National Aeronautics and Space Administration

Academy of Program/Project & Engineering Leadership

Launching New Horizons: The RP-1 Tank Decision

LAUNCHING NEW HORIZONS: THE RP-1 FUEL TANK DECISION

In early September 2005, the Launch Services Program at Kennedy Space Center received an unexpected call from Lockheed Martin, the manufacturer of the launch vehicle for NASA's long-planned mission to Pluto. The news on the other end of the phone was not good. The launch vehicle's fuel tank had experienced a catastrophic failure during the final stages of qualification testing. With just over four months until the planned launch date, work began immediately to determine the cause of the failure and the implications for the mission.

A Complex Mission with a Tight Launch Window

New Horizons, the first-ever mission to Pluto, posed a number of technical challenges simply due to the sheer difficulty of reaching its destination. Slated to launch on January 11, 2006, it had a 17-day launch window (the period during which it could be launched) in the winter of 2006 that would put it on the shortest trajectory, allowing it to reach Pluto in 2015. If it failed to lift off during this early window and launched between January 28 and February 2, its arrival at Pluto would be delayed until 2016 or 2017. A little more schedule slippage, to as late as February 14, meant that the spacecraft would lose the benefit of a "Jupiter gravity assist"—a swing past the huge planet to gain energy from its gravitational field—and the missed opportunity to pick up speed would push back the rendezvous with Pluto until 2019 or even 2020. If the launch was delayed beyond February 14, the next opportunity to launch New Horizons would not come until 2007.

Many Fingerprints

As is the case with many NASA missions, New Horizons comprised a dense web of partnerships among many organizations. (See Figure 1.) NASA provided overall project management through its Science Mission Directorate's (SMD) New Frontiers program. The mission's Principal Investigator, Dr. Alan Stern, was not affiliated directly with NASA at the time, but rather with the Southwest Research Institute, a non-profit applied engineering and physical sciences research organization.[1] The Applied Physics Laboratory (APL) at Johns Hopkins University designed and developed the spacecraft. Responsibility for the launch rested with NASA's Launch Services Program (LSP) at Kennedy Space Center (KSC) in Florida, which was using an Atlas V expendable launch vehicle (ELV) manufactured by Lockheed Martin. In short, there were numerous organizations that could rightfully claim important stakes in New Horizons.

[1] Dr. Stern later served as NASA's Associate Administrator of its Science Mission Directorate from April 2007 through March 2008.

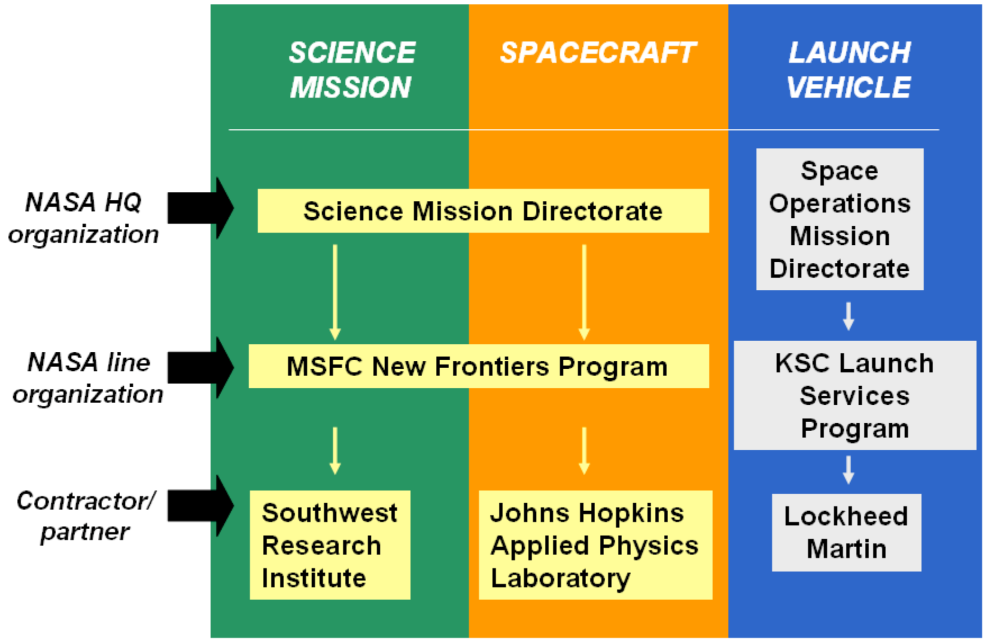

Figure 1. Many organizations had responsibility for different aspects of the New Horizons mission.

A New Configuration for a Young Launch Vehicle

The Atlas V launch vehicle, a relatively new rocket developed by Lockheed Martin Commercial Launch Services as part of the U.S. Air Force's Evolved Expendable Launch Vehicle program, had been launched successfully seven times before New Horizons.

The KSC Launch Services Program (LSP) and the Safety & Mission Assurance (S&MA) organizations had extensive experience with the Atlas "family" of vehicles. But NASA had flown the Atlas V just once before, in August 2005 to launch the Mars Reconnaissance Orbiter (MRO). In order to achieve a record-breaking velocity that would put it on the fastest-possible trajectory to Pluto, New Horizons required Atlas V's "heavy" configuration, featuring five solid rocket motors. Since this configuration had not been flown before, the vehicle had to undergo a rigorous set of re-qualification tests prior to flight. The vehicle assigned for New Horizons was serial number AV-010.

The Atlas V uses RP-1 (Rocket Propellant 1), a highly refined form of kerosene similar to jet fuel, in combination with liquid oxygen (LO_2) to provide thrust. The failure of the RP-1 tank during qualification testing in September 2005 marked the first time that the Atlas V program had encountered this difficulty.

Under NASA's arrangement with its launch vehicle contractor, Lockheed Martin had responsibility for setting up its own internal failure review board to investigate the fuel tank failure. As the customer for the launch vehicle, NASA had significant leverage to request data and cooperation regarding the problem, but it could not run Lockheed's review.

> The Problem in Context: Qualification Testing
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> The qualification testing process consists of a formally defined series of evaluations of the functional, environmental, and reliability performance of a component or system. This testing places loads and stresses on hardware in excess of actual flight conditions in order to establish a factor of safety that can account for imperfections in materials or manufacturing as well as uncertainty in load estimates.

The Nuclear Dimension

Since New Horizons would travel far beyond the distance where it could utilize solar energy, its electrical power would come instead from a single radioisotope thermoelectric generator (RTG), which would provide power through the natural radioactive decay of plutonium dioxide fuel (plutonium-238). (See Figure 2.) RTGs are a long-proven technology for providing power in space, having been used on more than 25 U.S. space missions, including Apollo, Viking, Voyager, Pioneer, Galileo, and Cassini. The Department of Energy (DOE) provided the nuclear fuel for New Horizons as well as an extra layer of regulations: the mission was subject to DOE procedures, since a failure within Earth's atmosphere could potentially result in the release of radiation.

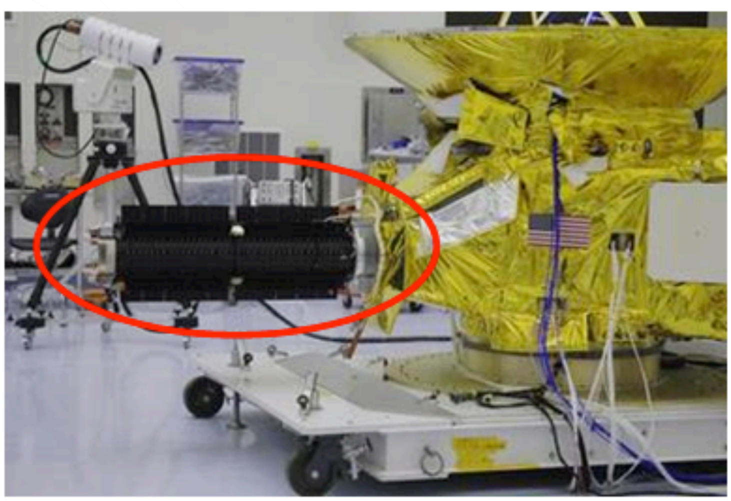

Figure 2. The RTG provides electrical power the spacecraft. (Source: NASA)

The actual possibility of an environmental or public health hazard resulting from a RTG radiation release was extremely low. Over three decades (and rigorous stress testing), RTGs have never been the cause of an accident and have performed as designed in three instances where a spacecraft failed for other reasons.

Regardless of the actual danger as understood by engineers and safety experts, however, the NASA team was well aware that the mere presence of a nuclear payload meant the launch would attract attention from environmentalists and anti-nuclear activists. A launch failure would be a public relations disaster for the agency.

A New Team at NASA Headquarters

The New Horizons RP-1 tank problem presented a test case for NASA's new leadership. Virtually the entire senior management team had turned over since the loss of the space shuttle *Columbia* two and a half years earlier. A new set of leaders, including Administrator Dr. Michael Griffin, brought fresh perspectives informed by NASA's recent history. Among the senior leadership involved in this case, only Bryan O'Connor, the Associate Administrator for Safety and Mission Assurance, had been in his position for more than a year when the New Horizons RP-1 tank issue reached the top tier of NASA management. Chief Engineer Chris Scolese came to his new position at NASA headquarters the same month that the tank failure occurred. The team would face its first technical decision that required the involvement of the highest levels of agency management.

The Flight Planning Board

As soon as the call came from Lockheed Martin, KSC Launch Services Program (LSP) Manager Steve Francois notified Bill Gerstenmaier, Associate Administrator for Space Operations at NASA headquarters in Washington, D.C., about the RP-1 tank failure. Francois kept the mission moving toward a January 11 launch date while the LSP engineering team worked with Lockheed Martin to determine the scope of the problem.

Francois began reporting developments about the tank issue to officials at NASA headquarters through regular teleconferences with the Flight Planning Board (FPB). The formal members of the FPB, chaired by Bill Gerstenmaier in his role as the Associate Administrator for Space Operations, included the Associate Administrators for the Science Mission Directorate (Mary Cleave) and Safety & Mission Assurance (Bryan O'Connor) as well as NASA Chief Engineer Chris Scolese. (In practice, some organizations had deputies participate in place of principals on FPB teleconferences about the RP-1 tank.) Among other functions, the FPB provided a forum for senior agency management to authorize launch services for new missions and launch date changes, to identify and resolve conflicts, to make launch vehicle assignments, and to approve launch risk mitigation strategy for individual missions.

Multiple Teams Working the Problem

LSP Chief Engineer James Wood immediately began working with Lockheed Martin to understand what had happened from a technical standpoint, while KSC's Safety and Mission Assurance (S&MA) team approached the problem separately from the LSP engineers or the Lockheed Martin team. It engaged the Aerospace Corporation, its contractor, to conduct an independent analysis. The KSC S&MA team reported its progress to Bryan O'Connor, the Associate Administrator (AA) for S&MA at NASA headquarters, just as the LSP team kept Gerstenmaier, the AA for Space Operations, informed about developments.

As facts emerged and the LSP Engineering Review Board meetings and FPB teleconferences became increasingly complex, Gerstenmaier asked Wood to write an engineering white paper that would serve as the key technical documentation of the problem and proposed mitigations. The white paper evolved significantly over the course of the RP-1 tank decision, and it played a key role as a communications tool throughout.[2]

The Technical Problem

While examining closeout photos—final images of the qualification tank before testing—one of the Launch Services Program engineers found something highly unexpected: an existing crack in the tank even before the rigors of qualification testing had begun.

The fact that the qualification tank started testing with cracks suggested to the LSP team leaders that a crack-free tank could withstand a lot of pressure.

The evidence pointed to the region of the tank around the tubular liquid oxygen (LO_2) feed line that ran along the outside of the tank. (See Figure 4.) The feed line was not shielded by a nose cone or fairing that would make it aerodynamically smooth, which meant that under maximum flight conditions it would encounter great stresses. It was mounted to the tank with a series of brackets—not visible from the outside—built directly into the tank wall.

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[2] For more information about the development of the white paper, see James Wood, "A Powerful Communication Tool: the Engineering White Paper," *ASK Magazine*, Issue 24, available at <http://appel.nasa.gov/ask/issues/24/24s_powerful.php>

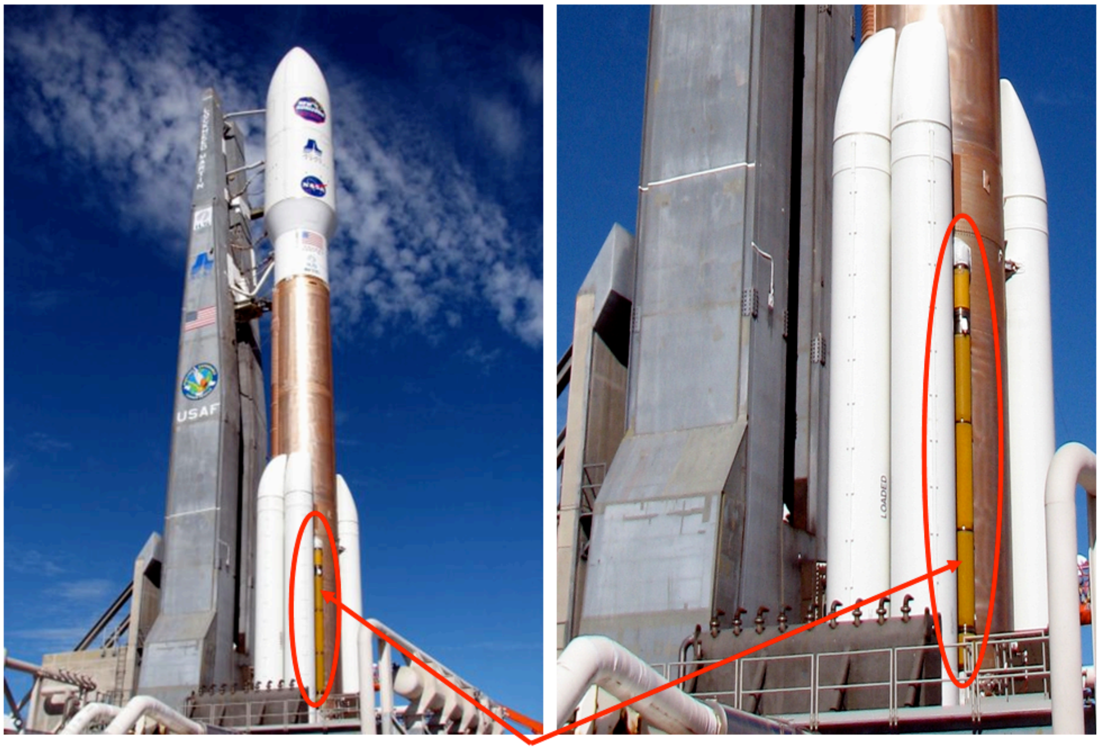

Figure 4. The liquid oxygen (LO_2) feed line on the Atlas V 500 series launch vehicle. (Source: NASA)

Subsequent analysis led to the conclusion that the failure stemmed from a weakness in the design in this area of the tank, which had been modified as the Atlas V matured. “It appeared that the design was deficient, and that allowed cracks to occur in certain tanks but not in all tanks,” said Bill Gerstenmaier.

The discovery of the design flaw all but eliminated the possibility of having a fully qualified tank by January for the loads that New Horizons would be flying. A catastrophic failure such as the one that had occurred during the RP-1 qualification test would require months of analysis and testing beyond the 2006 launch window.

Given that it would be impossible to fly a fully qualified tank in the early launch window, the LSP team focused its efforts on determining if it could establish flight rationale that would justify a launch under the specific conditions of New Horizons—the loads, stresses, trajectory, and other variables that were unique to the mission.

“There was not a process where you could use classical structural mechanics to say that this particular design was acceptable to go fly. But from the basic evidence, from the material that was available, we had enough information that we thought it was acceptable to go fly,” said Gerstenmaier.

The investigations employed modeling analyses as well as physical inspections of tanks. The analytical team was developing enormous finite element models—computer simulations deconstructing the launch vehicle into tiny elements—that would take days on the fastest processors at KSC. Given the shortage of time, the LSP arranged to run these models on the Columbia supercomputer at the NASA Advanced Supercomputing (NAS) facility at Ames Research Center, one of the fastest supercomputers in the world.

A critical activity the teams performed was "mapping the family: examining all the existing RP-1 tanks built for the Atlas V. It turned out that five of seven tanks, including one on the launch pad at Vandenberg Air Force Base in California, had cracks or corrosion problems. There were also inconsistencies in the materials used to manufacture the tanks (depending on the lot numbers of the materials used for each individual tank) that could cause the tank to tear under certain conditions, as the qualification test tank had. The tank at Vandenberg was particularly bad: engineers discovered seven cracks in the first twelve locations they inspected. They didn't even finish checking the last four critical areas because the overall condition of the tank was so poor.

The physical inspections of the New Horizons flight tank took place on October 29-30, 2005, at KSC, where the launch vehicle already sat stacked on the launch pad. The technical team had to go inside the booster of the vehicle, and, at a distance of about 35 feet, inspect interior locations of the RP-1 tank with a tool called a borescope. There was a great deal of risk associated with the borescope inspections because they had never been performed before on a vehicle that was already on the launch pad. The process called for lowering a thick cable through a three-inch wide hole and down the center of the propellant tank to take detailed video footage and photographs. It was not easy to maneuver or guide the cable to different locations near the wall within the tank without damaging it. There was a distinct possibility that the technical team would drop something—a tool or other piece of hardware—in the tank during the inspection that it wouldn't be able to retrieve. If that happened, the launch would be scrubbed for 2006.

A Stroke of Luck

The borescope analysis revealed what the LSP team considered a considerable stroke of luck: the flight tank was one of the two clean ones in the fleet.

To Bill Gerstenmaier, the condition of the flight tank was crucial evidence. "We looked at where the fasteners were located around the tank. This particular tank, for whatever reason, had already seen actually pressure cycles greater than it would see in flight, and had no evidence of cracks. So although not traditional, that's a pretty strong indication that this tank is OK to go fly. And then the fact that the qual (qualification) tank failed so late in this process with corrosion evidenced in it. It had cracks in the tank throughout the qual process that were not observed. We knew some were observed when they did the measurements to go look at the strain gauge had failed, as we saw happened to capture a crack in the picture so we could see that crack was there. So we knew we could take cracks and they wouldn't grow."

The absence of cracks was also significant to Gerstenmaier as an indicator of margin. "There were two directions of the cracks. There was a principal direction and a secondary direction. That was important because the failure had to occur in the secondary direction that the crack would then propagate from the stringer into the tank wall itself and then eventually let the tank wall go. You would see evidence of this first direction of the crack first before you'd pick up the secondary crack direction. So the fact that we didn't have any cracks said we had some margin, and it was debatable amongst the team how much margin we had, but it was clearly some margin. The fact that the tank could already see pressures greater than it would see in flight added to the flight rationale.

LSP's solution was to modify the mission profile based on the specific loads it was flying so as to mitigate the risk at key points during the launch. Gerstenmaier said, "We could essentially tailor the flight environment to give it a more relaxed pressure profile for the tank than it would normally see allowed us to fly *this individual tank on this individual mission*—and again, it's a function of mission design—most missions wouldn't allow us to go do this—but this particular mission allowed us to go do it. So the fact that we had a tank with no cracks, we understood the failure mechanism fairly well, we could control it, the tank had already seen pressures (in excess of what it would see in flight), gave us enough rationale in my mind to say we'd go fly."

A Difference of Opinion

The KSC Safety and Mission Assurance (S&MA) organization interpreted the situation in a fundamentally different way. In keeping with its name, S&MA categorized the risk in two ways: safety risk and mission risk. "The safety risk means if you were to have a failure of this tank early in ascent, in the first 20 seconds or so, and the range would have to blow it up, then there would be a nuclear payload, there would be the normal higher risk to the public that goes with early destruct, and so on," said Bryan O'Connor, Associate Administrator for S&MA. The mission risk concerned any launch failure that would impede the spacecraft's planned journey to Pluto. As understanding of the problem grew, the mission risk became the primary focus of the S&MA team.

By November, clear differences of opinion had emerged between the LSP and S&MA teams at KSC. "In this case, Steve (Francois) and James (Wood), who are part of the program, said they're ready to fly, they think there's enough technical justification. We said no, we don't believe there's technical justification," said Humberto "Bert" Garrido, deputy director of S&MA at KSC.

S&MA requested the assistance of the NASA Engineering Safety Center (NESC), an independent body within the agency that conducts testing, analysis, and assessments of

NASA's high-risk projects upon request. The NESC is part of the Office of the Chief Engineer, but in this instance it supported KSC's S&MA organization. (See below for a notional explanation of the governance structure.)

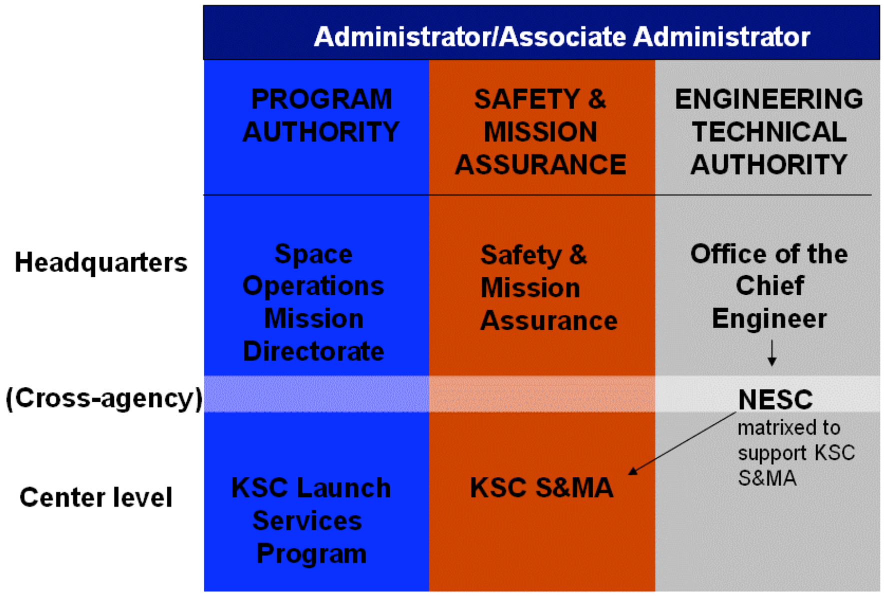

Figure 3. The KSC Launch Services Program, KSC Safety & Mission Assurance organization, and the NASA Engineering Safety Center (NESC) were all accountable to different top-level organizations at NASA Headquarters.

S&MA initially requested that the NESC team assist with its own investigation, but in practice the NESC worked in parallel with S&MA while sharing the same information.

"The (LSP) program has a strong engineering team with several really good leaders of it, and in this case we looked at them as not an independent engineering input but as the program's engineering input, and we felt like we needed to get some support for our Safety & MA team," said Bryan O'Connor, the Associate Administrator for S&MA. "So we got (NESC director) Ralph Roe to provide some technical support, and he got a couple of the best guys in the Agency to help our S&MA team down there see what's going on, ask questions, do their own separate analysis."

The NESC team had not worked extensively with the expendable launch vehicle (ELV) program at KSC, so they did not have established long-term relationships with the teams that were already working the problem. "I think prior to this the ELV (team at KSC) hadn't really been exposed to NESC other than an overview briefing of what we were doing. They weren't at all comfortable with calling us in from a program or engineering standpoint," said Ralph Roe.

Michael Gilbert, the NESC Chief Engineer for the Langley Research Center and NESC team leader for New Horizons, thought the data were insufficient to develop flight rationale. Typically NASA's structural engineering community would conduct the full qualification test program and post-test analysis. It would then construct a fully correlated math model that matched the ground test results, adapt the model to a flight-like configuration, and then further correlate the flight configuration model with available flight data. He contrasted that approach with New Horizons. "As a result of the failure analysis effort that the program and the contractor had gone through, we knew that there was a design flaw, and that the standard acceptance test—the hydroproof—was more than likely causing the cracks. What we didn't have was a converged finite-element model giving proper stress/strain results in the crack regions, and we did not understand why one tank in the fleet had seven cracks, while others, including the Pluto/New Horizons tank, had none."

As time went on, there was growing frustration within both S&MA and NESC that the data were not made available from Lockheed Martin in a timely manner. "I don't believe they were releasing information fast enough," Garrido said. Roe echoed his concern. "At Thanksgiving time the guys requested that data, and they really didn't get it until around Christmas time," he said.

On December 14, Garrido wrote a letter to Steve Francois of the Launch Services Program, which served the purpose of formally notifying NASA's senior leadership of the extent of his concerns. "Clearing the tank for flight using only empirical information without engineering analysis validation does not explain the failure mechanisms and margins," he wrote. "This makes one ponder how close tank failure is to the expected operating pressures and flight environments. There is much uncertainty associated with the integrity of the tank, as we don't know where the 'cliff' is."

Two days later, when it was clear that New Horizons could not make the January 11 launch date, the launch was postponed until January 17. The early launch window was now just over two weeks. The delay allowed time for another borescope examination of the interior of the RP-1 fuel tank.

Christmas Week

With frustrations about the flow of data mounting, the engineers from NESC wanted a face-to-face meeting with Lockheed Martin. After pushing the Launch Services Program on this request, a date was set for just after Christmas.

"Lockheed Martin didn't feel some of this analysis was needed—they didn't feel the tank visit was needed by NASA," said Bill Gerstenmaier, Associate Administrator for Space Operations. "So with some responsibility for the contracting, I had to authorize KSC to spend additional contracting funds to have Lockheed Martin do the borescope inspection, take the delay to go do that, and also go spend some money to go up with Lockheed Martin and inspect the tanks to see what was happening."

While the meeting did not lead to a solution to the technical problem, it served another important purpose for the various technical teams involved. "The meeting produced no 'aha,' but it seemed to improve the communications among all the parties," said Mike Luther, Administrator for Programs for SMD.

On January 3, 2006, at the urging of the NESC and S&MA teams, the flight tank underwent a second borescope analysis. Once again, the inspection found no evidence of cracks. A final Flight Planning Board meeting was scheduled for a week later, at which the Launch Services Program, S&MA, and NESC would have the opportunity to present their cases.

The Final Flight Planning Board Meeting

The Flight Planning Board (FPB) convened one final time on January 10, 2006, eight days before the scheduled launch. Anticipating that there would not be unanimity among the voting members, FPB chairman Bill Gerstenmaier asked NASA Administrator Dr. Michael Griffin and Associate Administrator Rex Geveden to attend the meeting. More than 30 people attended the meeting, with several more participating through teleconference.

James Wood presented the case in favor of going forward with the launch as planned. In the absence of a fully qualified RP-1 tank, the actual flight tank had been visually inspected twice and found flawless. The mission profile had been tailored to minimize the possibility of a launch failure over land, which addressed the greatest danger posed by the nuclear payload. The qualification tank that had failed was already cracked when it began the qualification testing process, and even so it had survived until the final stages of the process. This indicated that a perfect tank would have adequate margin under the specific flight conditions for this mission.

Raoul Caimi of KSC, with support from the NESC team, presented the S&MA position for delaying the launch and continuing to work the problem. The tank had not undergone that the full qualification test and validation process for flight hardware. (See page 6 for a fuller description of this process.) It had an inadequate design that had failed catastrophically during qualification testing. The flight rationale offered by the program was based solely on evidence about the flight tank, which meant that the tank's failure mechanisms and margin could not be properly established by traditional engineering validation practices. There had not been enough time to develop the necessary models to determine these characteristics.

After hearing the presentations, Gerstenmaier polled the room—both voting members as well as some non-voting participants—for "go/no-go" decisions. Among the voting members of the Flight Planning Board, Chief Engineer Chris Scolese and Associate Administrator for S&MA Bryan O'Connor voted "no-go."

Chris Scolese's primary concern was the possibility of failure with the nuclear payload. While Scolese, who began his career in the Navy's nuclear reactor program, knew full well that the risk of radiological contamination due to a launch failure was low, he also knew that such a failure would be a catastrophe on multiple levels for the agency, which was still in the process of recovering from the *Columbia* accident. "If it fails for any reason, it's going to be 'NASA launches flawed rocket that drops nuclear waste.'" Scolese said. "I was "go" for Pluto and "not go" because of (the) nuclear (issue). Had this not been a nuclear payload, the recommendation I'm sure from everybody would've (said), you're taking more risk with this payload, but we all believe you're going in the right direction."

O'Connor's vote reflected the opinion of the S&MA team. "Because the rationale for flight included a delayed pressurization and some of these other things, the (KSC) Safety (community's) vote really was that from a human safety viewpoint, this thing is acceptable. But from a mission success viewpoint, they felt like it was higher risk than was acceptable, and that the program ought to go fix this tank before they fly it in order to bring the loss of mission risk down to an acceptable level."

According to the NASA governance model, which had recently been revised by the new administration, a "no" vote from either of these officials required that Gerstenmaier appeal to the Administrator, Dr. Michael Griffin.

Associate Administrator Rex Geveden spoke first. He sided with the "go" votes. "If you looked at it from a formal, strict point of view, we didn't have a qualified tank, and you shouldn't fly. You look at it from another point of view, (and) practically speaking, I thought there was almost no chance that this tank would fail. That's just an engineering judgment thing.

"The other thing is if you decided to delay by another year, which is when the next launch window would open—assuming you could get the tank qualified in that period of a year—it has some very negative consequences for the mission. You don't get a Jupiter gravity assist, the cruise time on the mission takes five years longer, and so you're out there cruising for 15 years instead of 10, which means your operations team runs for a longer period, etc. So it had a $100 million financial consequence, it had a five-year penalty in terms of missions operations time, and all of that to me stacked up to the thought that we should be willing to take some risk on this and we should lean forward. You're trading one kind of risk against the other. You're trading the launch risk against the five extra years of mission operations, and that's not a small amount of risk there. Requiring your instruments, your systems, your power unit, to run for five years longer is not an insubstantial risk, and so I felt like we were balancing risks there.

"One of the things that I said was, there were folks who really wanted more time to study the issue, who really would have liked to look at it longer and harder—NESC in particular wanted more time—and I made the point that it does not matter how long we study this problem because it doesn't change the risk to this mission. All it does is improve our understanding of it. And I don't think that's valuable enough to spend

$100M on. Time doesn't change the risk. The only way you change the risk is if you change the component out."

Then the Administrator spoke. He pointed out that there were a number of ways to rationalize flight readiness, and he put the question in basic terms. He acknowledged the lack of qualified hardware, noting that from a standpoint of formal process, it wasn't possible to make the case that the vehicle should fly. At the same time, he said that good engineering requires the application of judgment. The more relevant question from his perspective was if this particular tank was good enough to fly.

He summarized what he'd heard around the room, both the formal presentations from the Launch Services Program and Safety and Mission Assurance as well as representative from the range operations team at KSC, the mission control team, and others who had spoken.

He also addressed the question of the nuclear payload. The radiological health risk was tiny even in the event of a release. Even under very severe test conditions, which exceeded the reality of most accident scenarios, RTGs hadn't released radioactive material. He was convinced that even in the event of a launch failure, the risk of release of nuclear material wasn't a credible concern.

After reviewing all points of view, he said he supported the program's recommendation to launch. He gave his approval to move forward.

The Final Week

New Horizons still had plenty of other hurdles to clear—including the Flight Readiness Review (FRR), the Launch Readiness Review (LRR), and a third borescope inspection—but the Administrator's decision at the final Flight Planning Board meeting assured that, barring new data, the RP-1 tank issue would not delay the launch.

On the documentation accompanying the official Launch Readiness Certificate issued at the LRR, NASA Administrator Michael Griffin wrote:

"The Flight Planning Board understands the residual risk associated with the AV-010 1 tank and the mitigations taken by the Launch Service Contractor and Launch Services Program's engineering staff. In the view of the Flight Planning Board Chairman, the risk from the RP-1 tank is understood and acceptable. The Flight Planning Board recognizes the independent risk ratings provided by the Program's technical team and the SMA/NESC. The efforts in mitigating the risk and rationale for the flight provide highest practical probability of mission success for the New Horizon mission."

New Horizons was ready for launch on January 17. After two days of weather-related delays, the launch vehicle lifted off successfully on January 19, 2006, and the spacecraft soared toward its destination at the fastest speed of any spacecraft launched from Earth, reaching an escape velocity of approximately 10 miles per second as it departed Earth's orbit.

Appendix 1. Discussion Notes for Readers

This case study has been designed to be delivered in a classroom setting. Please read the full case prior to in-class discussion to allow ample time for analysis and reflection.

Consider the following questions:

- How did the specifics of the New Horizons mission shape the problem?
  - Schedule?
  - Technical considerations?

- What was the role of the NASA governance model in the outcome of this case? What about independent technical authority?

- How would you characterize the decision-making process employed in this case? Did it represent a new way of doing business at NASA, or was it no different than in the past?

Be prepared to discuss these in small groups with other participants. Draw analogies to your own experience and develop as many interpretations as possible. The small groups will then share their conclusions with the larger group.