IAC-10-B4.8.2

LCROSS LUNAR IMPACTOR – LESSONS LEARNED FROM A SMALL SATELLITE MISSION

Daniel Andrews
NASA Ames Research Center, USA, daniel.r.andrews@nasa.gov

The Lunar CRater Observation and Sensing Satellite (LCROSS) launched with the Lunar Reconnaissance Orbiter (LRO) on June 18, 2009. While the science purpose of the LCROSS mission was to determine the presence of water-ice in a permanently-shadowed crater on the moon, the functional purpose was to be a pioneer for future low-cost, risk-tolerant small satellite NASA missions. Recent strategic changes at the Agency level have only furthered the importance of small satellite missions. NASA Ames Research Center and its industry partner, Northrop-Grumman, initiated this spacecraft project two-years after its co-manifest mission had started, with less than one-fifth the budget. With a $79M total cost cap (including operations and reserves) and 31-months until launch, LCROSS needed a game-changing approach to be successful. At the LCROSS Confirmation Review, the ESMD Associate Administrator asked the Project team to keep a close record of lessons learned through the course of the mission and share their findings with the Agency at the end of the mission. This paper summarizes the Project, the mission, its risk position, and some of the more notable lessons learned.

I. THE LCROSS MISSION PROOSAL

Early in 2006, the NASA Exploration Systems Mission Directorate (ESMD) held a competition for NASA Centers to propose innovative ideas for a secondary payload mission to launch with the Lunar Reconnaissance Orbiter (LRO) to the Moon. The successful proposal could cost no more than $80 million dollars (less was preferred), would have to be ready to launch with the LRO in 31 months, could weigh no more than 1000 kg (fuelled), and would be designated a risk-tolerant "Class D" mission. In effect, NASA was offering a fixed-price contract to the winning NASA team to stay within a cost and schedule cap by accepting an unusually elevated risk position.

To address this Announcement of Opportunity to develop a cost-and-schedule-capped secondary payload mission to fly with LRO, NASA Ames Research Center (ARC) in Moffett Field, CA, USA embarked on a brainstorming effort termed "Blue Ice" in which a small team was asked to explore a number of mission scenarios that might have a good chance for success and still fit within the stated programmatic constraints. From this work, ARC developed and submitted six of the nineteen mission proposals received by ESMD from throughout the Agency, one of which was LCROSS - a collaborative effort between ARC and its industrial partner, Northrop-Grumman (NG) in Redondo Beach, CA, USA.

In the LCROSS proposal, ARC would manage the mission, perform systems engineering and mission design (teaming with NASA Goddard Space Flight Center (GSFC) and the Jet Propulsion Laboratory (JPL)), conduct mission and science operations, and design/develop the payload instrument suite while NG would design and build the innovative spacecraft bus.

Fig. 1: The LCROSS Spacecraft

If successful, the LCROSS mission (Fig.1) would conduct the first *in-situ* study of a pristine, permanently shadowed lunar crater and test for the presence of water ice in a permanently shadowed region, building on previous lunar missions, *Clementine* and *Lunar Prospector*.

II. THE LCROSS SELECTION

After a period of evaluation by ESMD and the Robotic Lunar Exploration Program (RLEP), LCROSS was selected in a somewhat dramatic "reveal" in Washington DC shortly before it was announced at a NASA press conference. Just prior to the television cameras going live, ESMD Associate Administrator (AA) Scott "Doc" Horowitz informed LCROSS Project Manager Dan Andrews that ESMD had a very focused purpose for LCROSS because it represented a type of mission that "is not your father's NASA". Horowitz acknowledged that there was a place for the heft and conservatism of traditional NASA missions, primarily in manned spaceflight, but that the Agency also needed a way to accomplish tactical missions inexpensively, given the financial constraints facing future Agency budgets. In LCROSS, he saw an exciting mission, able to inspire the public by determining if water-ice is present on the Moon, while at the same time proving there is a cost-effective way to execute meaningful missions on a budget.

Horowitz and Andrews later discussed how LCROSS could be a pathfinder project for the Agency's ability to make practical use of excess launch capacity, while staying within tough cost & schedule constraints. Noting that the Agency would increasingly need to rely on smaller, high-leverage, cost-capped missions, Horowitz asked Andrews to track all that he learned in bringing LCROSS to a successful conclusion. This would include how well the NASA Policy Requirements (NPRs) served the project, the effectiveness of acquisition processes, and how the Program Office and Headquarters behaved with this unconventional project. Using the LCROSS mission as a prototype, Horowitz had a clear vision of how and where this type of mission would fit within the NASA portfolio. As he later stated in an interview, "I could triple the cost to try and guarantee no failure, or I could do three projects and even if one fails, I still get more done" [1].

This key dialogue with the principal mission stakeholder established the context for what would make a successful LCROSS mission, i.e., cost and schedule were key drivers and risks could be taken.

III. THE LCROSS SCIENCE BASIS

The scientific basis for the LCROSS mission had roots in the *Clementine* (1994) and *Lunar Prospector* (1998) *Missions* which performed complementary forms of resource mapping. This mapping led the lunar science community to conclude that there might be water-ice trapped in permanently shadowed craters on the Moon[2]. Both of these missions were instrumental in the lunar ice question. In particular, the Lunar Prospector Mission (LP) neutron measurements indicated elevated hydrogen signatures in permanently-shadowed craters on both the North and South poles of the Moon. In light of these data, the science community wondered if these elevated hydrogen signatures could be an indication of the presence of water-ice, trapped just beneath the regolith surface of the crater floors.

IV. THE LCROSS MISSION

LCROSS proposed to conduct a low-cost, fast-track companion mission to launch with LRO. The Atlas launch vehicle used for the LRO mission consists of a

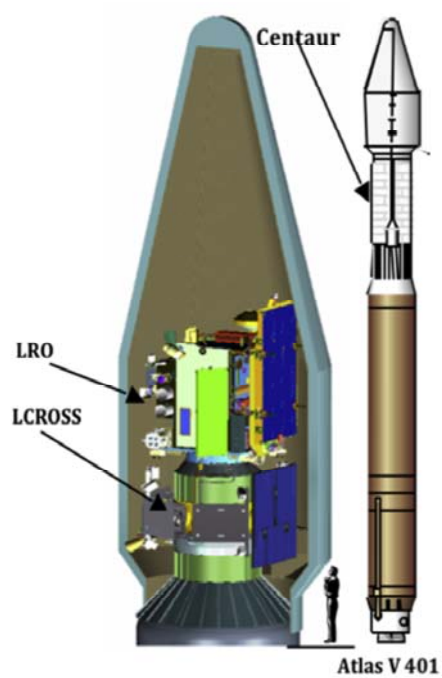

Fig. 2: The LRO/LCROSS Launch Vehicle Stack

booster stage and the Centaur upper stage. The LCROSS spacecraft would be mounted atop the Centaur with the LRO spacecraft mounted atop LCROSS (Fig. 2).

With a mass constraint of 1000 Kg, LCROSS proposed to use the upper stage of the Atlas-V rocket (the "Centaur"), normally space junk after delivering a payload, to effectively triple the size of its working payload. By repurposing the spent Centaur to LCROSS, mission planners were able to stay within the 1000 Kg mass budget allotted to the secondary payload while gaining approximately 2300 Kg of mass "for free".

Proposing the use of the Centaur as a lunar kinetic impactor, LCROSS would "drop" the 2300 Kg rocket (about the weight of a large sports utility vehicle) into a permanently-shadowed crater, at a speed of 1.5 miles/second (2.5 km/s) or three times the speed of a bullet, to kick-up a plume of material from the crater floor. The 1000 Kg LCROSS "Shepherding Spacecraft" would then collect and transmit data about the impact and plume back to LCROSS mission control using nine on-board science instruments before impacting the surface itself, about 4 minutes after the Centaur.

On June 18, 2009, LCROSS and LRO launched aboard an Atlas V rocket from Cape Canaveral, in Florida, USA. Once the Atlas V achieved the LRO lunar insertion requirement, LRO separated, enabling it to independently move forward on its mission, leaving LCROSS and the still-attached Centaur behind. The Centaur then performed a series of venting maneuvers to eliminate gasses which could contaminate the lunar impact measurement. The Centaur then became an inert, empty vessel and an official part of the LCROSS mission. Approximately five days after launch, LCROSS entered into an extended Lunar Gravity-Assist, Lunar Return Orbit (LGALRO) by performing a lunar-swing-by of the moon. The cruise phase of the mission lasted slightly more than 100 days before entering into the terminal phase of the mission. In the meantime, LCROSS' long, high-inclination orbit around the Earth gave the LRO mission time to commission its instruments and collect data about the South Pole craters to help the LCROSS science team refine target crater selection. In fact, this LRO data led to LCROSS changing the impact crater from Cabeus-A to Cabeus. Cabeus had more relevant conditions related to the fundamental water question, but was a much deeper crater. Although it was known that this crater change would negatively impact Earth observations, it was the scientifically proper strategy for the mission because the first priority of the LCROSS PM and science team was to assure scientific relevance.

During the cruise phase, LCROSS maintained its Earth cruise orbit by executing several Trajectory Correction Maneuvers (TCMs) to provide for the final lunar approach required to position the Centaur for its ballistic lunar impact. Following the final TCM, the Centaur and the Shepherding Spacecraft separated about nine hours before impact (Fig. 3) followed by the Shepherding Spacecraft performing a braking maneuver to enable the release Centaur to impact the Moon first. This delay provided time for the Shepherding spacecraft

Fig. 3: LCROSS Separating from Centaur

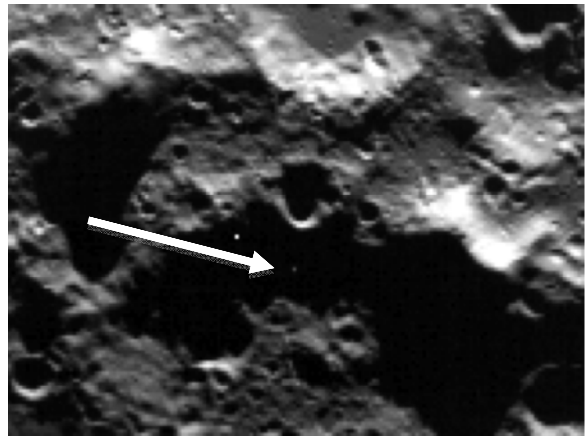

Fig. 4: LCROSS Impact Plume

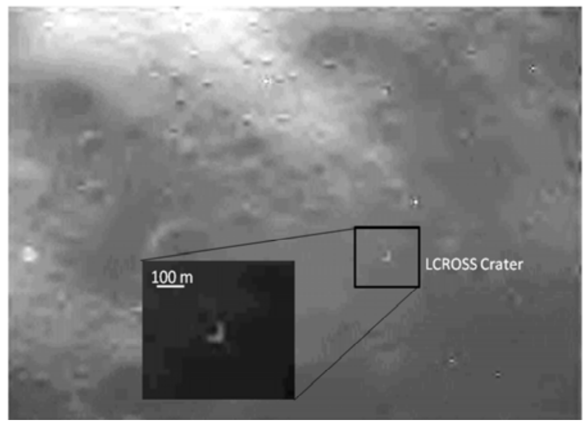

Fig. 5: LCROSS Centaur Impact Crater

to observe the ejecta plume arising from the Centaur impact. The Centaur's impact is estimated to have excavated 250-350 metric tons of regolith, leaving an impact crater approximately 82 feet (25 m) in diameter. LCROSS thermal images of the ejecta plume development and the resultant Centaur crater as seen by the LCROSS NIR camera while 14km above the crater floor, can be seen in Fig. 4 and the resultant Centaur impact crater in Fig. 5 [3].

LCROSS discovered that regolith in this permanently shadowed crater was very fine with a talc-like consistency. Much of the kinetic energy of the Centaur impact was converted into thermal energy into the local soil creating a notable vapor cloud. Less energy went into rock and dirt ejecta being thrown upward given the nature of the crater floor regolith. As the Shepherding Spacecraft continued its delayed decent, cameras and sensors in the instrument suite were able to measure the constituents of the Centaur ejecta plume, observing and measuring all the way down to the inevitable second impact on the Moon four minutes later. The sensors on LRO were able to make notable measurements of the nature of the ejecta and impact plume, providing excellent complementary data on the LCROSS impact.

V. THE LCROSS PAYLOAD INSTRUMENTS

The LCROSS instrument payload was designed to provide mission scientists with multiple complimentary views of the debris plume created by the Centaur impact. The instrument suite consisted of nine instruments: one visible, two near-infrared and two mid-infrared cameras; one visible and two near-infrared spectrometers; and a photometer - all optimized to answer the fundamental question about water ice.

These instruments were selected to be low-cost, rugged, commercially available components for an Earth environment. However, to ensure survival in both space and launch environments, the LCROSS payload team needed to put the individual instruments though rigorous testing to simulate launch and the conditions in space. When that testing revealed weaknesses, the team worked with the manufacturers to strengthen their designs for satisfactory use in the LCROSS mission.

VI. LCROSS AS A CLASS D MISSION

A key enabling factor for LCROSS success was its designation by the ESMD Associate Administrator as a risk-tolerant Class D mission. NASA classifies all spaceflight missions into one of four categories based on risk tolerance: Class A, B, C, and D. This classification system has origins in the Department of Defense (DoD) Military Standards (Mil-STDS) documents which NASA has tailored into a Safety and Mission Assurance (S&MA) NASA Procedural Requirement (NPR 8705.4) [4].

Class D missions are the most *risk-tolerant* missions in NASA. While safety concerns are treated no differently for a Class D mission than a Class A mission, Class D missions are allowed to be “single strung”, which means there is no redundancy required. In fact, as it states in NPR 8705.4, “Medium or significant risk of not achieving mission success is permitted”, so this type of mission *can fail*. Class D designation is typically applied to small missions that are constrained in some way making it harder to assure mission success. For LCROSS, the Agency Class D designation was in place to improve the likelihood it could make the LRO launch date, within budget.

When LCROSS was cast as a Class D mission, technical risk officially became part of the mission trade space. Because the mission was cost-capped, cost maintenance was essential. The Project cost cap had to be maintained even if at the expense of technical requirements as the mission could be cancelled if the cost cap was exceeded. LCROSS was also schedule-constrained since it had to make the LRO launch date. As a result, LCROSS was permitted to waive performance requirements or take additional risk as necessary to fit into the schedule and cost constraints.

Managing the mission success risk for LCROSS involved management of the three traditional elements – cost, schedule, and technical capabilities. Because cost and schedule were constrained, technical capability was really the only element that could be actively managed.

Cost Risk + Schedule Risk + Technical Risk = Mission Risk

Although LCROSS had a Class D mission designation allowing a higher-than-normal mission risk, it was in everyone’s interest to keep that risk as low as possible to increase the chances of success. By definition then, the technical capability risk also had to be kept as low as possible, primarily by keeping the complexity level as low as possible [5].

VI.I Capabilities-Driven Missions Lower Risk

Keeping that technical risk in check meant the LCROSS mission was not about pushing the limits of technology and performance. This particular mission was about doing as much as possible within existing capabilities of the system. Capability-driven missions like LCROSS are exactly what the name implies: working to achieve requirements by staying as much as possible within the capabilities of the system. This is very different than many science-driven NASA missions where needed capabilities are defined and then efforts to meet them are defined to meet the mission requirements. That approach is too open-ended and can involve a full development and test cycle which is fraught with risk and can be costly in schedule consumption. LCROSS was a Design-to-Cost [6] project, working within cost and schedule constraints that were the principal drivers for the project. By working as much as possible with existing designs, LCROSS had a set of proven capabilities that helped to contain cost and schedule.

The perfect incarnation of a capability-driven project requires little to no modifications over what has been done before. Everything is not only flight-proven, but proven in the identical arrangement and configuration of how it will be used on the project. Clearly, this scenario is not typical, so a real Design-to-Cost project needs to carry sufficient risk margins for not only the unknowns, but for the inevitable effort required to address the risk associated with expanding capabilities where required. Of course, requirements descope is always an option as it effectively designs in technical risk margin to accommodate more mass or power needs as the project evolves.

VI.II "Glue Missions" Lower Risk

By using and "gluing together" already-proven hardware, software, and Integration & Test (I&T) approaches, the residual technical risk for LCROSS resided primarily in the design effort of "gluing" the components together, as well as general component workmanship issues which are always present. In addition to lowering technical risk, "Glue Missions" also tend to keep cost and schedule risk in check because the simplicity and heritage extensibility makes it less likely extra time and money will be needed to remediate a problem.

VII. MANAGING LCROSS REQUIREMENTS

Given the LCROSS mission success equation with its cost-and-schedule constraints, managing technical capabilities in the form of project requirements became even more important. LCROSS project requirements defined the critical performance metrics of the mission as well as the previously mentioned success criteria.
Although the LCROSS minimum success criteria required *no performance from the payload at all*, the spacecraft pointing performance was still required to meet the minimum mission success requirements of directing the Centaur into the chosen crater, so those requirements were primary. Secondary requirements were those that would achieve *Full Mission Success* for LCROSS. Secondary requirements necessarily involved the payload instruments because Full Success Criteria required the LCROSS spacecraft to perform in-situ measurements determining the presence and quantity of water-ice. Tertiary requirements, then, were those that would be interesting to have, but not required for achieving primary or secondary success criteria.

Thus, the LCROSS mission requirements could be categorized as follows:

Minimum (primary) Success Requirements - needed to assure the impactor is sent into a targeted, permanently shadowed crater.

Full (secondary) Success Requirements - needed to assure the impactor is sent into a targeted, permanently shadowed crater, *and* the LCROSS spacecraft is able to make in-situ water-ice measurements of the ejecta plume.

Extended Full (tertiary) Success Requirements – needed to assure the impactor is sent into a targeted, permanently shadowed crater, *and* the LCROSS spacecraft is able to make in-situ water-ice measurements of the ejecta plume *and* make other interesting measurements related to the ejecta plume.

By prioritizing requirements in this manner, requirements could be cut from the third category, and possibly the second without endangering mission success, should the need arise. For example, if it were determined that the LCROSS Shepherding Spacecraft could not be separated from the Centaur on orbit, all requirements from the second and third categories would be eliminated because the payload instruments would become part of the Centaur impact. However, the mission would still be considered a success even if the entire stack was crashed into the Moon, as long as the Minimum Success Requirements were met and impact took place in a targeted, permanently shadowed crater.

VIII. LESSONS LEARNED

When LCROSS successfully passed its Confirmation Review in which the Project was officially green-lighted to be a flight mission, the LCROSS Project Manager provided a courtesy outbrief to the ESMD Associate Administrator, Scott "Doc" Horowitz. The outbrief discussed LCROSS scope, approaches, and plans. Very interested in the execution of this novel mission, Horowitz made the following request of the LCROSS team in front of his executive staff:

"I want you to take lots of notes as you go through the mission and come back here and brief me on what you've learned over the course of LCROSS. I think there will be much that can be applied even to Class A missions."

Although Horowitz was no longer the AA for ESMD when the mission struck the moon in 2009,the LCROSS Team honored their commitment and briefed ESMD with the following series of top "Lessons-Learned" which were culled from the hundreds collected and officially submitted to The Agency Office of Chief Engineer.

VIII.I LESSON: Embed Mission Operations System (MOS) Staff in Spacecraft Testing

The LCROSS cost-capped mission did not have the budget for a shadow MOS team to be available throughout project development that could then fly the mission and develop all the requisite products required during development. So a novel approach was formulated to make use of embedded NASA engineers at Northrop-Grumman. The first NASA engineer was embeded with Northrop-Grumman during LCROSS spacecraft "FlatSat" testing, when all the avionics were connected together and tested with the flight software. This "Liaison Engineer" did not simply observe activities as if in a mission assurance role. He was there to truly embed with the technical work doing early verification of the flight software and avionics. This approach proved to be so effective that the Liaison Engineer started writing scripts and executing them as a full member of the team, quickly garnering full trust and even accolades from the NG team.

The same approach was taken later in the project when LCROSS entered into spacecraft Integration & Test (I&T) and embedded *another* NASA engineer with the NG team. This engineer also got closely involved in the verification activities, and in doing so, was able to participate in the resolution of integration issues and witness the emerging "personality" of the spacecraft.

While this embedding clearly benefitted the LCROSS Project Manager and Project Systems Engineer by providing a virtual presence in the I&T activities, it also proved to have other benefits when the two embedded engineers became the Flight Controllers for the LCROSS mission. These NASA engineers became the people who issued all commands to the spacecraft and had some of the best understanding of that spacecraft's behavior. Also, when anomalous events did occur, the experience these engineers gained by being embedded with the NG team brought valuable insight to discussion of those anomalies. Of course, the NASA LCROSS Ops team had employed NG in a "back room" capacity for monitoring the spacecraft, but having that first-hand knowledge available in the Mission Ops Control Room proved to be invaluable.

The lesson here is to carefully consider the best application of embedding staff, *within existing budget constraints*. If there are sufficient funds, then a very large MOS team shadowing S/C I&T may be an option. If not, then the careful, thrifty application of skills in the mix of activities can still be very helpful.

VIII.II LESSON: Have Technical Freeboard Somewhere

LCROSS was cast as a Class D mission, which means it can accept more technical risk than other mission types in NASA. So why have "freeboard", a.k.a. extra technical margin? As noted earlier, one of the ways that LCROSS kept its risk in check was by keeping complexity as low as possible while satisfying project requirements. To address the remaining complexity in the design, having technical performance measures which have a fair amount of margin could be invaluable. This extra margin is a commodity that can be used in many different and sometimes unplanned ways during the mission. Extra fuel, power, thermal, or RF link can provide operational degrees of freedom when anomalies are encountered.

LCROSS had "freeboard" margin with its power system. The LCROSS solar array was electrically "hot", meaning it generated much more power than was actually needed to execute the mission. As a result, LCROSS could point as much as 60 degrees off of sun before the power generated by the system was insufficient, or "power negative". This freeboard on electrical power meant not only that the mission could consume more power than planned; it could also be used as an added resource to handle emergencies.

For example, on orbit it was discovered that two of the thruster propellant lines were getting sufficiently cold to be dangerously close to freezing the propellant in the lines, thereby running the risk of a line breach. The root cause of this proved to be related to the location of the heater thermostats. The mitigation option would be to consider re-writing the flight software to trigger the heaters earlier based on thermister feedback, but flight software changes are very dangerous as they break systems verification which can result in unintended consequences elsewhere in the code. Having a power "freeboard", however, meant that instead of changing the flight software code, LCROSS could tolerate being pointed a fair amount off sun, using the sun to heat the thrusters and lines directly. This was accomplished by yawing spacecraft 20[deg] toward the sun which effectively raised the rear thrusters out from behind the shadow of the spacecraft, exposing them directly to the sun's heat. .Although this maneuver caused the solar array to no longer be pointing directly at the sun, the existence of the LCROSS power "freeboard" still meant there were still sufficient power resources for the mission. Additionally, LCROSS had plenty of battery capacity onboard which meant that the hot solar array could store more energy for use in failsafe scenarios where the spacecraft is put into a non-solar facing "drift" state, allowing it to go power-negative to preserve propellant. Having that extra power capacity meant the spacecraft could be in such a state for longer periods of time, providing a more robust recovery.

Another LCROSS "freeboard" area was with its fuel margin. This margin was a product of having made use of an existing tank size which was larger than needed for the mission, but was available (recall the importance of capabilities-driven). This extra capacity proved its worth at least twice during the mission. In one case, the Centaur fill/drain valves leaked more than anticipated and represented a disturbance force to LCROSS which consumed more propellant to offset. In another case, an on-orbit anomaly caused excessive firing of the LCROSS thrusters which consumed considerably more propellant than planned.. In each of these cases, having the freeboard on fuel reserves helped the mission survive.

VIII.III LESSON: TTAYF: Test/Train As You Fly

The mantras, "Test, Test, Test" and, "Train, Train, Train" are good policies because they are the best way to understand both the capabilities and limits of the spacecraft and of the team. Unfortunately, these labor and facility-intensive activities may consume a great deal of financial resources – the cost-capped project's most precious commodity. TTAYF was employed on

LCROSS to attempt to strike a balance between the value of testing and training and the cost of doing so. As a result, LCROSS had to focus on the most meaningful and relevant performance of both the hardware and the people.

Test As You Fly verifies spacecraft functionality in the ways it will be required to perform on orbit. LCROSS could not perform a full suite of qualification testing due to cost constraints, but still needed to ensure that the basic mission was viable. Qualification testing for off-nominal anomaly-handling although nice to have would have to be addressed by the Ops team when anomalies actually surfaced.

Train As You Fly verifies that the Ops team can handle the actual nominal activities of the mission. This training was done first with "Engineering Readiness Tests" (ERTs), and then later with "Operational Readiness Tests" (ORTs). ERTs required all operational functionality be in place to fly the mission (telemetry, commanding, ground station connectivity operator screens complete, etc), but was not conducted in real time. ORTs were the exact same thing, but conducted *in real time*. In fact, they were not only conducted in real time *duration*, but at the real *time of the day*, so that the team could experience carrying a shift in the middle of the night when they might be tired and hungry. The value of the ERTs was that it revealed any technical or procedural flaws with the plan and could be adapted as needed to make sure everything was feasible. The value of the ORTs was that staff had to endure real-time decision-making and mission stress, revealing weaknesses with a small team. Further, during the ORTs, the Test Conductor, who did not have an official console position, would "throw sticks in the spokes" of the operations folks to test their responsiveness. At the end of an ORT, the Test Conductor would discuss all he did to the team, and most importantly, evaluate how quickly they were able to see anomalies he introduced, and in some cases, minor anomalies they never saw. The Test Conductor addition to the ORTs cost only one additional FTE and proved to be invaluable. It was common during an ORT for the spacecraft to lose an Inertial Reference Unit (IRU), or the telemetry would grow stale due to a lost ground station link, or a console location would lose power, etc, etc. The team treated these ORT exercises very seriously as if they were actually flying a spacecraft. Further, since ORTs are run in real time, the operation crew had to react in a timely manner, noting things like a communication pass about to expire and having to deal with potential declaration of emergency to get more time to safe the spacecraft. The operations team definitely benefitted from this type of training when the real mission was flown and real anomalies were experienced.

<u>VIII.IV LESSON: NASA Policy Documents Do Not Cross-Cut Mission Class</u>

The lesson only applies to NASA missions, but it is a critical one. As discussed earlier, the whole Class D premise comes from a NASA Policy Requirement called NPR 8705.4. This document defines, in somewhat vague terms, what it means to be a Class A, B, C, or D mission. LCROSS' approaches with Class D were based in this NPR, and similar NG policy documents.

NPR 8705.4 is helpful in providing a construct, but is somewhat vague, which gives projects and stakeholders some room to tailor their activities – a good thing; however, where the problem surfaces is with the many other NASA Policy Requirements which do not address mission class at all. Good examples are NPR 7120.5 which is the Policy document covering the management of projects and programs, and NPR 7123.1 which is the Agency's Systems Engineering NPR defining technical performance requirements. These two NPRs are critical, foundational NPRs which the stakeholders use to assure that the NASA project is executing to the defined standards of the Agency. The problem of course is that these NPRs apply to missions of all costs, sizes, importance levels, and yes, mission class. Without separate delineation of mission class in these foundational requirements documents, small team Class D projects are carrying the same requirements as much larger Flagship missions. There is the ability to waive requirements, but the process of waiving necessarily comes with the burden of advocating, explaining, and defending the waiver. Unintentionally, these one-size-fits-all rules encumber the small team with adjudication efforts of the stakeholders.

Classification of a mission as "D" is put in place to help it be successful with programmatic constraints, but the reality is that the small team finds itself in the position of having to define/justify Class D activities to multiple stakeholder parties of different views – making more work for the team. The Agency is thus advised to consider creating a lightweight pathway for small satellite / small-team missions which is not overly prescriptive, but offers requirements options that can achieve lower project overhead.

<u>VIII.V LESSON: Risk Tolerant Missions Require Good Risk Management</u>

Perhaps the most important lesson learned by the LCROSS team was that even risk-tolerant missions need to employ good risk management practices to be successful.

Given the cost constraints of mission, LCROSS could not afford to eliminate risk – a goal more appropriately associated with Class A missions where people's lives hang in the balance. For Class D missions like LCROSS, there is simply not enough time or money. So if the LCROSS team could not eliminate risk, what risks should be mitigated and what risks left alone*?* It became apparent that LCROSS required very careful risk management *specifically because* it could accept elevated levels of technical risk. LCROSS Risk Management Boards (RMBs) had to study risk impact/likelihood and carefully trade risks against each other. Although initially thought to be a tedious, long, and encumbering process, RMBs were ultimately seen by the LCROSS team as having great importance. They were never fun, but the team leads were always good with their attendance because they knew they had to strike a balance to meet their own schedule and cost objectives.

An interesting example of this, which occurred in many RMBs, was when a risk mitigation discussion led to *not executing a mitigation.* During a discussion of a payload instrument risk, the engineering team was discussing ways to mitigate the risk with this change or that, adding heaters or making some aspect redundant, etc. when they realized that the risk under discussion was being driven lower than the composite spacecraft risk, i.e., they were assuring the payload was less likely to experience a failure *than the spacecraft that was carrying it!* This was when the team really understood what it meant to be Class D. It meant having a sufficient understanding of the risks to know when to not mitigate and, instead, liquidate, i.e. save the mitigation money and schedule for other purposes. This approach is not easy, but if cost/schedule are independent variables, technical risk needs to managed as the dependent variable.

VIII.VI LESSON: Stable Stakeholder Requirements Are Essential

LCROSS was "decommissioned" with the same requirements set in which it was initiated. Period. The LCROSS team benefitted from having a stakeholder community that was willing to establish a set of requirements they could stand behind and not change. It is difficult to explain how important this is to the executing team. There are many examples, both inside and outside the Agency, where requirements creep by the stakeholders becomes the undoing of the project, leading to its ultimate failure in requirements, schedule and/or budget. Requirements creep usually manifests itself by a multitude of "minor change requests" that slowly disrupt the team's focus and eventually lead to some systems engineering difficulties.

Stable requirements are essential to minimize perturbations to the team momentum. An example came early in the LCROSS mission prior to the Preliminary Design Review (PDR). The LCROSS PM was approached by a senior stakeholder asking to add the capability of two wireless routers from a local high-tech firm to the mission, along with accompanying wireless cameras to be able to demonstrate the first use of wireless routers in space. Although an enticing idea at first, (who wouldn't want to do this!) the team conducted an investigation on what such an implementation would involve and found that while this was not a big tax on any single performance metric, it was a small tax on *nearly every performance metric*. Everything from mass, to volume, to power, to thermal, to flight worthiness, to testing, etc was affected. This "small change", even pre-PDR was not only going to change most everything, it would consume "freeboard margins". Further, it crossed ownership lines since one of these units would have to fly on the Centuar, thereby involving the launch provider's design as well, changing Interface Control Documents (ICDs) growing system complexity. This was a mess. This genuinely clever idea that the team actually wanted to implement, was growing the project risk substantially, distracting the team from the core project objectives. To the stakeholder's credit, they were able to back away from this request.

VIII.VII LESSON: Be Decisive

As noted, the LCROSS Project had an aggressive schedule, so it was essential to be decisive when pivotal project decisions were required. This can make engineers nervous because it often means that decisions must be made before all the information is available.

The LCROSS team found that if they could achieve ~80% confidence on a decisive topic, it was time to make that call and move on. Good engineering judgment will assure that most of those decisions are the right ones, but perhaps even more interesting when they are not. The team evaluated the trade of the time associated with changing course (corrective action after the fact) versus having studied the original decision further and delaying that original decision. Which is the right way to go? The LCROSS team discovered two principles:

- The odds of making wise decisions in the first place are improved by keeping the design simple. The simpler the system, the easier it is to make good judgments about the proper way forward.

- In the choice between making a responsive decision that needs changing later versus waiting for 100% confidence prior to making a decision, it is better to make a decision and adjust course later. The time spent seeking perfect understanding is usually longer than the time of corrective action.

VIII.VII LESSON: Watch Out for that Last 10% of Performance

Augustine's Law #15: *"The last 10 percent of performance generates one-third of the cost and two-thirds of the problems"* [7].

This premise was very much on the minds of the technical and programmatic team on the LCROSS Project. As discussed earlier, the team even experienced this with the requirements creep request for adding a wireless router and cameras to the mission prior to PDR. This was not pushing the state of the art very hard and on the surface appeared a small step forward; but when it was studied closer, such a change affected nearly every technical aspect of the spacecraft design, and even that of the launch vehicle. While technology was not being stretched too far, the degree to which the system design, systems test, systems verification, and mission operations was affected was notable.

Early in this mission, a wise person stated, "This mission is not about maximum performance, but about cost containment" [8]. This is another angle on the same lesson. Design the mission to fit within existing capabilities everywhere you can, and then live within those capabilities.

IX. LCROSS PROGRAMMATIC SUMMARY

The key to capabilities-driven, cost-capped missions like LCROSS is to keep it simple and to manage the risk equation. It is not about eliminating risk, which is very costly. It is about managing risk to a level commensurate with project programmatic constraints. LCROSS did this by making use of existing investments by the Agency, existing commercial hardware, and being sufficiently creative to see opportunities to buy-down risk.

Ultimately, LCROSS succeeded because the individuals and organizations in the LCROSS team walked a shared road on a mission to the Moon and worked together to make it succeed. Each party on this team had both mutual and self-interests for why they wanted to participate. The Agency wanted to show that there was an effective way to make use of excess launch capability and to work cheaply; NASA ARC wanted to show it was able to run small, fast-paced, lightweight missions; NG wanted to show that it could be nimble and carve out a new market for itself; and the commercial sector found an onramp to space and lunar applications which could propel their businesses into a new market. One of the great successes of LCROSS was aligning each the team member's needs into a common purpose which benefited everyone in a win-win-win scenario.

X. REFERENCES

1. Milstein M., "Inside NASA's Plan to Bomb the Moon and Find Water", Popular Mechanics, September 2008.
2. Dino J. and Day B., NASA LCROSS Press Kit, 2009.
3. Colaprete, A., Shultz, P. et al, "An Overview of Results from the LCROSS Impact", LPSC, March 2, 2010
4. NASA NPR 8705.4: **http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8705&s=4**
5. Andrews, D. "LCROSS: A High Return Small Satellite Mission", Small Satellites Systems and Services Conference, June, 2010.
6. Atkins, K., "How to Plan and Manage Reserves Effectively", IEEE Aerospace Conference Proceedings, 2004.
7. Augustine, N., *Augustine's Laws – 6th Edition*, American Institute of Aeronautics & Astronautics, Inc., page 103, 1997.
8. Eller, H., Northrop-Grumman, 2006