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NOAA-17 Break-up Engineering Investigation Board Final Report

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National Aeronautics and
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Prepared for the NOAA National Environmental Satellite, Data, and Information Service
and the NASA Science Mission Directorate

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Abstract

The NOAA-17 break-up was found to be a single, localized debris event producing about100 trackable pieces; 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 ("The Big Four") share the same debris source. DMSP F13 break-up occurred simultaneous with a known battery overcharge and therefore battery rupture is most likely intermediate cause of the Big Four break-ups; this is a low confidence assessment 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 commanding from a "bad actor." All related spacecraft pose a risk of similar break-ups 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.
Keywords: NOAA-17, TIROS, DMSP, Break-up, Orbital Debris, Battery

In this public-distribution of the report, some Figures have been deleted at the request of the US Space Force. Apologies for any resulting confusion.

Background

The NOAA-17 spacecraft broke up on 10 March 2021 producing about 100 trackable objects. This follows the break-ups of NOAA-16, DMSP F11, and DMSP F13 which also produced between 80 and 500 trackable objects. An investigation was made in order to find out the cause of the NOAA-17 break-up and to make recommendations about how to better operate or decommission spacecraft in the future. The NOAA-17 Break-up 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) to begin on June 14, 2021 and reported out on August 20, 2021. The EIB Letter of Appointment is given in Appendix A. A list of the board members and experts and consultants is given in Appendix B.

The Break-up Event Timeline

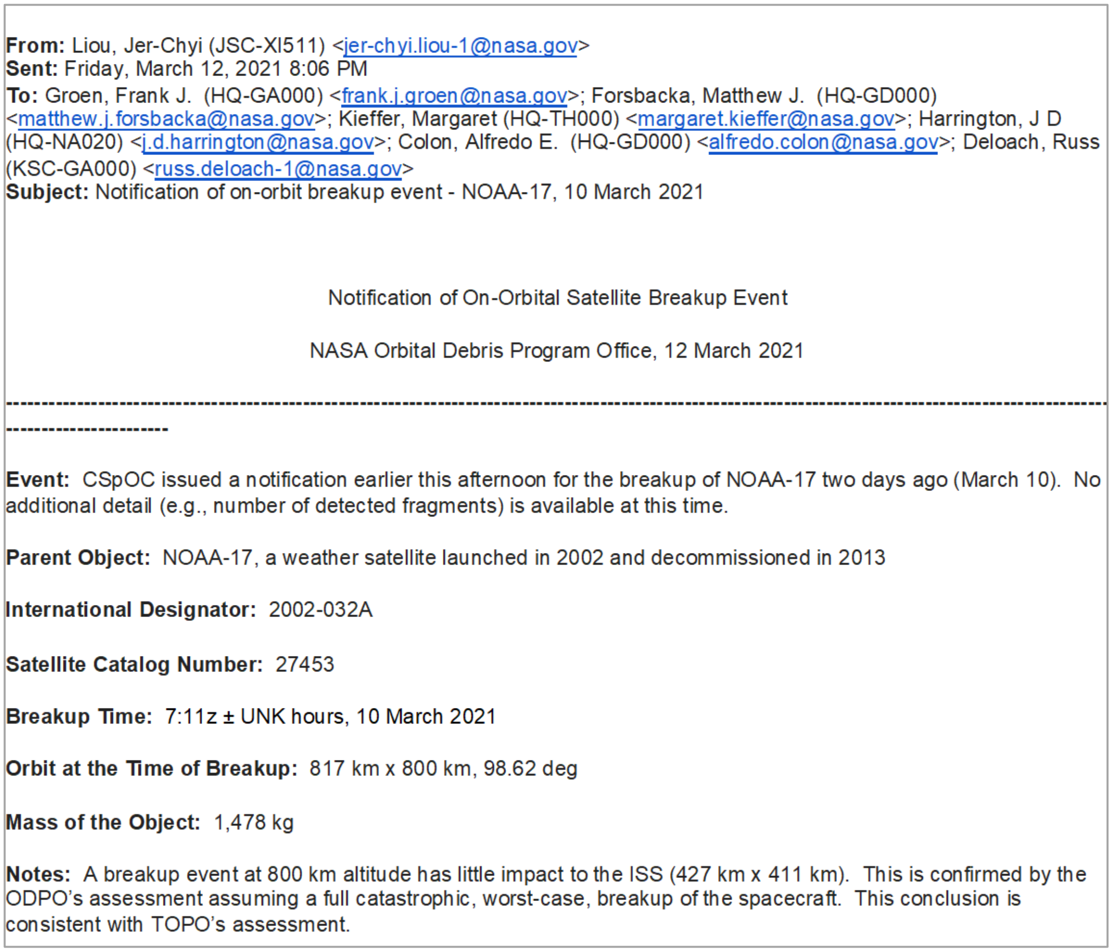
NOAA-17 was launched on 24 June 2002 into the morning orbit to support the NOAA climate mission. NASA launched and performed Post Launch testing. The operations was taken over by NOAA operations on 15 Oct 2002 with a final Post Launch Test Review on Oct 31, 2022 and declared NOAA's POES Primary Reference Morning Mission spacecraft in Aug 2004. It was replaced as the primary satellite by EUMETSAT MetOp-A spacecraft as part of the IJPS which was launched on 19 Oct 2006 and became operational in 25 May 2007, declared the Primary Morning Reference mission in ~ June 2007. NOAA-17 continued to operate as a back-up mission until it was decommissioned on 10 Apr 2013. A history of NOAA-17 operations can be found at https://www.ospo.noaa.gov/Operations/POES/decommissioned.html#noaa17.

The high level events leading up to its decommissioning and break-up eight years later are as follows:

Date	Event
24 June 2002	Launched into the morning orbit
15 Oct 2002	NOAA-17 Operations transitioned to NOAA
31 Oct 2002	Handover from NASA to NOAA following On-Orbit Verification Testing
June 2007	NOAA-17 Declared AM Back-up
10 Jan 2013	Test of Nitrogen Thruster Firings
19-29 Feb 2013	Battery 3 Reconditioning End of Life Test Preparation to perform it on NOAA-16 batteries to improve performance 1st time done in-orbit for any POES satellite Improved performance and was monitored until the decommissioning
11-20 Mar 2013	Nitrogen Depletion
10 Apr 2013	Decommissioning primary factor - degraded shunt performance

10 Mar 2021	NOAA-17 break-up observed. To date ~100 pieces are being tracked

On March 15, 2021 NOAA's Assistant Administrator for Satellite and Information Services, Dr. Stephen Volz, was notified of an on-orbit breakup of NOAA-17. The break-up was detected on 10 March 2021 by the US Space Force Space Surveillance Network and communicated through the NASA Orbital Debris Program Office on 12 March 2021. The relevant email is shown here:



From: Liou, Jer-Chyi (JSC-XI511) <jer-chyi.liou-1@nasa.gov>
Sent: Friday, March 12, 2021 8:06 PM
To: Groen, Frank J. (HQ-GA000) <frank.j.groen@nasa.gov>; Forsbacka, Matthew J. (HQ-GD000) <matthew.j.forsbacka@nasa.gov>; Kieffer, Margaret (HQ-TH000) <margaret.kieffer@nasa.gov>; Harrington, J D (HQ-NA020) <j.d.harrington@nasa.gov>; Colon, Alfredo E. (HQ-GD000) <alfredo.colon@nasa.gov>; Deloach, Russ (KSC-GA000) <russ.deloach-1@nasa.gov>
Subject: Notification of on-orbit breakup event - NOAA-17, 10 March 2021

Notification of On-Orbital Satellite Breakup Event

NASA Orbital Debris Program Office, 12 March 2021

Event: CSpOC issued a notification earlier this afternoon for the breakup of NOAA-17 two days ago (March 10). No additional detail (e.g., number of detected fragments) is available at this time.

Parent Object: NOAA-17, a weather satellite launched in 2002 and decommissioned in 2013

International Designator: 2002-032A

Satellite Catalog Number: 27453

Breakup Time: 7:11z ± UNK hours, 10 March 2021

Orbit at the Time of Breakup: 817 km x 800 km, 98.62 deg

Mass of the Object: 1,478 kg

Notes: A breakup event at 800 km altitude has little impact to the ISS (427 km x 411 km). This is confirmed by the ODPO's assessment assuming a full catastrophic, worst-case, breakup of the spacecraft. This conclusion is consistent with TOPO's assessment.

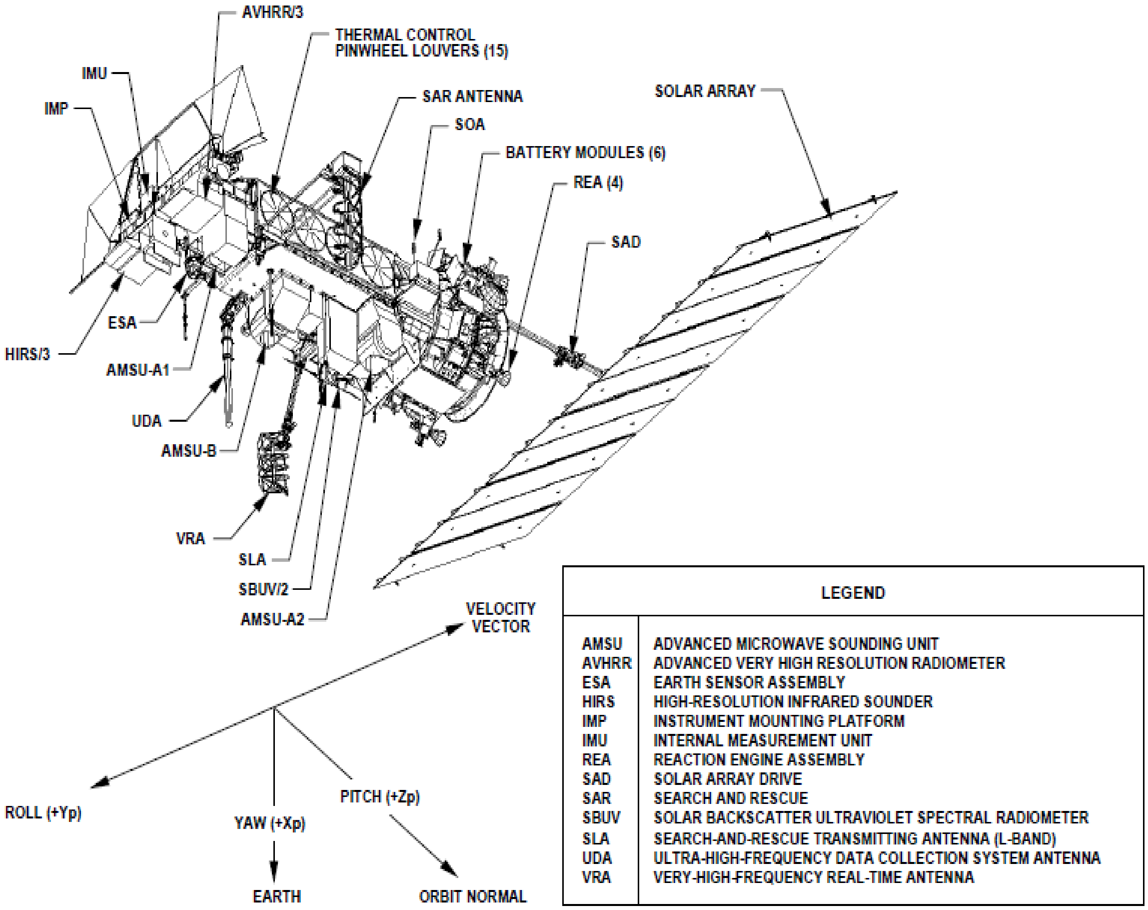
Upon notification, NOAA NESIDS Office of Satellite and Product Operations (OSPO) immediately started investigating the breakup. This included determining the location at the time of the breakup, reviewing the decommissioning timeline, and began investigation possible causes including inquiring for possible debris strikes. On April 30, 2021 NASA and NOAA jointly issued a memorandum establishing the NOAA-17 Breakup Event Engineering Investigation Board (EIB), see Appendix A.

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; see pre-launch photo in Figure 1. 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. It was launched from Vandenberg Airforce Base on 24 Jun 2002. On-orbit verification was completed by NASA and then handover over to NOAA operations on Oct 15, 2002. After products were verified by NOAA, NOAA-17 was designated the Prime Reference mission for the morning (AM) orbit – 98.7 deg inclination and 810 km altitude.

Figure 1: NOAA-17 before launch.

The structure is made of a titanium truss which is 165 in. high x 74 in. diameter, excluding solar array. The mass is 1430.63 kg (3154 lbs.) in orbit. Figure 2 shows the deployed configuration and defines the axes and direction of flight.



LEGEND	
AMSU	ADVANCED MICROWAVE SOUNDING UNIT
AVHRR	ADVANCED VERY HIGH RESOLUTION RADIOMETER
ESA	EARTH SENSOR ASSEMBLY
HIRS	HIGH-RESOLUTION INFRARED SOUNDER
IMP	INSTRUMENT MOUNTING PLATFORM
IMU	INTERNAL MEASUREMENT UNIT
REA	REACTION ENGINE ASSEMBLY
SAD	SOLAR ARRAY DRIVE
SAR	SEARCH AND RESCUE
SBUV	SOLAR BACKSCATTER ULTRAVIOLET SPECTRAL RADIOMETER
SLA	SEARCH-AND-RESCUE TRANSMITTING ANTENNA (L-BAND)
UDA	ULTRA-HIGH-FREQUENCY DATA COLLECTION SYSTEM ANTENNA
VRA	VERY-HIGH-FREQUENCY REAL-TIME ANTENNA

Figure 2: NOAA-KLM Spacecraft in Orbit Mode (NOAA-K Configuration)

All POES satellites lack maneuver capability after launch and 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. A hydrazine propulsion system was used for attitude corrections during the AKM burn and for post AKM burn velocity corrections required to achieve the final orbit. The hydrazine tank was then isolated via pyro-initiated valves and the lines vented to relieve the majority of the pressure in them. At launch 27.44* kg (60.5* lbs.) of hydrazine was loaded, 4.98 kg(10.98 lbs.) remaining after isolated. The two 13.2 in diameter ‘acorn’ shaped tanks were fabricated from 6AL4V titanium alloy. The maximum expected operating pressure was 480 psi. Lastly there is a nitrogen propulsion system. This is used for attitude corrections only when using the hydrazine thrusters or as needed throughout the operational life. At launch 4.17 kg (9.2 lbs.) was loaded, 2.39 kg(5.272 lbs.) at handover from NASA to NOAA, remaining depleted before decommissioning. The two 9.75 diameter tanks were fabricated from 6AL4V titanium alloy. The pressure at launch was 4500 psi and <5 psi after venting was executed before decommissioning. Figure 3 is a high level diagram of the NOAA-17 propulsion subsystems.

Figure 3: Block 5D2 and 5D3 RCS Schematic Diagram, from Programming and Control Handbook for NOAA-KLM, Figure 12-1.

The electrical power subsystem (EPS) is a Boost-Discharge Direct Energy Transfer (DET) system consisting of a Solar Array (SA), Two Regulated Voltage Buses, Three Nickel Cadmium Batteries, Partial Shunts, a Battery Control Unit (BCU) and a Battery Reconditioning Units (BRU). The following table and diagram give a high level description of the EPS subsystem. Figure 4 shows the high level EPS block diagram including the solar array and the three batteries with their charge and discharge paths.

Component	Description
Solar array	• Produces avg 880 Watts • Size 107.5 in. x 24.2 in per panel • Weight 18.8 lbs.(8.5 kg) per panel • 10 coplanar solar panels • Canted 37º for morning orbit • 210 string (70 circuits of 3 string) • 88-90 cells per string
Partial Shunts	140 shunt transistors (2 in parallel with 70 solar cell circuits) located on the back of the Solar Array
3 NiCd Batteries	• Manufacturer: SAFT • Each produces 40 Ah • 17 (8 cell pack & 9 cell pack) • Weight 43.6lb (19.78 kg) & 48.1 lb (21.82 kg) • Size 15.2 x 8.1 x 7.4 in. & 16.1 x 8.1 x 7.4 in.
Regulated Voltage Buses	+28V, 10V regulated voltages
Battery Reconditioning Unit	• Pull-up Resistor (4) 689 Ω in parallel • Let-down Resistor (2) 3.01 Ω in parallel
Battery Control Unit	• 12.5, 10.0, 7.5, 0.5 Ω Charge Rates • Voltage-Temperature Limiting Overcharge Protection • Weight 19.5 kg (43.0 lbs.) • Size 25.0 x 13.8 x 12.0 inches

Figure 4: Electrical Power System Block Diagram, from Programming and Control Handbook for NOAA-KLM,Figure 9-1a.

The Passive Thermal Subsystem is a combination of the following:

- Paints, tapes and chemical surface finishes
- Shields & Sunshades
- Thermal conductors and insulators
- Multilayer insulation blankets
    - 10 layers of double-sided aluminized mylar separated by alternate layers of Dacron mesh
    - Does not cover the propellant tanks
- Outer layer
    - Teflon-aluminum or Kapton-aluminum sheets

The Active Thermal Subsystem includes the following:

- Thermal Control Electronics (TCE) assemblies
- Bimetallic thermostats
- Proportional Controllers
- Heater Circuits
- Pinwheel and Vane Louvers/Radiator Assemblies

The Attitude Determination and Control Subsystem (ADACS) which provide the attitude control of the spacecraft includes the following:

- Sun Sensor Assembly (SSA)
- Earth Sensor Assembly (ESA)
- Inertial Measurement Unit (IMU)
    - Three dual-axis rate integrating gyro (1-YA,ZA; 2-XA,ZB; 3-XB, YB)
- Reaction Wheel Assemblies (RWAs)
    - X-Axis, Y-Axis, Z-Axis and Skew RWA
- Magnetic Torquing Coils (MTCs)
    - Pitch (1A, 1B, 2A, 2B)
    - Roll-Yaw (1A, 1B, 2A, 2B)

The Communication Subsystem (COMM) which provided the RF downlinks includes the following:

- 2 Beacon XMTRs - 137.35 & 137.77 MHz
- 2 VHF XMTRs - 137.50 & 137.62 MHz
- 4 ‘S-Band’ XMTRs – 1698, 1702.5, 1707 & 2247.5 MHZ
- configurable for all data types

The Command and Control Subsystem (CCS) is the hub for all the subsystems. It controls the commanding from the ground or spacecraft FSW to maintain operations and spacecraft health and safety, commanding decryption and is the timing source for the spacecraft. The major components are the following:

- Controls Interface Unit (CIU)
- 2 Central Processing Unit (CPU)
- 2 Decryption Authentication Unit (DAU)
- 2 Ground Station Receiver/Demodulator
- 2 Redundant Crystal Oscillators

The Data Handling Subsystem (DHS) formats, processes and routes all the spacecraft and payload data. It includes the following:

- Advanced Microwave Sounding Unit (AMSU) Information Processor (AIP)
- 5 Digital Data Recorders each consisting of 2 sides
- Manipulated Information Rate Processor (MIRP)
- 2 TIROS Information Processors (TIP)
- 2 Cross-Strap Units for data routing

The NOAA-17 Payload consists of the following:

AVHRR	Advanced High Resolution Radiometer
HIRS	High Resolution Infrared Radiometer
AMSU-A1	Advanced Microwave Sounding Unit-A1
AMSU-A2	Advanced Microwave Sounding Unit-A2
AMSU-B	Advanced Microwave Sounding Unit-B
SEM	Space Environment Monitor
SBUV	Solar Back Scatter UV Spectral Radiometer
DCS	Data Collection System
SAR	Search and Recovery
SEM	Space Environment Monitor

Fleet History

The full fleet of associated spacecraft, those with very similar designs launched over roughly the same time period, consist of two designs for two customers. The customers were the National Oceanic and Atmospheric Agency (NOAA) and the Defense Meteorological Satellite Program (DMSP). The most convenient designation for the designs uses the DMSP Block designations 5D2 and 5D3. While the DMSP designs are not strictly identical to those used for NOAA, the similarities in the spacecraft bus designs and the evolutions between blocks allow the consideration of the NOAA 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 Reaction Control (propulsion) Subsystem pressure vessels. There are typically also small changes even within the blocks, and where those are significant to the study they will be noted.

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 NOAA fleet includes six of the Block 5D2 family designs and five of the Block 5D3 family. The DMSP fleet includes nine Block 5D2 spacecraft and five Block 5D3 spacecraft. 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 casually referred to in this report as being the origin for 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). These four debris generating events created at least 85 individual pieces of debris with sufficient size and radar reflectivity to be tracked and cataloged by the Combined Force Space Component Command’s 18th Space Control Squadron. The minimum size of such objects is commonly referred to as 10 cm diameter, but that threshold likely 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.

Several spacecraft missions have special significance to this study:

NOAA-8 A power system anomaly occurred, ending the mission and generating 6 pieces of cataloged debris in 1986.

NOAA-12 Designated NOAA-D before launch, this spacecraft uses an earlier design, and does not appear in the fleet history table.

NOAA-13 The spacecraft failed shortly after launch, and is shown as a gray row in the fleet history table.

NOAA-16 One of the Big Four breakups. A power system failure (too much unregulated power) in June 2014 led to failure of many spacecraft systems. Passivation commands were sent but not likely to be effective and failed communications prevented confirmation of passivation commands. The spacecraft broke up 17 months later, releasing at least 458 cataloged debris objects.

NOAA-17 One of the Big Four breakups, and the subject of this study. The spacecraft was decommissioned and passivated in April 2013 due to degraded solar array shunt performance, and broke up nearly eight years later. At the time of this report, space-track.org shows 97 cataloged debris objects.

DMSP F11 One of the Big Four breakups. Decommissioned August 2000, and broke up about 3.5 years later, releasing 85 cataloged objects.

DMSP F13 One of the Big Four breakups. Operational and experiencing a power anomaly when it broke up, releasing 236 cataloged objects.

DMSP F15 Had a non-flight battery rupture during ground testing. Decommissioned during this study, and passivated per standard procedures.

This table shows a summary of the Block 5D2 and Block 5D3 design spacecraft histories.

Mission	Block	Launch	Decommissioned	Breakup Date	Pieces	Age at Breakup	Passivated?
NOAA-							
8 (E)	5D2 Family	**3/28/1983**	**1/9/1986**		6		**Failed due to batter**
9 (F)	5D2 Family	**12/12/1984**	**2/13/1998**				**Passivated**
10 (G)	5D2 Family	**9/17/1986**	**8/30/2001**		4		**Passivated**
11 (H)	5D2 Family	**9/24/1988**	**6/16/2004**		2		**Passivated**
13 (I)	5D2 Family	8/9/1993	8/21/1993				Failed in orbit
14 (J)	5D2 Family	**12/30/1994**	**5/23/2007**		1		
15 (K)	5D3 Family	**5/13/1998**					**Currently Operatio**
16 (L)	5D3 Family	9/21/2000	6/9/2014	11/25/2015	458	15.2	Attempted
17 (M)	5D3 Family	6/24/2002	4/10/2013	3/10/2021	97	18.7	Passivated
18 (N)	5D3 Family	**5/20/2005**					**Currently Operatio**
19 (N')	5D3 Family	**2/6/2009**					**Currently Operatio**
DMSP-							
F6 (OPS 9845)	5D2	**12/21/1982**	**6/1/1998**				
F7 (OPS 1294)	5D2	**11/18/1983**	**10/15/1988**				
F8 (USA 26)	5D2	**6/20/1987**	**10/16/2006**				
F9 (USA 29)	5D2	**2/3/1988**	**8/15/1994**		7		
F10 (USA 68)	5D2	**12/1/1990**	**11/14/1997**				
F11 (USA 73)	5D2	11/28/1991	8/30/2000	4/15/2004	85	12.4	
F12 (USA 106)	5D2	**8/29/1994**	**10/13/2008**		4		
F13 (USA 109)	5D2	3/24/1995	2/3/2015	2/3/2015	236	19.9	Operating at the tim breakup
F14 (USA 131)	5D2	**4/4/1997**	**2/11/2020**				**Passivated**
F15 (USA 147)	5D3	**12/12/1999**	•8/9/2021				Emergency Passiva ACS failure
F16 (USA 172)	5D3	**10/18/2003**					**Currently Operatio**
F17 (USA 191)	5D3	**11/4/2006**					**Currently Operatio**
F18 (USA 210)	5D3	**10/18/2009**					**Currently Operatio**
F19 (USA 249)	5D3	**4/3/2014**	**8/7/2017**				

The Investigation

Possible Causes

A fault tree, or fishbone diagram, was created and then expanded over the course of the investigation to map out likely causes. At the left of the diagram is the break-up itself followed by the type of break-up and then the source of energy of the break-up. The right half of the diagram are the specific subsystems and components that would have led to the energetic event. As the elements of the fault tree are explored, certain "bones" on the fishbone can be exonerated as the likely cause if there is evidence for exoneration.

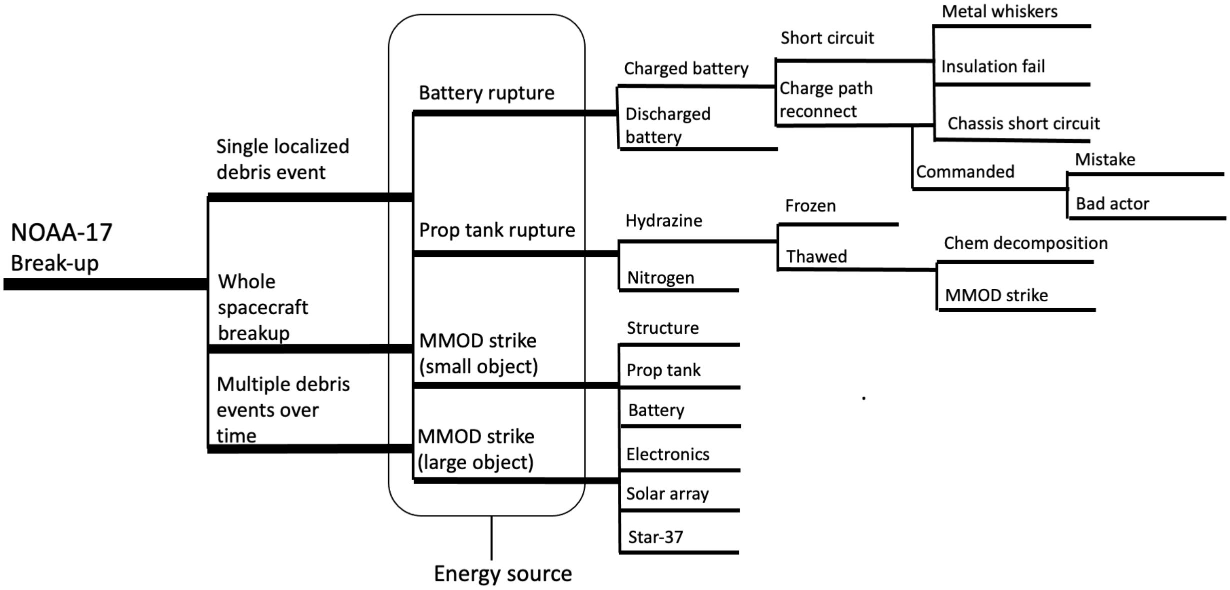


Figure 5: The likely cause fault tree was developed and explored through the investigation.

Comparative Debris Analysis

The 18th Space Control Squadron (18 SPCS) of the U.S. Space Force uses the global Space Surveillance Network (SSN) to track objects in space. The SSN can detect on-orbit fragmentation events, identify the origins of new fragments, and track objects approximately 10 cm and larger in low Earth orbit (LEO, the region below 2000 km altitude). With the addition of the Space Fence to the SSN in March 2020, the SSN tracking limit has been extended to somewhat smaller objects. The SSN tracking data includes each object's radar cross section (RCS) and its orbital elements, which may be updated multiple times a day. The orbital elements are maintained and updated as two-line element sets (TLEs) in the public satellite catalog (SATCAT) on the space-track.org website. The table below lists the numbers of the tracked fragments associated with the breakups of NOAA-17, NOAA-16, DMSP F11, and DMSP F13 as of July 2021.

Parent object	Number of tracked fragments	Tracked fragments remaining on-orbit as of July 2021
NOAA-17	96	96
NOAA-16	458	457
DMSP F11	85	61
DMSP F13	238	221

Debris Size

The physical size of a tracked fragmentation debris can be estimated from its RCS, based on the NASA radar Size Estimation Model (SEM). Figure 6 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 size distributions of the four fragment clouds.

The cumulative size distributions seem to suggest that those fragments were generated from similar "localized, component-level" breakups. The spacecraft remained 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.

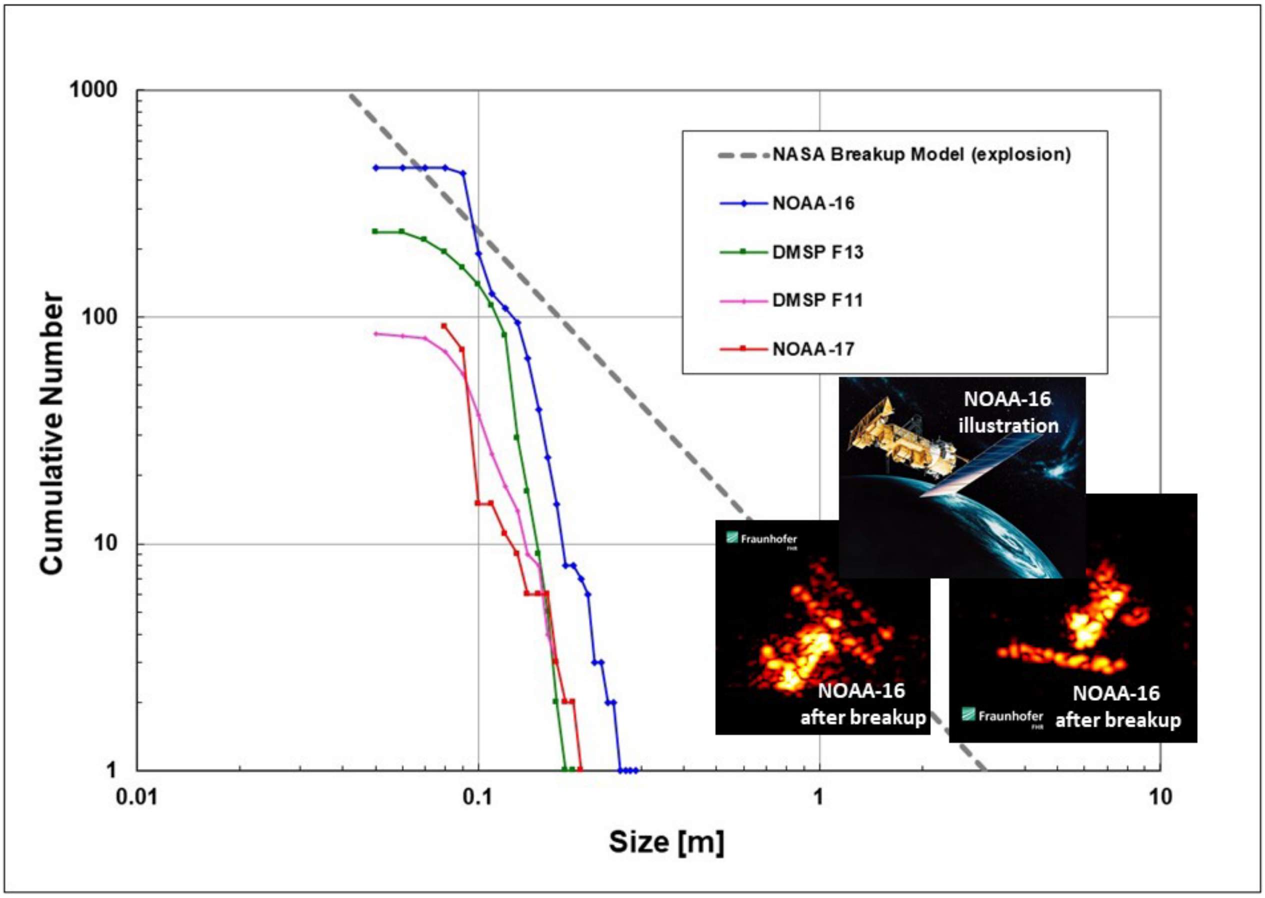


Figure 6: Cumulative size distributions of the NOAA-16, NOAA-17, DMSP F11, and DMSP F13 fragments. The gray dashed line is the power-law fragment size distribution as predicted by the

NASA Standard Satellite Breakup Model for the full explosion of a spacecraft. Credit the German Fraunhofer Society for the inset radar images of NOAA-16.

Debris Spread

A Gabbard diagram provides useful information on the spread and evolution of a fragment cloud. The diagram simply plots apogee altitudes and perigee altitudes of fragments against their orbital periods at a given epoch. Figure 2 shows the Gabbard diagrams of the four fragment clouds about 3 months after the event dates. The spread along the cross pattern is an indication of the delta velocities of the fragments (with respect to the parent object) after the breakup. The similarity, especially among NOAA-16, NOAA-17, and DMSP F13 fragments, suggests that the nature and the intensity of the breakups were similar.

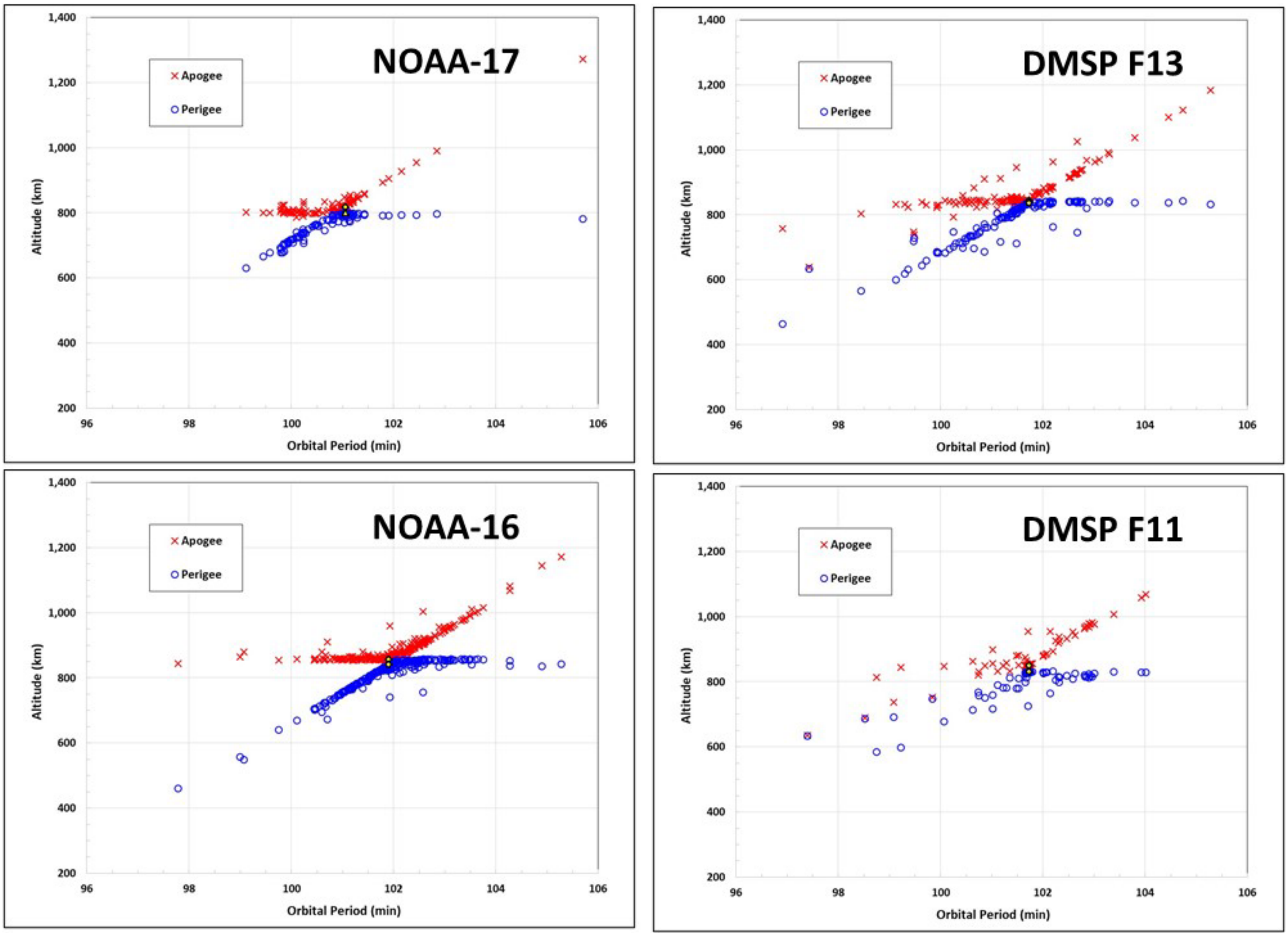


Figure 7: Gabbard diagrams of the four fragment clouds about 3 months after the breakups. Parent object's apogee and perigee altitudes are indicated by the yellow-filled symbols.

One can analyze the orbital history of a fragment to examine how its orbit was affected by the atmospheric drag perturbations and to estimate its area-to-mass ratio. Figure 8 shows the area-to-mass ratio distributions of the four fragment clouds. For NOAA-16 and DMSP F13 fragments (the plot to the lower left and the plot to the upper right, respectively), there are two obvious concentrations. The major one is 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, seen in the plot to the upper left, share comparable concentrations. The histogram in Figure 9 is another way to see the concentrations where all four fragment clouds have the same peak at 0.2-to-0.3 m^2/kg.

Debris Area to Mass

An area-to-mass ratio below 0.1 m^2/kg is 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 area-to-mass ratios of titanium tank fragments to 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 area-to-mass ratios significantly higher than about 1 m^2/kg are likely to be multi-layer insulation (MLI), thermal blanket pieces. Fragments with area-to-mass ratios between 0.1 and 1 m^2/kg are not as heavy as metallic pieces, but at the same time, not as light as thermal blanket pieces. They are similar in nature to lightweight compositive materials. The two area-to-mass ratio concentrations suggest that fragments from the four events share similar physical properties and that they belong to two distinct material types.

Although the numbers 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, as shown by the two left-hand plots in Figure 8. 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).

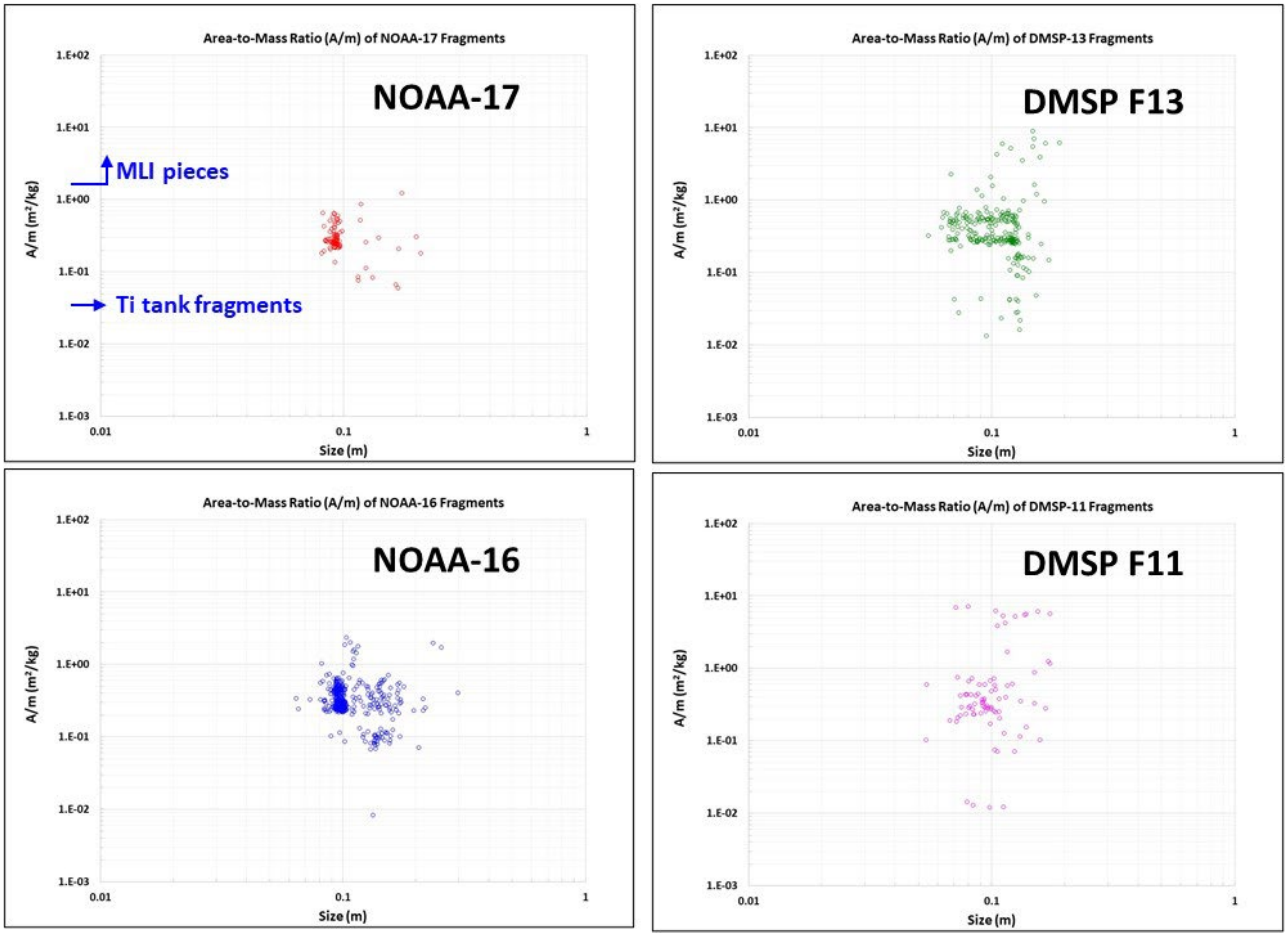


Figure 8: Area-to-mass ratio distributions of the four fragment clouds. Most of the fragments have values between 0.1 and 1 m^2/kg, with a strong concentration at 0.2-to-0.3 m2/kg and a secondary concentration at 0.4-to-0.6 m^2/kg.

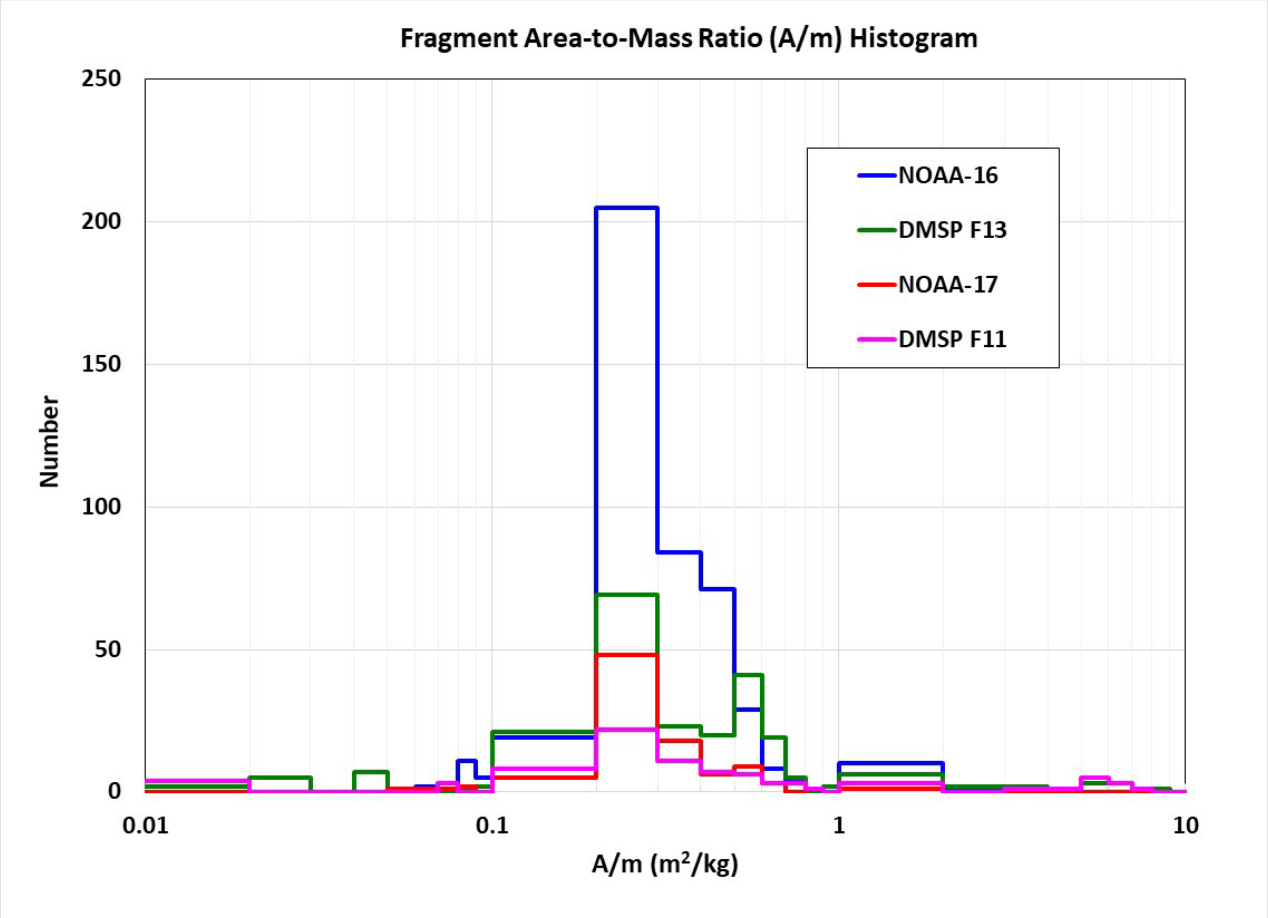


Figure 9: Area-to-mass ratio distribution histogram. All four fragment clouds share the same peak at 0.2-to-0.3 m^2/kg.

Area to Mass Comparisons

The Area to Mass Ratio (AMR) of a tracked object is an important component in assessing and predicting the effects of drag on a given orbiting object. 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. In this way, tracking data from the Combined Force Space Component Command's 18th Space Control Squadron can be used to identify candidates for the objects' origin. Such tracking data for objects from the breakup of NOAA-17 reveal that there are large clusters of objects with AMR of 0.2 m^2/kg and 0.3 m^2/kg. For perspective, most entire spacecraft have an AMR near 0.01 m^2/kg. The table 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 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. 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. It is noted that pieces of the Titanium propellant tank are too thick and heavy to match the observed pieces while solar cells and spacecraft blanketing are too thin and light. The porous electrode plates from the inside of the battery cells do 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.

Table of AMR Values for Various Spacecraft Components

Orbital Debris Strike?

One of the proposed sources of energy for the break-up is a strike from a piece of orbital debris. There was no tracked (greater than approximately 10cm of radar cross section) object seen by the US Space Surveillance Network that conjuncted with NOAA-17 or any of the other three of the Big Four break-ups. This implies that any OD strike would have to be from an object smaller than about a softball. The current estimate of risk 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 break-ups exhibit such similarity in debris properties, the victim 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. Since the debris characteristics do not match likely shed elements of these components, an OD strike as the energy sources seems unlikely. 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 used ones. 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 break-ups as there would be many 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 break-ups. Typically a small strike will appear as a bullet and go through a structure. If, however, a bullet-like small strike were to impact a component with another source of energy such as batteries or propellant tanks, that possibility was investigated.

Battery and Tank Locations

Figure 10 shows the circumference of the Block 5D3 design, through the region containing the RCS and battery components. One way to envision it is if the spacecraft were cut at the +Y axis and unwrapped to lay flat. It denotes the locations of the Battery Packs (red ovals), Battery Reconditioning Units (BRUs; blue squares), RCS tanks (red circles), and the velocity and nadir directions during nominal spacecraft operations. Also shown in the figure are the thrusters (NEA and REA) and the Battery Charge Assembly (BCA).

From this figure it is clear that the RCS tanks are located adjacent to four of the battery packs, so that a rupture of a battery pack or tank could easily impose mechanical stress onto the adjacent component. The only Battery Packs that are not adjacent to a pressure vessel are packs 3A and 3B (which are coincidentally the only Battery Packs with discharge lines left connected after passivation). Note that at the time of breakup NOAA-17 GN2 tanks had been depleted to less than 5 psia, and the hydrazine tanks contained about 5 kg of (presumably frozen) hydrazine.

Figure 10: Component Location Drawing from Programming and Control Handbook for NOAA-KLM, Figure 11-1.

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 century or more during orbit decay. At launch, a solid rocket motor raises the spacecraft to near its final orbit. The hydrazine thrusters are used to refine that final orbit, and are then isolated from the thrusters using a pyro-activated valve. The GN2 system serves a dual purpose: it pressurizes the hydrazine tank in order to expel the hydrazine, and it is used throughout the operational mission for attitude control through a separate set of cold gas thrusters. 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. The Block 5D2 design family used nominally 10 inches diameter spherical pressure vessels, with Maximum Expected Operating Pressure (MEOP) of 600 psig and burst pressure rating of 1200 psig minimum. The Block 5D3 design family used pressure vessels described as "acorn" shaped, nominally 13.2 inches diameter, 12.35 inches long, with MEOP of 480 psig; no burst pressure rating was found in the literature, but it is believed to be 960 psig minimum. Both tank designs use Ti-6Al-4V titanium alloy for the wall material, and an internal elastomeric diaphragm to separate the hydrazine from the nitrogen pressurant. The NOAA 18 and 19 spacecraft did not use hydrazine or a Star-37 solid rocket motor as the launch vehicle delivered these spacecraft to the operational orbit.

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 Block 5D2 design family used nominally 8 inches diameter spherical pressure vessels, with MEOP of 4500 psig and burst pressure rating of 9000 psig minimum. The Block 5D3 design family used nominally 9.75 inches diameter spherical pressure vessels, with MEOP of 4500 psig and burst pressure rating of 9000 psig minimum. Both tank designs use Ti-6Al-4V titanium alloy for the wall material.

Relevant to the tank and potential leakage, the history of the NOAA-17 spacecraft operations reveals three occurrences of unexpected attitude disturbances. While these anomalies have been explained and found to not contribute to the NOAA-17 debris generation in 2021, a summary of the events is included here. Two small attitude disturbances occurred in late 2005. Both of these events were attributed to momentary leaks in the hydrazine manifold, downstream of the isolation valves. The leaks occurred through a thruster valve, imparting a small impulse that caused the spacecraft attitude to deviate from the nominal. This mechanism was verified by studying the telemetry for the downstream pressure transducer, which showed small pressure drops correlating with the hydrazine "burps". A third disturbance occurred in mid-2007, which was consistent with the two previous events. Because these events involve small thruster leaks downstream of the hydrazine isolation valves, where there is a only a small volume of hydrazine under very low pressure, these anomalies from more than 14 years ago are believed to be unrelated to the 2021 debris release.

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 will rupture and even be expelled from the pack. 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. DMSP F11 and F13 battery packs were of the design with tie rods providing the constraining structure; when rupturing the rod breaks and cell wall pressure is suddenly released from the ends which is tangential to the circular wall of the spacecraft where mounted.

A shorted cell in a workhorse battery led to a rupture of a battery pack on DMSP F15 while still on the ground at the launch base; Figure 11. The overcharge event led to a thermal runaway where the temperature and pressure in the cells continued to climb even after power had been removed. The tie rods broke and the nine cells were all overpressured with several breaking open and debris scattered about the room including at least one component crossing the room to embed in the wall. NOAA-16 and -17 have a battery pack construction such that the aluminum housing of the pack provided constraint to the cells which are stack facing perpendicular to the wall of the spacecraft mounting. Overcharging in this configuration would lead to a constraint failure where the steel bolt fasteners holding the walls of the pack together release and the pressurized cells would break open shoot out from the spacecraft. There has been no documented case of such a rupture of this pack design on the ground.

Figure 11: A DMSP F15 non-flight "workhorse" battery internal short led to overcharge and thermal runaway during ground testing. 9 cells swelled and broke the constraining tie rod. 3 cells were completely ejected and several leaked electrolyte.

Battery Composition and Evolution

Across the series of Block 5D2 and 5D3 design families, there were three basic designs used for the Battery Packs: single-row packs, the NOAA-K unique design, and two-row packs. According to documentation found in the NOAA-HIJ System Design Report (SDR), the Block 5D2 family designs appear to have all used 8-cell and 9-cell packs with the cells arranged in a single row (Figures 12 and 13), compressed across the cells using "tension stringers" (aka tie rods). Battery cells used in the 5D2 design family batteries were 26.5 Ampere-hour (A-hr) nameplate rated nickel-cadmium cells made by General Electric in Gainesville, FL (also known as Gates Aerospace Batteries). The 8-cell pack includes a dummy cell, so that the battery packs all have the same dimensions. Each battery cell is mounted inside an aluminum shell to provide a heat path to the header.

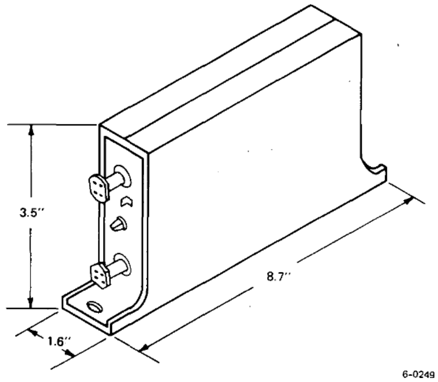


Figure 12: Block 5D2 Battery Cell Module, from HIJ SDR Figure 4.6-46

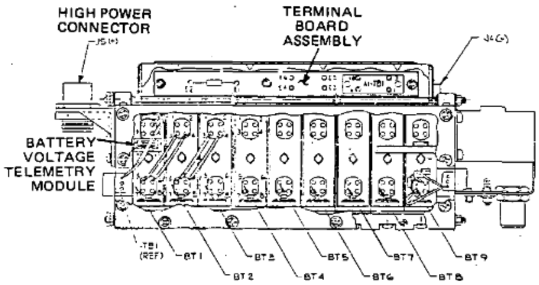


Figure 13: Block 5D2 Battery Pack, from HIJ SDR Figure 4.6-47

Between the Block 5D2 and Block 5D3 design families the battery design evolved to a higher capacity and a different mounting arrangement. The design of the battery is described in detail in a paper for the NASA Aerospace Battery Workshop in 1998: “Design and Flight performance of NOAA-K Spacecraft Batteries”. Subsequent documentation indicates that the details of this battery design were unique to NOAA-K (NOAA-15 after launch). Note that the KLM SDR report was apparently issued before the design evolution had settled, and it describes a battery construction that does not seem to have been flown on any of these spacecraft. The NOAA-K battery used 17 cells in packs of 8 and 9 cells, but the cells were 40 A-hr capacity made by SAFT. The cells of each battery pack were arranged in two balanced rows of four cells (8-cell pack) and five cells (9-cell pack); see Figure 14. A dummy cell was used in the 9-cell pack in order to balance the two rows. The Battery Pack chassis appears to have been used to restrict cell bulging, as opposed to the tie rods used in the Block 5D2 design. While the battery sleeve material is not described in the paper, it is believed to be magnesium as reported in the N N’ SDR.

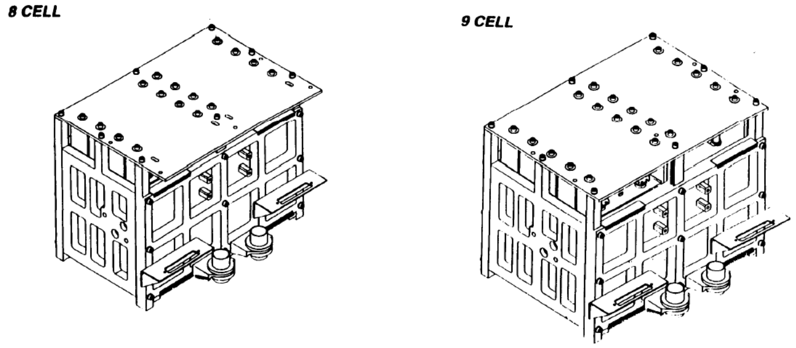


Figure 14: NOAA-K Battery Packs, from workshop paper

The Block 5D3 design family battery used for spacecraft after NOAA-K is very similar to that used for NOAA-K, but with a different arrangement of the cells. This design used no dummy cells, so the 9-cell packs had rows of 4 and 5 cells; see Figure 15. The mass of the battery packs was also lower than that for the NOAA-K packs, so there are likely other undescribed packaging differences as well. This design is best described in the NOAA N N’ SDR.

Figure 15: Block 5D3 Design Family Battery Packs with (left) and without (right) the radiator, from NOAA N N’ SDR, Figure 4.6.5-46.

This table describes the designs of the Block 5D2 family, NOAA-K, and Block 5D3 family Battery Packs

	5D2 (NOAA-H, I, J)	NOAA-K	5D3 (NOAA-L, M, N, N')
Cell Capacity	26.5 A-hr	40 A-hr	40 A-hr
Mass (8-cell/9-cell)	27.4 lb. / 30.3 lb.	46.6 lb. / 52.5 lb.	43.6 lb. / 48.1 lb.
Dimensions (inches)	13.8 x 9.1 x 5.5	11.9 x 8.2 x 8.8 (8-cell) 11.9 x 9.6 x 8.8 (9-cells)	15.2 x 8.1 x 7.4 (8-cell) 16.1 x 8.1 x 7.4 (9-cell)
Cell Arrangement	1 x 8 / 1 x 9	2 x 4 / 2 x 5	2 x 4 / 4 + 5
Cell Manufacturer	GE / Gates	SAFT	SAFT
Cell Mounting Shell Mat'l.	Aluminum	Magnesium	Magnesium
Info Source	HIJ SDR	Battery Workshop Paper	N N' SDR

Battery Charging

Looking now more closely at the EPS with an eye to how at least one battery could become reconnected and overcharge to the point of rupture. The EPS consists of three major components, the solar array (energy conversion), battery (energy storage), and power electronics (power management, distribution, and control). The overall EPS architecture is that of a "Boost Regulated" power bus, regulating a 28V nominal bus voltage, with redundant charging units. The solar array current segments are connected directly to the power bus. The batteries consist of three parallel 40Ah nickel cadmium (Ni-Cd) assemblies manufactured by SAFT. The major EPS components are highlighted in the photo of Figure 16.

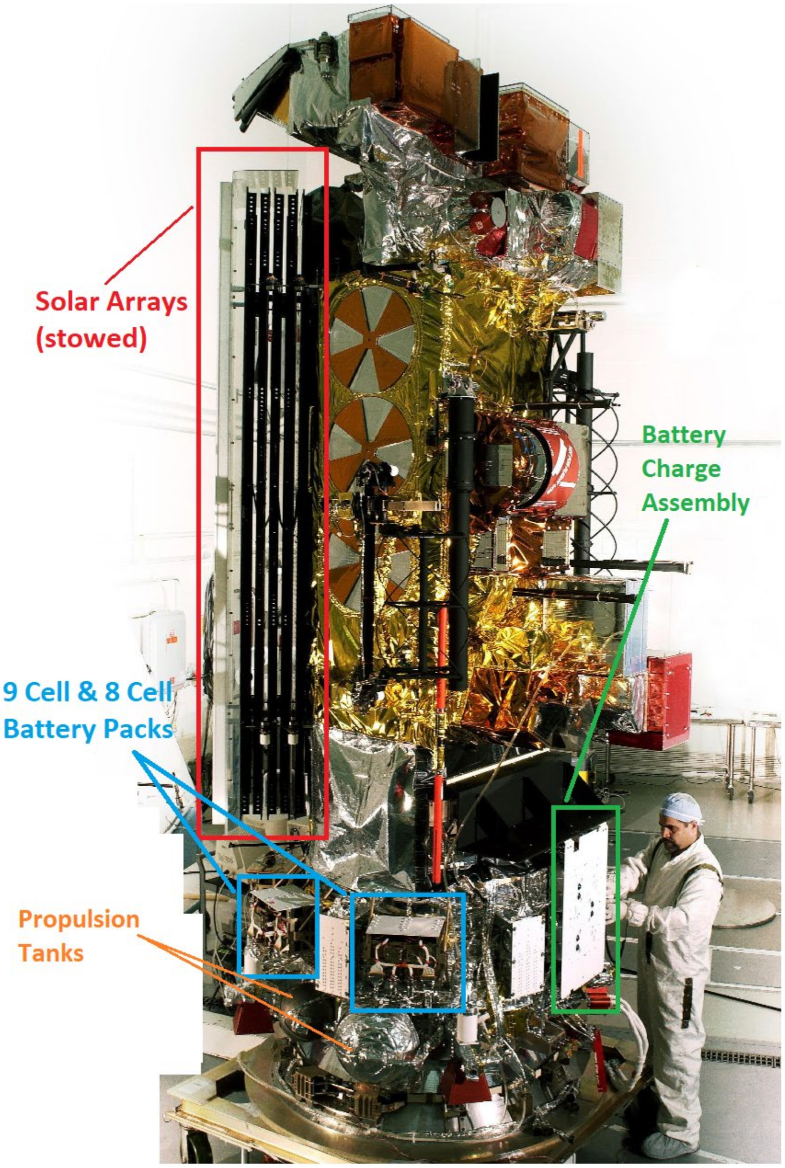


Figure 16 – NOAA-17 (pre-launch), Solar Arrays in stowed configuration.

Solar Array

The solar array configuration consists of 210 parallel strings of 90 series Silicon cells each. The nominal beginning of life open circuit voltage for the 90 series cells is approximately 54V. This voltage would represent the maximum bus voltage after decommissioning with zero load current drawn from any satellite load source. At an operating point of 28V the array would produce approximately 1900 Watts peak at beginning of life. The designed solar array power level allows additional capability above the required 880 Watts of orbital average power required by the spacecraft. Mounted to the solar array panels are 70 analog shunt circuits that dissipate any excess power not needed by the spacecraft or for battery charging. These shunt circuits are part of the overall control system of the EPS and are controlled by analog signals generated by the mode control portion of the Power Supply Electronics (PSE). These shunt circuits are required to avoid the risk of overcharging the batteries. The EPS block diagram shows the solar array assembly Figure 17 encircled by a red box.

Figure 17: Electrical Power Subsystem Block Diagram.

Batteries

There are three separate 40 Ah Ni-Cd batteries mounted on the spacecraft bus structure, each serviced by dedicated Battery Reconditioning Units (BRU). Each battery is composed of two separate battery cell packs (8 cell and 9 cell) for a total of 17 Ni-Cd battery cells electrically connected in series. Each cell is nominally 1.5V, which yields 25.5V nominal battery voltage for the 17 series cell pack. The EPS block diagram shows the "A" and "B" battery packs (combining to form a single battery) encircled by blue boxes (Figure 17).

Power Electronics

The Power Electronics section performs several critical functions. At the highest level it manages available solar array power, battery charge-discharge control, and provides tightly regulated bus voltage for any loads or instruments on the 28V power bus. The boost regulator converts 25.5V battery voltage to a solid regulated 28V during sunlight (battery charging) or eclipse orbital periods (battery discharging). Control circuits in the Battery Charge Assembly (BCA) can be seen on the EPS block diagram in Figure 17, encircled in green. The BCA provides controlled charging and tapering of batteries to extend life and maintains balance between batteries in an overall safe charge condition. The battery disconnect relays in the BCA and similar relays in the BRUs were used in the spacecraft decommissioning process to break charge paths on all three batteries, and discharge paths on two of the batteries. The "Sunlight Energized" solar array power does remain connected to the power bus (likely unregulated) and connected to any satellite loads that remain connected to the bus. If the shunt regulators were inoperable, the power bus open circuit voltage could increase to as high as 54V.

The mechanical design of the cell pack structure maintains uniform pressure on the prismatic SAFT Ni-Cd cells and provides for mechanical mounting to the spacecraft primary bus structure. Each cell pack has multiple cell to cell series electrical connections (bus bars) as seen in Figure 18. The containment structure is made of black aluminum and a thermal radiator plate ("roof"). Struts are used to mount the cell pack containment assemblies to the spacecraft, see Figure 19. A picture of the representative mounting locations for the 8 and 9 cell pack assemblies on the spacecraft can be seen in Figure 20.

Figure 18: NOAA-17's 9 cell battery pack.

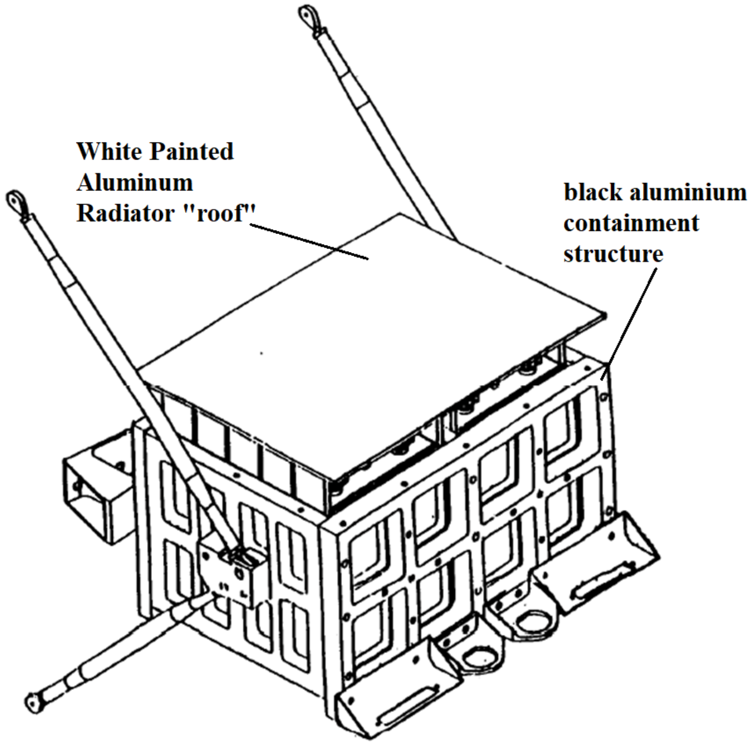


Figure 19: 8 cell pack with containment and mounting struts

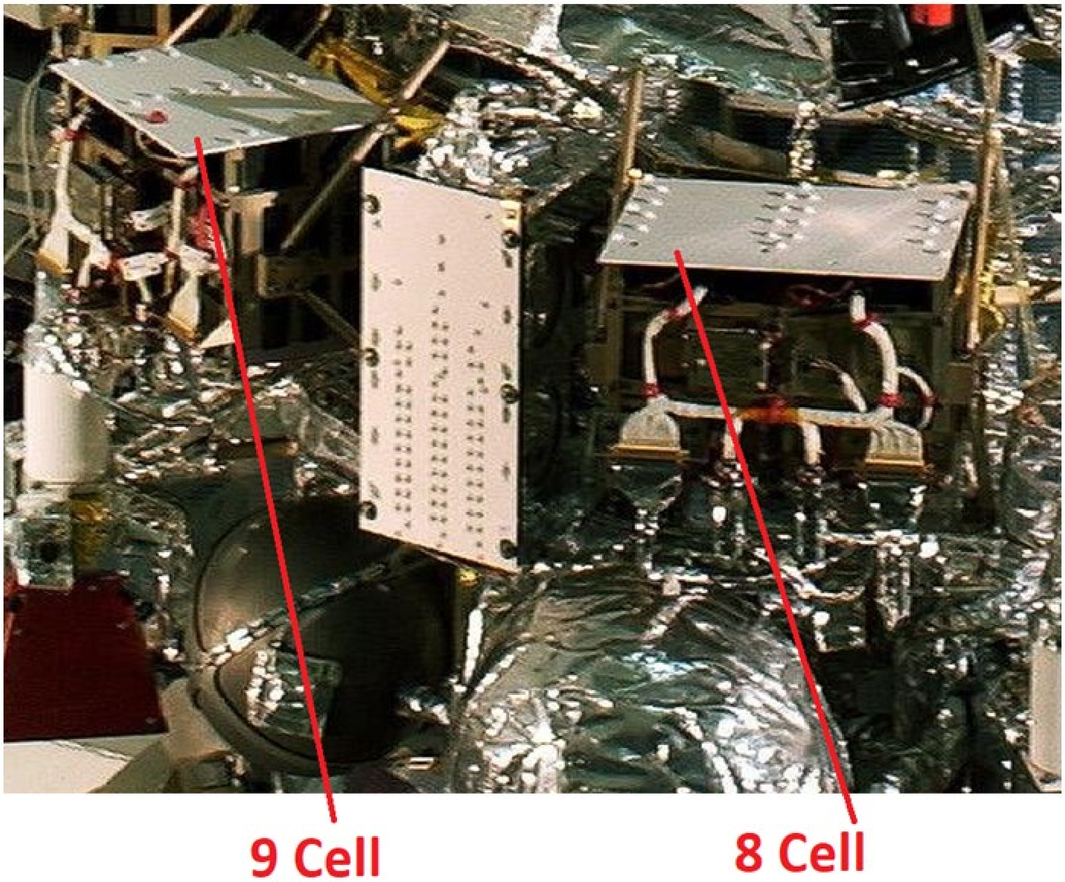


Figure 20: 8 and 9 Cell packs (with radiator "roof") mounted on spacecraft bus structure.

The sealed SAFT battery cell construction consists of 13 nickel positive electrode plates (~30-45 grams each); 14 cadmium negative electrode plates (~23-25 grams each); and 26 thin "plastic" separators used to electrically isolate the positive and negative electrode plates. During cell manufacturing, cells are filled with aqueous potassium hydroxide (KOH) electrolyte via a pinch tube attached to the cell header subassembly. The terminal seals are ceramic-to-metal compression type seals. The 304 stainless steel cell case is electrically neutral. The circumference of the cell header is TIG welded to the stainless case. The cell was qualified as a leak-before-burst design. It is thought that rapid overcharging could increase cell internal pressure 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. This very porous surface allows the electrolyte the highest electroreactive contact area to form more effective battery. 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 Figure 21.

Weight : 1.62 kg.

Figure 21: SAFT 40Ah Ni-Cd cell construction details (each battery pack consists of 8 or 9 cells, 17 cells in the complete battery of two packs)

Connections to the Batteries

The batteries have several connections for charge, discharge, reconditioning, and telemetry. Figure 22 shows a schematic with solar array power coming in from the upper left and the batteries in the lower right. Under charging, the charge path relay K1 is closed and the solar array power goes through the primary or redundant charge regulators to the battery (primary or redundant selected by relay K2). When providing power from the batteries to the spacecraft (discharge), relay K3 is engaged and the current flows through a parallel/series set of four diodes from the battery to the loads. Finally, there is a battery reconditioning circuit intended to more fully discharge and then recharge an isolated battery to extend the performance of the battery. The Battery Reconditioning Unit (BRU) contains the "let-down" and "pull-up" resistor sets by which the battery is reconditioned. There are also current and voltage telemetry point for each battery pack that also were considered.

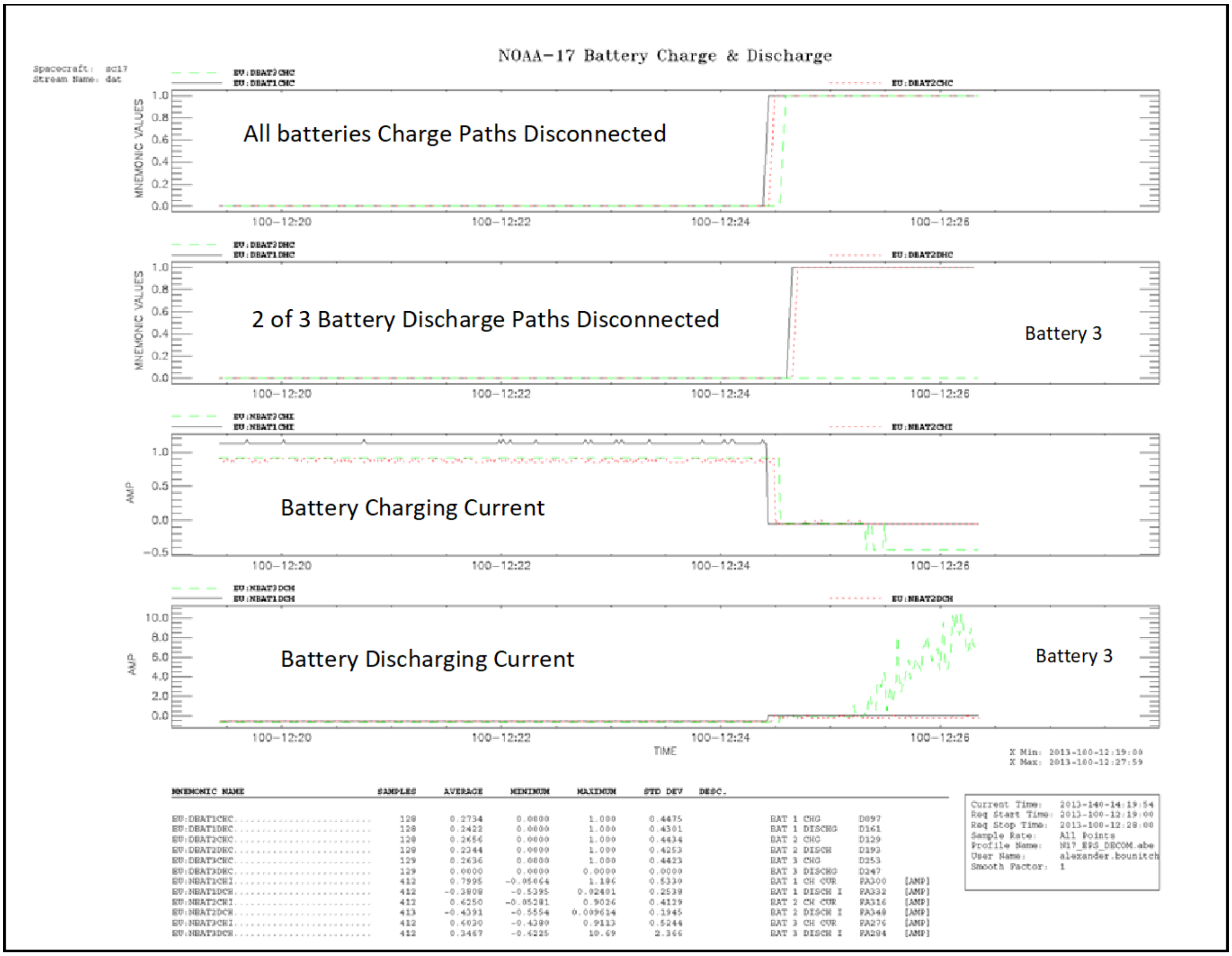
Figure 22: Detail schematic of battery connections.

The Reconnection Mystery

The following causes were investigated for how a disconnected battery could charge:

- Decommissioning was not successfully executed
- Short Circuits
  - Sneak paths
  - Chassis short or insulation failure
  - Metal vapor whiskers
- Bad actor commanding

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 does it this happen? Figure 23 shows the telemetry from the batteries during the decommissioning process with clear indications that the battery charging path was disconnected.



X Min: 2013-100-12:19:00
X Max: 2013-100-12:27:59

MNEMONIC NAME	SAMPLES	AVERAGE	MINIMUM	MAXIMUM	STD DEV	DESC.		
EU:DBAT1CHC	128	0.2734	0.0000	1.000	0.4475	BAT 1 CHG	D097	
EU:DBAT1DHC	128	0.2422	0.0000	1.000	0.4301	BAT 1 DISCHG	D161	
EU:DBAT2CHC	128	0.2656	0.0000	1.000	0.4434	BAT 2 CHG	D129	
EU:DBAT2DHC	128	0.2344	0.0000	1.000	0.4253	BAT 2 DISCH	D193	
EU:DBAT3CHC	129	0.2636	0.0000	1.000	0.4423	BAT 3 CHG	D253	
EU:DBAT3DHC	129	0.0000	0.0000	0.0000	0.0000	BAT 3 DISCHG	D247	
EU:NBAT1CHI	412	0.7995	-0.05064	1.186	0.5330	BAT 1 CH CUR	PA300	[AMP]
EU:NBAT1DCH	412	-0.3808	-0.5395	0.02401	0.2538	BAT 1 DISCH I	PA332	[AMP]
EU:NBAT2CHI	412	0.6250	-0.05281	0.9026	0.4129	BAT 2 CH CUR	PA316	[AMP]
EU:NBAT2DCH	413	-0.4391	-0.5554	0.009614	0.1945	BAT 2 DISCH I	PA348	[AMP]
EU:NBAT3CHI	412	0.6030	-0.4390	0.9113	0.5244	BAT 3 CH CUR	PA276	[AMP]
EU:NBAT3DCH	412	0.3467	-0.6225	10.69	2.366	BAT 3 DISCH I	PA284	[AMP]

Current Time: 2013-140-14:19:54
Req Start Time: 2013-100-12:19:00
Req Stop Time: 2013-100-12:28:00
Sample Rate: All Points
Profile Name: N17_EPS_DECOM.abe
User Name: alexander.bounitch
Smooth Factor: 1

Figure 23: Battery decommissioning telemetry

Sneak paths

The 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 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.

Chassis short or insulation failure

Here we considered wire harness cables in a space environment as a possible but unlikely candidate to cause an electrical short to chassis ground. Besides workmanship, cracking of insulation and defective materials that can all be ruled out by the long period of time NOAA-17 was in operations. Instead, the cold flow of electrical cable insulation caused by the thermal extremes of the space environment (spacecraft no longer under thermal control) and mechanical pressure. Wire harness cables to and in fully populated subsystem units are under mechanical pressure that could result in the cold flow of cable insulation material resulting in a short to chassis ground.

Metal vapor whiskers

One possible unintentional battery charging path involves the phenomenon of metal whisker formation[1]. Metal whiskers are 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. Such metal coatings are commonly used for corrosion protection of the underlying base metal (e.g., copper or iron alloys) of electronic components and mechanical hardware and in the case of tin coatings as a solderable surface finish. NOTE: the co-deposition of Pb into tin coatings (> 3% Pb by weight) is an accepted industry practice to inhibit the formation of tin whiskers from tin-based coatings.

The growth of metal whiskers is spontaneous such that neither electrification of the metal surface nor any particular environmental condition is required for whisker nucleation and growth to occur. Metal whiskers will grow with or without electrical bias, in air or vacuum, in dry or moist conditions, etc. Metal whisker growth is highly unpredictable with dormancy periods ranging from days to years (if ever) and subsequent growth rates (microns/year) spanning many orders of magnitude and with growth periods lasting from days to decades. Similarly, whisker densities (# per unit area) may vary over many orders of magnitude from specimen to specimen. Metal whiskers up to several millimeters long are possible. The first public reports of harm caused by metal whiskers date back to the end of World War II and since then, many hundreds of field failure events have been attributed to them affecting all classes of hardware (e.g., commercial, industrial, automotive, military, aerospace, etc.).

The primary failure mode associated with metal whiskers is that of an unintended electrical short circuit (resistive pathway) when a metal whisker bridges between 2 conductors at different electrical potentials. There are 3 basic types of shorting behaviors that depend on various factors including, but not limited to, the available voltage, current, ambient air pressure and the gap distance bridged by the whisker.

1. Enduring short
    - capable of carrying from microamps up to tens of milliamps
2. Intermittent short
    - current flow becomes interrupted if the whisker melts open due to Joule heating or is otherwise moved from its bridging position (e.g., air flow, mechanical vibration)
3. Metal vapor arc
    - With sufficient energy from the power source, a whisker may be abruptly vaporized (i.e., become a metal gas), then be ionized into a plasma (metal ions) by the electric field in which the metal gas resides and finally, have the metal ions accelerated by the electric field towards the cathode leading to an enduring arc capable of carrying up to hundreds of amperes and causing massive damage.
    - Metal vapor arc likelihood increases with applied voltage (at least ~12V is needed to initiate), reduced arc gap distance and reduced air pressure where removal of air molecules also removes their arc quenching effects
    - As an example, metal vapor arcs have been documented to occur with a metal whisker bridging 2 conductors spaced by a few millimeters or less at 50V at pressures of ~0.1 atm.

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. Certain types of electromagnetic relays used in the NOAA-17 battery control circuitry may have used pure tin coatings on the device package and/or solder terminals. Multiple tin whisker induced field failures have been previously reported from such relays for other satellite systems (e.g., Hughes/Boeing HS601 satellite control processors)[2].

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.

1 NASA Tin Whisker and Other Metal Whisker www site, https://nepp.nasa.gov/whisker

2 On-orbit commercial satellite failures due to tin whiskers on electromagnetic relays https://nepp.nasa.gov/whisker/failures/index.htm#satellite

"Bad-actor" commanding

The possibility of a bad actor attempting to command the satellite was investigated as it has been seen previously on likely attempts to contact Landsat 7 and Terra from a non-user terminal. In order for the batteries to be commanded back to connected charge path via a ground station the following prerequisites would be required:

- Spacecraft is power positive as it is in a flat spin most likely around yaw
- Command receiver and sub carrier lock was accomplished
- Correct commanding was sent
    - Note: Onboard processors are in Power-On Processing Software (POPS) mode. This a non-nominal operational mode as no FSW is running
- Complete path of commanding required was powered up and able to receive and process the commands. See Figure Below:
    - Note in this scenario command encryption would be disabled

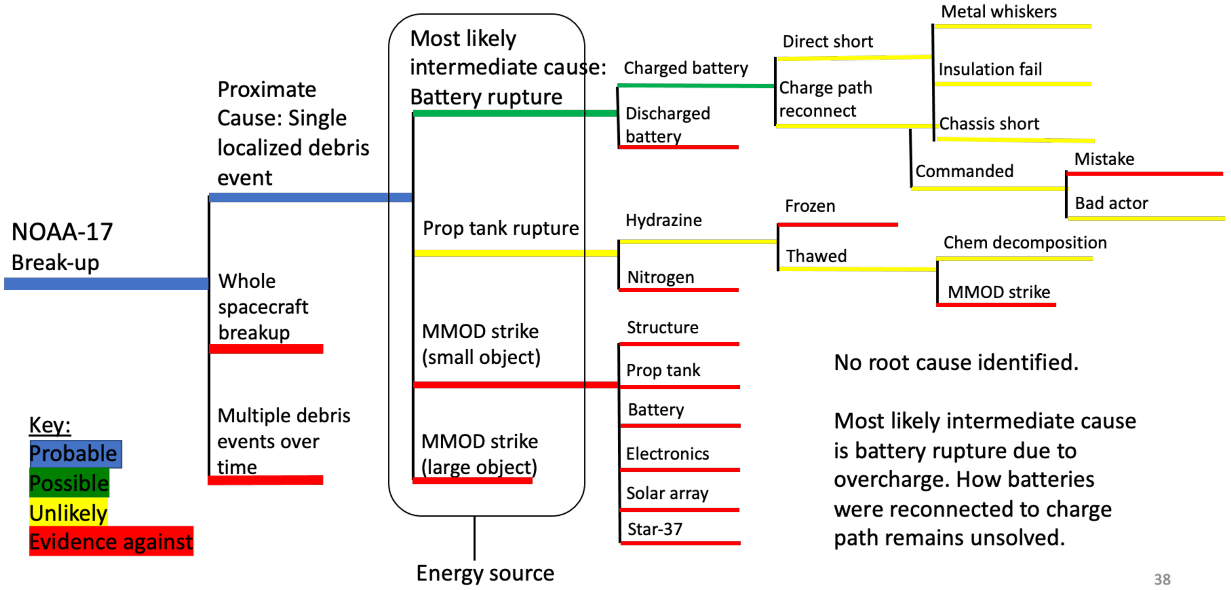
Figure 24: Command path to battery reconnection possibility.

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.

Findings

Likely Cause

Throughout the investigation, the tree of possible causes for the break-up was colored in as more was learned. The proximate cause for the break-up is a single, localized debris event; there is evidence against a whole spacecraft break-up and no additional debris events. The most likely intermediate cause is the rupture of a battery pack; Figure 25. 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.



No root cause identified.

Most likely intermediate cause is battery rupture due to overcharge. How batteries were reconnected to charge path remains unsolved.

Figure 25: The likely cause fault tree has been colored in based on the results of the investigation.

Future Risks

There have now been four significant break-up and many smaller debris events of the TIROS/DMSP spacecraft of at least two design generations. If it is, indeed, rupture of a battery pack that is at fault, then it is possible that any of the remaining battery packs (multiple per spacecraft) throughout the fleet of similar spacecraft could also rupture. To look for any patterns in the break-ups, the spacecraft timelines were analyzed.

The spacecraft histories above were arranged by both calendar date and spacecraft age (Figures 26 and 27), to observe any trends in the breakup occurrences. The timelines shown below include both the Big Four events and the smaller quantity debris shedding events. 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.

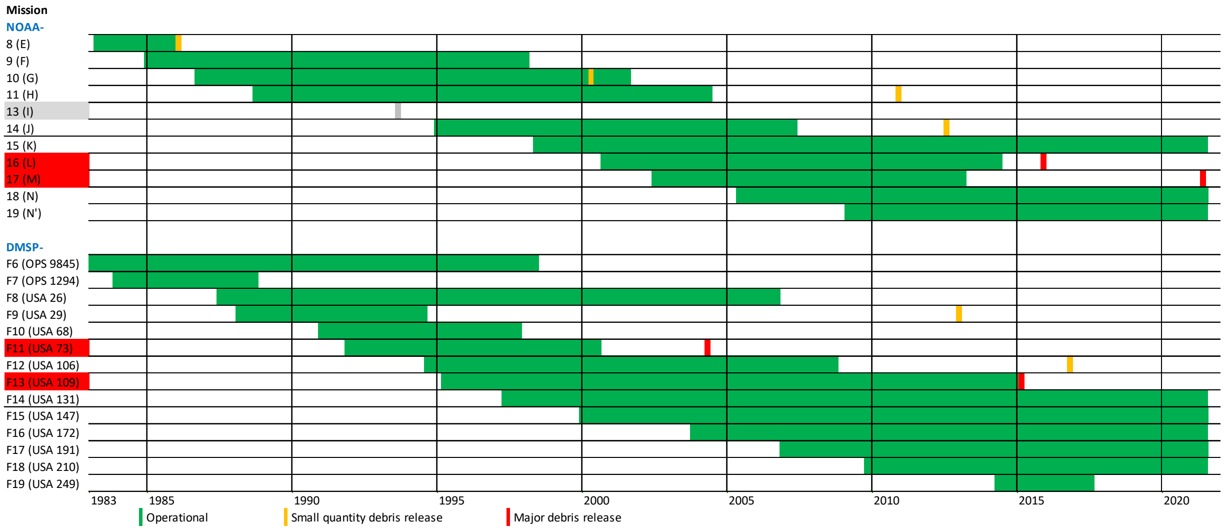


Figure 26: Fleet timeline organized with respect to calendar years.

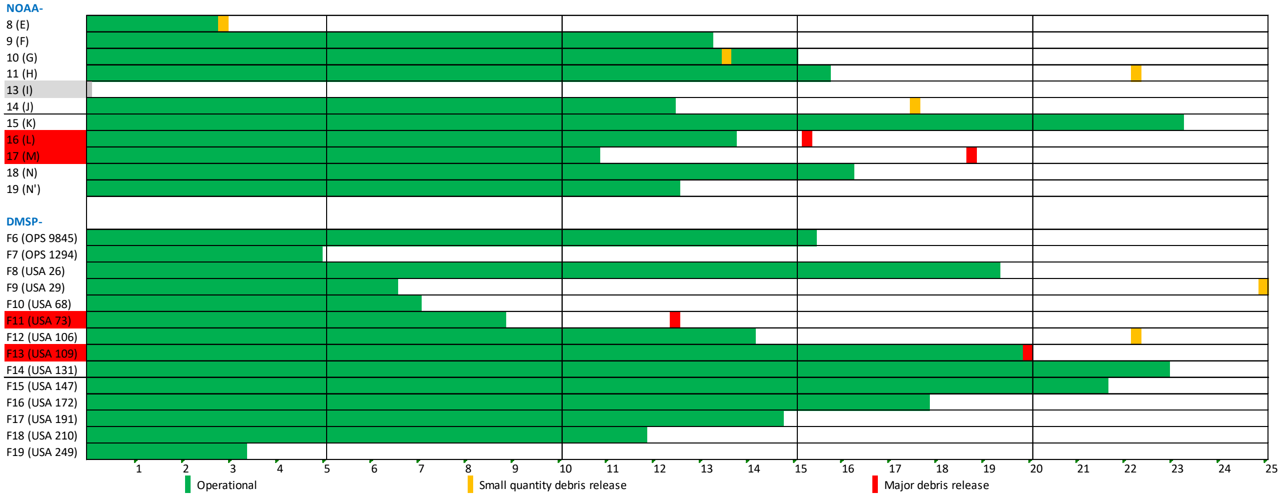


Figure 27: Fleet timeline is organized with respect to spacecraft age.

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.

Almost 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.
Collision with tracked debris or space debris too small to be tracked were eliminated as causes of the NOAA-17 breakup. Despite this, it is worth noting that the entire fleet of these spacecraft has (to-date) been left in orbits higher than 786 km, where their postmission orbital lifetimes will likely exceed 100 years. The risk of random collision for each spacecraft with a currently-cataloged object (assumed to be > 10 cm in size), which would result in catastrophic breakup, is estimated at 0.00011 per spacecraft per year (> 1 percent per spacecraft over the orbital lifetime). The risk of collision with a smaller 1 cm object, which would likely result in more limited but still significant debris generation is 0.0024 per spacecraft per year (about 21 percent per spacecraft over the orbital lifetime). These risks are expected to increase over time as the popular ~800 km orbit region becomes more crowded.

Autonomous Decommissioning Control (ADC) software and JPSS/Metop-A de-orbit

After the failure (9 June 2014) and subsequent break-up (25 Nov 2015) of NOAA-16, NOAA, NASA and Lockheed Martin team began investigating mitigation strategies for this event. Quickly after the initial failure the team implemented some minor spacecraft configuration changes for the Power Shunt Assemblies (PSA) to provide better redundancy; restoring VHF communication capabilities at the NOAA CDAS; increasing monitoring passes for secondary POES spacecraft from 7-9 out of 14 possible a day to ~9 a day. A Back Orbit Limiting Checking was implemented in ground software to supplement for the passes not taken every orbit on stored data from the spacecraft. Discussions began for an onboard Automated Decommissioning Control (ADC) software capability to safely passivate the spacecraft. This Flight Software (FSW) will passivate the spacecraft as similar to the ground commanded decommissioning as possible. The differences are listed below.

	Ground	**ADC**
Disconnect Battery Charge Paths	All	All
Disconnect Battery Discharge Paths	2 out of 3	None
Disable Transmitters	All	All
Deplete Nitrogen Gas	Thruster valves opened	Thruster valves opened
Disable SCPs	SCP1 Powered OFF, SCP2 POPed	Both SCPs configured for infinite loop
Offset Solar Array	Set to -180 deg	N/A
Enable Recorders	All	Only Current

The triggers to execute the software are

- Regulated bus voltage over limit
- Regulated bus voltage under limit
  - indicating that discharge is approaching capacity of batteries
- Battery temperature indicates “thermal run-away”
- Unrecoverable loss of attitude control

The ADC software was implemented on the remaining operational POES spacecraft as of:

- NOAA-15 as of Jun 29, 2020
- NOAA-18 as of Jun 9, 2021
- NOAA-19 as of Feb 10, 2021

From the ADC procedure:

The purpose of ADC is to monitor key parameters, primarily related to the power bus, such as bus voltage, battery voltage/temperature, and ESA lock. If a condition is identified such that total failure of the bus is imminent, the software will execute commands to decommission the spacecraft similar to expected ground commanding in such a situation. This involves disconnecting all battery charge paths, disabling all transmitters, depleting nitrogen gas, and placing the fight computers into an infinite loop. These actions will passivate the spacecraft and make it impossible for ground actions to recover the spacecraft.

Once installed, ADC functions in the background and requires no monitoring.

As this is a significant code modification, the process of upload, linking, monitoring and fully enabling is extend over multiple passes, multiple days. Implementation involves both the new ADC software and a new version of the Power Management (PMS) software.

From team member writeup:

Following the loss of NOAA-16 in June 2014 due to a failure that resulted in loss of regulation of spacecraft bus voltage, Engineers and Operations crews could not fully decommission NOAA-16 after multiple attempts at ‘blind’ commanding. This culminated in a JSpOC-identified breakup of NOAA-16 in November 2015 - which almost certainly was due to the rupture of a battery as a result of gas pressurization after the inability to properly decommission it.

As a result of that event, a tiger team of POES Subject Matter Experts (SMEs) was convened to identify ways of mitigating this risk, and the Autonomous Decommissioning Software (ADC) design was developed by that team to perform Decommissioning actions from on-board memory in the event that ground Operations is not able to command the vehicle. When triggered, ADC disconnects all battery charge paths, discharges all remaining propellant, turns off all transmitters, and places both flight computers in an infinite loop, which disables any software action and locks out most command functionality.

The combined NOAA Team performed Independent Verification and Validation (IV&V) testing of the Software modifications created by NASA support team and Lockheed Martin (S/C Manufacturer) - refining the process and the code over many months. The ADC Flight Software package was loaded to NOAA-15 over the course of two weeks - one for the primary spacecraft computer, and the next for the backup computer, both with the 'kill' triggers disabled. This allowed for a 5-day period of on-orbit monitoring to ensure proper functioning of unprecedented code prior to the activation of non-reversable autonomous 'kill' decommissioning actions. The ADC decommissioning action (kill) was enabled on June 29, 2020 at 15:56:46z on both of NOAA-15's spacecraft computers, and is silently awaiting End of Mission indications for it to perform its' function. With ADC, there is a high level of confidence that the spacecraft will be pacified in the event of most catastrophic bus failures - allowing maximum lifetime utilization of this valuable national asset. This ADC software was than developed and deployed for NOAA-18 and NOAA-19.

Metop-A de-orbit:

EUMETSAT deorbiting strategy for Metop-A is to lower the orbit altitude from the operational 817 km to 525 km for a 25 year re-entry. After reaching that attitude, they will deplete any remaining fuel, disconnect all 5 batteries and turn off any RF transmitters. This activity is scheduled for Nov 14-Dec 1, 2021.

Recommendations

Based on the investigation, the following recommendations are made:

1. Implement auto-decommissioning software on all remaining operational related spacecraft.

    a. This has been accomplished for the three remaining operational POES spacecraft.

    b. While battery charge disconnect appears to have been overcome in the case of NOAA-17, it is still the prudent thing to do.

2. At decommission, leave all battery discharge path connected.

    a. If by some condition, a charge path is reconnected, at least the charge has an out.

    b. This already is the action of ADC; it should also be in the commanded decommission.

    c. The DSMP procedure is also to leave all discharge paths connected.

3. Seek tumble rate information for the whole fleet on a periodic basis to better inform investigations of subsequent break-ups.

4. Consider further investigation to find root cause of NOAA-16, 17 breakups:

   a. Test a battery to rupture with measurements of fragment AMRs (recommended)

   b. On-orbit inspection (recommended)

   c. Testing of any remaining Battery Charge Assemblies (not recommended)

      i. LM states the only remaining BCA is on DMSP F20 on display at SMC, GSE would need to be recreated, paper end-item data packages are in deep storage with no working electronic index

5. For the future, ensure passivation includes energy generation as well as storage.

6. Consider active debris removal (ADR), consistent with US & NOAA/NASA policies.

Summary

The break-up 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 break-ups 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 break-up was found and it remains a mystery how an appropriately decommissioned spacecraft had at least one battery reconnected so as to be overcharged even eight years after decommissioning. Based on the investigation, it appears all 25 of the spacecraft of related designs remain at risk of future break-ups for decades to come, even if they were or will be appropriately decommissioned.

Appendix A: Letter of Appointment

June 8, 2021

TO: Distribution

FROM: Deputy Associate Administrator for the Science Mission Directorate, NASA
Assistant Administrator for Satellite and Information Service, NOAA

SUBJECT: Appointment of Engineering Investigation Board (EIB) for the NOAA-17 On Orbit Breakup Event, March 10, 2021

This memorandum establishes the NOAA-17 Breakup Event Engineering Investigation Board (EIB) and sets forth its responsibilities and membership. The chairperson and members of the EIB are listed in the enclosure.

The co-Appointing Officials hereby establish the NOAA-17 On-Orbit Breakup Event EIB to gather information, analyze facts, identify the proximate causes, root causes, and contributing factors relating to the breakup event, and to recommend appropriate actions to prevent or mitigate, to the extent possible, a decommissioned TIROS-N series spacecraft on-orbit breakup event from occurring again.

The Board chairperson will report to the co-Appointing Officials on all aspects regarding this investigation.

The EIB will complete the following actions:

- Obtain and analyze whatever evidence, facts, opinions it considers relevant, including passivation procedures and reports, and all available information related to the breakup event;
- Conduct tests and any other activity it deems appropriate;
- To the extent possible, determine the proximate causes, intermediate causes, root causes, and contributing factors relating to the breakup event;
- Develop recommendations that address the problem, and are clear, verifiable, and achievable in order to prevent or mitigate the risk of similar occurrences of on-orbit breakup from happening again; and
- Provide a final out-brief to the co-Appointing Officials and relevant stakeholders.

The Board chairperson will complete the following actions:

- Establish and document, as necessary, rules and procedures for organizing and operating the EIB, including any subgroups, and for the format and content of oral or written reports to and by the EIB;
- Designate any additional consultants, experts, or other individuals who may be required to support the activities of the EIB and define the duties and responsibilities of those persons;
- Document meetings and retain records.

The EIB will kick-off its investigation on June 14, 2021 and will provide a final out-brief by September 14, 2021.

The co-Appointing Officials will dismiss the EIB when it has fulfilled its requirements.

Sandra Connelly
Digitally signed by Sandra Connelly
Date: 2021.06.09 17:10:30 -04'00'

Sandra Connelly
Deputy Associate Administrator
Science Mission Directorate

VOLZ.STEPHEN.MICHAEL.1504223694
Digitally signed by VOLZ.STEPHEN.MICHAEL.1504223694
Date: 2021.06.21 08:50:38 -04'00'

Stephen Volz
NOAA, Assistant Administrator for
Satellite and Information Service

Enclosure

Distribution:
HQ/SMD/Ms. Peters
HQ/SMD/Ms. Montrose
HQ/JASD/Mr. Lee
HQ/JASD/Mr. Gagosian
HQ/JASD/Dr. Nguyen
HQ/OSMA/Mr. Panetta
HQ/OCE/Mr. Jedrich
GSFC/Mr. Andrucyk
GSFC/Ms. Kinney
GSFC/Dr. Hyde
GSFC/Mr. Mitchell
GSFC/Mr. McCarthy
GSFC/Mr. Young
GSFC/Mr. Hull
JSC/Dr. Liou
NOAA/Dr. Volz
NOAA/Mr. Marlow
NOAA/Mr. Walsh
NOAA/Mr. Walling
NOAA/Mr. Sisko
NOAA (ASRC)/Ms. Atkinson
NOAA/Dr. Talaat

Appendix B: List of Participants

Board

Name	Organization	Current Position	Responsibility on Board
Dr. Tupper Hyde	NASA GSFC	GSFC Chief Engineer	Chair
Mr. Brian Walling	NOAA OSPO	Engineering Branch Chief	POES S/C Ops SME
Ms. Maggie Atkinson	NOAA OSPO	LEO Lead Engineer (ASRC)	POES S/C Bus SME
Dr. Jer-Chyi (J.C.) Liou	NASA ODPO	Chief Scientist for Orbital Debris	Orbital Debris SME
Mr. Eric Young	NASA GSFC	Chief, Flight Power Systems Branch	Power Systems SME
Mr. Scott Hull	NASA GSFC	Orbital Debris Group Leader	Orbital Debris SME
Maj. Bryan Sanchez	USSF Space Delta 2	Director, Operations, Cyber, and Exercises	DMSP

Consultants/Experts

Quang-Viet Nguyen, NASA HQ, stakeholder liaison
Carl Gliniak, NOAA, POES Spacecraft SME
Ed Malinowski, NOAA contractor, Bus SME
Alex Bounitch, NOAA contractor, Bus SME
John Walthall, LM, Power SME
Dave Rust, LM, Power SME
Pete Kunzler, LM, Power SME
Ryan Thurber, LM, Bus SME
Jay Brusse, NASA contractor, metal whiskers
Mike Squire, NASA NESC, orbital debris
Darren McKnight, former DoD, spacecraft anomalies
David Adams, NASA HQ, Enterprise Protection
Alistair Funge, NASA MRPP
Joshua Hohlman, NASA HQ, intelligence division
Tom Barrera, NASA NESC consultant, batteries
Major Ronald Davies, USSF