Lightning - Apollo To Shuttle

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ABSTRACT

The lightning discharge that struck the Apollo 12 spacecraft thirty-six seconds after launch pointed up a whole series of problems that called out for answers if the Manned Space Program were to proceed with minimum impact to future missions and the crews that would fly them. This paper traces the history of lightning study by the Kennedy Space Center from then to now with particular emphasis on the potential problems that may arise in the process of getting ready for and carrying out the Space Shuttle Program.

LIGHTNING - APOLLO TO SHUTTLE

The experiences of the Apollo Program with lightning strikes at the Kennedy Space Center began with very little formality and with almost no lost time. On May 25, 1966, the first Apollo vehicle rolled out of the Vehicle Assembly Building. This was the 500F proof-test vehicle - a full-scale mockup of a Saturn V moon mission vehicle mounted on the Mobile Launcher and identical in size and weight to the real thing. Its purpose was to provide a full dress exercise of the Crawler and to validate the facilities at Pad A of Launch Complex 39. The rollout was a success, and the vehicle was on the pad as of that afternoon. Two days later, May 27, 1966, the Launcher Umbilical Tower (LUT) on the Mobile Launcher (ML) took a strike. The hook on the hammerhead crane on top of the LUT began dropping in free fall as its brakes let go, and struck the side of the second stage. The damage was not severe, but the Apollo/lightning interface had begun. Examination showed the brake drum solenoid contacts welded open.

The lightning protection design for Apollo had been adopted after consideration of many concepts for protection of the vehicle during rollout and while at the pad. The concepts examined covered almost every possible approach: masts along the crawlerway, balloons carrying grounded wires, balloons carrying lightning rods, kites, folding screens enclosing the flight vehicle until launch time, towed structures carrying shielding enclosures that moved back for launch, telescoping shrouds mounted on the LUT, removable grounded shrouds mounted above the vehicle - the solutions were literally legion. Each one was looked at carefully for the protection offered, cost, operational practicality, ruggedness, and safety. Nothing was considered "crackpot" at this stage. Every solution was given the same screening. The final choice was, as nearly always, compromise. There were concepts that offered better pad protection than the one selected, and concepts that offered better rollout protection, but none that cost less or that did both jobs any better. The design consisted of a folding mast (to allow access in and out of the VAB doors) mounted on top of the hammerhead crane on top of the LUT, with a lightning rod on top. The assembly extended above the vehicle sufficiently so that a lightning stroke would terminate on the lightning rod and not strike the vehicle itself. This concept is known as the 1:1 cone of protection: as long as the mast is higher above the tip of the vehicle than it is displaced from it horizontally, the 1:1 concept is satisfied. Historically, the 1:1 cone of protection provides an almost perfect protection umbrella from lightning striking anything under it, and it proved so in Apollo - no flight vehicle was ever struck on the pad, although the LUT itself was struck many times. When this occurred, the strike current passed from the lightning rod down the mast structure, past the hammerhead crane through wiping shoes (that allowed crane movement) and through the welded LUT structure and Mobile Launcher to ground. The whole pad area had an elaborate buried ground counterpoise of many copper cables, and at the pad the Mobile Launcher was connected to it by ground jumpers on each of the six outer pedestals that supported the Mobile Launcher. There were, in addition, many other ground paths from the structure by way of hyper-golic lines, fuel lines, and the multitude of other installed paths that exist when a moon rocket is connected to its ground support equipment for checkout prior to launch.

There was no lightning instrumentation on the LUT for that first rollout, but by October of 1968, for the first manned Saturn V (Apollo 8) rollout, magnetic slugs (to record peak stroke current) and a lightning stroke counter had been added to the lightning mast above the LUT's crane. The pad was under TV surveillance, but the video was not recorded.
Apollo's busiest launch year was 1969. Five vehicles went to the pads in that twelve-month period. There had been no strikes since the first one in 1966, but in 1967 and 1968 the pads were empty during the summer storm months, and no LUT's had been there to be targets. This was not the case in 1969, but even so, no strikes to the complex were recorded. Apollo 11 took off on July 16 for its moon landing after being on the pad for substantially the full 1969 storm season, but it took no strokes.

This period of bliss disappeared abruptly on November 9, 1969, when Apollo 12, thirty-six seconds into its flight, triggered a cloud-to-ground stroke that momentarily put the spacecraft's guidance system out of commission. The booster's guidance system, in command at this point of the mission, was not disrupted, and the mission continued. It wasn't a strike on the pad, but the distinction didn't really amount to much; from that day forward the Kennedy Space Center became lightning conscious.

The year 1970 was a repeat of 1967 and 1968 in that there were no launches during the summer months:- Apollo 13 was launched on April 11 and Apollo 14 did not rollout until November 9. There were no known strikes that year.

(The Mobile Service Structure, almost as tall as the LUT, had been at its parksite south of the pads since 1965 when it was not on the pad for checkout. It had magnetic slugs mounted on the various lightning rods that protected its vent stacks and extremities but their locations were almost inaccessible and they had not been serviced regularly because of the hazard to servicing personnel. Although it is possible that it had been struck at the parksite, there was no valid data to support known strike activity.)

In 1971 the picture changed drastically. Storms delayed Apollo 14's launch on January 31, but it was rainshowers, not lightning. Apollo 15 went to the pad on May 11 and was launched on July 26. Its stay on the pad nicely spanned the lightning season, and in this two-month stretch, lightning hit the complex on six different days:- June 14, 15, and 25, and July 2, 19, and 21. The first strike, recorded at 98,000 amperes, vaporized the top three feet of the LUT lightning rod and blew the face off the stroke counter. The 1971 storms were severe, and the three June storms caused damage to ground equipment. Examination revealed some cable shields that had not been properly grounded, allowing induced voltages to be fed into the electronics and overload them. This was corrected, and the last three strike days (in July) saw no damage. The launch went on schedule.

(The is no way of knowing for sure how many times the complex was struck during those six days. A single lightning flash can include anywhere from one to fifteen discrete strokes, of varying polarities, magnitudes and durations. Magnetic slugs show only the aggregate of the stroke current magnetic fields they have been exposed to, and the stroke counter could not be relied on to resolve every separate stroke - its reaction time did not exceed 0.1 seconds even when working. In those six strike days it is not inconceivable that the complex may have taken forty to fifty separate lightning strokes.)

The year 1972 again had vacant pads during the summer; Apollo 16 launched April 11, and Apollo 17 was on the pad from September 13 through December 6. There were two strike days in March, the 5th and 31st. No damage resulted.

The lightning mast from Pad 34 was mounted on the MSS in 1972. Wide and deep as well as tall, much of the MSS was not inside the 1:1 cone of protection of the LUT's lightning mast and was subject to being struck at almost any point on its upper surfaces. The mast gave it a single preferred attach point for a stroke. This permitted accessible instrumentation to be mounted and also provided the flight vehicle on the pad with protection from an additional 1:1 cone.

(The tip of the MSS mast was 25 ft. lower than the LUT mast and 130 ft. south of it when the MSS and LUT were both on the pad during checkout. This, of course, left the MSS mast as a secondary strike point, and as experience showed, it did take a few low-energy strikes which came in from a generally southerly direction. The stronger strokes invariably went to the LUT mast.)

The storms of 1971 had taught two lessons:- improve instrumentation, and pay attention to indirect lightning effects. Strike current that went down the LUT mast to ground didn't go just through the LUT. Some of it went across the swing arms and to ground through the skin of the vehicle and even NOO structures. This did no direct damage to the bird, but the current in the arm structures induced voltages in the umbilical cables leading from the LUT to the vehicle. Some of these cables ran for part of their lengths along the tops of the arm structures and were thus exposed to the maximum induction fields set up by the stroke current flowing in the swing arms. An analysis revealed that 31.6% of the total current from a stroke to the LUT of a Skylab/ASTP configuration would flow across Swing Arms #8 and #7, which carried the umbilical cables which led to the spacecraft's guidance system, and the cables going to the Instrument Unit mounted on top of the S-IVB third stage and containing the booster launch guidance system.

To monitor these effects, peak reading voltmeters were installed to record the voltages on selected cables that ran across Swing Arms #6, #7, and #8. This was done for Apollo 17, but no data was gathered because Apollo 17 took no strikes during its time on the pad. The system was then carried over into 1973 and the Skylab Program.

Instrumentation on the pad was not the only lightning measuring done. Operations on the launch pad involved many people working on,
around and with tall metal structures, liquid and gaseous oxygen, large volumes of volatiles and combustibles, cryogenics, hypergolic fuels, and pyrotechnics. This carried a large danger quotient if the hazards of a thunderstorm were ignored. To this end KSC had, in 1965, commenced the installation of a wide area network of thunderstorm monitors to report to a central weather office the existing potential gradient of the atmosphere above each monitor instrument. When high readings began to appear, indicating a rising electrification of the air, the weather office was able to issue an adverse weather warming to the operating areas so that the proper safety measures could be taken before bad weather arrived. This network, constructed in phases, consisted of twenty-five monitoring stations spread over almost a hundred square miles by the time Apollo 11 rolled out in May of 1969. The original Sweeney instruments were phased out in favor of rotating field mills, and by the end of 1972, steps were in process to present the output of the field mills in the weather office as an integrated display.

The year 1973 opened with a known heavy launch schedule for the Skylab Program. Pad B had been refitted to handle the Saturn IB vehicle to be used as astronaut carriers up to and back from the lab, and there were exactly eighty-five days in the year when vehicle checkout was not in progress on the pad. Lightning coverage of this program was comprehensive. The field mill network was in full operation. The KSC Weather Office had a new experimental X-band weather radar that could probe developing cloud masses for glaciation and precipitation levels to help in the task of predicting thunderstorms. The pads were under surveillance by three lightning-triggered fish-eye lens cameras that photographed the entire sky and by the operational television system that put selected cameras in a video recording mode when an adverse weather warning was in force. Instrumentation coils sensed any stroke current that appeared in the Mobile Launcher and MSS pedestals and current sensing coils had been mounted on the ML and MSS lightning masts just below the magnetic slugs. Lightning induced voltages were monitored in thirteen selected circuits whose cables ran across the upper sensing arms of the LUT, with control readings to winnow out powerline surges.

The 1973 storm season did its part. Multiple stroke flashes hit both Pad A and Pad B on May 9. The Pad A strike, where the Skylab itself sat on a moon configuration booster, was 36,000 amperes to the LUT mast. The Pad B stroke, 76,000 amperes, hit the astronaut’s safety slidewire about halfway out its 2200 ft. length. On May 24, a 4,100 ampere single stroke hit the MSS mast. No damage anywhere and the Skylab 1 and 2 launches went off on May 14 and 24. Skylab 3 went to the pad on June 11, and got slapped hard on June 17 when a severe storm sat above the pad for over an hour. Multiple strokes were recorded to both LUT and MSS. The maximum stroke magnitudes were above the 100,000 ampere (saturation) level of the magnetic slugs on the LUT, with a 64,000 ampere peak on the MSS. The mast-mounted coils did not provide reliable data; the coil output leads running down the lightning masts of both LUT and MSS were picking up induced voltages that invalidated the readings. Induction-proof output leads were needed, a difficult task when the leads ran within inches of 100,000 ampere plus pulsed currents. The June 17 strokes were not severe enough to damage the sensitive on-board instrumentation signal conditioners which were mounted close to the skin of the vehicle, but repairs did not delay the launch on July 28.

The MSS had two strike days right after the launch. A 57,000 ampere multiple stroke was recorded on July 29, and three separate flashes containing a total of nine strokes occurred on August 1. This last gave a good illustration of the weakness of magnetic slugs as recorders. The peak magnitude recorded by the slugs for August 1 was 4,200 amperes, while the peak sensing coil recorded 200,000+ amperes. The coil reading was admittedly not valid by previous experience, but the difference shows that the slugs did not record the actual peak magnitude. Obviously there had been polarity differences in the nine strokes.

Skylab 4 showed again the importance of high integrity in the overall shields of cables that are exposed to the induced effects of lighting currents. A multiple-stroke 100,000+ ampere bolt hit the LUT on August 15, a few hours after its arrival on the pad after rollout on August 14. All the cabling changes to pad configuration had not been completed, and a temporary cable on Swing Arm #8 was still connected into the Command Module with its shield grounded only at one end. Damage occurred in the Inertial Measurement Unit blower motor control system, and again some of the more sensitive instrumentation signal conditioners mounted near the skin were affected. Repairs did not delay the launch on November 16.

The lightning and weather encountered in the Apollo and Skylab Programs prompted a thorough study of the adverse effects they might impose on the Apollo Soyuz Test Project. This mission had to work with unusually narrow launch windows that were dictated by the orbital requirements for rendezvous and docking with Soyuz, and it was scheduled for launch on July 15, the middle of KSC’s thunderstorm season. Weather that did not fall inside the limits given by the Launch-Mission Rules, or retesting required because of a lightning stroke that occurred late in the count, could scrub a launch and jeopardize the mission. A series of tests was performed at KSC on the Command and Service Modules and on the Saturn IB booster stages to determine what induced currents could be withstood safely and to provide an analysis of where the Launch Mission Rules might be revised to help assure an on-schedule launch. Full scale tests were conducted in which
simulated lightning strikes were fed into the stages and the induced voltages monitored.

At the same time, a design effort was begun to come up with a lightning protection system for the pad that would eliminate or minimize the induced effects that had been noted during Skylab. This meant either eliminating lightning strikes completely to the LUT and MSS or minimizing the flow of stroke current in the LUT swing arms. Studies were made to evaluate various methods of preventing lightning strokes from hitting the complex. It was obvious very quickly that any proven solutions would be very expensive, and attention turned to reduction of the swing arm currents. The design modification settled on involving replaced the folding metal lightning mast in the LUT with an insulated mast which would support an overhead wire running over the mast and to ground out 1000 ft. on each side of the pad. Strike current would go through the wire, not through the LUT structure, and there would be no stroke current flow across the swing arms. The overhead wire was oriented to be at 90° to the swing arms, minimizing any induced currents in the arms from the strike current in the overhead wire. The mast was made tall enough (80 ft.) to hold the wire at least 50 ft. from the nearest grounded metal portion of the LUT to prevent arc-over from the wire. Laboratory tests showed this design would reduce the induced voltage in the most sensitive swing arm to 4% of the Apollo/Skylab configuration, and would afford as good or better direct stroke protection to the vehicle. The instrumentation that had been on the old folding mast was removed and installed at each end of the overhead wire, thus making two identical sets. At each station, the peak sensing coil output was converted to light energy and taken back to the readout instrumentation by fiber-optic light pipes, which are not sensitive to heavy induction fields from stroke current. The magnetic slugs were retained and a second sensing coil installed. This coil was a special di/dt coil, sensitive to rate of change of current rather than current value. Both peak and di/dt coils fed separate transient analyzers, which reconstructed and read out the stroke's waveform as well as its magnitude. This permitted the analysis of the strike for duration and rise time as well as magnitude, and better intelligence of what damage (if it occurred) was actually due to.

The instrumentation was mocked up in the VAB and tested in the same kind of tests that were used to determine the sensitivity of the CSM and the S-IB booster to simulated lightning. The simulated lightning tests conducted in 1974 at KSC showed that both the CSM and the S-IB were subject to large induced voltages in their cabling from a strike. This emphasized the importance of protection from induced effects on the pad, and good knowledge of the electrification of the air over the pad at launch time, particularly at higher altitudes.

There were no manned launches in 1974, and consequently the only tall structure on the pad at LC-39 was the MSS. It was used as a test bed to investigate the possibility that dissipation arrays might have some effect on the frequency or nature of lightning strokes, and several configurations were erected on the MSS and monitored. Another array was mounted on a 500 ft. AFS tower about 3-1/2 miles northwest of the pad. After two years of observation (1974 and 1975), there is some data that suggests that the arrays may have an effect on the ratio of positive to negative strokes that hit, but it is far from conclusive. There is no indication of any effect at all on the frequency of strikes; both structures took hits in both years, five on the MSS and four on the weather tower. Peak magnitudes ranged from 18,000 amperes to 80,000 amperes.

During 1975, there were three noteworthy launches - the Apollo-Soyuz mission and two Viking unmanned launches to Mars. Both projects had launch constraints. The Apollo launch, made with the Soyuz spacecraft already in orbit, had launch windows measured in minutes and only the first two could be missed without seriously limiting the mission's objectives. The first Viking lander was to touch down on Mars on July 4, 1976, as a Bicentennial event, which put a cutoff on launch date slips. All would launch in the summer, during the normal thunderstorm season. Plans were made for instrumented aircraft to monitor the air electrification at various altitudes on launch day for all three launches. This, in conjunction with the ground field mill readings, would permit the weather office to make the best possible launch weather forecasts. In this connection, the weather office had two new tools to work with in 1975. In the past, the field mill readouts in the weather office were printed out individually on strip charts and the data had to be hand correlated by weather station personnel. An improved presentation concept had the outputs of all 25 ground field mills computerized and presented to the weather personnel as an integrated display on a TV screen which showed the whole KSC area with the field mill data plotted out in lines of equal potential gradient. This display was updated each minute and gave a dynamic, overall picture of the size, growth and movement of the charge centers over the entire launch area.

A second development was the Lightning Detection and Ranging (LDAR) system, a KSC development following early work by Dr. E. T. Pierce of Stanford Research Institute. It senses and plots RF emissions in the 30-50 MHz range. These emissions are apparently associated with atmospheric discharges and the LDAR plots them on a TV display in altitude, azimuth and range. The system is still in development, but it has shown some good correlation to the charge centers plotted by the field mill network. It stands to be a good lightning locator and plotter, particularly for storm activity outside the range of the field mills.
The ASTP Apollo rolled out on March 24 and lifted off on schedule on July 16. The late-in-count strikes which could have been a problem did not materialize, nor were there any thunderstorms in the near vicinity of the pad to threaten a launch hold. KSC's weather had been kind to the Apollo Soyuz Test Project - in some respects too kind. It had been hoped that the weather would give the mast and wire design and its instrumentation a good enough workout to prove that it truly would reduce the induced effects of a strike the way its laboratory tests predicted. As it was, the new mast and overhead wire pad protection design was struck four times in 1975. The first two occurred three minutes apart on May 14, with too low a peak magnitude (<10,000 amperes) to register on the wire-end instrumentation. Television pictures of both flashes showed that both were low energy, single strokes. A 35,000 ampere stroke hit the overhead wire on June 9, and a 100,000 ampere stroke to the LUT mast occurred on July 20. This last stroke came with the LUT still on the pad but five days after the launch. It was recorded and measured by both coil systems and the magnetic slugs with good agreement, and this did demonstrate the validity of the wire-end instrumentation under actual conditions.

During the full stay of the vehicle on the pad, the peak reading voltmeters monitoring the critical circuits on Swing Arm #7 had been monitored carefully; their readings were the criteria for determining whether retest would be required after a strike. None of the first three strokes caused any detectable current induction. The last stroke yielded no valid induction data since, after the launch, the current path across the arm down the vehicle skin and the MSS to ground was not there.

The Viking I and II launches had lightning problems of their own. A stroke to ground is believed to have been responsible for a surge in one of Viking I's control circuits that caused a partial switch closure in the payload that prematurely drained a flight battery, requiring a payload changeout before launch. Viking II, however, gave proof that the airborne charge measurements planned to be made in the face of marginal weather had measurable operational value. A storm moved into the vicinity of Viking's launch complex as the count approached T-0. According to conventional conditions it was a "launch hold" situation until the storm moved out of the area. The aircraft readings, however, showed that the storm's charge centers were moving more slowly than predicted. This was relayed to the launch director, and Viking II lifted off on schedule. Five minutes later the pad was in heavy rain and the storm did not clear the pad before the launch window would have closed.

Investigating other possible means of preventing lightning, an experiment was run following the ASTP launch that involved the seeding of selected thunderstorms with conductive chaff from aircraft to ascertain if this would diminish lightning occurrence, and if so, what seeding procedures gave the best results. The National Oceanic and Atmospheric Administration (NOAA) had done some preliminary study in this area that showed promise. The experiment showed that a different seeding technique would be required for Florida storms than was used in the western mountain storms that NOAA had studied earlier. Florida storms have their freezing level well up inside the cloud mass, while mountain storms have their lower down, toward cloud base, and for the seeding to be effective, it must be done so that the charge is drawn into the freezing area. In Florida this means penetrating the storm with the aircraft - seeding just under the clouds is insufficient. That can be hazardous, and needs to be studied in more detail. NOAA plans to continue investigation of chaff seeding at KSC during the summer of 1976 as part of Thunderstorm Project II, the nationwide study being conducted over the next three years by the scientific and academic community to investigate the electrical properties of thunderstorms. This effort should result in a much fuller understanding of how thunderstorms tick. We hope to learn what properties must exist before lightning comes into being, and how charges in the air and in various cloud formations relate to the instrument readings probing that same area from ground level. Hopefully in the future, the possibility of lightning in a storm can be predicted before the storm develops, and the storm's development and growth charted well ahead of the actual thing. The Shuttle is to be an operational vehicle, and routine launch operations at present planned launch rates will need the best weather knowledge and predictability that is available.

The insulated mast and overhead wire is the baseline design for lightning protection of the Shuttle while on the pad, so the instrumentation and lightning protection developed for ASTP will carry over and be the lightning system for the Space Shuttle era. The mast will be permanently mounted on the Shuttle Service and Access Tower. The stainless steel overhead wire will be oriented north and south instead of ASTP's east and west, but will extend out approximately the same distance.

The Shuttle, with its sophisticated electronics, stands to be particularly vulnerable to lightning and design criteria point specifically to protect against harmful lightning effects were drawn up by a lightning task team early in the design phase. Special attention is being given to cable shielding and to the levels of transients that equipment will be able to withstand without disruption or damage. The Orbiter will undergo an extensive test before it comes to KSC in which it will be subjected to full-strength simulated lightning entering and leaving the vehicle at various points. There is a development program in work at KSC that takes toward deliberate triggering of a natural stroke to the Service and Access Tower, thus permitting the determination of induced effects on ground support equipment, and measurement under controlled conditions of any induced effects that could affect critical
equipment placement or be transmitted from the complex to the vehicle through checkout cabling. All the electrical leads from the ground leading into the Shuttle will interface with the flight vehicle as close to the Mobile Launcher Platform as possible, to eliminate the high current induction of the Apollo configuration.

When the Shuttle lifts off Pad A in 1979, it will be a lightning-proofed vehicle launched from a lightning-proofed complex. Jove's thunderbolt will undoubtedly be with us for many years to come, but not as the mystery it has been in the past, and the Manned Space Programs will have done their share toward drawing the veil.