

Root Cause Classification of Breakup Events 1961-2018

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This paper uses the updated NASA “History of On-Orbit Satellite Fragmentations 15th Edition,” to examine and categorize the root cause of historical breakup events to the greatest degree possible. Classes of debris progenitors have evolved, as many classes of Cold War-era spacecraft are now extinct, only to be replaced by new classes of payloads and rocket bodies statistically likely to experience debris-producing events. The efficacy of international debris mitigation implementation and root cause/fault tree analyses and lessons learned is examined in relation to the breakup of satellite classes or specific events. In select cases, the remaining on-orbit inventory of specific classes is identified in the context of possible future events. The environmental impact of these specific classes is examined and compared to nominal space environment projections. When appropriate, recommendations for debris remediation are made for specific satellite classes.

1 INTRODUCTION

In the 62 years since the beginning of the space age, the major contributor to the production of space debris large enough to be tracked by the U.S. Space Surveillance Network (greater than about 10 cm) has been explosions of rocket bodies and satellites. Both rocket bodies and spacecraft typically have multiple types of on-board stored energy sources, any of which might result in energetic breakups and the creation of debris. These include propulsion systems, pressure systems, electrical power systems, reaction wheels, heat pipes, and energetic materials (such as range-safety or self-destruct explosives). Unlike accidental collisions, accidental explosions may be minimized by the implementation of debris mitigation standard practices.

Figure 1 shows the growth over time in the number of catalogued objects, including debris. Note that for the purposes of this chart, debris objects that were identified and catalogued by the U.S. Combined Space Operations Center (CSPOC) some length of time after the breakup (even years later) were “back filled” to the time of breakup. Large breakups show “jumps” in number, with a gradual decay as the debris are gradually removed from the environment due to atmospheric drag.

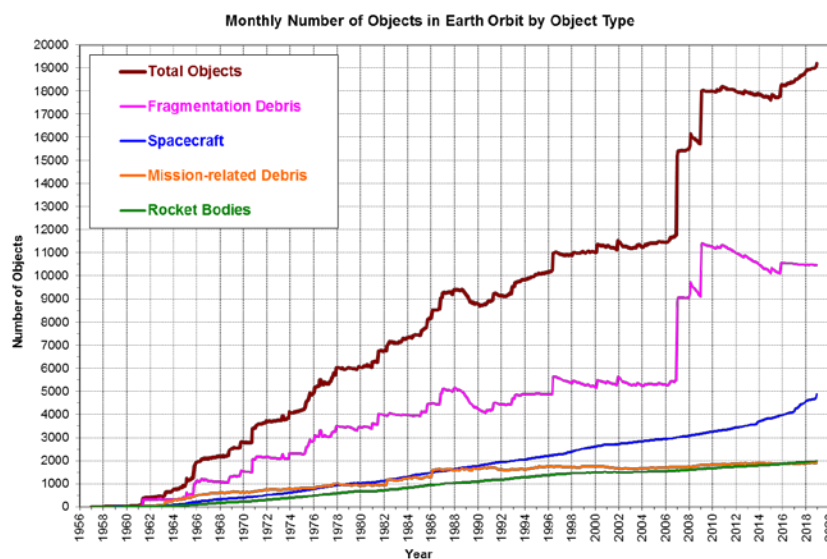


Fig. 1. The growth of debris populations over time. Major breakups show sudden “jumps” at the date of breakup.

Another way to understand the debris distribution is to plot it as a function of altitude. Figure 2 shows this distribution of trackable objects, using the concept of spatial density – where the volume is a spherical shell around the Earth – and the number is weighted by the fraction of time the orbiting object spends at each altitude. Debris dominates the orbit population between about 600 km and 1400 km altitude.

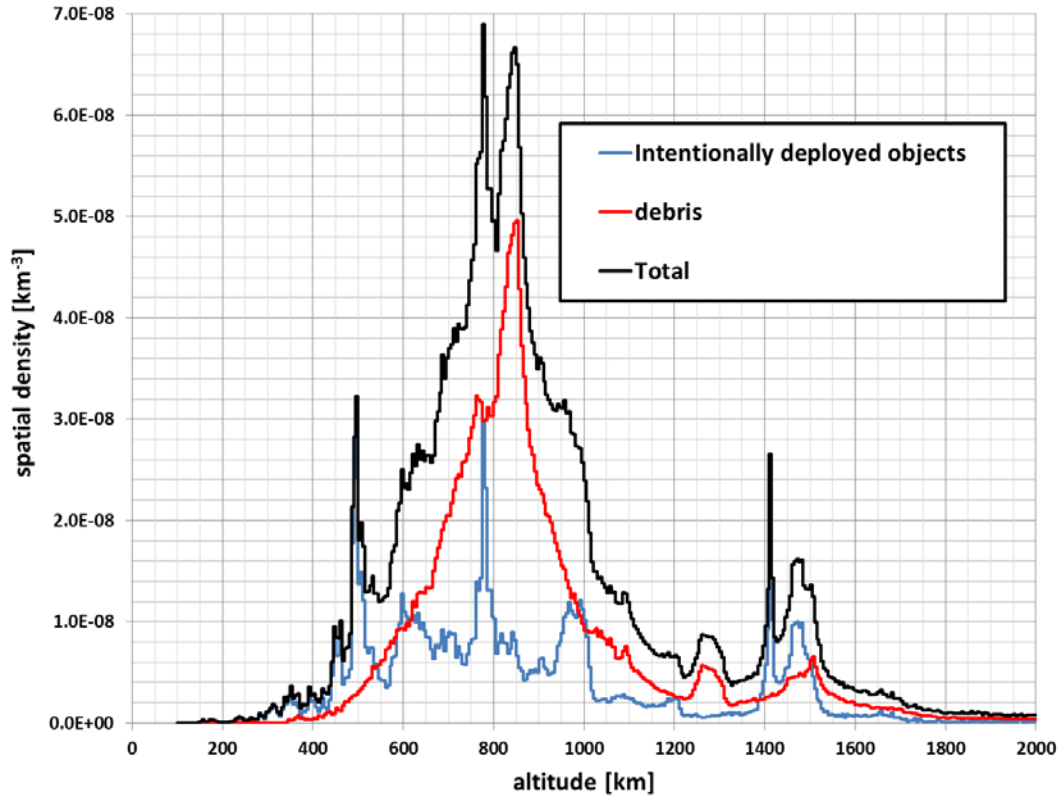


Fig. 2. The relative population of debris and intact objects at various altitudes. From about 600 km to 1400 km altitude, debris is the major contributor to the population of tracked objects (> 10 cm in size).

NASA’s Orbital Debris Program Office publishes and maintains the “History of On-Orbit Satellite Fragmentations” (HOOSF), now in its 15th edition [1]. At the time of cutoff for publication (4 July 2018), there were 246 recorded breakups identified in orbit. The overall rate of explosions has been relatively steady since the mid-1970s, despite widespread adoption of national and international mitigation standards to limit on-orbit explosions. This behavior requires a more detailed look at which satellites break up and why.

2 CAUSE ATTRIBUTION

Using the HOOSF data, it is possible to accrue statistics on the causes of the various breakups, as shown in Fig. 3. Note that a largest category of (known) breakups consists of propulsion-related explosions. However, nearly half of those are due to explosions of a single type of rocket body – the Russian SOZ (*Sistema Obespecheniya Zapuska*) units from Proton 4th stage ullage motors. Cause – in isolation – however, is insufficient to understand the temporal behavior of orbital debris generation, as technology, practices, and operations evolve over time. Figure 4 presents Fig. 3’s events over time.

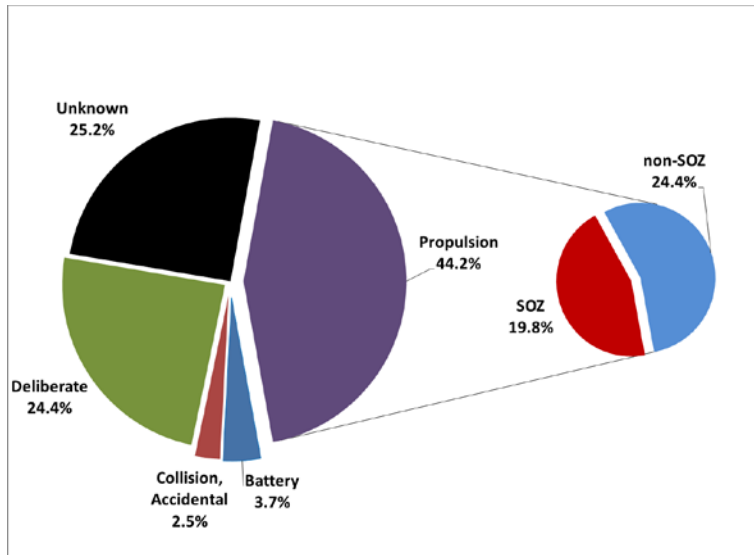


Fig. 3. This pie chart shows a proportion of various historical on-orbit breakup causes. The largest category of breakups is due to propulsion-related events, although a significant fraction of these is due to a single type of rocket body – the Russian SOZ units. Most of the deliberate events were intentional self-destruction of Russian military satellites before the 1990s. Note the significant fraction of breakups where the root cause was never uniquely identified.

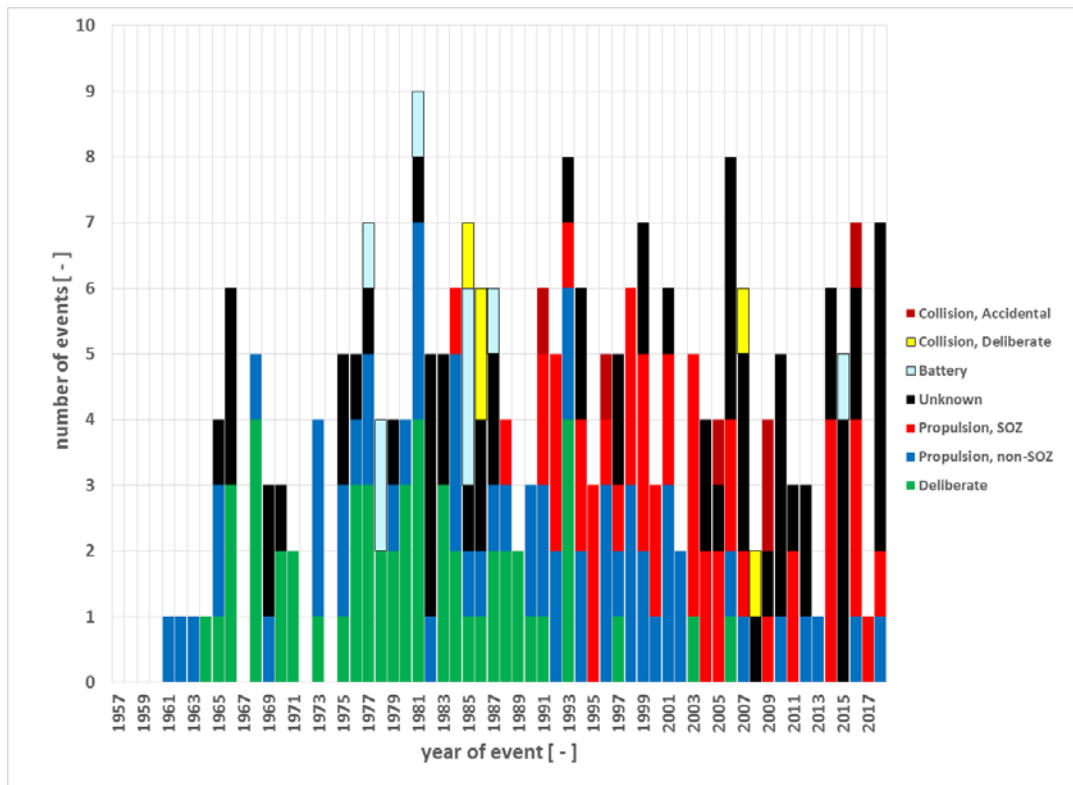


Fig. 4. Cause attribution by time. The largest category of breakups is due to propulsion-related events, although a significant fraction of these is due to a single type of rocket body – the Russian SOZ units. Most of the deliberate events were intentional self-destruction of Russian military satellites before the 1990s. Note the significant fraction of breakups where the root cause was never uniquely identified.

Figure 4 clearly identifies several salient features of debris production. Most of the deliberate breakups are due to a number of Soviet military satellite self-destruct events before the 1990s. These were motivated by payload recovery concerns (*i.e.*, payloads whose recovery within the Soviet Union was uncertain were destroyed on-orbit), apparent end-of-mission activities, or loss of signal. No deliberate explosions have occurred in the last decade. Rather, this category has been supplanted in its entirety by a lone battery-related breakup, propulsion-related explosive breakups (including those of SOZ units), and accidental collisions. Failures due to causes unknown remain a major contributor to the overall yearly totals over the last decade.

It is important to note that the SOZ statistics mask the history of other types of breakups. Figure 5 shows the breakup history from Fig. 3, but in a cumulative form, plotted both with and without the SOZ breakups. In the curve without the SOZ breakups, there is a noticeable change in slope in the late 1980s that corresponds to the beginning of widespread mitigation activities, primarily due to efforts by NASA and other agencies to educate the space community and implement mitigation standard practices. In essence, the SOZ units were a “grandfathered” system with known issues, but where no mitigation changes were made. Despite the reduction in fragmentation rate due to mitigation practices, fragmentations continue, albeit at a reduced rate. When a satellite or upper stage shows a pattern of fragmentation, changes are typically made to correct the problem for future launches. However, new systems or updates of older systems are continually being deployed, which sometimes introduce new failure modes that must be remedied.

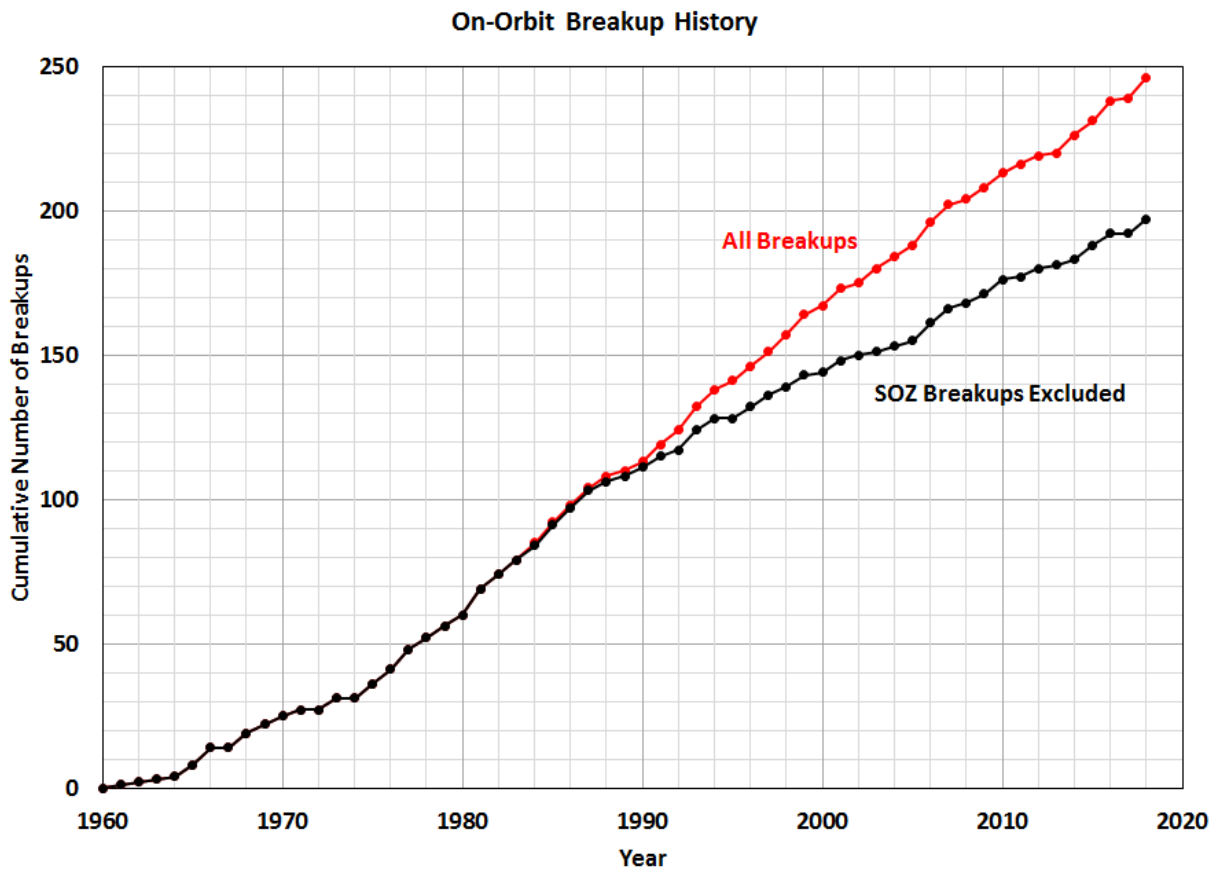


Fig. 5. Here, the data from Fig. 3 is plotted as a cumulative distribution, this time both with and without the SOZ breakups included. Note that ongoing SOZ breakups mask a noticeable reduction in explosion rates of other satellites beginning in the late 1980s. This is the time when widespread mitigation measures were implemented on a regular basis. Because the SOZ units are a “grandfathered” system (see text), they exhibit a similar slope to the steeper pre-mitigation fragmentations of the 1970s and 1980s.

3 CASE STUDIES

3.1 Cosmos 862 Class Spacecraft

The first case study is that of the Soviet/Russian Cosmos 862 class spacecraft (named after the first spacecraft to break up). This type of spacecraft had explosives onboard that were designed to self-destruct by ground command or a loss of communication with a ground station [2]. Eighteen of the first 31 flights (pre-1983) equipped with this self-destruct system are known to have experienced fragmentations on the mission time scale. Analysis by ground engineers determined that all were attributable to the self-destruct mode due to accidental loss of communication. This self-destruct system was removed in 1983 following the flight of Cosmos 1481. No known fragmentations of these satellites occurred for post-1983 flights.

3.2 DMSP-5D2 Spacecraft

The next case study concerns the U.S. Defense Meteorological Satellite Program (DMSP) Block 5D2 spacecraft (Tiros-N bus) launched into low-Earth orbit (LEO) sun-synchronous orbits. There were nine flights of the Block 5D2 spacecraft from 1982-1997. Of these, four are known to have fragmented: USA 29 (F9 = flight 9 of the 5D series), USA 68 (F10), USA 73 (F11), and USA 109 (F13). The USA 68 event was assessed to be an issue with the integrated upper stage (propellant-related), but the other three suffered a different type of failure. Investigations following the USA 109 failure (2 February 2015), found the problem to be due to a short circuit in the battery charger leading to an explosive battery rupture. The design was modified on all follow-on Block 5D3 spacecraft, and no further events have occurred. Unfortunately, there are no on-orbit mitigation procedures possible for those 5D2 spacecraft remaining in orbit, and future breakups may still occur.

3.3 SOZ Units

The next case study concerns the Soviet/Russian Proton fourth stages. These stages were designed to be restarted, and have two small ullage (SOZ) motors used to settle the fuel before restart and to provide three-axis control to the stage. The two ullage motors are then jettisoned, and left in transfer orbits to middle Earth orbit or in LEO. With many historic flights of these stages, the last flight separating the SOZ units occurred in 2012. There have been 50 known explosions of these SOZ units, some many years after launch. Sixty-four remain in orbit, of which 30 have fragmented. Fragmentation of the remaining SOZ units remains likely. Attribution is either to the over-pressurization of the residual propellants or to a mixing of the hypergolic propellants due to a breach in the common bulkhead [2]. The problem was identified in 1992 and modifications made to the Proton stages; however, it was decided to use up the remaining SOZ units still in stock, which now appears to have concluded. These units are abandoned after jettison, so there is no way to mitigate the possibility that the remaining tanks may yet explode.

3.4 Delta & Delta II Second Stages

The next case study concerns the U.S. Delta and Delta II second stages. The first identified fragmentation of this rocket body was Delta 62 in November 1973, and many more major LEO events followed. The manufacturer examined all available data, including estimates of the residual propellants on each stage [3], and concluded the breakups were caused by a mixing of the residual hypergolic propellants due to breaching of the common bulkhead, leading to an inefficient explosion. Studies by the NASA Orbital Debris Program Office and imaging by German radar of the Landsat 2 rocket body confirmed that large hulks remained in orbit after the breakups, corroborating the hypothesis of inefficient explosions. Figure 6 shows the debris cloud sizes of the Delta breakups (and one Indian Polar Satellite Launch Vehicle [PSLV] breakup) as a function of remaining fuel and oxidizer. The low correlation of debris cloud size to available energy also argues for inefficient mixing of the propellants in an explosion.

Cataloged Debris as a function of Residual Propellants

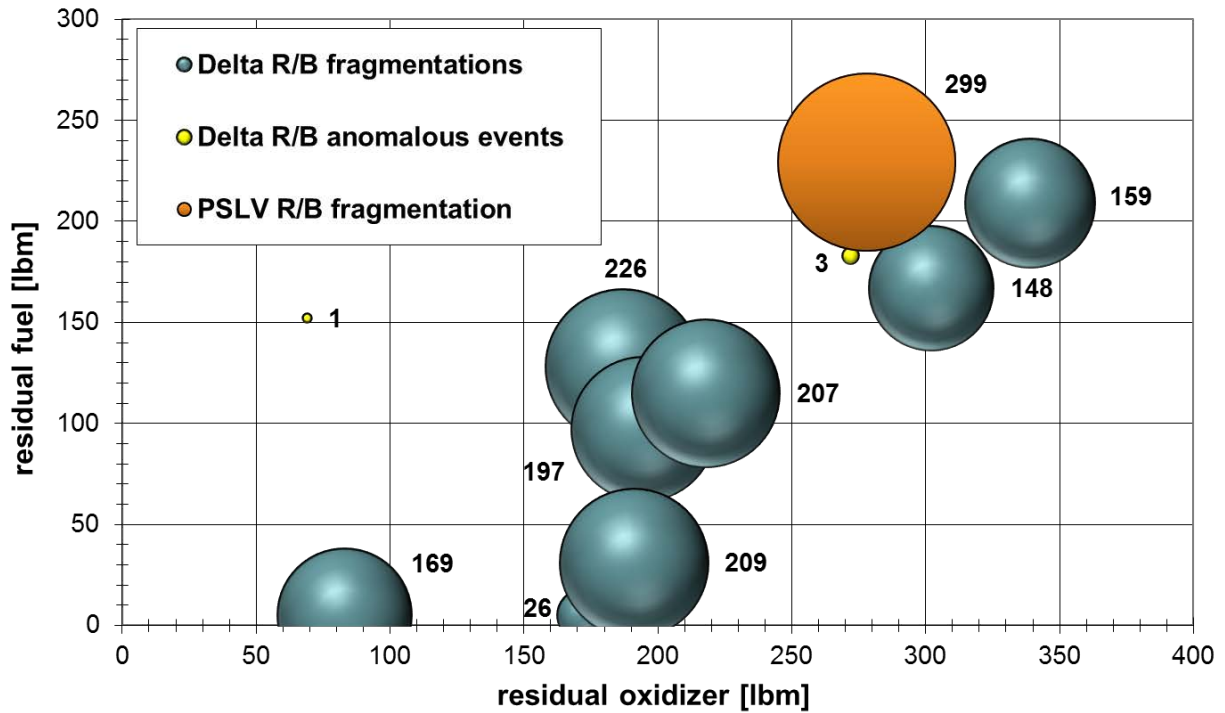


Fig. 6. The relative number of tracked debris of several explosions (shown graphically as size of the circles) as a function of both residual fuel and oxidizer. The low correlation between cloud size and amount of remaining propellants suggests a very inefficient explosion process.

While no single cause fits all the historical Delta second stage fragmentation data, the highest-likelihood attribution is to mixing of hypergolic propellants through a breach in the common bulkhead separating the fuel and oxidizer tanks. With this attribution, now-standard mitigation practices were introduced with the launch of Delta 155 in August 1981. These practices consist of disabling the range safety ordnance and burning remaining propellants to depletion during a payload evasive burn or, expending propellants by starting the main engine and holding propellant valves open for one minute and venting the nitrogen-gas ullage jets for five minutes. Figures 7 and 8 illustrate the effect of mitigation procedures upon the second stage.

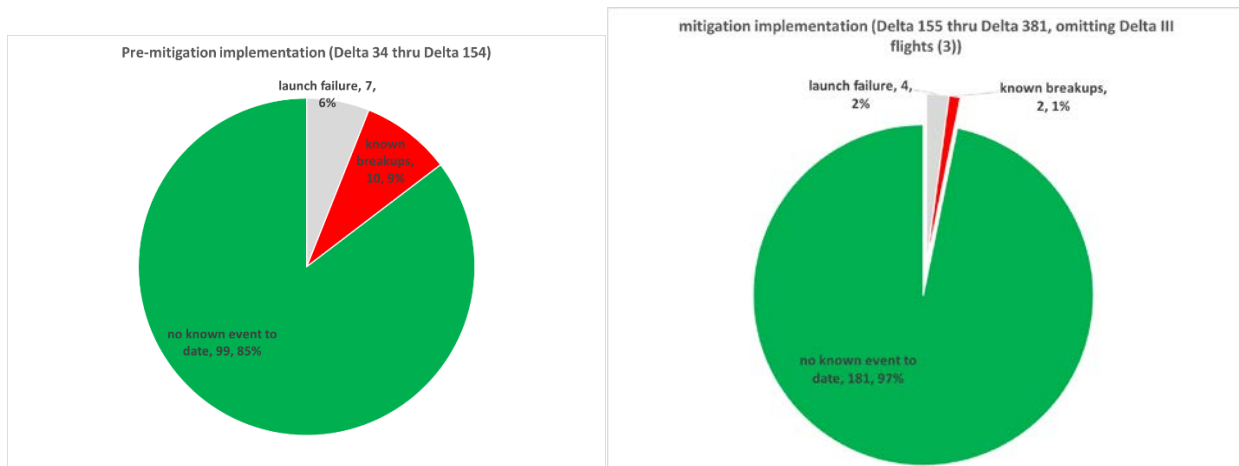


Fig. 7. Breakup events pre- (left) and post-implementation (right) of mitigation standard practices.

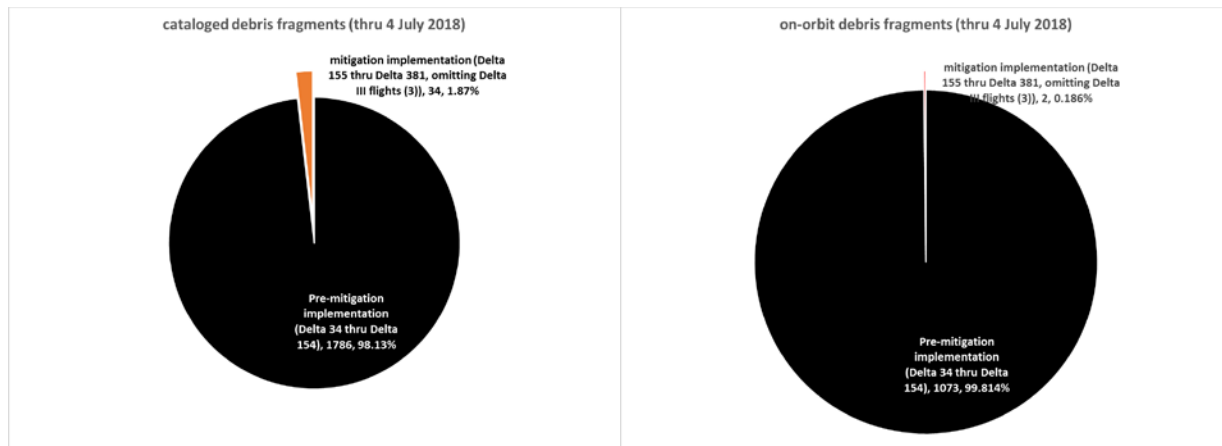


Fig. 8. Pre- (black) and post-implementation (orange) debris cataloged (left) and on-orbit (right).

Prior to this mitigation-driven operational procedure, Delta flights 34–154 inclusive experienced 10 known breakups, for a 9% rate. Afterwards, Delta flights 155–381 inclusive (but omitting three flights of the Delta III model) experienced only two known breakups, for a 1% rate. However, noting the number of debris cataloged in the pre- and post-mitigation operational regimes, pre-mitigation flights produced 1786 (98.13% of the total cataloged) debris while post-mitigation flights produced only 34 (1.87% of the total cataloged). Further, examining debris remaining on-orbit as of 4 July 2018, the information cut-off date of the 15th edition of the NASA “History of On-orbit Satellite Fragmentations,” 1073 (99.814% of remaining cataloged debris) pre-mitigation flight debris remain, versus only two (0.186%) for post-mitigation Delta fragmentation events. The significantly different nature of the post-mitigation events argues strongly that, indeed, the operational procedures for stage passivation introduced with Delta 155 resulted in a complete success in addressing the highest likelihood fragmentation scenario.

This record, for a completed launch program of Delta and Delta II second stages, reinforces the effectiveness of standard mitigation practices in ensuring the long-term viability of the LEO environment.

3.5 Ariane 1-4 Third Stages

The final case summarized herein is that of the model H8 and H10 variant third stages used by the Ariane 1, 2, 3, and 4 rockets. These cryogenic stages usually were used for geosynchronous orbit (GEO)-transfer orbits, but occasionally were used for LEO launches. In November 1986, there was a major fragmentation of Ariane flight V16, which was used to launch the SPOT-1 and Viking satellites into a sun-synchronous orbit. This breakup produced the most breakup fragments observed up until that date. However, it is quite possible that other Ariane stages left in GEO-transfer orbits experienced fragmentations, but due to the limited ability of the U.S. Space Surveillance Network to observe objects in those orbits, they went unidentified.

The manufacturer examined the available data, and was able to exclude causes due to battery explosions, accidental initiation of range-safety explosives, a mechanical breakup due to venting-imparted spin, or electrostatic discharge. Possible root causes included a common bulkhead reversal due to hydrogen or oxygen tank leakage, or rupture of the hydrogen tank due to structural fatigue induced by the orbit day/night thermal cycle. Mitigation practices were first introduced for the launch of SPOT-2 in 1989 (flight V36). These procedures consisted of vehicle reorientation after final payload separation, followed by irreversible opening of the oxygen vent valve [4, 5]. After a “proper time lag,” the pressure release valve on the hydrogen tank was opened irreversibly. Figure 9 graphically shows the effects of mitigation procedures on the rate of explosions.

From the lessons learned with the Ariane program, Ariane 5 became the first launch system where passivation of the upper stage was part of the engineering requirements and designs from day one. Other legacy systems have had to change pre-existing designs to limit explosions.

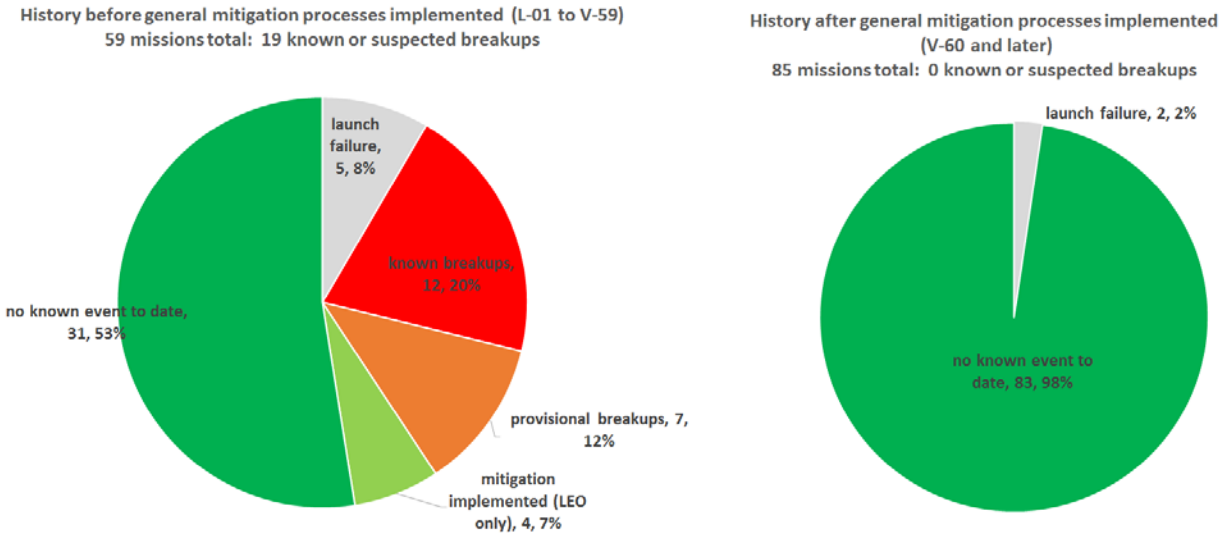


Fig. 9. The proportion of observed or suspected Ariane fragmentations that occurred before and after mitigation procedures were generally implemented. When LEO mitigation was implemented (left chart), no more explosions occurred, and when general mitigation procedures were implemented in all flights (right chart), no more on-orbit explosions occurred.

4 DISCUSSION AND CONCLUSIONS

This paper has reviewed several important aspects of on-orbit explosions. Explosions in space represent a major – but potentially controllable – source of orbital debris. This has resulted in a steadily growing population of debris in Earth orbit. In the case of several rocket body/spacecraft classes, repeated explosions have prompted careful study and implementation of changes in design or in changes of procedures or operations that have proven effective at mitigating future explosions.

With the implementation of widespread mitigation practices beginning in the late 1980s, the rate of on-orbit fragmentations dropped (with the exception of the “grandfathered” SOZ units). Indeed, the late 1980s to date may come to be known as the “Age of Mitigation” in future. Case studies of the Delta and Delta II second stages and the Ariane 1-4 third stage demonstrate the efficacy of systematic stage passivation.

Despite progress made in fixing older designs, many older examples of these spacecraft or rocket bodies that predate the changes remain in space, where they still have the potential to fragment. As discussed in the SOZ case study, 34 units remain in orbit. An examination of explosion probabilities indicates a peak probability at approximately 11 years elapsed time on-orbit, with non-negligible probabilities out to 27 years. Thus, a significant fraction of the remaining units may fragment in the future. While many SOZ unit events have resulted in less than 10 debris entering the public satellite catalog, in many cases only one object, 120 debris were cataloged for a unit associated with the launch of the Cosmos 2022-2024 satellite triplet. The reader is cautioned that due to the difficulty of tracking and cataloging debris in eccentric and deep space orbits, this cataloging record may be more representative of a typical SOZ breakup event than those events with only one or a few cataloged debris. A limited inventory of Cosmos 862-class spacecraft, and Delta, Delta II, and Ariane third stages remain in orbit, also in higher and/or eccentric transfer orbits, with the same difficulties in cataloging.

Nine DMSP-5D2 model spacecraft were launched between 1983 and 1997. Of these, three have experienced energetic breakup events (again, discounting the USA 68 integrated solid motor event). DMSP-5D2 flight 9 (the ninth flight of a Block 5D model, the fourth flight of a 5D2; USA 29) terminated its data collection mission in August 1994 but fragmented in December 2012; flight 11 (USA 73) ended its mission in August 2000 and fragmented in April 2004. USA 109 was partially functional when its mission was terminated by the February 2015 energetic breakup event. Breakup events may occur either when powered or long after formal flight activities have concluded. Flight 12 (USA 106) experienced a low-energy separation event, with four cataloged debris objects, in 2016, after 8 years of inactivity. Flights 6, 7, 8, 10, and 14 remain in orbit and have not experienced known spacecraft-related events, with select instruments on flight 14 (USA 131) still in use at the time of writing. Thus, an

inventory of this spacecraft model remains on orbit and may fragment in the future. Non-technical considerations aside, the DMSP Block-5D2 spacecraft may be good candidates for proposed debris remediation activities in future.

Upgrades of older systems are continually being introduced, as well as totally new launcher and spacecraft designs. These can introduce new failure modes not previously identified. Domestic (*e.g.*, the Spacecraft Anomalies and Failures, SCAF) and international (*e.g.*, the Spacecraft Environmental Anomalies and Failures, SEAF) workshop participants are actively working to better define a taxonomy and standardized methodology for describing, reporting, documenting, and sharing spacecraft anomalies and failures and assembling and disseminating lessons learned. Their mission is recognized and encouraged.

5 REFERENCES

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