LCROSS - LUNAR IMPACTOR:
PIONEERING RISK-TOLERANT EXPLORATION
IN A SEARCH FOR WATER ON THE MOON

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ABSTRACT

The Lunar CRater Observation and Sensing Satellite (LCROSS) was launched with the Lunar Reconnaissance Orbiter (LRO) on June 18, 2009 to determine the presence of water-ice in a permanently shadowed crater on the south pole of the Moon. However, an equally important purpose was to pioneer low-cost, quick-turnaround NASA missions that could accept a higher-than-normal level of technical risk.

When the LCROSS mission proposal was competitively selected by the NASA Exploration Systems Mission Directorate to design, build, and launch a spacecraft in 31 months with a $79M cost-capped budget and a fixed mass allocation, NASA Ames Research Center and its industry partner, Northrop-Grumman, needed a game-changing approach to be successful. That approach was a ground-breaking combination of having a risk-tolerant NASA Class D mission status and finding the right balance point between the inflexible elements of cost and schedule and the newly-flexible element of technical capability.

1. THE LCROSS MISSION PROPOSAL

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 would:

- Confirm the presence of water ice in a permanently shadowed region
- Determine the nature of hydrogen signatures detected at the lunar poles on the previous

lunar missions, *Clementine* and *Lunar Prospector*

- Determine the amount of water, if present, in the lunar regolith or soil
- Determine the composition of the lunar regolith

2. THE LCROSS SELECTION

After a period of evaluation by ESMD and the Robotic Lunar Exploration Program (RLEP), LCROSS was selected (Fig. 2), in a somewhat dramatic "reveal" in Washington DC barely an hour before it was announced at a NASA press conference. Just prior to stepping in front of the television cameras, 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 weight 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.

Fig. 2. The NASA-Ames congratulations banner

After the press conference, Horowitz and Andrews 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 over the next 31 months 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.

3. THE LCROSS SCIENCE MISSION

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.

The *Clementine Mission* [2] was launched in 1994 from Vandenberg Air Force Base in California aboard a Titan IIG rocket. It was a joint project between the Strategic Defense Initiative Organization in Washington and NASA, with the objective of making scientific observations of the Moon, assessing the surface mineralogy, and obtaining lunar altimetry or imagery from a fixed altitude.

The *Lunar Prospector Mission* [2] was launched in 1998 aboard a Lockheed Martin solid-fuel, three-stage Athena II rocket. The *Lunar Prospector Mission* was the third selected by NASA for the Discovery Program. *Lunar Prospector* was managed out of NASA ARC, with Lockheed Martin as the prime contractor. The 19-month mission was designed for a low polar orbit investigation of the Moon, including mapping of surface composition and possible polar ice deposits, completely covering the lunar surface twice a month. Originally, the mission was to have simply ended with the spacecraft inevitably crashing into the lunar surface once it expended all its fuel. As the mission neared its end, however, the suggestion was made to use the crash as part of an experiment to confirm the existence of water on the Moon. The spacecraft was successfully directed into a crater near the lunar South Pole, but the impact plume was not significant, probably due to a poor impact angle and low spacecraft mass.

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.

If water does exist on the Moon, it could have arrived the same way water did on Earth - through billions of years of bombardment by meteors and comets. However, because the Moon's gravity is less than one fifth of Earth's gravity, the Moon retains practically no atmosphere and any deposition on the moon's surface would be subject to direct exposure to both the vacuum of space and daylight temperatures that reach up to 250° Fahrenheit.

In the North and South polar regions, however, the sun never rises above certain crater rims so sunlight never reaches the crater floor. With temperatures estimated to be near -328° Fahrenheit (-200° C), these craters can 'cold trap' or capture most volatiles, such as water.

Fig. 3. ½ litre of water

Given the expense of bringing water from Earth to the surface of the moon (from $15K to $50K for the equivalent of a ½ litre bottle (Fig. 3)), finding water-ice in sufficient quantities in these permanently shadowed craters could result in a compelling rationale for locating lunar outposts in the vicinity of this valuable resource. An in-situ resource like water that could be converted to consumable water, breathable oxygen, rocket fuel, and potentially even used as a means for construction when combined with regolith, or as a shielding means from solar radiation, would make inhabitation and exploration of the Moon a much more achievable future reality.

4. THE LCROSS MISSION

LCROSS proposed to conduct a low-cost, fast-track companion mission to launch with the LRO that would confirm if, and in what form, water might exist in a permanently shadowed lunar crater.

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 another 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.

The Atlas launch vehicle used for the LRO mission consists of a booster stage and the Centaur upper stage. The LCROSS spacecraft would be mounted atop the Centaur with the LRO spacecraft mounted atop LCROSS (Fig. 4).

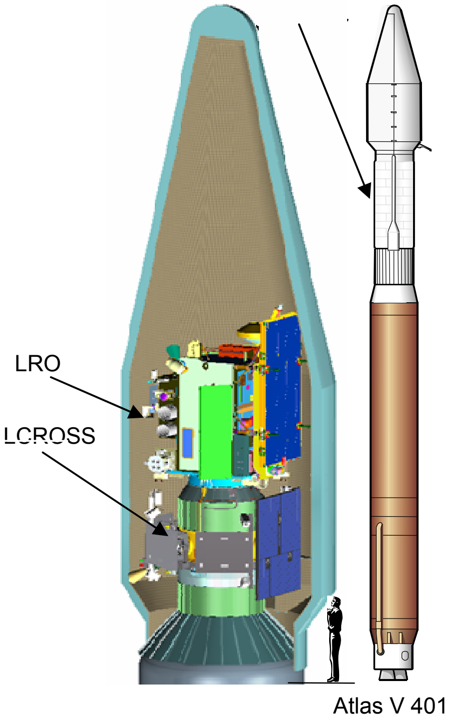

Fig. 4. The LRO/LCROSS launch vehicle stack

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 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, the 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 its target crater selection. In fact, LRO data led to LCROSS changing the impact crater from Cabeus-A to Cabeus. Cabeus had far more relevant conditions related to fundamental water question, but was a much deeper crater. The team knew this crater change would be to the detriment of Earth observations, but it was the scientifically proper strategy for the mission; the team's first priority was to assure scientific/exploration relevance.

During 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. 5) followed by the Shepherding Spacecraft performing a braking maneuver to enable the released Centaur to impact the Moon first. This delay provided time for the Shepherding spacecraft 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 (Fig. 6). 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 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 LCROSS.

Fig. 5. Illustration of LCROSS after separation

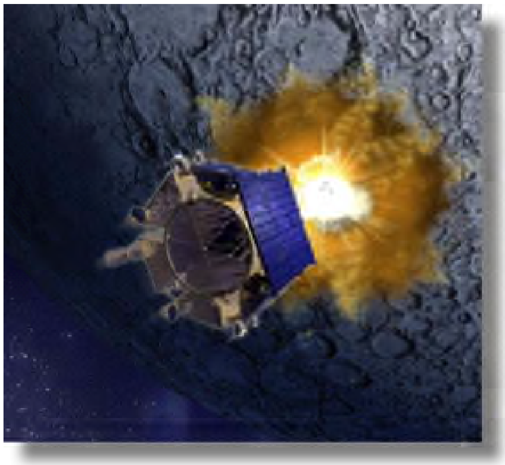

Fig. 6. Illustration of LCROSS after impact

5. 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.

5.1 LCROSS Science

As the impact debris plume rises above the target crater's rim, it is exposed to sunlight and any water-ice, hydrocarbons or organics are vaporized and break down into their basic components. These components are primarily monitored by the visible and infrared spectrometers. The near-infrared and mid-infrared cameras determine the total amount and distribution of water in the debris plume. The spacecraft's visible camera tracks the impact location and the behaviour of the debris plume while the visible photometer measures the flash created by the Centaur impact. Finally, to gather all this instrument data together LCROSS employs a Data Handling Unit (DHU) for transmission back to LCROSS Mission Control.

These instruments were selected to be low-cost, rugged, commercially available components…. in 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.

6. NASA CLASS D MISSIONS

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) [3].

Class A missions, at the risk *intolerant* end of the spectrum, tend to be large, expensive missions, and/or manned spaceflight missions where human lives are put in harm's way. Class A missions are typically formulated with generous technical margins, schedule slack and reserve dollars to address the need for redundant systems and extensive testing to assure requirements satisfaction with reliability – all of which lead to elevated cost.

Class D missions, at the other end of the risk spectrum, 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.

7. LCROSS AS A CLASS D MISSION

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.

The Program Office handled the Level 2 (L2) requirements levied on the LCROSS Project in a similar vein, establishing "Minimum" and "Full Success Criteria" to set priorities if requirements trades had to be made. (Sec. 9) The L2 requirements document specifically listed, by number, the requirements which were Minimum Success criteria, leaving the rest to be Full Success criteria and able to be traded if required. This document effectively told LCROSS Project Management, "if you are forced to start dumping some of your requirements, here's how we'd like you to prioritize them". Achieving concurrence up-front on acceptable ways to make contingency trades saved time and heartache as the mission progressed.

7.1 Class D Challenges

As a Class D mission, LCROSS quickly discovered that although the designation was adequately defined in the cited NPR, there was little or no reference to this risk classification in other NASA policy documents. Further, approaches that the LCROSS team had the latitude to execute, may not have been permitted by other NPRs, effectively driving the mission class higher. As pioneers for the Class D mission designation, LCROSS Project Management soon found that internal contradictions and discontinuities between policy documents were their problems to resolve.

Another issue associated with the Class D risk designation was its extensibility to the spacecraft contractor, Northrop-Grumman. The NASA Class D designation established a performance standard for the execution of the Project, but it was not necessarily in alignment with how the spacecraft contractor could operate. The NG part of the LCROSS team started the process of finding their own equivalent of a Class D approach within their existing, approved corporate processes. Although they were able to find an existing approach that streamlined oversight and approval processes to helped them to come into Class D alignment, it required them to address two important issues: 1) Is a corporate entity willing/able to take the same risks of failure defined by the NASA Class D mission designation and 2) Does this work within their own framework of shareholders? In the end, the answers were the same for NG and ARC. Neither organization came together to manage the LCROSS Project just to see it fail, regardless of mission class. So the LCROSS team had to find ways to keep risk in check while staying within the cost and schedule caps.

One of the burdens being a pathfinder for the Class D mission construct was the need to advocate for new approaches with stakeholders. For NASA stakeholders, LCROSS advocated for approaches that involved tailoring existing policies rather than waiving policies altogether. This approach avoided time-consuming resistance to waiving which leads to stakeholder questions such as, "This procedural requirement is in place because past experience shows that this requirement is a wise thing to do… so justify why you do not feel it is wise for your project"? For NG corporate stakeholders, both tailoring and waiving existing processes had to be employed to gain acceptance, particularly from NG mission assurance organizations. In fact, the NG Project Manager for LCROSS once said, "We had to create a waiver to the waiver process", since he had to overcome the same difficulties as the ARC Project Manager did with NASA stakeholders.

Finally, there was the challenge of integrating the Class D LCROSS mission with the Class B/C LRO and the Class A Atlas launch vehicle. In the end, the lowest common denominator, i.e., least risk-tolerant approach, prevailed, which was counter to the LCROSS context. For example, in the case of structural margins, LCROSS had done some analysis calculations which showed generous margins on natural frequencies of the propulsion tank and the secondary structure. Atlas and LRO concurred that the computed frequencies were good numbers, but wanted additional verification of those numbers which were based only on analysis. Because this level of additional verification was in alignment with the mission risk position for LRO, LCROSS was forced to conduct testing on the structure and propellant tank to verify the analysis. Because the monies expended to satisfy *another mission's risk position* exceeded the LCROSS cost cap, Project Management successfully advocated for the Program Office to pay for the cost of enhanced LCROSS testing.

8. MANAGING THE LCROSS RISK EQUATION

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

Cost Risk + Schedule Risk + Technical Risk = Mission Risk

Although LCROSS had 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.

8.1 Lowering Complexity Lowers Risk

If a system is designed to be low in complexity, extra margin is effectively added to the technical risk element – margin that can be traded if developmental difficulties are encountered later on in the project. For example, if procurement is taking longer than planned, thereby increasing schedule risk in this schedule-capped mission, that risk can be reduced by reducing the unit-level testing that was originally planned. While not testing at a unit level runs the risk of problems not emerging until box-level testing occurs, if the system is of low-complexity, the risk of that occurring might be worth the trade. If that unit-level device has been proven on a previous mission and is being re-used in the same way as on that previous mission, the risk may be small. If the card in which testing is reduced is easily removed/replaced from the avionics box, making a later discovery of a problem would not represent a large problem and thus, may be worth the trade. Alternately, you might continue with all the unit and subsystem level testing, but reduce the degree of integrated systems testing to a minimum to recover schedule. A lot of judgment is required to make these trades, and there is technical risk. The key is to find ways to keep that risk in check, even in a risk-tolerant environment.

8.2 Capabilities-Driven Missions Lower Risk

Keeping 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. Someone once said, “We want it all, but we know we need appetite suppressants” [4]. 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 [5] 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.

8.3 “Glue Missions” Lower Risk

By using and “gluing together” already-proven hardware, software, and proven 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 makes it less likely extra time and money will be needed to remediate a problem.

Payload Glue: LCROSS was conceived using Commercial Off The Shelf (COTS) instruments from various vendors best suited to meet the mission needs. When COTS instruments are used, however, the issue of getting all the instruments to successfully communicate with the spacecraft avionics inevitably arises. The visible camera vendor for the LCROSS payload had an interface unit which enabled a number of their cameras to be connected to a single interface point, and was a standard product. If the cameras and instruments from other vendors could be configured to interface with this unit as well, LCROSS could avoid the risk of developing custom, flight-ready blackbox solutions for each instrument, thereby saving both development effort and risk. In the end, the other instrument vendors were able to deploy an RS-422 interface option that enabled their units to work with the visible camera vendor’s single-point data handling unit. Once the instruments were “glued” to the data handling unit through the use of a common RS-422 data format, the data handler was “glued” to the spacecraft avionics through the use of another standard data protocol – again saving untold hours in development and in-flight suitability testing.

Spacecraft Glue: In science-driven missions, the development of a spacecraft bus frequently involves a custom design tailored to the particular needs of the mission – a labor-intensive effort that also requires costly verification for flight suitability. In the capabilities-driven LCROSS mission, an existing, proven piece of hardware called an ESPA (Evolvable Secondary Payload Adaptor) (Fig. 7) ring, which was already designed for flight on the launch vehicle, was chosen to be the basis of the LCROSS spacecraft bus.

Fig. 7. The LCROSS ESPA ring

Originally designed to carry multiple secondary payloads at six circular ports around the perimeter of the ring while simultaneously supporting the loads from a primary payload mounted on top, the ESPA ring’s purpose was to make use of excess launch capability for multiple secondary payloads. LCROSS, however, was the first to use this standardized capability to develop the backbone of an entire mission, using the ports to mount various elements of a single spacecraft. One port supported the solar array; another port supported the battery panel; another port supported the payload instruments, etc. (Fig. 8).

Fig. 8. The LCROSS ESPA with secondary panels

The standardized ESPA hardware provided the “glue” to connect the primary and secondary mission payloads together without the need for costly customized systems or components. As an added bonus, using the ESPA ring resulted in a more resilient assembly process for LCROSS as each of the panels could be worked-on independently.

Fig. 9. LCROSS Mission Operations control room

Mission Operations Glue: Traditional spacecraft control rooms are expensive operations, filling large rooms with wall-to-wall people and monitor screens. To stay under the cost cap, LCROSS had to find a different approach, so a humble control room with a series of personal computers was set up and “glued” together over a local secure network (Fig. 9). Not flashy, but fully functional, the LCROSS Ground Data System (GDS) ran the same software that was used During Integration & Test to leverage training and investments made earlier in the project.

9. 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 very important. Secondary requirements were those that would achieve *Full Mission Success* for LCROSS. These 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 Success Requirements - needed to assure the impactor is sent into a targeted, permanently shadowed crater.
- Full 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 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, all requirements from the second and third categories would be eliminated because the payload instruments would become part of the 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.

10. MANAGING CAPABILITIES-DRIVEN MISSIONS

With the list of mission requirements clearly prioritized, LCROSS implemented the previously discussed Design-to-Cost process using existing capabilities. COTS instruments were sought for payloads. Although flight-proven instruments were preferred (the visible camera was flight-proven), well-established instruments from the commercial or industrial world that were already ruggedized to improve the feasibility of use in a space and launch environment were accepted. Those instruments were subsequently tested in relevant environments (vacuum, temperature extremes, vibration, etc.) to see if the units could withstand anticipated mission conditions. Instrument vendors, interested in opening new markets for their products and happy that such rigorous use-testing was being funded by the government, were cooperative in upgrading their products when issues were discovered. For example, one instrument failed because a screw came loose during vibrational testing. It was discovered that no adhesive had been applied to the screw threads to help secure the screws in a dynamic load environment. Once adhesive was applied, the device passed testing and was accepted for use. In another case, a cable came loose inside an instrument because the cable was not staked-down to help reduce the length of unsupported cable experiencing the loads of a launch environment. This, too, was easily remedied.

The final suite of LCROSS instruments included a thermal camera (MID-IR1) used in motorsports applications, Near-IR spectrometers (NSP1 & NSP2) used in beer-making and carpet fiber analysis for assessing recyclability, UV visible spectrometers (UVS) used in standard bench-top laboratory equipment, a visible camera routinely used in shuttle launch imagery, and Near-IR cameras (NIR-cam) used in fiber optic communications applications. All of these were existing hardware that was repurposed for the LCROSS space mission.

To employ existing capabilities for the LCROSS spacecraft, well-proven, flight-demonstrated hardware was chosen, some of which was even re-purposed. The best example of this was the previously described ESPA ring, originally designed to mount between a launch vehicle and spacecraft it is carrying, but used by LCROSS *as a spacecraft structure*. Avionics, batteries, propellant tank, thrusters, transponder, and other equipment - all proven on other missions – reduced the risk/uncertainty of performance on LCROSS. Along with proven capabilities came improved cost risk. By using existing hardware, cost risk remained in check. When existing designs are altered, development risk - and the cost for covering that risk - increases.

By employing capabilities-driven management, LCROSS adhered to the Design-to-Cost process and was able to meet all cost, schedule, and technical capability mission requirements.

11. DESIGNING-TO-COST USING RESERVE MANAGEMENT

If design risk can be combated by applying quantified "reserves", then assessing a design's heritage is critical in understanding how the reserve position should look. [5]

- Existing designs: 5-15% reserve. This choice covers the residual risk associated with any particular instantiation of the design. It may be used exactly as it was in another application, but it is still is a new application.
- Modified designs: 15-50% reserve. This choice accepts that the design is charting new territory. While the basis for the design may be proven, uncertainty and new risk is being introduced with the modification.
- New designs: 50%-100% reserve. This choice the most difficult to assess because there is little to no basis for the design. It is largely a new construct, and depending how complex the system, could be carrying moderate to significant cost and schedule risk.

The LCROSS Project, at selection, carried a starting reserve position of ~15%, which is small by NASA metrics, but well-aligned with the "existing design" category – an approach LCROSS wholeheartedly adopted. By choosing this risk reserve category, the LCROSS team understood that tackling a new design would be an unacceptably risky venture.

It is important to note, however, that while the project is carrying reserves to address risk, it is not there to support requirements creep or design enhancement. Risk reserves exist to address unknowns in the risk position so unanticipated risks that emerge during the project can be accommodated without adversely affecting either cost or schedule.

Mission risk reserve can be monitored throughout the project by determining the "Cost-to-Go" (CTG) at any given time. The CTG is the amount of reserve remaining compared with anticipated reserve expenditure. There are many different standards to manage to, but 10% - 30% were the thresholds LCROSS employed to strike a good balance between financial concern and reserve expenditure opportunity. The strength of using a CTG metric for making decisions is that it is derivate, so problems can be anticipated in time to change a risk position.

LCROSS grew its CTG reserves position in the first half of the project lifecycle by refraining from dipping into the reserves which automatically makes the CTG reserve position grow over time. When the CTG exceeded 30%, additional activities that would buy-down risk somewhere were considered, such as performing additional spacecraft testing, but only as the schedule margin position would allow. Near the end of the project, the CTG was allowed to hover in the teens because a fair amount of risk had been retired by then getting through spacecraft Integration and Testing (I&T), but was never allowed to drop below 10% until the endpoint was in sight. The history of LCROSS CTG management can be seen in Fig 10.

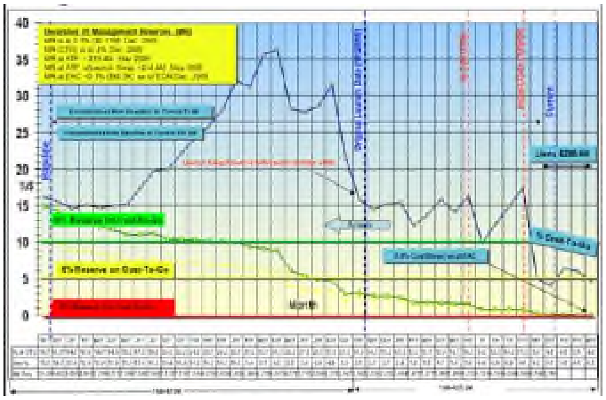

Fig. 10. LCROSS Cost-To-Go chart

At the end of a project where the remaining work is getting small and the reserves position is also getting small, the CTG calculation becomes less useful. The denominator in the calculation starts to become a small number which can cause the CTG% to vary widely. At this point, LCROSS simply managed the remaining work, assigned values/liens to that work, and then carefully managed the remaining reserve to a declining percent through project close. Using the CTG% chart (Fig. 10) was a very powerful way to understand where the project stood, financially, on a monthly basis.

12. 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.

13. REFERENCES

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