Decommissioning A Geosynchronous Satellite

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I. Abstract

Due to factors relating to normal satellite degradation or unexpected anomalous conditions, a satellite will be taken out of commission and placed in a storage mode and eventually powered OFF. Performing end of life (EOL) testing and decommissioning activities require strategic planning. This is to ensure that the satellite can be powered OFF and meet the guidelines to decommission.

II. Background

At the end of a satellite's design life, the satellite can either continue on with its mission, be placed in storage at a higher altitude orbit, or be decommissioned. Most likely, the satellite will continue on with its mission until a replacement satellite is launched and placed in that slot. At that time, the older satellite will be placed in a super-synchronous orbit and be commanded into a storage mode. A satellite in storage mode could mean several things, but generally, the satellite will not be performing its mission and it will not be transmitting radio frequency signals. The satellite will still have the capability to receive commands and able to perform its mission in the event that the satellite can be used as a replacement or for added capabilities in a constellation of satellites.

A satellite will also be placed in the super-synchronous orbit due to normal degradation or due to an anomaly that limits the satellite's capability. The most likely cause would be depletion of fuel. A satellite is designed to carry enough fuel to last through its design life plus enough to move it out of its orbit. At a geosynchronous orbit, it is more economical to place the satellite into a higher orbit, usually a couple hundred kilometers above geo-sync. Long term monitoring of fuel levels, based on pressure and temperature, will allow operators to predict when to place the satellite into super-sync. Of course, any anomaly that results in the fuel levels to decrease rapidly will hasten this trend and quite possibly require sudden actions to raise orbit if the anomaly is severe enough.

Another likely scenario that will result in super-syncing a satellite would be loss of mission capability. Again, depending on the severity of the anomaly, the satellite would either continue on with mission, be placed in storage at super-sync or be decommissioned after being super-synced. There is a slight chance that with the loss of mission capability, the customer will choose to keep the satellite in storage at the super-sync orbit to perform longevity studies on the satellite or further testing that can provide insight to other satellites in the constellation or for future builds. The most likely scenario would be to decommission the satellite since the purpose of any satellite is to perform the mission it was designed for. Loss of mission capability includes loss of the payload or payloads, loss of power to the payload, loss of the ability to transmit mission data, loss of the ability to maintain mission attitude.

Once in super-sync and in storage mode, the extended life of the satellite can last for years, even lasting as long as the original design life. This is due to minimal use of fuel and most equipment in an off-state or a safe-state. At this stage of a geo-satellite, the decision to decommission is based on the ability to maintain the satellite in storage and its capability to perform mission when needed. Fuel maintenance has become less significant, since the satellite has already been taken out of the mission orbit. The ability to maintain power levels and attitude become more significant. A geo-satellite will have to be able to maintain power levels while in sunlight and through eclipse. A geo-satellite will experience 2 seasons of eclipse a year that can last anywhere from 30 minutes to 1 hour daily. Because of this non-daily eclipse throughout the year, the battery will deteriorate more quickly than a low earth orbiting satellite and require more maintenance as the satellite ages. Either the loss of the batteries ability to maintain charge or the excess maintenance of the batteries are both reasons to decommission.

Since the attitude control systems is so complex, various anomalies can result in difficulties in maintaining attitude or maintaining momentum. So losing either capability will affect performing mission and thus can result in decommissioning a satellite.

Minor factors include the ability to maintain communication and maintain operable temperatures. For communication, most satellite design will have enough communication back up in both command uplink and telemetry downlink. So communication is usually not a major factor, but if enough anomalies compile on top of each other, then the difficulty of communicating to the satellite might be cause to decommission a satellite. And losing the ability to transmit mission data is obviously a life limiting factor, as mentioned earlier. As for temperatures, as the satellite ages, thermal properties diminish, resulting in higher than ideal temperatures. Higher temperature can affect mission by changing the payloads pointing capability. Numerous tests are performed at the beginning of life to calibrate the payload(s), so any warping due to temperature increase would require further calibration. Therefore, constant maintenance to temperature or payload accuracy can become excessive and require more resources than desired. Though decommissioning due to temperatures is still highly unlikely.

III. Testing Opportunity

Once decommissioning has been decided, and timing allows, various tests can be performed prior to actual decommissioning activities. In determining which tests to perform, care must be taken to choose tests that will not compromise decommissioning activities. The order in which tests are performed should be determined based on probability and severity of a failure occurring and how it affects decommissioning. For decommissioning, it is import to be able to communicate to the satellite and to properly dispose of fuel. Anytime during testing, if any of the decommissioning criteria, which will be discussed in a later section, are compromised, then immediate actions will need to be taken and all other testing opportunities will have to be halted. The appendix section contains a decommissioning report of a military satellite. The report discusses the list of test performed and the order in which they were performed.

Any tests performed on the payload would generally get priority since it will provide further knowledge to future payload designs or to maximize mission capability for satellites in a constellation. The other benefit of performing payload testing is that they are normally an isolated system such that they will have little to no effects on the rest of the satellite.

Tests that require minimum commanding to the satellite will generally be performed earlier on in the end of life (EOL) testing phase. Though since these tests are deemed low risk and minimally invasive, they can also be spread out during the testing phase. These tests would just require gathering of telemetry and comparisons made against beginning of life (BOL) testing or tests that only deviate slightly from normal operations. These include field of view (FOV) testing, uplink and downlink margin measurement, and any kind of thermal testing.

Redundancy checking tests can also be performed. These tests will give insight on how the redundant units perform at EOL and how they perform after so many years of dormancy. Scheduling these redundancy checks should be based on complexity of commanding to the redundant unit and the team's confidence in being able to perform nominally in the redundant side. If switching to the redundant unit requires minimal commanding, then these will be schedule first. For example, commanding on the redundant receiver would usually be a ground configuration change and result in little to no change on the satellite, thus this would be a prime candidate as an earlier test. More complex redundancy tests would be to use the redundant attitude control system (ACS) or the redundant satellite processor. Depending on the satellite design, both types of testing could require sending the satellite into a safe state (or tumbling state) prior to switching to the redundant side. This would mean that after the switch, steps would be taken to place the satellite back into a mission pointing state, similar to the steps taken at BOL. The satellite discussed in the appendix was already in a tumbling state, so using the redundant side to get to a mission point state was not any more complex than using the primary side.

Tests can also be developed based on anomalies that the satellite has experienced throughout its lifetime or anomalies that another satellite in the constellation has experienced. During an anomaly investigation, the anomaly resolution team might have recommended actions to recover the failed unit. If the team opted to use the redundant unit instead of the recovery actions, then testing out the recovery actions become a perfect candidate for an EOL test. Also, any equipment that has been switched to the redundant unit can also be a candidate to test and verify the failed primary unit. Again, care must be taken to schedule these tests so that they do not affect preceding tests and decommissioning activities.

Once all approved tests have been performed, then final decommissioning activities can commence.

IV. Decommissioning Activities

In order to decommission the satellite, several activities needed to be performed according to the Space Safety requirements of AFI91-202, paragraph 11.2.2.3.2. It states that "end-of-life safing actions for systems disposed of in space include, but are not limited to: venting all pressure vessels, safing batteries, safing any remaining ordnance systems and turning off any transmitters." The primary purpose to these requirements would be to reduce the chances of any explosion and stop the satellite from transmitting any signals that can interfere with any current or future satellites.

The first steps in decommissioning would be to remove fuel and reduce pressurant to safe levels. This is generally done first since it will take the longest time to perform. This can be done by performing several delta-Vs and monitoring fuel tank pressures. Depending on the satellite design, this can result in loss of attitude, but since the satellite should be able to receive commands in a non-nominal attitude, then this should not be a factor in performing this activity.

Though not necessary, the team may decide to drain the batteries of charge. This is done using a reconditioning transistor that can remove charge from the battery. Care must be taken to ensure that the battery is no longer needed to complete decommissioning activities. Since reconditioning a battery usually requires it to be offline, this will meet one of the requirements of decommissioning. If draining the battery is not needed, then disconnecting the battery from the main power bus can be done at any time after the battery is not needed.

At this stage, since the only thing left to do is to command the satellite off, the order in which remaining decommissioning activities are scheduled are of little importance except for the last few commands. The least critical equipment should be powered OFF first: It is best to power off the attitude system nearer the end to allow the best possible commanding. Again, it is not critical that attitude be maintained at this point, but it might be more advantageous and quicker if attitude pointing is maintained by allowing easier commanding. The telemetry downlink system should be powered OFF second to last. Having downlink telemetry during most of the decommissioning phase is preferred to get verification that actual equipment has been powered OFF. The final command would be to power off the satellite by turning OFF the power converter. This command would be done "in the blind" since the downlink transmitters were turned OFF prior. After powering OFF the satellite, tracking is transferred to Cheyenne Mountain Operations Center (CMOC) and will officially be deemed decommissioned.

V. Conclusion

Numerous factors are taken into consideration when planning to decommission a satellite. With careful consideration, all EOL testing and decommissioning activities can be performed without affecting other tests. After the satellite is decommissioned, all the testing performed should have provided insight for future unit design and lifetime predictions. Once the final OFF command is sent, no further action is necessary and resources can be focused on future satellites or remaining satellites in a constellation.

Appendix
Decommissioning Report of A Military Geosynchronous Satellite

I. Abstract

The satellite was decommissioned after being on orbit for 16 years and 7 months. Pre end of life (EOL) tests were conducted on the satellite starting in December and final tests were conducted the following June just prior to decommission. Some of the tests completed in June verified the redundancy of equipment while others tested their operability at the end of life. Sets of tests were executed in an attempt to open stuck low level attitude control thrusters and increase the spin control thruster performance as recommended during the anomaly investigation. Unfortunately, the stuck thrusters remained closed. All tests were completed without any adverse results and decommissioning activities were completed with the satellite downlink communications systems being powered off.

II. Introduction

This satellite, with a design life of 5 years, was launched into a geosynchronous orbit as part of a constellation of satellites. The constellation is used for military defense purposes. This satellite was in operational service for nearly 12 years and an additional 5 years in a super synchronous orbit, where it was used intermittently for tests and additional observations.

The satellite is a spinning satellite, maintained by a reaction wheel and momentum-managed by spin control thrusters. Activation sequence includes several modes that take the satellite from a tumbling attitude to a sun-acquired attitude to an Earth-acquired attitude to a coarse-pointing attitude and finally to a fine-pointing attitude. The difference between coarse-pointing and fine-pointing is the level of pointing dead-band maintained by high-level thrusters for coarse-pointing and low-level thrusters for fine-pointing. Note that thrusters are named for the level of thrusts (e.g. low thrust for the low-level thrusters) and would therefore produce appropriate torques suitable for their respective attitude control.

The high-level thrusters are directly connected to the propellant tank, which contain not only the propellant, but also pressurant to expel the propellant whenever the thruster valves are fired/opened. Both the low level thrusters and the spin control thrusters are connected to a gas chamber, which contains decomposed propellant. The chamber receives the propellant from the main tank and decomposes it to its basic element. The decomposition process causes an increase in pressure in the chamber and thus allowing the pressure to force the gas out of the low level thrusters and spin control thrusters whenever their valves are fired/opened. The chamber automatically maintains its pressure level by decomposing more propellant whenever the pressure drops a designated level.

The satellite contains redundancy or functional redundancy for most equipment, including the commanding system, telemetry system, attitude control system, thruster system, thermal system and power system.

During its lifetime, the satellite experienced some anomalies including a failure with the primary command receiver in year 2, a failed low level thruster in year 5, failure of the secondary command decoder in year 9, and decreased performance of the remaining low-level thrusters beginning in year 10. Due to further degradation and failure of the low-level thrusters, the satellite was configured to maintain attitude control using the high-level control thrusters. Because of the high rate of fuel usage in this configuration and the limited fuel remaining, this spacecraft was removed from the operational constellation and placed in a super synchronous orbit (300 km above geosynchronous orbit) in year 12.

Though used only intermittently in the super synchronous orbit, the satellite experienced further reduction in spin control thrusters in year 13. While removing negative momentum from the satellite, subsystem engineers noted that the procedure took twice as long as expected. It was later calculated that the spin thrusters were at 43% performance capability with the possible assumption that one pair of spin jets are completely inoperable.

III. Testing Activities

After 16 years in orbit, due to increased maintenance of the satellite, the customer requested that End-of-Life (EOL) testing be initiated with the deactivation occurring in year 17. A list of possible tests was gathered from subsystem specialists and operators. The list was then narrowed down to those that the customer deemed safe (i.e. tests that do not affect the ability to decommission but still provide insight in operating the remaining satellites in the constellation). The remaining list was prioritized and ordered to minimize adverse effects on remaining tests and decommissioning activities. The list of tests can be found in Table 1 and discussed in further detail below.

Table 1: Test Activities

Sub-system	Test	Description
ACS	A2. Determine prime and alt SSA field of view	Determine degradation of sensors at EOL
	A5. B-side ACS Earth acquisition	Verify back-up sensors and ACS equipment still work at EOL
	A6. RWA-B side motor test	Verify RWEA-B still works at EOL and get B-bearing thermal response
	A8. IPAD test	Verifty the IPAD still works at EOL
	A9. Latch Test	Evaluate the anomaly in which a radiation hardened latch is shown stuck in the disabled position
	A10. RGA test	Test the constraint that directs minimizing the use of the RGA
CCS	C2. Using redundant Tlm downlink equipment	Verify back up equipment still work at EOL
	C3. Measure downlink margins on primary and redundant sides	Compare against BOL and gain a better idea of performance degradation
PROP	P1. Verify ISO valve operation	Add confidence that ISO valves still work after 17 year in orbit
	P2. Low-level thruster check out	Identify and determine the current status of anomalous thrusters
	P3. Increment gas chamber pressure and perform rapid cycling on low level control thrusters	Possibly regain low-level thruster performance and evaluate failed thrusters
	P4. Cycling spin thrusters and low level control thrusters simultaneously with manual commands	Possibly regain low level control thruster performance and evaluate failed thrusters

The tests were broken up into 3 different windows and scheduled over a 7 month period, with the first window in December, the second window in April, and the final window in June. The first two windows coincided with previously planned activities and therefore provided an opportunity to perform the least obtrusive tests. The final window included the decommissioning activities and so the majority of the tests were placed in this window. A timeline of the 3 windows can be seen in Figure 1.

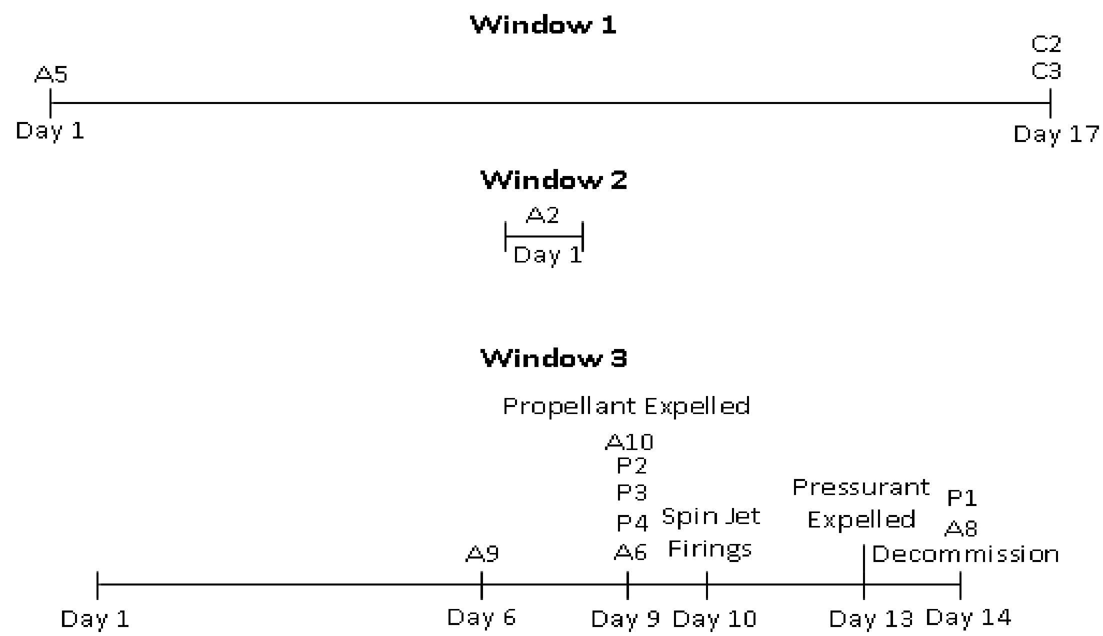

Figure 1: Activities Timeline

A. Determine Prime and Alternate SSA FOV (Test A2)

The purpose of this test is to determine the Field of View (FOV) of the Sun Sensor Assembly (SSA) at end of life and provide data on the degradation of the sun sensor's FOV, or the effectiveness of the equipment. Though this test was to determine the FOV for both primary and redundant SSA, only the redundant SSA was calculated since the satellite was only operated with the redundant ACS equipment.

Based on telemetry, it was calculated that the FOV at EOL was greater by 1.3 degrees than the specified end of life requirement. Though non-operational for more than 17 years, the sensor was subject to launch stress, as well as solar and ionizing radiation, which would have led to some degradation. No sun sensor FOV data was available for the beginning of life; therefore the degree of degradation cannot be determined. It can only be noted that the FOV at the end of life exceeded the design requirement.

B. B-side ACS Earth Acquisition (Test A5)

The purpose of this test was to exercise the redundant ACS hardware and verify their performance, which has been non-operational during the lifetime of the satellite. In order to test the redundant ACS equipment, the satellite was taken from non-controlled attitude to a coarse earth pointing attitude.

This test began with the satellite in tumble and the redundant ACS power converter being turned ON. With the power converter ON, the redundant sensors and redundant control processor were therefore receiving power and thus automatically powered ON. Thrusters were then enabled, which allowed the ACS processor to slow the tumble and place the satellite in a sun acquisition mode. The satellite was then commanded to begin the earth acquisition sequence, which will result in the satellite to automatically place itself in an Earth-pointing attitude. After verifying that the satellite acquired Earth and was able to maintain pointing attitude, the satellite was commanded to a coarse Earth-pointing mode. Though the satellite was designed to go to a fine Earth-pointing mode, the satellite was kept in the coarse-pointing mode due to the failure of fine earth-pointing thrusters, as mentioned earlier.

During the Earth acquisition sequence, redundant ACS equipments performed as expected and performed similarly as the primary side. This provided confirmation that the redundant equipment can be used after being non-operational for an extended period of time. After verifying that the redundant ACS equipment works, additional activities were performed using B-side equipment before transferring control back to the primary units. Additional activities on the redundant side include several momentum management actions and two additional earth acquisitions. There were no issues associated with using the redundant ACS equipment.

C. RWEA-B Motor Test (Test A6)

The objective of this test was to verify that the Reaction Wheel Electronic Assembly-B (RWEA-B) was operable at EOL. As mentioned previously, the reaction wheel is used to maintain the spin of the satellite by acting as the counter spin. The speed of the reaction wheel can be maintained by two motors on either side of the wheel, though only powered by the primary motor through all of its life.

In order to meet the objective, power was disengaged from A-side electronics after powering ON the B-side. Reaction wheel speed, temperature, and voltage of both primary and redundant motors were monitored and plotted. From the comparison of A-side and B-side, there were no discernible differences or deviation, thus showing that RWEA-B was operable at EOL.

At the end of this test, the satellite was left in this configuration until decommission in order to gather further information. Through the end of life, the reaction wheel operated nominal, thus adding confidence to the long term operability of RWEA-B.

D. Inertial Properties Adjustment Device (IPAD) Test (Test A8)

The satellite has the capability to adjust the inertial properties of the satellite in order to help calibrate the payload. This is achieved by using the Inertial Properties Adjustment Device (IPAD), which contains weights located along two perpendicular axes at one end of the spacecraft. Though generally not moved after initial on-orbit adjustments, this test was to verify the IPAD is able to function after an extended period of non-operation.

First, the primary motor was used to move the IPAD in the positive direction along the first axis for 5 minutes. This resulted in the IPAD moving in a near-nominal length. Next, the primary motor was engaged to move the IPAD in the positive direction along the second axis for 5 minutes, which also resulted in the IPAD moving in a near-nominal length. Then, using the redundant motors, the IPADs along both axes were moved in the negative direction for the same duration. This resulted in the IPADs returning to their original position. This test showed that not only can the IPAD be moved after years of non-movement, but that the redundant motors were operable at EOL.

E. Latch Test (Test A9)

The satellite has several radiation-hardened latches that are used to ensure that the software is configured properly. One of these latches, located in the attitude control processor, has been shown to be stuck in the enabled position, though all indication shows that the software is operating as though the latch is in the disabled position, which is the desired position. The purpose of this procedure was to exercise a recommended solution to the stuck bit and possibly pinpoint where the problem occurred. The recommended solution, which was to power cycle the attitude control processor, was not previously attempted because of the possibility of losing attitude control during the reset. For this test, it was hypothesized that after power-cycling the processor, quickly commanding the satellite into the coarse-earth pointing mode should maintain attitude control since the satellite would have had very little time to drift.

First, a software dump was executed in order to narrow the location of the problem. Unfortunately, the information gathered from the software dump was not captured properly, leaving the location of the error unknown. After the software dump, attitude control processor was power-cycled in an attempt to reset the stuck telemetry bit. Once the redundant processer was powered back ON, as planned, the satellite was quickly commanded into the coarse earth pointing attitude and the attitude control was quickly re-established. It was also noted that after the commanded reset, telemetry was indicating that the latch was disabled, as was previously thought it would be. The latch was then enabled, followed by sending commands to test the functionality of the latch. Similar to previous tests, the latch, though showing it was in an enabled position, reacted as though the latch was in a disabled position. Though no attempts were made to try and disable the latch, it was shown that the latch can be reset to the disable position by power-cycling the attitude control processor.

Though the latch was proven to work properly using redundant processor, the satellite was re-configured to use the primary processor for the duration of tests.

F. RGA Test (Test A10)

The satellite contains a constraint to minimize the ON-time for the Rate Gyro Assembly (RGA). The RGA is only used for a short period of time (usually less than 2 hours) during the initial portion of the earth acquisition sequence. For the majority of the satellite's lifetime, the RGA is powered OFF and uses other sensors to maintain attitude control. Therefore, the purpose of this test was to check the validity of the constraint and gather information to determine RGA failure. Though the constraint does not provide a lifetime estimate of how long the RGA can be powered ON, this test was set up to help fine-tune the constraint.

After depleting hydrazine from the propellant tanks, the rate gyro assembly (RGA) was powered ON and remained so until decommission. Overall, the RGA remained ON for more than 96 hours with no observed performance degradation. Since telemetry gave no indication that the RGA was near failure, a lifetime estimate for this equipment cannot be provided. It can only be said that the RGA can be left ON for up to 96 hours.

G. ISO Valve Test (Test P1)

Along the propulsion lines, several Isolation (ISO) valves are placed to help preserve fuel in the event of a fuel leak. The ISO valves on this satellite have been kept at their launch position, which would be in the open position. The purpose of this test was to check the functionality of the valves at EOL.

In this test, each ISO valve was closed and opened 5 times, waiting for a telemetry response in between commands. No further activities were attempted to determine if indeed the ISO valves were closed, since that could lead to some adverse affects on the subsystem. Therefore, verification of the closing and opening of the valves were provided by telemetry. The ISO valves responded as expected, which adds to the confidence that they can be operated after more than 16 years of dormancy in orbit.

H. Low Level Thruster Tests (Tests P2, P3, & P4)

As mentioned previously, the low level thrusters, which are used to maintain a fine-pointing attitude, has had several anomalies that led to the cease of their use. Therefore, the purposes of these tests were to first determine their current state, followed by two procedures that will hopefully increase their performance and regain their operability.

The Low-Level Thruster Tests began by establishing a baseline by firing the spin control thrusters and low level thrusters with the gas chamber pressure at the nominal level. Telemetry showed that the low level thrusters were still performing at the last known state: the spin control thrusters resulted in a one-count drop in chamber pressure, while control jet firings resulted in no change.

After establishing the baseline, the gas chamber was pressurized to 4 times the nominal value, which was the maximum allowable pressure. Once the pressure was reached and stabilized, the low-level thrusters were rapidly fired every 20 sec up to 90 times. Unfortunately, the firings resulted in no change to the natural rate of decrease in pressure, showing that these jets were still stuck closed. Then, the positive spin jets were fired 20 times, followed by 20 negative spin firings, both of which resulted in a decrease in chamber pressure by 2 psia. Again the spin thrusters were fired and GG pressure decreased by the same amount. Finally, both low-level control thrusters and the spin thrusters were fired simultaneously, with chamber pressure decreasing by only 2 psia. With pressure decrease similar to singular spin thruster firings, it was concluded that this procedure did not increase throughput for either positive or negative spin control thrusters.

I. B-side Link 1 Equipment Test (Tests C2 & C3)

The purpose of this test was to verify the redundant downlink equipment: redundant transmitter and redundant solid state power amplifier. After configuring the RF switches, Transmitter B was turned ON, followed by the solid state power amplifier (SSPA-B). Telemetry indicated proper turn-on and the ground site verified receiving a carrier with a signal strength of –85 dBm. Subsystem Engineers indicate that the signal strength was nominal and comparable to the signal strength of the other satellites in the constellation. All associated equipment operated as expected verifying full downlink redundancy at the end of life.

IV. Decommissioning Activities

In order to decommission the satellite, several activities needed to be performed according to the Space Safety requirements of AFI91-202, paragraph 11.2.2.3.2. It states that "end-of-life safing actions for systems disposed of in space include, but are not limited to: venting all pressure vessels, safing batteries, safing any remaining ordnance systems and turning off any transmitters." Table 2 lists major activities to be performed.

Table 2: Decommissioning Activities

Subsystem	Activity
PROP	Vent remaining propellant from tank and lines
	Vent pressurant from tank and gas chamber to safe levels
ACS	Turn OFF power to ACS equipment and RWEA
EPDS	Disconnect solar arrays
	Disconnect batteries
CCS	Turn OFF transmitters and power amplifier (if not already OFF)

As part of the decommissioning activities listed in Table 2, all remaining propellant had to be vented from the propellant tank and lines. First, propellant was vented from the propellant tank and delta-V lines. This was accomplished by commanding the satellite to perform 2,000 delta-V firings. Firings were performed in-plane to raise the orbit higher in its super-synchronous altitude. During the delta-V, the satellite was able to maintain attitude pointing though pointing error increased past the set deadband. This was expected, as seen on normal delta-V's, due to natural misalignment of the delta-V thrusters. After more than 800 firings, pointing error decreased to within the set deadband indicating that the delta-V thrusters were producing very little torque. This led to the conclusion that there was no more propellant coming out of the delta-V lines and only the pressurant was being expelled. The remaining delta-V firings were executed to help vent the pressurant and bring the propellant tank pressure to safe levels, as deemed by the propulsion subsystem engineer. Using tank pressure and temperature, final calculations confirmed that final fuel remaining was 0 lbm.

Though propellant was depleted from the tank, the satellite remained Earth pointing using only the pressurant. It had been suggested that this was possible, but now had been confirmed. The satellite remained Earth pointed through decommission.

After depleting fuel from the propellant tank, steps were taken to remove any remaining propellant in the lines feeding into the gas chamber. As mentioned previously, the gas chamber feeds the low level thrusters and spin control thrusters. Therefore, an option to deplete the gas would be to manually fire the spin control thrusters. Alternating between the positive and negative spin control thrusters allowed a net zero change in spin speed, making it the preferred option. After more than 2 hours and almost 2000 manual firings, telemetry indicated a change in the gas chamber performance. When maintaining its pressure levels, each decomposition activity would produce a nominal increase in pressure of 2.5 psia, but after the 2000 manual firings, pressure would only increase by about 1.0 psia. This gave indication that the propellant from the gas chamber line had been depleted. Subsequent gas generator firings produced unnoticeable increase in chamber pressure.

Decommission also required the reduction of pressurant to safe levels. To meet this criterion, it was decided to expel more pressurant such that tank pressure was less than 50 psia. Tank pressure was reduced by performing more than 4000 delta-V firings. Since propellant had been already expelled, these delta-V firings would not result in any noticeable change in altitude. Once all firings were completed, tank pressure had been reduced to just under the agreed upon level. Even at this decreased pressure level, the satellite was still able to maintain its Earth-pointing attitude.

On the planned day of decommissioning, the final two tests were completed successfully. First was the ISO valve test, followed by the IPAD test. Details of the tests were discussed above. Once all tests were completed, the decommission process commenced. Several commands were sent to the satellite to turn OFF various equipments starting with the least critical equipment. After turning OFF and disconnecting all necessary equipment, including disconnecting the batteries and solar arrays, the final two commands were sent: first, a command was sent to turn off the telemetry transmitter resulting in loss of telemetry; and the final command sent, in the blind, was to turn OFF the satellite's power converter.

V. Conclusion

After a year of planning, numerous tests were successfully performed on the satellite and was successfully decommissioned without any major issues. Though some tests could not be completed, the tests that were executed provided insight for future operations on satellites in the operational constellation. Along with the tests completed in December, redundancy was verified at EOL for the Attitude Control equipment, downlink equipment, reaction wheel electronics, and IPAD motor. Tests also proved confidence that rarely used equipment can be operable at EOL. These include the propellant ISO valves and the IPAD equipment. Apart from the tests completed, it was also verified that coarse Earth pointing attitude control could be maintained using pressurant only.

With the completion of EOL testing and all accompanying activities, the satellite had been officially decommissioned with the satellite being powered OFF and tracking transferred to Cheyenne Mountain Operations Center (CMOC).