expansion up into LEO and beyond, what we have to do is, again, look at our terrestrial model and the role that our government plays here on Earth. What I would like to see up there is, the government's role would be the tax incentives. You'll have a military role, because I, frankly, don't see the United States military letting a lot of people do a lot of activities in space unless they can bring them down at their—whenever they want to, frankly. I think that we would see a Coast Guard function provided by the government out there, and those types of activities.

But I also see this in partnership with that high goal of, shall we say, going to Mars. The going to Mars is like the fancy Crysler sports car that draws you into the dealership, and there you end up buying the smaller vehicle for yourself. In other words, people——

Senator BROWNBACK. You think we'd get it thrown in for—that this is part of the project of going to Mars, is going to the Moon.

Mr. TUMLINSON. Well, I think it's a duality, and I think the costs of going to Mars could be lowered by bringing in the private sector to handle that Earth-to-LEO function. You know, in the old days, up until now, NASA astronauts began their missions on the Earth, and that's where they began. I believe now that NASA begins its mission in LEO, and that from LEO down we can begin handing that off to the private sector. And, you know, rather than driving their cars to the space ports, they can take private-sector transportation to LEO.

Senator BROWNBACK. How many companies, credible companies—credible, the key word—could jump in if we said today, "We want to contract with a credible company to take this exploration device to the moon and set it there?"

Mr. TUMLINSON. It depends on how big a device you're talking about, and it depends on the price to put it there. I was a founder of a company called Lunar Corp. We were looking at lunar rovers that we were going to try and put on the Moon. Commercially, the Moon is at the edge of what I call "the giggle factor." That's where you start getting laughed out of the room when you're talking to investors, but it's right on the edge. And companies, like Radio Shack and others, actually seriously looked at lunar activities.

I think lunar orbiting activities could be contracted out to—there are a lot of—several small companies that could take a shot at that. And those types of——

Senator BROWNBACK. What sort of price range would we be talking about if we want to contract you to put something in orbit around the moon?

Mr. TUMLINSON. I would hesitate to guess on that one. I think that it's much lower than a NASA-owned and operated system, and you could competitively bid that, or you could also combine that with prizes, sets of prizes for showing that you could land something on the Moon.

Senator BROWNBACK. Like the Lindberg——

Mr. TUMLINSON. Lindberg Prize, exactly.

Senator BROWNBACK.—Prize of——

Mr. TUMLINSON. There are models out there now of prizes inspiring people, and starting a lot of people up.

But I do want to point out that there are at least a half dozen companies right now looking at carrying paying passengers to low-Earth orbit, and they are funded, real companies.

Senator BROWNBACK. I had a hearing of private commercial companies doing this with a couple of the entrepreneurs here testifying that, yes, they are, and they've got real dollars, and they're looking at the old Earth—or the old barnstorming model, as you somewhat point out, is that we started commercial aviation barnstorming, just a guy going up and coming into town and saying, "I'll give you a ride in the airplane for five bucks," and that kind of started the commercial industry. And they're saying, "We think that space can go some of the same way."

Mr. TUMLINSON. Now, I can tell you, too, sir, that, in their hearts, their end result, their end goal, is very much like Bob's and I, which is human settlement. These are people who grew up in the 1960s and 1970s watching *Apollo, Star Trek and Star Wars.* They made their money on the dot-coms, survived the meltdown, and now they're out there wanting to do something big and give back to civilization, and this is the entry level, sort of, market that they can see as a way of participating. But, again, it's a dual thing. The big goal, and then the operational activities.

Senator BROWNBACK. Dr. Zubrin, in your testimony you were very passionate, but also were mad. You're mad we haven't done this, or that this vision has been stolen from a generation?

Dr. ZUBRIN. I guess you could say that. You know, I was 17 when we landed on the moon, and if you had told me then that, you know, 34 years later, humans would not be doing anything beyond low-Earth orbit, that we wouldn't be established on the Moon, that we wouldn't have already gone to Mars—you know, NASA's plans in 1969 were for humans to Mars by 1981.

Senator BROWNBACK. Is that right?

Dr. ZUBRIN. Yes, take a look at the report of the Space Task Group that was done for the Nixon Administration in 1969. It's humans to Mars by 1981. And they could have, if they had been allowed to continue. We had a——

Senator BROWNBACK. Why weren't they allowed to continue then?

Dr. ZUBRIN. The Nixon Administration turned their back on the whole Apollo vision. It was not invented here. It's like Columbus coming back from the New World and Ferdinand and Isabella saying, "Aw, so what? Forget it. Burn the ships." OK? You know, that's what has happened in this country. And we should have been on Mars by 1981. We should have had a Mars base by the early 1990s. The first children born on Mars should be entering school right about now.

Senator BROWNBACK. And you have no question that technologically we've got the capacity—we had the capacity then, and we clearly have it now, to do this.

Dr. ZURBIN. Yes. OK? Now, there's various pieces of hardware that need to be developed, and it can be developed. I mean, you know, it's—we're not talking here about Los Alamos 1943, where we're going a scientific adventure into unknown realms of physics and we have no idea of what we're about to encounter. We understand how to do space engineering. This is a question of brass tacks engineering. Got to do it right, it's a lot of hard work, OK, but we can do it. And, you know, I also—I might say that I believe that this is doable within roughly the existing NASA budget. You're going to have to re-prioritize that budget, OK, within the context of an overall plan that guides expenditures to be spent on the hardware elements to implement your plan. OK? But that's what you can do. OK? You know, we spent, what, four billion, five billion a year on the Shuttle flights back to Earth orbit, up and down?

Senator BROWNBACK. Yes.

Dr. ZURBIN. OK, you could build a lot of hardware for that. And, indeed, within 10 years, you could build the hardware required to be flying humans to the Moon, and Mars and the near-Earth asteroids, with a common set of hardware.

Senator BROWNBACK. Are we learning much with the International Space Station?

Dr. ZURBIN. We're learning some things, but in a lot of cases we're solving the wrong problems. And, once again, this is a product of the constituency-driven mode of operation that we have.

The right way to go to Mars is with artificial gravity. Artificial gravity will get rid of all these loss of bone and musculature and all these problems that you have with zero gravity, because the human organism evolved in gravity and we're not adapted to this. However, because the NASA space research community is heavily dominated by zero-gravity health researchers. NASA has not even funded, in its entire history, a single artificial gravity mini satellite with mice in it or something, which would be an easy thing to do, and it costs, you know, $30 million or something. Who knows. Nothing.

So we're doing extended research on the effects of zero gravity, which is not the right way to go to Mars. Any space mission, and certainly Space Station missions included, you get some experience, there's a learning process, you're learning how to do things, you get some lessons. But if somebody was to say, "OK, look, here's $40 billion. Do humans to Mars," within the context of that program I would not be taking this amount of money and spending it on a space station and space-station operations for several decades. I might do something like take half module, launch it in low-Earth orbit, shake it down there, test it out, and get some experience with it in low-Earth orbit as part of my program. But the idea of making Earth orbital operation the centerpiece of the American, and virtually the world space program, at this point, for several decades, I think, is wrong.

In *Apollo,* we knew where we were going. We went to the Moon. Now, there were some things to be done in Earth orbit, so we built a Sky Lab, and, as an afterthought, with the Saturn 5, we launched the Space Station in the afternoon, and we did that as long as it was interesting to us, which was three missions, about over a year or a little more. I think, you know, it would have been worth saving Sky Lab, and there's more—there's things you can learn in low-Earth orbit.

But I think it is—I mean, imagine if Prince Henry, the navigator, the guy who initiative the European age of exploration, going to do maritime exploration. Instead of sending ships down the coast of Africa, you know, further and further and further, he devoted his program to sending ships a hundred miles out to sea and have them sit there and watch the health effects on the sailors. That is the space program that we have now, watching the health effects on the sailors. The purpose of spaceships is to actually travel across space and go to new worlds, not to hang out in space and observe the health effects of doing so. And that's what we're doing wrong.

Senator BROWNBACK. Well, it struck me when you described the period of Apollo and then the period afterwards, that is exactly the case we're without a vision. And instead of us driving it, as policy-makers, and setting vision, we're kind of, "Well, OK, what do you want," and looking at it, "Let me think about it. Well, we'll give you $10 billion instead of $12 billion," and that's been the extent of the—not completely. I mean, that's very oversimplified, but that's been somewhat of the discussion for the last decade or so.

Dr. ZUBRIN. Yes. And——

Senator BROWNBACK. I mean, and it does rob a society of vision. And I've looked and studied some in past societies. When you take that vision that really pushes them out sociologically, mentally, their soul, pushes it out there, when you take that away, and you pull it back in, it has a detrimental effect on the society, on the whole of society. It has a detrimental effect on the culture.

Conversely, you put an aggressive mission out there that this is going to stretch us and this is going to challenge us, and the people that are doing this, that are going to go on this Mars mission, are virtuous heroes, that stretches us to say. I think that's why China went into space, to stretch the society, as much, if not more, than anything else. And we've got to constantly stretch. But I don't feel like we've got a vision right now that stretches this much.

Dr. ZURBIN. Yes, it has a tremendously positive effect on all levels of society, most notable among the youth. During the 1960s, the number of science graduates in this country doubled at every level—high school, college, Ph.D. And, people asked what's the payback? What did we get paid back from Apollo? Teflon? Who cares? What we got paid back for were millions of scientists, engineers, doctors, medical researchers, inventors. OK? Who are the people who created the economic boom of the 1990s, these 40-year-old techno- billionaires who built Silicon Valley? These are the 12-year-olds of the 1960s, paying back huge, big time, to the economy, to national defense, advancing the human condition, medical cures. The intellectual capital is the wealth of the nation, and the way you get that is by inspiring people with a, you know, a vision of something they can do with their lives by developing their lives. And this would be tremendously valuable to the country if we were to do this.

Senator BROWNBACK. Gentlemen, thank you very much. I don't know if anybody else had a final thought that they wanted to put forward, but I did want to come back, and I would like to see the book——

Dr. ZURBIN. OK.

Senator BROWNBACK.—Dr. Zurbin.

Mr. TUMLINSON. I just wanted to concur with Bob on this. And, a lot of the hearing had to do with the safety issues. We've got an exploration agency that's totally consumed by safety. If you pay attention to the pop cultures that's out there, the modern youth are actually consumed about taking risks. They're out there doing X sports. They're doing all kinds of crazy things to take risks. And I think that that's a call inside. Because when you take a risk, you find out who you really are, and that needs to be exemplified in this sort of mission and these other sorts of activities.

So I think it's a very great idea that we could get onto this sort of thing. But, again, as a partnership.

Senator BROWNBACK. Dr. Huntress, did you want to comment?

Dr. HUNTRESS. Just a parting comment, that I really do believe that sooner or later we have to have a clear destination for human spaceflight or it simply won't survive, and America will be much poorer for it. I'm a Sputnik kid. I could tell you the exact same stories that Bob just told you about what happened to our generation and the explosion of scientists and engineers that came out of that generation because of the inspiration that we had there.

The country needs the challenge of grander exploration, simply, to justify the risk, kind of lift our sights, fuel human dreams, advance human discovery and knowledge. But to do that, we need to go somewhere.

Senator BROWNBACK. Well, I've learned, in my time in public life, that a big part of my job is inspiring, probably the biggest part of it. And you can speak to the body, or you can speak to the soul, and the body generally likes safer confines, and the soul likes to be yearned forward and pushed, and it's a far more powerful thing, the soul, than the body.

Thank you. You've been very instructional and educational. I appreciate it greatly.

The hearing's adjourned.

[Whereupon, at 11:50, the hearing was adjourned.]

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