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# Stage Survivability After Launch Abort

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## Executive Summary

This report summarizes findings for seven launch failures where launch vehicle stages experienced uncontrolled, unpowered flight prior to a destruct action or impacted essentially intact. The analysis used telemetry information for three launch failures, videos of three other launch failures, and a failure report provided by a launch vehicle contractor to estimate aerodynamic loading histories prior to surface impact or a destruct action. In two launch failure cases, a fully fueled upper stage separated from the first stage, continued to impact, and exploded. In three cases, the second stage would likely have continued falling to an intact impact were it not for destructive flight termination.

The study concluded that for off-nominal ascent, the typically applied aerodynamic loading limits appropriately predict interstage joint separation. However, the subsequent breakup of propellant tanks is not guaranteed, thus the potential to overestimate fragmentation and inert debris created by these conditions. Video evidence, processed telemetry, and trajectory reconstructions show that tank structures of these liquid-fueled vehicles will survive well past those aerodynamic limits. Depending on the launch vehicle and flight termination system, this may require additional consideration within the flight safety analysis procedure, including modeling survival of intact stages that might be released during a failed launch.

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# 1. From the Statement of Work

The recent trend toward Flight Safety Systems (FSS) that employ thrust termination only, in lieu of an explosive destruct system designed to disperse propellants, has led to situations where some launch vehicle stages have survived to impact and produced an explosion. Some upper stages have survived after FSS initiation during a lower stage (when there is no Inadvertent Separation Destruct System (ISDS)).

Jettisoned first stages can survive to impact, and the outcome of a jettisoned stage, in terms of break-up in flight or intact impact (with or without contained propellants), can have a significant effect of the size of ship and aircraft hazard areas.

The FAA seeks a better understanding of the empirical evidence on the conditions for survival and break-up of stages after failures and nominal jettison events.

Aerospace will provide FAA/AST with:

1. Any available data on the outcome of stages that experience uncontrolled, unpowered flight in terms of breakup prior to impact or essentially intact impact,

2. Estimates of the maximum product of dynamic pressure and orientation (Q-sin(alpha)) that each stage reached without breakup, and, if breakup occurred, the cause of initial breakup (e.g., bulkhead collapse, tank wall failure).

3. An analysis comparing the results of the different flights and identifying possible trends.

## 2. Assumption

Given that near-pad structural failure due to aerodynamic loads, not specifically extreme aerodynamic heating during atmospheric reentry, is of interest, we will assume that stages that burn to completion (solid motor stages) or return to earth following trajectories that expose the stage to extreme heating sufficient to cause high-altitude breakup and dispersal of remaining propellants before impact are not the primary focus of the study. We will look at cases where stages did or could have contained residual propellants at impact. These cases are most likely for near-launch pad accidents.

## 3. Data and Sources

Aerospace's Acquisition Support and Systems Engineering Toolset (ASSET), a dataset that contains validated technical and programmatic information for every launch and space vehicle that has been launched. ASSET is a major source of information on launch failures and a starting point for this investigation. This enterprise database contains:

- Unclassified, validated space system technical and programmatic information and non-catastrophic anomalies for US and foreign satellites and launch vehicles
- Technical and descriptive reference documentation, issue tracking, and lessons learned
- A historical record of all US and worldwide orbital launches dating back to Sputnik in 1957 and most recent information on planned launches
- Specific vehicle and program details such as launch weight, power, orbital type, agencies involved, mission and program categories plus
- Links to causes and corrective actions for launch mishaps and supporting documentation, and
- Specific mishap reports, data sources, video links, immediate failure cause, root cause, and related data.

ASSET's document domain is an extensive archive of programmatic and technical documentation, including design, operations, pre-flight, post-flight, production and test, requirements, cost schedule, cross program, and other document types.[1]

ASSET provided basic historical information on failed launches where stages experienced uncontrolled, unpowered flight in terms of break-up prior to impact or an essentially intact impact.

Aerospace acquired telemetry data for one launch where data was returned during free fall of the launch stage (3/18/2020 Falcon 9 booster) and one failure where data was available both before and after Stage 2 separation from the core stage (8/12/1998 Titan IV Centaur). The videos of four failed launches (9/12/2020 Astra Flight 3, 7/2/2013 Proton-M, 9/30/1977 Atlas Centaur-43, and 9/02/2021 Firefly Alpha) and a failure report for one launch (8/28/2021 Astra flight 5) provided sufficient information for reconstructions of the falling conditions (altitude, velocity, angle of attack) for each vehicle that were used to estimate aerodynamic pressures experienced during the fall.

[1] ASSET contains information of a sensitive nature, including, but not limited to: Contractor proprietary, Competition sensitive, FOUO, Export Controlled, and other information to which access should be tightly controlled and limited to Aerospace employees.

## 4. Aerodynamic Pressures (Q-sin(α), Q-α)

The aerodynamic pressures on an ascending launch vehicle are typically defined as a "Q-sin(α)" value where "Q" is the dynamic pressure that is based on vehicle velocity and surrounding air density and "α (alpha)" is the angle-of-attack of the vehicle. The sine of the α angle gives the component of the dynamic pressure force that acts laterally on the vehicle and incudes a bending moment that will tend to buckle the vehicle. These two terms are multiplied together and expressed in pounds per square-foot (psf). Also used is the nearly equivalent "Q-alpha" where the angle-of-attack is directly multiplied by the dynamic pressure, with units in pounds per square-foot degrees (psf-deg).

Launch vehicle manufacturers provide detailed reports and data to the requisite, responsible safety organization on the Q-sin(α) limit for a launch stage (the point where the structure of a launch vehicle or stage will fail due to aerodynamic pressure during launch) for launch approval. Typically included are estimates of aerodynamic pressure that will result in vehicle breakup during an anomalous ascent. Table 1 summarizes values given by contractors for various liquid-fueled launch vehicles. A range of values can signify dependency on additional parameters such as configuration, Mach number, or propellant level. Note these are breakup estimates; the nominal ascent profiles for all launch vehicles are designed to much lower limits.

Table 1. Contractor-Provided Q-Alpha Limits for Several Liquid-Fueled Launch Vehicles

| Launch Vehicle | Q-alpha limits (psf-deg) | |
|---|---|---|
| | Thrust on | Thrust off |
| Not identified for proprietary reasons | 4000 | Not specified |
| | 4600 to 8500 | Not specified |
| | 2600 to 4800 | Not specified |
| | 14000 | 25000 |
| | 4373 to 16819 | 42336 to 120960 |
| | 5280 to 50090 | 4900 to 33200 |
| | 12350 | Not specified |
| | 10000 | Not specified |

# 5. Trajectory Reconstructions

Seven launch failure cases were identified where launch stages experienced "uncontrolled, unpowered flight in terms of break-up prior to impact or essentially intact impact" and sufficient information is available to reconstruct trajectories after failures occurred. Either telemetry or video of these failures was used to "estimate the maximum product of dynamic pressure and orientation (Q-sin(α)) that each stage reached without breakup, and, if breakup occurred, the cause of initial breakup (e.g., bulkhead collapse, tank wall failure.") Reconstructions were possible using telemetry data on four launch failure cases; videos provided sufficient details for reconstruction on three other failure cases. Three additional cases in which telemetry data was available were examined. In each case, the dynamic pressure at loss-of-signal was well below the likely vehicle threshold, thus not informative as to stage survivability.

## 5.1 Reconstructions Based on Telemetry Data

Empirical evidence on the conditions for survival and break-up of stages after failures and nominal jettison events was developed from telemetry data on three launch failures: Falcon 9 booster recovery failure on 18 March 2020, Titan IV Centaur A-20 launch failure on 12 August 1998, and the 2 September 2021 Firefly Alpha launch failure. A summary and data reconstruction of these failures are provided below.

### 5.1.1 8/12/1998 Titan IV Centaur Failure

The Titan IV guidance system short-circuited at T+40 seconds due to frayed wire, the vehicle then lost control and activated the inadvertent separation destruct system (ISDS). Archived data was obtained from Aerospace's Space lift Telemetry Acquisition and Reporting System (STARS) that facilitated reconstructing the Titan IV Centaur (TIVA-20) failure. A video of the launch is available at https://www.military.com/video/explosions/blast/titan-explodes-with-1-billion-satelite-onboard/1116793430001.

This vehicle had two guidance systems that were active during booster ascent: the core (Titan) guidance was steering the vehicle, while the Centaur upper stage guidance was monitoring flight in preparation for its post-staging burns to orbit. Titan telemetry data was at a one-second interval up until destruct, and the Centaur telemetry continued past the initial destruct action at a 0.02 second interval for an additional 1.6 seconds. This would indicate that the Centaur survived the core stage explosion and was still intact through high aerodynamic pressures until the telemetry stream ended. MFCO (Mission Flight Control Officer) destruct command was sent a few seconds after loss of telemetry. It is unclear if the Centaur was still intact at that time. The Centaur was in a rapid turn rate just prior to loss-of-signal, withstanding very high values of Q-alpha and Q-sin(α). The Titan version of Centaur was shorter and fatter than the Atlas version, so that could explain the high threshold.

### 5.1.2 3/18/2020 Falcon 9 Booster Recovery Failure

On this attempted drone ship recovery, the Falcon 9 booster suffered a premature shutdown of one engine during ascent. The engine failed to restart during the booster descent, hence reduced thrust and possible propellant depletion resulted in a failed landing, with the booster never reaching the drone ship.

Aerodynamic limits were calculated based on a reconstruction of the Falcon 9 booster trajectory using telemetry data. The vehicle was decelerated by the reentry burn and appeared to maintain attitude control until higher density altitude followed by a rapidly increasing angle-of-attack. The booster may have broken apart at or after the last telemetry point, but it is unclear as to the breaking limit. Nevertheless, the vehicle had just withstood high values of Q-alpha and Q-sin(α), and possibly about exceed those values as alpha increased. It earlier experienced high g-loading, but then decreased.

### 5.1.3 9/02/2021 Firefly Alpha Failure

On its first launch, Firefly Alpha failed to achieve orbit due to a first stage engine, Engine 2, that unexpectedly shut down 15 seconds into flight. The thrust vector control provided by the three remaining first stage engines, proved insufficient when the vehicle reached supersonic speeds about 140 seconds into flight. At this point, Firefly Alpha began to tumble out of control and was destroyed when Vandenberg's Western Range Safety crew initiated the self-destruct command.

Aerodynamic pressure was processed from telemetry. Results indicate the vehicle was tumbling and decelerating, having passed through high maximum Q-alpha and Q-sin(α). Of note is that the pressure was decreasing at the destruct time. Therefore, the vehicle may have continued flight, without breakup, for an extended period if no destruct action had occurred. Video[2] imagery of the flight was available, and a structural break of the fairing is seen soon after loss of control. The rocket continues with no subsequent breakup until MFCO destruct command.

## 5.2 Other Telemetry Data

Three additional cases in which telemetry data was available were examined. In each case, the dynamic pressure at loss-of-signal was well below the likely vehicle threshold, thus not informative as to stage survivability in terms of Q-alpha.

### 5.2.1 12/8/2010 Falcon 9 -002 Booster Entry

This early, demonstration flight of Falcon 9 was unique because there were assets deployed to track the booster entry via radar and video. Telemetry data was used to reconstruct the booster entry trajectory. The dynamic pressure was rather low, this indicates that aero heating may have caused high internal pressure, combined with deceleration g-load as being the factors leading to breakup.

### 5.2.2 1/19/2020 Falcon 9 Crew Dragon In-Flight Abort Test

The telemetry data from the Falcon 9 Crew Dragon In-Flight Abort test was processed. After an intentional early propulsive shutdown of the booster, the Dragon capsule escaped, followed by booster breakup. The last Stage 1 telemetry data point indicated both low angle-of-attack and low dynamic pressure. It is unclear if that data accurately represents the last vehicle state at breakup, or if some factor other than bending due to pressure caused breakup, such as axial pressure on the forward tank. In any case, the final, low Q-alpha value is not informative in terms of a breakup limit.

### 5.2.3 2/10/2022 Astra Flight 7 Failure

Also known as Astra LV0008, this vehicle had a payload fairing separation failure, resulting in the rocket's upper stage tumbling out of control shortly after engine ignition and stage separation. Telemetry data was received for an extended period showing a tumbling vehicle that passed through high apogee altitude followed by descent. Trajectory simulation shows the stage at rather low Q-sin(α), low aero heating, and low g-load at loss-of-signal. Continuing the vehicle fall by simulation indicates rapidly increasing pressure, g-load, and temperature, any of which may have caused a breakup. It is unclear if the spherical LOX and fuel tanks survived to ocean impact. Due to the loss of telemetry at high altitude, no determination can be made on the aerodynamic pressure limits experienced by this vehicle.

[2] https://www.youtube.com/watch?v=NisZvIs4SKk&t=277s

## 5.3 Reconstruction Based on Failure Report

### 5.3.1 8/28/2021 Astra Flight 5 Failure

Astra conducted an orbital launch attempt at Pacific Spaceport Complex – Alaska (PSCA) with LV0006. After losing an engine at liftoff, the flight was terminated at high altitude. The vehicle immediately tumbled with the fairing and upper stage still attached. The last data point received from the upper stage was at relatively low altitude. Reconstruction shows the Q-alpha and Q-sin(α) would have occurred at much higher altitude and then decreased. Thus, both stages may have impacted the ocean intact.

## 5.4 Reconstructions Based on Video Data

Many launch failures have been captured by video, and videos provide additional means of reconstructing an anomalous trajectory. The Aerospace Corporation has expertise in modeling launch trajectories including flight anomalies. The following launches were selected for developing trajectory simulations and corresponding aerodynamic pressure analysis based on the video recordings.

### 5.4.1 9/30/1977 Atlas Centaur-43 (AC-43) Failure

An attempted launch of an Intelsat communications satellite took place on AC-43. Shortly after liftoff, abnormal temperatures were detected in the Atlas's thrust section and continued to rise as the booster ascended. A visible thrust section fire could be seen starting at T+33 seconds and sustainer thrust vector control hydraulic pressure was lost at T+56 seconds, causing total loss of vehicle control. The payload fairing and satellite were stripped from the booster, followed by explosion of the Atlas stage at T+58 seconds as the thrust section fire touched off the propellant tanks. The Centaur flew free until being destructed by the Range Safety Officer several seconds later.

Slow motion video[3] clearly shows the Centaur ejected forward from the booster explosion and continued in a tumbling motion until the range-commanded destruct. Although no telemetry information for this case has been found, the Atlas geosynchronous transfer orbit mission is well-established; therefore, simulating a malfunction turn 56 seconds into flight, with subsequent destruct can be readily accomplished. Trajectory simulation indicates the Centaur experienced Q-alpha greater than 25,000 psf-deg and Q-sin(α) of 306 psf (Figure 1). Drag on the vehicle was quickly slowing it down and decreasing dynamic pressure-- if not destructed, the upper stage could have survived to an intact impact.

[3] https://www.youtube.com/watch?v=yfynkcSoFWY&list=PLvy6N6HWNj24rHW1arBHksR3bFc0Ec9Cd&index=98

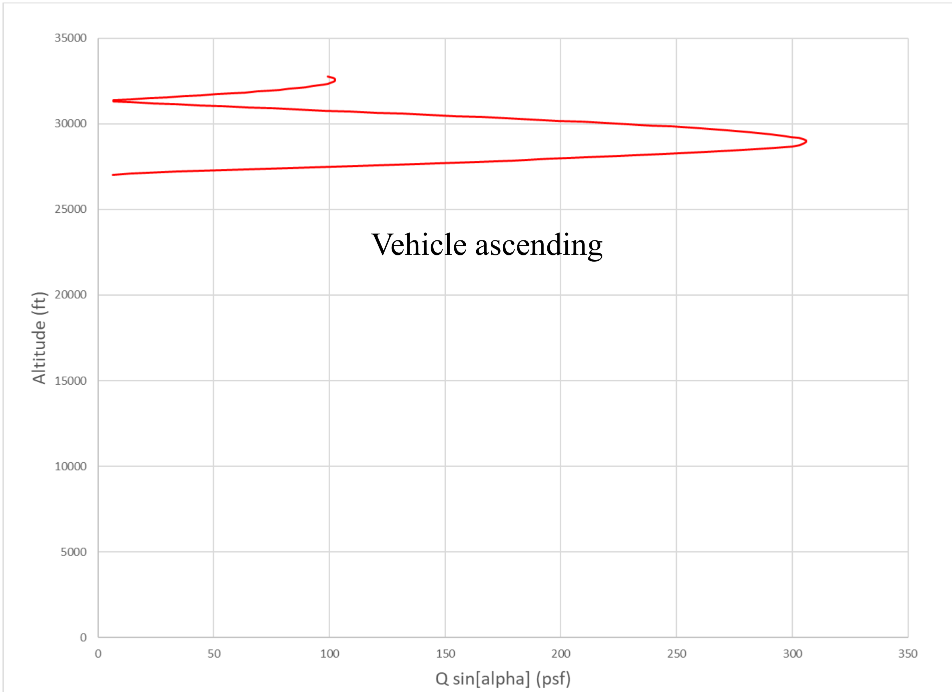


Figure 1. Aerodynamic pressure during Atlas AC-43 Centaur free flight until destruct.

### 5.4.2 7/2/2013 Proton-M Failure

A Proton-M launching three GLONASS navigation satellites experienced a failure shortly after liftoff when the booster crashed near the launch complex at Baikonur. The vehicle lost control very early in flight, never recovered and eventually exploded on impact.

Numerous videos from various perspectives can be found on this failure. A high-definition, slow-motion video[4] provided detailed views of the anomalous pitch-over, separation at the Stage 3 interstage, flameout of engines, tumbling of the stages, and the resulting explosive impact. A trajectory simulation was produced to mimic this behavior, which included a malfunction turn at low altitude. The simulation data (Figure 2) shows the Q-sin(α) pressure reached a maximum shortly before impact. The Stage 1 and Stage 2 segments of the Proton remained attached throughout the descent, likely withstanding Q-alpha more than 26,000 psf-deg and Q-sin(α) of 329 psf.

[4] https://www.youtube.com/watch?v=vqW0LEcTAYg

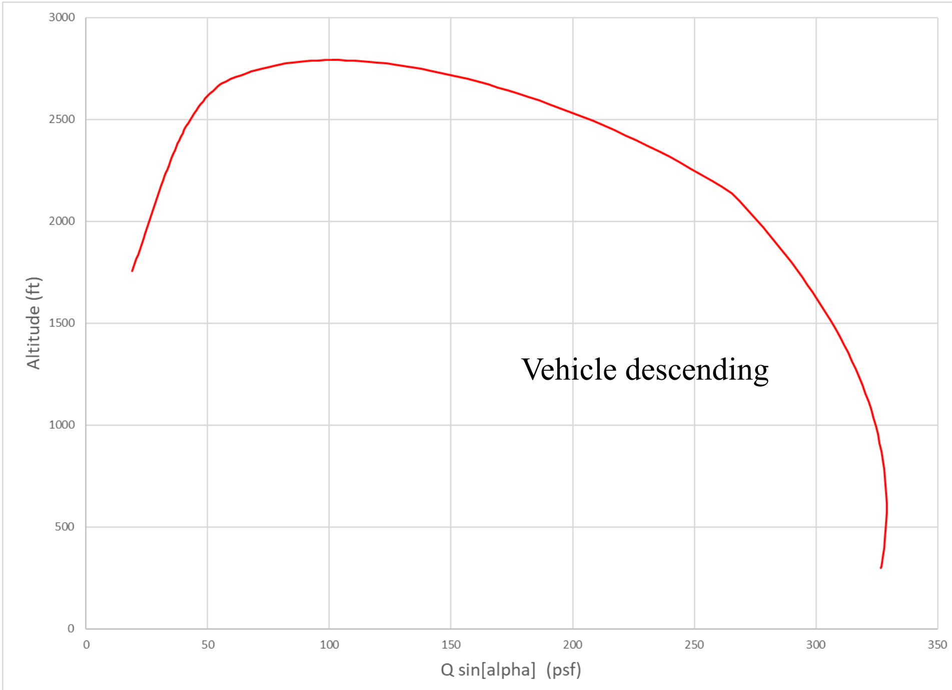


Figure 2. Aerodynamic pressure on Proton-M Stages 1&2 until impact.

### 5.4.3 9/12/2020 Astra Flight 3 Failure

Astra conducted an orbital launch attempt at Pacific Spaceport Complex – Alaska (PSCA) with Rocket 3.1 on September 12, 2020. The flight was terminated at T+26.2 seconds by range safety personnel due in part to a control anomaly the rocket experienced at liftoff and continued during powered flight. According to an Astra report[5], dynamic pressure and angle-of-attack were recorded. There is visual evidence of inadvertent stage separation at the onset of flight termination when Q-alpha and Q-sin(α) were still at relatively moderate levels.

The video[6] of the flight and failure was used for modeling the tumbling during descent. A structural break at the interstage is clearly seen early on, however both stages continue in free fall, with no subsequent breakup, to ground impact. Simulation shows the maximum Q-alpha of 23,500 psf-deg and Q-sin(α) of 271 psf (Figure 3) occurred just prior to explosive impact.

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[5] Astra, "Rocket 3.3 Max Q Analysis Report", SSP-00615 Rev2, 9 March 2022.
[6] https://www.kodiakdailymirror.com/community/health/video_d5029922-9835-5123-9aa7-6d764ef8b363.html

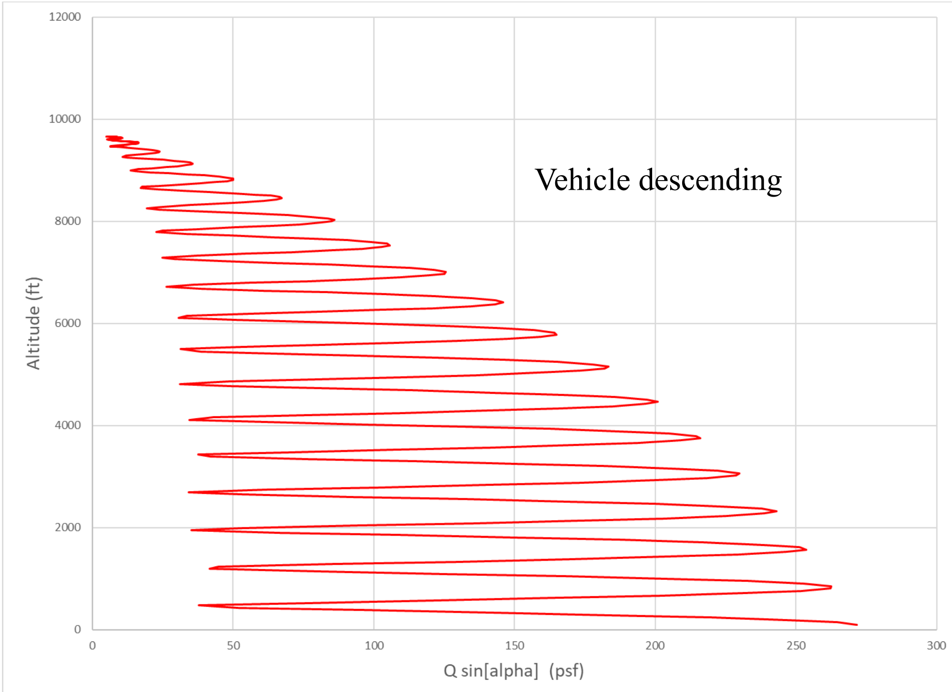


Figure 3. Aerodynamic pressure history for Astra flight 3 until impact.

### 5.5 Summary of Failure Data from Reconstructed Trajectories

This review of failure data indicates that explosive impact occurred for two cases and intact impact might have been the outcome for a third. Also, if not for destruct action, both the Titan and Atlas Centaur stages might have survived to surface impact, as well as the Firefly stages. Table 2 summarizes the key parameters of the maximum aerodynamics from the trajectory reconstructions described above. Table 3 summarizes the fairing and interstage breakups from the reconstructions. The mishaps having proprietary telemetry data were processed and resulted in Q-alpha values that are consistent with the ranges shown in Table 2 and Table 3.

Table 2. Summary of Maximum Aerodynamics Based on Reconstructed Trajectories

| **Mishap** | | **Flight time[7]** | **Max Qα altitude** | **Max Qα velocity** | **Max Q** | **Max α** | **Max Qα** | **Max Qsin(α)** | **Outcome** |
|---|---|---|---|---|---|---|---|---|---|
| **Date UTC** | **LV** | **sec** | **ft** | **ft/sec** | **psf** | **deg** | **deg-psf** | **psf** | |
| 9/30/1977 | Atlas Centaur 43 | 59 | 29460 | 788 | 286 | 89 | 25570 | 306 | MFCO destruct |
| 7/2/2013 | Proton M | 30 | 300 | 570 | 383 | 90 | 26340 | 329 | Explosive impact |
| 9/12/2020 | Astra flt 3 | 70 | 100 | 480 | 272 | 87 | 23580 | 271 | Explosive impact |

[7] Time from liftoff of maximum Q-alpha.

Table 3. Summary of Intermediate Breakups Based on Reconstructed Trajectories

| Mishap | | Flight time | Max Qα altitude | Max Qα velocity | Max Q | Max α | Max Qα | Max Qsin(α) |
|---|---|---|---|---|---|---|---|---|
| **Date UTC** | **LV** | **sec** | **ft** | **ft/sec** | **psf** | **deg** | **deg-psf** | **psf** |
| 9/30/1977 | Atlas Centaur 43 fairing break | 57 | 27860 | 863 | 360 | 30 | 10730 | 195 |
| 7/2/2013 | Proton M interstage break | 23 | 2630 | 425 | 200 | 63 | 12600 | 178 |
| 9/12/2020 | Astra flt 3 interstage break | 28 | 6800 | 524 | 270 | 15 | 4050 | 70 |

## 6. Findings

The study provides some valuable insights as to what can be anticipated from launch anomalies that involve a stage in uncontrolled flight. In the event of a rapid pitch or yaw turn during ascent, often referred to as a malfunction turn, the fairing would quickly break loose, likely followed by a break at the interstage connection. The remaining boost and upper stages, especially if unpowered, can withstand high aerodynamic pressure, and for each of the mishaps examined, at least one of the stages withstood high aerodynamic pressure.

For surviving stages, the average maximum Q-alpha was 28,500 psf-deg, and average Q-sin($\alpha$) was 365 psf. For the intermediate breakups, the average maximum Q-alpha was 12,380 psf-deg, and average Q-sin($\alpha$) was 185 psf. Depending on the altitude of the anomalous event, it is quite possible for an unpowered stage to remain intact, resulting in an explosive impact some distance from the impact location of the primary stage. For example, in the absence of a destruct scenario, simulation of the AC-43 failure would result in the booster and upper stage impacts downrange separated by 0.5 nmi or roughly one kilometer.

It is of note that launch vehicle manufacturers provide reasonable Q-alpha limits for triggering a failed ascent – a break at the interstage while still thrusting. However, video evidence, processed telemetry, and trajectory reconstructions show that the tank structures of these liquid-fueled vehicles will survive well past those limits. Depending on the launch vehicle and flight termination used, this may require additional consideration within the flight safety analysis procedure, such as modeling an intact stage instead of inert debris fragments.

## 7. Summary

Telemetry information is available for three launch failures that experienced uncontrolled, unpowered flight in terms of break-up prior to impact or essentially intact impact, and videos of three other launch failures were used to estimate Q-alpha and Q-sin(α) histories prior to surface impact or destruct. An additional Q-sin(α) history was developed from the failure report provided by the launch vehicle contractor.

The launch failures examined in this study indicate a trend of a high-threshold Q-sin(α) before an unpowered stage will completely break apart. For off-nominal ascent, aerodynamic limits causing interstage separation may be appropriately predicted, yet the fragmentation of the individual stages does not occur. In two cases, the fully fueled, upper stage separated from the first stage, continued to impact, and exploded. In three cases, the second stage would likely have continued falling to an intact impact were it not for a destructive flight termination. Two other cases experienced high aerodynamic pressures prior to an undetermined outcome.

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