NOAA-17 Breakup Engineering Investigation

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Abstract

The NOAA-17 weather satellite operated in polar orbit near 800 km from 2002 until it was decommissioned in April 2013. The spacecraft broke up almost eight years later in March 2021 producing about 100 trackable objects. This follows the breakups of similar spacecraft NOAA-16, DMSP F11, and DMSP F13 which also produced between 80 and 500 trackable objects. An investigation was made into the cause of the breakup and recommend how to better operate or decommission spacecraft in the future. The NOAA-17 breakup was found to be a single, localized debris event; there is likely no catastrophic damage to the whole spacecraft. NOAA-17 debris is very much in family with NOAA-16 debris, and DMSP F11 and F13 are very much in family with each other and share similarities with NOAA-16 and 17; it is likely all four share the same breakup cause. DMSP F13 breakup occurred simultaneous with a known battery overcharge and therefore battery rupture is most likely intermediate cause of all four of the breakups. This is a low confidence assessment, however, since other debris sources cannot be definitively ruled out. No root cause was found as the NOAA-17 batteries were all confirmed to have been disconnected from the charge path as intended. Possible conditions for reconnection are all unlikely including short circuits and ground commanding. All 25 related spacecraft pose a risk of similar breakups for decades to come and are a threat to the critical 800-850 km polar orbit regime; even appropriately decommissioned spacecraft appear to be at risk. Recommendations include an update to the decommissioning procedure and consideration of further investigations and active debris removal, consistent with national policy.

1 Background

The NOAA-17 spacecraft broke up on 10 March 2021 producing about 100 trackable objects. This follows the breakups of NOAA-16, DMSP F11, and DMSP F13 which also produced between 80 and 500 trackable objects. An investigation was made in order to determine the cause of the NOAA-17 breakup and to make recommendations about how to better operate or decommission spacecraft in the future. The NOAA-17 Breakup Engineering Investigation Board (EIB) was created at the request of the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) and the NASA Science Mission Directorate (SMD). This paper summarizes the 44 page EIB report.

2 Spacecraft and Mission Description

NOAA-17 was launched on 24 June 2002 into the morning orbit to support the NOAA weather mission. The spacecraft operated nominally until 2013, when the decommissioning process was initiated due to degraded shunt performance. Two months before decommissioning Battery 3 was reconditioned as a successful first-ever test of a process intended to improve performance. Nitrogen depletion took place about one month before final decommissioning on April 10, 2013. The spacecraft broke up almost 8 years after being decommissioned. To date, 114 cataloged objects have been associated with this breakup, 109 of which are still in orbit.

2.1 Overview of the NOAA-17 Spacecraft

NOAA-17 (called NOAA-M before launch) was built by Lockheed Martin and is part of the NOAA KLM series. The KLM series is very similar to DMSP 5D3 and was a continuation of the Television Infrared Observation Satellite (TIROS) Program known as the NOAA Polar Operational Environmental Satellites (POES) System. The structure is made of a titanium truss which is 4.19 m high x 1.90 m diameter, excluding the solar array. The mass is 1430 kg in orbit. Figure 1 shows the spacecraft before launch.

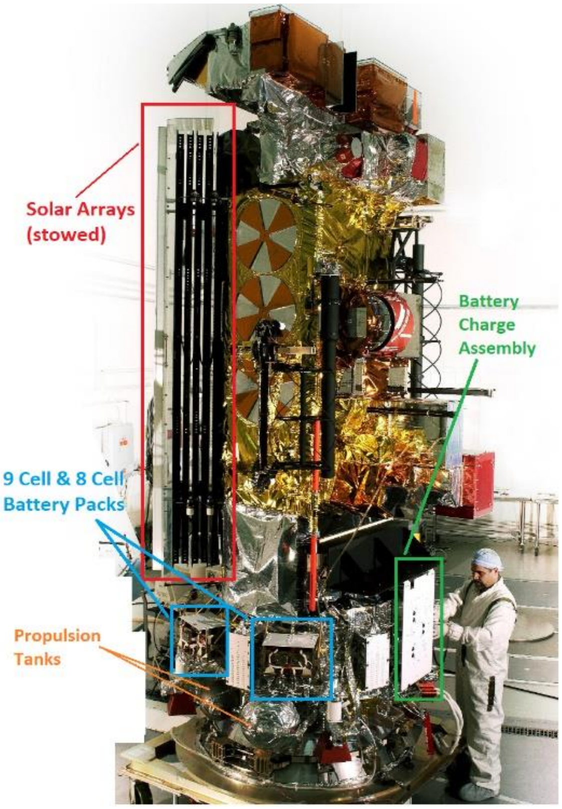

Fig. 1: NOAA-17 before launch.

All POES satellites lack maneuver capability after orbit insertion. The Reaction Control Subsystem (RCS) for NOAA-17 has an Apogee Kick Motor (Star-37 AKM) used for orbit insertion after separation from the launch vehicle, and fully depleted. A hydrazine propulsion system was used for attitude corrections during the AKM burn and for post AKM burn corrections to achieve final orbit, then isolated via pyro-initiated valves and the lines vented to relieve the majority of the pressure in them. At launch 27.44 kg of hydrazine was loaded, and 4.98 kg remaining after isolation. The two hydrazine tanks were fabricated from 6AL4V titanium alloy, and had maximum expected operating pressure of 480 psi. Lastly there is a nitrogen cold-gas propulsion system. At launch 4.17 kg was loaded, and the remainder was nominally depleted before decommissioning. The two spherical tanks were fabricated from 6AL4V titanium alloy. The pressure at launch was 4500 psi, and less than 5 psi after venting before decommissioning.

The electrical power subsystem (EPS) includes a Solar Array, three Ni-Cd Batteries, Partial Shunts, a Battery Control Unit and a Battery Reconditioning Unit with each Battery. Located on the back of the Solar Array, 140 transistors (2 in parallel with 70 solar cell circuits) served as Partial Shunts to control the array output. The Batteries were each composed of 17 cells, in separate packs of 8 and 9 cells. Batteries were manufactures by SAFT, and are described in further detail in subsequent sections. Power was supplied to the spacecraft on regulated buses of 10 and 28 volts.

2.2 Fleet History

The full fleet of associated spacecraft consists of two designs each for two customers: NOAA and the Defense Meteorological Satellite Program (DMSP). The most convenient designation for the designs uses the DMSP Block designations 5D2 and 5D3. The similarities in the spacecraft bus designs and the evolutions between blocks allow the consideration of the spacecraft as “Block 5D2 Family” and “Block 5D3 Family” groupings. Among the most significant changes between the block designs is the redesign of the Battery Charge Assembly, the Battery Packs, and the RCS pressure vessels.

Across the Block 5D2 and 5D3 families, there were a total of 25 spacecraft constructed and launched: 15 in the 5D2 family and 10 in the 5D3 family. The majority of those spacecraft (19 of the 25) have been decommissioned, with only three Block 5D3 family spacecraft still operational in each fleet.

In terms of debris generation, four of the spacecraft stand out, and are referred to in this report as the “Big Four” events. The Big Four spacecraft are NOAA-16, NOAA-17 (both in the 5D3 family), DMSP F11, and DMSP F13 (both in the 5D2 family), with tracked debris quantities of 458, 114, 85, and 236 objects respectively. The Orbital Debris Quarterly New 25-4 provides an analysis of the debris tracked from these four breakups. These four events created debris with sufficient size and radar reflectivity to be cataloged by the US Space Force . The minimum size of such objects is commonly referred to as 10 cm diameter, but that threshold varies with the object’s material composition, shape, altitude, and other factors. There have also been at least six smaller debris shedding events associated with the 5D2 and 5D3 family spacecraft, releasing less than 10 objects each.

3 Investigation

A fault tree was created and expanded over the course of the investigation to map likely causes. At the left is the breakup itself followed by the type of breakup and the source of energy. The right half of the diagram are the specific subsystems and components that could have led to the energetic event. As the elements of the fault tree are explored, certain causes can be exonerated as a likely cause if with evidence. The completed fault tree diagram is shown later in this report.

3.1 Debris Size

The physical size of a tracked fragmentation debris can be estimated from its Radar Cross Section (RCS), based on the NASA radar Size Estimation Model (SEM). Figure 2 shows the cumulative size distributions of fragments from the four breakups. Most of the fragments are between approximately 8 and 20 cm in size. The four fragment clouds have similar distributions. The gray dashed line is the power-law fragment size distribution predicted by the NASA Standard Satellite Breakup Model for the full explosion of a spacecraft, which is very different from the breakup size distributions. The cumulative size distributions seem to suggest that those fragments were generated from similar “localized, component-level” breakups. The spacecraft remained mostly intact after the localized breakups. This is consistent with radar images provided by the German Fraunhofer Society to NOAA after the breakup of NOAA-16. Although 458 fragments were detected and tracked by the SSN after the breakup of NOAA-16, the radar images show the spacecraft remained mostly intact afterward.

3.2 Debris Distribution

A Gabbard diagram provides useful information on evolution of a fragment cloud. The diagram simply plots apogee altitudes and perigee altitudes of fragments against orbital periods at a given epoch. Figure 3 shows the Gabbard diagrams for NOAA-16 and 17 three months after breakup. The spread along the cross pattern is an indication of the velocities of the fragments (relative to the parent object).

The similarity suggests that the nature and the intensity of the breakups were similar. The diagrams for DMSP F11 and F13 also appear very similar.

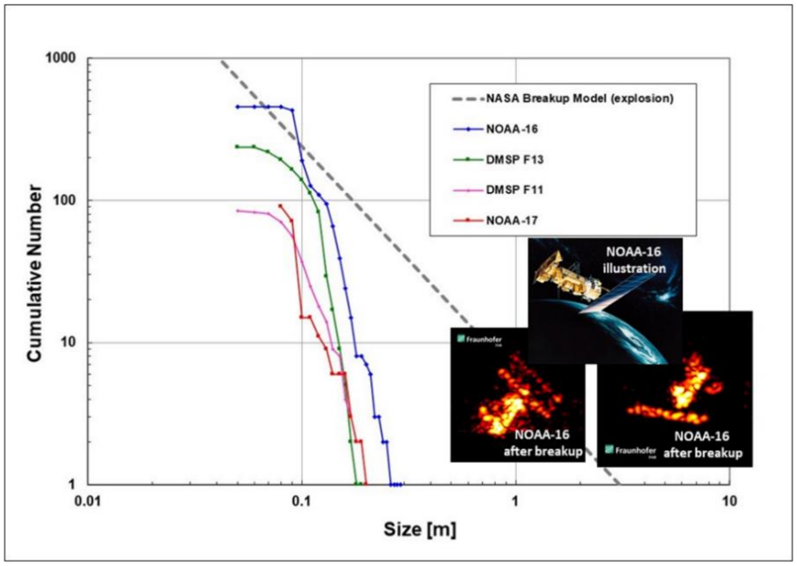

Fig. 2: Cumulative size distributions of the Big Four event fragments. The gray dashed line is the NASA Standard Satellite Breakup Model for a full explosion of a spacecraft. German Fraunhofer Society provided the radar images of NOAA-16.

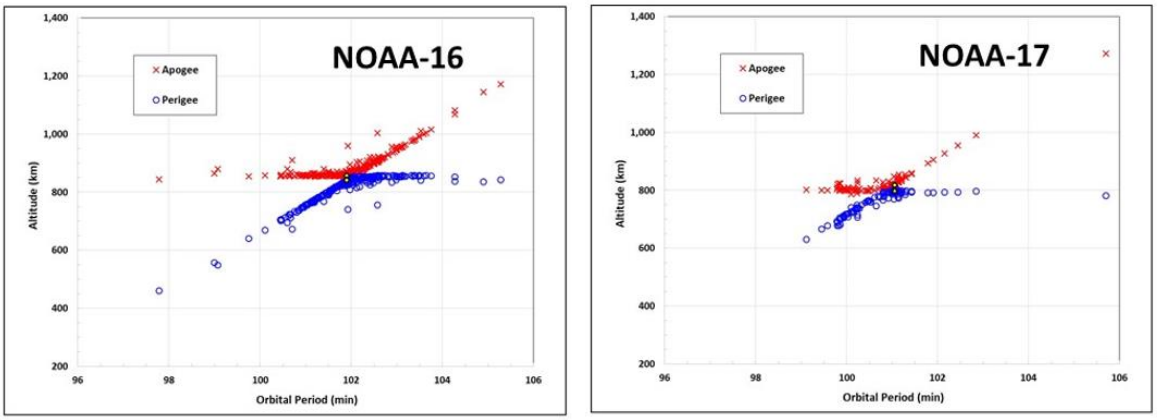

Fig. 3: Gabbard diagrams of the fragment clouds of NOAA-16 and 17 about 3 months after the breakups.

3.3 Debris Area to Mass Ratios

One can analyze the orbital history of a fragment to examine how its orbit was affected by the atmospheric drag to estimate its effective area-to-mass ratio (AMR). Figure 4 shows the AMR distributions from NOAA-16 and 17. For NOAA-16, there are two obvious concentrations between 0.2 and 0.3 m^2/kg. There is a secondary concentration at about 0.4 to 0.6 m^2/kg. Similarly, NOAA-17 fragments share comparable concentrations. The histogram in Fig. 5 is another way to see the concentrations where aAll four fragment clouds have the same peak at 0.2-to-0.3 m^2/kg. For perspective, most intact spacecraft have an AMR near 0.01 m^2/kg.

An AMR below 0.1 m^2/kg is typically an indication of metallic fragments. For example, using the NOAA-17 propulsion tank specifications, including the titanium material property and the thickness of the tank wall, one can calculate the AMR of titanium tank fragments would be about 0.03 m^2/kg, as indicated by the blue arrow on the NOAA-17 plot. Clearly, most fragments from the four breakups are not consistent with propulsion tank pieces. Fragments with AMRs significantly higher than about 1 m^2/kg are likely to be thermal blanket pieces. Fragments with AMRs between 0.1 and 1 m^2/kg are not as heavy as metallic pieces and not as light as thermal blanket pieces. They are similar in nature to lightweight composite materials. The two AMR concentrations observed suggest that fragments from the four events share similar physical properties and that they belong to two distinct material types.

Although the quantities of the tracked fragments from NOAA-16 and NOAA-17 differ by close to a factor of five, the concentrations of the fragments line up very well in size, between 9 and 10 cm. This is another indication that fragments from the two breakups are similar in size and material type. It is likely that they were generated in a similar manner from the same component(s).

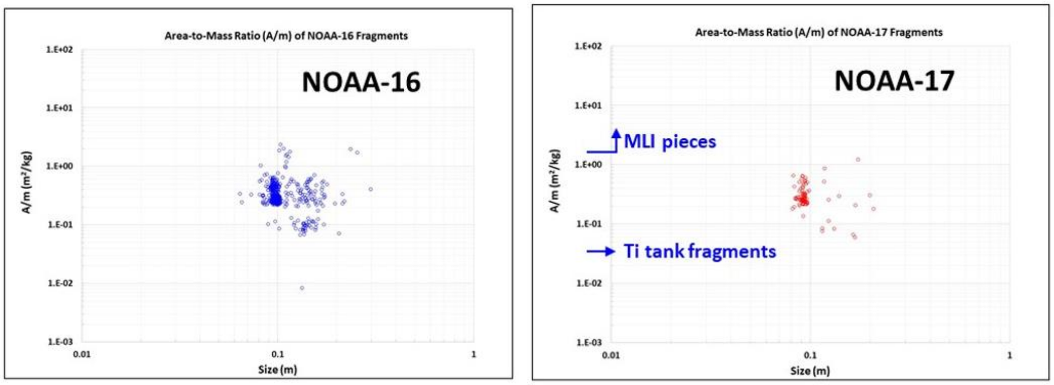

Fig. 4: AMR distributions of the fragment clouds for NOAA-16 and 17.

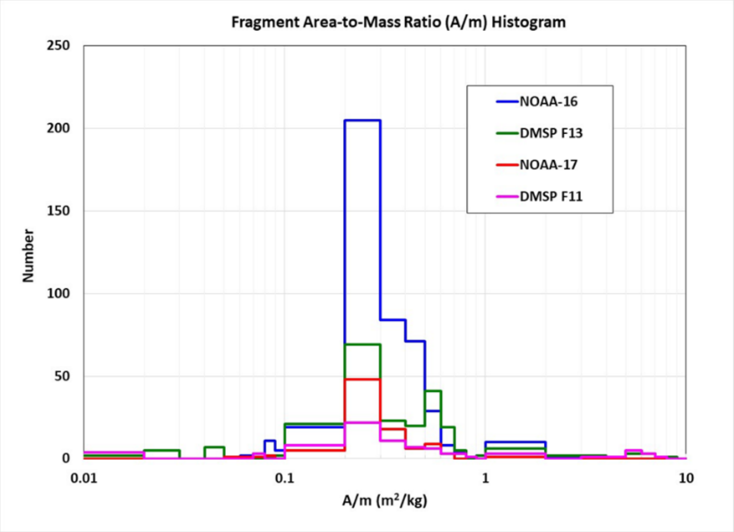

Fig. 5: AMR distribution histogram. All four fragment clouds share the same peak at 0.2-to-0.3 m^2/kg.

3.4. Equivalent AMRs

The AMR can be derived from an object's historical tracked orbit trajectory, but it can also be calculated from the physical object's average area and mass. The AMR for a flat plate can be estimated using its bulk density (including any porosity) multiplied by the thickness of the plate, to yield an areal density (AD). For a randomly tumbling thin plate, the effective drag area is half of the face area, so the AMR becomes the inverse of twice the areal density [AMR = 1/(2x AD)]. The values in the table below have been further corrected into standard units of m^2/kg.

Table 1 below shows the approximate AMR for various common spacecraft components, and how the nickel and cadmium battery cell plates align with the clusters of observed AMR values. The porous plates from the inside of the battery cells fit the observed debris AMR but there is no other direct evidence that the debris pieces are, indeed, made up of mostly the battery electrode plates.

Table1. AMR Values for Various Spacecraft Components

Object	Material	Density (g/cm^3)	Thickness (cm)	Areal Density (g/cm^2)	Tumbling AMR (m^2/kg)
Prop Tank Wall	Ti-6Al-4V	4.41	0.34	1.499	0.033
100 mil Al box wall	Aluminum	2.70	0.254	0.686	0.073
Battery Cell Case	304L SS	8.03	0.048	0.388	0.129
Cd Battery Cell	**Cadmium**	**1.96**	**0.092**	**0.180**	**0.278**
Ni Battery Cell Plate	**Nickel**	**1.74**	**0.079**	**0.138**	**0.362**
Solar Cell	Silicon	2.33	0.0254	0.059	0.845
Solar Cell Cover	Fused Silica	2.32	0.015	0.035	1.437
Typical MLI Blanket	Kapton/Mylar	1.42	0.014	0.020	2.515

3.5 Orbital Debris Strike?

One of the proposed sources of energy for the breakup is a strike from a piece of orbital debris. There was no tracked object seen by the US Space Surveillance Network that approached NOAA-17 or any of the other three of the Big Four breakups. This implies that any OD strike would have to be from an object smaller than about a softball. The current estimate of the probability of an OD strike of objects of that size is about 1 in 10,000 per year per spacecraft. Since all of the Big Four breakups exhibit such similarity in debris properties, the impacted component of a moderate sized OD strike would have to be the same in each of the four. This seems unlikely unless it is one of the large projected area components such as solar array or bus structure. Also, there is the very low chance that four spacecraft would have all experienced a strike that was predicted to have such a small likelihood.

The possibility of an OD-strike creating a shock event to the spacecraft that liberated pieces of char or slag from the inside of the Star-37 solid rocket motor (SRM) was also considered. While orbital debris production from SRMs while firing is well studied, there have been no documented cases of debris from exhausted motors. As there are many hundreds of such motors existing on orbit for decades, it is not credible that this is the source of the debris for the Big Four breakups as there would be dozens of other such cases and these are not seen.

The chances of a small (less than 1 cm) OD strike are larger and it is conceivable that four spacecraft could have received small strikes over the many years they have been in orbit. Small strikes, however, do not have the energy to liberate the 80 to 400 pieces of trackable debris seen in the big four breakups.

3.6 Tank Rupture?

The propulsion subsystem on these spacecraft is also known as the Reaction Control Subsystem (RCS). Energy is stored in the propulsion subsystem of each spacecraft during the mission. While that stored energy is reduced at the end of the mission through passivation procedures, there is still a small amount of energy stored in the gaseous nitrogen (GN2) and hydrazine tanks after the mission for up to a century or more during orbit decay. The GN2 is nominally vented at the end of the mission, so that the remaining pressure on NOAA-17 was less than 5 psia. The amount of hydrazine remaining on-board NOAA-17 was estimated as 5 kg, believed to be frozen.

Hydrazine monopropellant is stored in two tanks, located near the +Y and -Y axes of the spacecraft (velocity and anti-velocity directions). They are adjacent to Battery Packs 1A and 2B. GN2 is stored in two tanks, located near the +Y and -Y axes of the spacecraft (velocity and anti-velocity directions). They are adjacent to Battery Packs 1B and 2A. The AMR assessments shown above indicate few if any of the tracked objects with AMR are consistent with pressure vessel wall pieces, so tank rupture as either a main debris-producing event or an initiating event for a secondary breakup is considered highly unlikely.

3.7 Battery Rupture?

When a Nickel Cadmium battery is overcharged, a gas is developed which pressurizes the cell. The cell stack is mechanically constrained from the ends so that each cell cannot “balloon out” on its sides. This side pressure, however, across the stack can become as large as several hundred psi and the mechanical constraint can fail. When this happens a large amount of stored mechanical and gas pressure energy is released instantaneously and the unconstrained cells can rupture and even be expelled from the pack. A overcharging/thermal run-away incident occurred on a similar battery on another satellite during ground testing resulting in a violent mechanical battery rupture. This is not a battery explosion as there is no chemical energy involved, it is a mechanical rupture of the battery pack constraint and rupture of one or more of the cells. The Battery used in NOAA-17 was composed of 17 cells in two packs; one with 8 cells in two rows of four cells, and one with 9 cells in rows of four and five cells

The sealed SAFT battery cell construction consists of 13 nickel electrode plates (~30-45 grams each); 14 cadmium electrode plates (~23-25 grams each); and 26 thin “plastic” separators used to electrically isolate the plates. During manufacturing, cells are filled with potassium hydroxide . The terminal seals are ceramic-to-metal compression type seals. The 304 stainless steel cell case is electrically neutral. The cell was qualified as a leak-before-burst design, but it is thought that rapid overcharging could increase cell internal pressure rapidly which may cause a cell to eventually burst. The positive and negative electrodes are very thin metal with a very porous metal salt that is baked onto the surface. The porous surface on a very thin metallic substrate also puts the potential AMR of scattered plates closer to debris measurements of AMR. Other SAFT battery cell details can be seen in Fig. 6. Note that there are 27 plates per battery, so that rupture of an entire four cell row could release approximately the same quantity of cells as the number of observed debris objects.

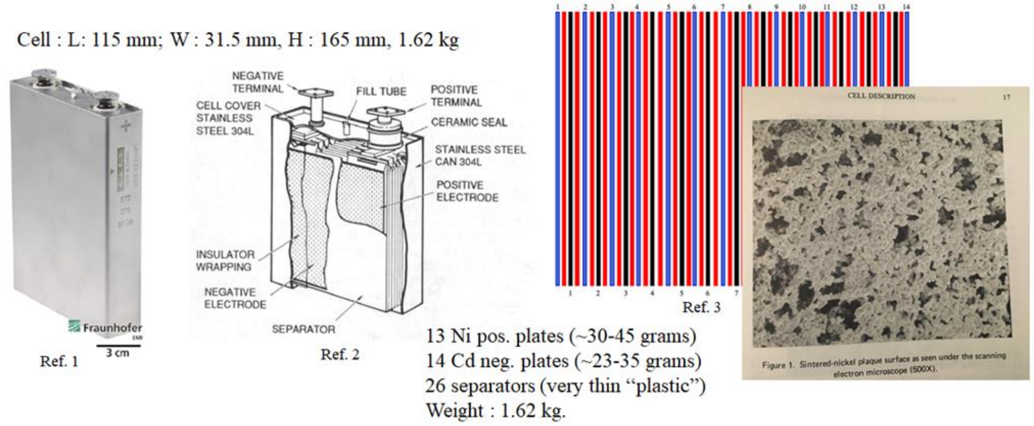

Fig. 6: SAFT 40Ah Ni-Cd cell construction details.

3.8 The Reconnection Mystery

The NOAA-17 decommissioning steps were all verified via telemetry and executed as planned with no anomalies and has been completed on numerous POES spacecraft previously without a significant breakup event; so how can over-charging happen? The following causes were investigated for how a disconnected battery could subsequently charge: Short circuits from sneak paths, chassis shorts, or metal whiskers, and ground commanding.

"Sneak paths" are basically ways that power from the bus might make its way to a battery even though the charge relay is disconnected; the discharge path (Battery 3 was left connected to the discharge path) and the reconditioning let-down resistor provide possible physical paths. However, in order for power to flow into the battery via those connections, that implies that other aspects of the power bus are compromised. It is perhaps possible that the sneak paths could lead to an overcharge of a disconnected battery, especially considering the over-voltage condition. But it's also entirely speculative, and thus not specific beyond noting those two physical paths. Detailed review of the battery charging schematics identified no potential sneak paths.

A chassis short or insulation failure was considered as a potential source of charging current. Here we considered wire harness cables in a space environment as a possible but unlikely candidate to cause an electrical short to chassis ground. In addition to workmanship issues, cracking of insulation and defective materials can all be ruled out by the long period of time NOAA-17 was in operation successfully. Instead, the cold flow of electrical cable insulation is a known potential failure mechanism for space-borne electronic components. Cold flow is caused by the thermal extremes of the space environment (spacecraft no longer under thermal control) and mechanical pressure, resulting in a short to chassis ground. While no specific locations for an insulation failure were identified, this potential mechanism can not be ruled out.

The last short circuit possibility considered was metal whiskers, hair-like, metallic crystals that sometimes grow outward from certain types of metal coatings, especially those comprised of pure tin (i.e., without lead (Pb)), zinc or cadmium. Metal whiskers up to several millimeters long are possible.

The failure mode of metal whiskers is an unintended electrical short when a whisker bridges two conductors at different potentials. There are three basic types of shorting behaviors that depend on various factors including the available voltage, current, ambient air pressure and the gap distance bridged by the whisker. An enduring low current short is capable of carrying up to tens of milliamps briefly before fusing open. Such a short circuit can also become intermittent if it regrows. The third mechanism is a high current metal vapor arc, where a whisker may be abruptly vaporized, then be ionized into a plasma leading to an enduring arc capable of carrying up to hundreds of amperes and causing massive damage. Metal vapor arc can occur with as little as 12 volts, and can continue to grow as long as base metal is available to be consumed by the arc.

The hardware for NOAA-17 was reportedly built at a time when there was no programmatic prohibition in place to prevent the use of whisker-prone pure tin-plated components. It is reasonable to speculate that a tin whisker bridging event between two relay terminals (or between a relay terminal and the case) might result in changing the state of the battery charging relays for Battery 1 or 2 leading to a continuous charging state since these batteries have no discharge path after they have been passivated as part of the on-orbit retirement of the spacecraft. Another possibility might be that a whisker-induced metal vapor arc might be initiated if a whisker were to grow between the solar array supply and the battery charging line allowing for unregulated high current to be delivered directly to the battery. Again, no conclusive evidence is available to indicate metal whiskers as a possible root cause, but it can not be ruled out.

Another possibility, though unlikely, is that ground commands were sent to re-enable part of NOAA-17 in an uncontrolled fashion that caused a battery to overcharge. Existing controls prevent the NOAA operations team from sending such a command, so ground commanding could only come from an unauthorized so-called “bad actor”. Such an event would need to be both skilled and intentional, since it would be necessary to achieve command receiver and sub carrier lock, and then send the correct command to the spacecraft which is in a non-nominal mode. Further, additional commanding would need to be sent to actually reactivate the spacecraft. It is possible, therefore, but not likely that an unauthorized user had attempted to contact the decommissioned NOAA-17 spacecraft and turn it back on. The user would have to attempt contact during a period where the spacecraft was powered from the sun and also know the low level commands to recommission the batteries.

4 Findings

Throughout the investigation, the fault tree of possible causes for the breakup was colored in as more was learned. The proximate cause for the breakup is a single, localized debris event; there is evidence against a whole spacecraft breakup and no additional debris events. The most likely intermediate cause is the rupture of a battery pack, as shown in Fig. 7. There was no root cause found as the decommissioning telemetry clearly showed the batteries were disconnected from the charge path as intended. Several short circuit or sneak path modes of reconnecting solar array current to at least one battery were investigated and none found to have any evidence to support. So it remains a mystery how a battery could become overcharged after being disconnected. Tank rupture remains on the unlikely list since it could not be exonerated with evidence but the debris generated is not consistent with other known tank ruptures.

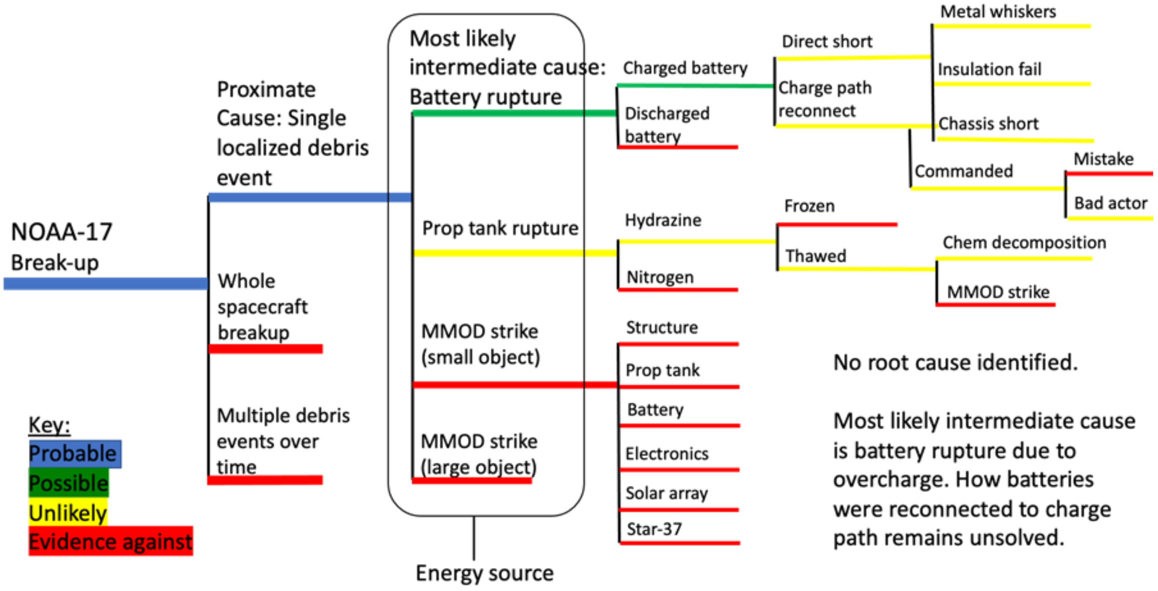

Fig. 7: The likely cause fault tree has been colored in based on the results of the investigation.

5 Assessment of Future Risks

One goal of this study was to understand whether the remainder of the Block 5D2 and 5D3 design spacecraft have a risk of unpredictable breakup due to the same mechanism experienced by NOAA-17. Because there has been no clear root cause identified, it is impossible to say with confidence that the other spacecraft either are or are not at risk due to the same mechanism. Based on the most likely causes of the NOAA-17 breakup, it can be said that all Block 5D2 and 5D3 design family spacecraft have roughly the same risk of breakup that NOAA-17 carried.

There have now been four significant breakups and many smaller debris events of the TIROS/DMSP spacecraft of at least two design generations. To look for any patterns in the breakups, the spacecraft timelines were analyzed. The spacecraft histories were arranged by both calendar date and spacecraft age, to observe any trends in the breakup occurrences. No clear trends were observed for the events. Both major and minor breakups occurred at times when the spacecraft were operational and previously decommissioned; one spacecraft even remained operational after a minor debris shedding event. The events ranged from as little as three years into the mission to as much as 25 years after launch. The Big Four events all occurred between 12 and 20 years after launch, but there is no reason to expect that breakups could not occur outside that range.

Every potential cause that was identified involved a failure mechanism initiated by energy that is either stored (battery charge or hydrazine), or generated (solar array power) on the spacecraft. The other spacecraft in the fleet have been, or likely will be, passivated in approximately the same manner as NOAA-17. Battery passivation to-date has been performed by the same procedure (where possible), leaving the charge paths to all batteries disconnected and only one battery discharge path connected. Hydrazine is nearly consumed by orbit adjustments, then any residual is isolated and believed to freeze when no longer actively heated; except in the case of NOAA-18 and 19, which do not use a hydrazine subsystem. The solar arrays can not be disconnected from the spacecraft power bus at the end of the mission, and will continue to generate power. Despite the fleet spacecraft being passivated to the greatest extent that the hardware design will allow, it is believed that they carry the same risk of breakup that NOAA-17 carried. Further, there is nothing in the available evidence that would necessarily preclude even further breakup of the Big Four spacecraft.

6 Recommendations

Based on the investigation, the following recommendations were made:

1. Implement auto-decommissioning software on all remaining operational related spacecraft.
2. At decommission, leave all battery discharge paths connected.
3. Seek tumble rate information for the whole fleet on a periodic basis to better inform investigations of subsequent breakups.
4. Consider further investigation to find root cause of NOAA-16, 17 breakups.
5. For future designs, ensure passivation includes energy generation as well as storage.
6. Consider active debris removal (ADR), consistent with US & NOAA/NASA policies

7 Summary

The breakup of NOAA-17 on 10 March 2021 releasing about 100 pieces of trackable debris was found through debris analysis to be in family with the three earlier breakups of NOAA-16, DMSP F11, and DMSP F13. These “Big Four” were likely to share the same debris source and since DMSP F13 broke up simultaneously with a battery overcharge, it is likely that all four suffered battery pack ruptures each releasing between 80 and 400 pieces of trackable debris. No root cause for NOAA-17’s breakup was found and it remains a mystery how an appropriately decommissioned spacecraft had at least one battery reconnected so as to become overcharged eight years after decommissioning. Based on the investigation, it appears all 25 of the spacecraft of related designs remain at risk of future breakups for decades to come, even if they were or will be appropriately decommissioned.