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Mission Success of U.S. Launch Vehicle Flights from a Propulsion Stage-based Perspective: 1980-2015

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This report documents a study of the historical safety and reliability trends of U.S. space launch vehicles from 1980 to 2015. The report contains three sections: a baseline survey of historical launch vehicle failure data, an interpretation of the survey data in terms of vehicle safety for crewed vehicles, and a summary of key findings and safety interpretations. The report is supplemented with three appendices with data tables and detailed descriptions of safety and reliability historical data for flights that experienced launch vehicle error.

Introduction

This study began as an investigation into the relative safety and reliability associated with launch propulsion technologies. Because the scope was general, and not limited to any specific launch architecture, it was impossible to make specific predictions about risk implications. As a result, the study became an assessment of the historical record, with the goal of extracting trends that are applicable at a general level. As many such surveys have been done before [1] [2] [3], the expectation was that the current effort would simply be an update that included flights since the previous historical summaries, with a specific emphasis on propulsion technology as a differentiator.

As we went through the detailed failure reports, we quickly realized that using the traditional approach of counting failures that manifested in the propulsion systems was incomplete. Instead, the required support subsystems for a propulsion system must be considered as part of the propulsion system success rate. For example, a liquid rocket engine (LRE) requires the propellant management system to function, and failures in the propellant management are a reflection of the complexity of LRE systems. However, while tracking where the launch vehicle failures manifest is important, it does not in itself provide a complete picture. Conversely, considering failures at the vehicle level tends to be more about the heritage of the specific systems than the propulsion technology. For this reason, we consider historical failures of launch vehicle stages, as this is the lowest level that contains the propulsion system and its support subsystems.

By considering failures at the stage level, we also identify key interactions that can lead to failures. These interactions not only broaden the scope of propulsion system robustness, but also provide additional insight into the proximate causes of launch vehicle failures in general.

Ultimately we would also like to understand the implications of propulsion system reliability on crew safety. Since the vast majority of launches are for cargo missions, a direct assessment of accidents and crew safety is under-supported by data. However, by considering the interactions between the failure-initiating system and the ultimate manifestation of the failure, some rudimentary inference can be made.

The following sections discuss the historical study in detail. The launch data was examined to specifically test whether, historically, propulsion technology choices drive launch system risk. The data was processed per launch vehicle stage, where by definition a stage could consist of only a single propulsion technology. Results are aggregated in terms of gross failure trends as a functions of successive stage attempts. The data is then presented in terms of the underlying causes associated with the failures. Interactions between failure initiation and manifestation are then presented, broken down by the different propulsion technologies. Finally, the failures are discussed in terms of the potential implications for similar failures on crewed missions. All of the historical data sources were extensively cross-referenced to ensure consistency. However, some interpretation is often required for classifying failures into meaningful groups, and we have taken steps to identify the assumptions made. The raw data is included in Appendix B so the reader can form their own conclusions for assumptions aligned with their own needs.

Section 1: Historical Launch Vehicle Survey

This section presents an overview of the present historical launch vehicle survey, covering the survey methodology, the survey data, and the role of vulnerabilities and subsystem interactions. Because the records and failure investigation reports of non-U.S. launches are much less accessible and complete than their U.S. counterparts, this survey was limited to domestic missions.

1.1 Methodology

Launch vehicle and space launch flight and failure data were collected from multiple public sources [4] [5] [6] [7] [8] and compared, cross-referenced, and reconciled for discrepancies. Since no single data source had all the information needed or was found to be significantly more reliable than the others in reporting flight status, whenever there were disagreements, details appearing in the largest number of independent sources were used. One day differences in launch dates were not resolved. The resulting flight manifest database combines the collective information from all of these sources.

The database generated from this study contains all domestic orbital launches between 1980 and 2015 (inclusive), including failure data for launches that either failed to reach the intended orbit (too low or too high), achieved the intended orbit but not as originally planned (short first or second stage burns compensated by enough upper stage or satellite margin), or delivered a damaged payload. Many sources would consider some of these latter launches to be successes, especially if some mission objectives were met. In this study, all of them were included in the database as a way of tracking the frequency of launches that resulted in contingency activities (close calls or successfully mitigated cases). Thus, “failure” in this document refers to any flight that experienced a documented off-nominal event, even if the event was successfully mitigated. Scrubbed flights were not included. Appendix B consists of two tables that summarize the data for the failure fields for each flight included in this report.

In addition to the launch date and vehicle name, all flights in the flight manifest database contain the following fields:

- **Launch status** – Launch status is the commonly encountered success-fail field for a flight, but with more information about the flight’s failure element and/or severity. The values of this field are:
  - *success* = a successful flight without documented incident,
  - *latent error* = a successful flight with anomalous events that did not manifest as issues during flight, e.g. tile damage on Space Shuttle,

  - *minor error* = a successful flight with completed mission objectives but not without incident,
  - *post-separation error* = a successful flight but with an error by the payload spacecraft itself following deployment, that was not caused by the launch vehicle, and
  - *launch vehicle error* = a flight with a launch vehicle error or anomaly leading to a failure to correctly deliver all payloads to their proper orbits, or a flight that damaged the payload during ascent or separation. In this database, failure to properly deliver all payloads, even if the error was successfully mitigated by the satellite, is considered a loss-of-mission (LOM) event.

- **Stage type –** Additional fields that indicate the type of propellant for each stage in a launch system, one type per stage (numbered 0-5). Valid stage type values are *solid*, *liquid*, or *aircraft* (for the air-launched Pegasus vehicle). Strap-on boosters, regardless of number, are treated collectively as a single stage. Strap-on boosters and aircraft are listed as "Stage 0" in this database.

- **Vehicle type –** A field indicating whether the launch vehicle was configured with *solid stages only*, *liquid stages only*, or a *combination* of both types of stages. Solid strap-on boosters were included as a solid stage in the vehicle type, while aircraft, in the case of air-launched launch systems, were excluded as a stage for the vehicle type.

- **Payload orbit achieved** – A field indicating whether the payload(s) reached the correct target orbit(s), including any mitigation by the payload. For missions with multiple payloads, the least successful target orbit reached is tracked. Values for this field include: *failed to orbit, reached an unintended orbit,* or *reached the final intended orbit*.

For flights that encountered a launch vehicle error, additional failure-specific fields were included that could be used to mine for trends beyond the commonly encountered demonstrated launch vehicle reliabilities. Launches with post-separation failures were excluded as they were not considered to be launch vehicle ascent incidents. Also not included in the vehicle failure-specific database were the flights with minor errors or latent errors. Many of the flights with latent errors involved the Space Shuttle and resulted in foam insulation, blanket, and tile damage discovered after a successful mission. The flights with post-separation or minor errors often show up in other sources as spacecraft or launch vehicle failures and, for completeness, are listed in Table A-1 in Appendix A. Appendix A also includes short descriptions of a number of flights with notable anomalous events during ascent, but were not included in the failure database because they did not fit the formal failure definition.

The failure-specific database fields for flights with launch vehicle errors include:

- **Failure class** – A high-level classification of the failure source. Valid values are *design, process, weather*, or *unknown*. The classification of *process* or *design* was based on the corrective actions recommended in the accident investigation reports and whether the primary recommendations involved a procedural or design change. Although multiple failure classifications were reasonable to describe the launch errors in a few cases, a rule to choose only one was observed, which introduces some uncertainty to the compiled data. Process failures include: manufacturing errors, assembly errors, quality assurance errors, repair errors, and software errors. Design flaws include unexpected flight conditions resulting from a lack of understanding of the physical phenomena encountered by the launch vehicle, such as aerodynamics, temperature, vibrations, fluid dynamics, and corrosion. Weather failures were launch errors externally induced by weather conditions. Flights whose failure source was not identified by the investigation board, or whose investigation documentation was not found were classified as unknown failures.

- **Failed stage type** – The type of the stage *where* the failure initiator occurred, either solid stage, liquid stage, or staging, if the error occurred during a separation event between two stages, while jettisoning boosters or fairings, or during payload deployment.

- **Failed stage number** – The failed stage number indicates *when* during flight the initiating error occurred. Strap-on boosters are labeled as "Stage 0." Failures that occurred during staging were assigned the stage number of the stage that initiated the error, or the stage operating nearest the event (as in fairing jettison events). Failures that occurred during payload deployment are listed with failed stage number 5.

- **Initiating subsystem** – The subsystem where anomalies were first detected. The subsystems were split into the following categories: *engine/motor*; *avionics* (software and electronics); *main propulsion system (MPS)*, namely the propellant management system consisting of propellant tanks, feed lines, and regulation/pressurization tanks and systems external to a liquid engine itself; *guidance, navigation, and control (GNC)*; *structures*; *staging systems*; *thermal protection systems (TPS)*; and *unknown*, which was used when the initiating subsystem was not identified. This categorization approach separates the MPS from the engine itself in order to differentiate propellant management issues from engine-specific failures.

- **Manifesting subsystem** – The subsystem where the anomalies manifested themselves as an obvious flight problem (i.e. an error initiates in the avionics subsystem which momentarily triggers a loss of power and manifests in the engine as an inadvertent engine shut down leading to a LOM).

- **Initial manifestation type** – The localized failure state of the vehicle resulting from failure. These conditions represent the initial conditions of failure propagation from the manifesting subsystem to other elements/stages of the launch vehicle architecture. Examples include *loss of control, explosion, low thrust*, *propellant leak*, *case breach, case burst,* and *unknown*. See Section 2.3, Table 4 for the full list of initial manifestation types.

- **Manifestation class** – A high-level classification of the initial manifestation type (*contained, uncontained, loss of control*), useful in identifying the potential of a failure event to propagate into a full vehicle failure. See Section 2.3 for detailed information on these classes.

- **Launch Vehicle Demise** – This classification categorizes the propagation mode by which the failure manifestation evolves into destruction of the vehicle during the ascent phase. Valid values for launch vehicle demise are: *Environment* (propagation to demise as result of the environments produced by the failure), *Loss of Function* (demise results from loss of critical functionality, e.g., loss of control), or *None* (no ascent phase breakup). See Section 2.4 for more details.

1.2 Historical Survey: Launch Vehicle Configuration Summary

Table 1 lists the stage configurations of all the launch vehicles flown from 1980 to 2015.

Table 1. U.S. Launch vehicle configuration summary, 1980 – 2015.

Launch Vehicle Family	Stage 0 Type	Stage 1 Type	Stage 2 Type	Stage 3 Type	Stage 4 Type	Combo	Liquid only	Solid only	Grand Total
Antares	None	Liquid	Solid	None	None	5			5
Athena	None	Solid	Solid	Liquid	None	4			4
				Solid	Liquid	3			3
Atlas	None	Liquid	Liquid	None	None		67		67
			Solid	None	None	26			26
				Solid	None	7			7
	Solid	Liquid	Liquid	None	None	30			30
Atlas-5	None	Liquid	Liquid	None	None		36		36
	Solid	Liquid	Liquid	None	None	24			24
Castor-4/ Conestoga 1620	None	Solid	Solid	Solid	Solid			1	1
Delta-4	Liquid	Liquid	Liquid	None	None		8		8
	None	Liquid	Liquid	None	None		3		3
	Solid	Liquid	Liquid	None	None	19			19
Falcon-1	None	Liquid	Liquid	None	None		5		5
Falcon-9	None	Liquid	Liquid	None	None		20		20
Minotaur	None	Solid	Solid	Solid	Solid			7	7
Minuteman	None	Solid	Solid	Solid	Solid			8	8
Pegasus	Aircraft	Solid	Solid	Solid	Liquid	8			8
					None			34	34
Scout	None	Solid	Solid	Solid	Solid			17	17
Space Shuttle	Solid	Liquid	None	None	None	135			135
Strypi	None	Solid	Solid	Solid	None			1	1
Taurus	None	Solid	Solid	Solid	Solid			9	9
Thor/Delta	None	Liquid	Solid	Solid	None	1			1
	Solid	Liquid	Liquid	None	None	71			71
				Solid	None	121			121
Titan	None	Liquid	Liquid	Liquid	None		10		10
				None	None		6		6
				Solid	None	7			7
	Solid	Liquid	Liquid	Liquid	None	26			26
				None	None	31			31
				Solid	Solid	9			9
Zenit-3SL	None	Liquid	Liquid	Liquid	None		36		36
Grand Total						**527**	**191**	**77**	**795**

There were 795 domestic orbital flights, including 36 Zenit flights launched from Sea Launch's floating launch platform (Sea Launch is a multinational consortium with U.S. membership).

Zenits not operated by Sea Launch were excluded from the survey. Among the flights listed in Table 2, 66% used both liquid and solid propulsion stages, while 24% used only liquid engine stages and 10% used only solid motor stages.

Table 2 summarizes the entire 795-flight history by vehicle family, launch status, and payload orbit achieved. Of the 52 flights with launch vehicle errors, 31 failed to place their payloads into orbit, 13 reached an unintended orbit, and 8 reached the intended orbit but not as planned or with payload damaged by the launch vehicle during ascent. The Space Shuttle Columbia failure of 2003 is one of the 8 flights in this category. These 52 flights are the focus of this survey. Appendix C contains a brief description of the major events that occurred in each of these flights.

Table 2. U.S. launch vehicle accident status summary, 1980-2015.

	Launch Vehicle Error			Post-separation error			Minor error	Latent error	None	Grand Total
Family	Failed to orbit	Final orbit reached	Unintended orbit	Failed to orbit	Final orbit reached	Unintended orbit	Final orbit reached	Final orbit reached	Final orbit reached	
Antares	1	--	--	--	--	--	--	--	4	5
Athena	2	--	--	--	--	--	--	--	5	7
Atlas	5	1	3	--	4	1	--	--	116	130
Atlas-5	--	1	--	--	--	--	--	--	59	60
Castor-4	1	--	--	--	--	--	--	--	--	1
Delta-4	--	--	1	--	--	--	--	--	29	30
Falcon-1	3	--	--	--	--	--	--	--	2	5
Falcon-9	1	1	--	--	--	--	--	--	18	20
Minotaur	--	--	--	--	--	--	--	--	7	7
Minuteman	--	--	--	--	--	--	--	--	8	8
Pegasus	2	1	3	--	3	--	--	--	33	42
Scout	--	--	--	--	--	--	--	--	17	17
Space Shuttle	1	1	1	--	3	2	2	11	114	135
Strypi	1	--	--	--	--	--	--	--	--	1
Taurus	3	--	1	--	--	--	--	--	5	9
Thor/Delta	4	1	2	--	1	1	1	1	182	193
Titan	4	1	2	1	1	2	--	--	78	89
Zenit-3	3	1	--	--	1	--	--	--	31	36
Grand Total	**31**	**8**	**13**	**1**	**13**	**6**	**3**	**12**	**708**	**795**

Figure 1 shows the total number of flights per year by each launch vehicle type. Although vehicles using both propulsion types were the most common configuration during most years, liquid-only vehicles were more prevalent in the last four years.

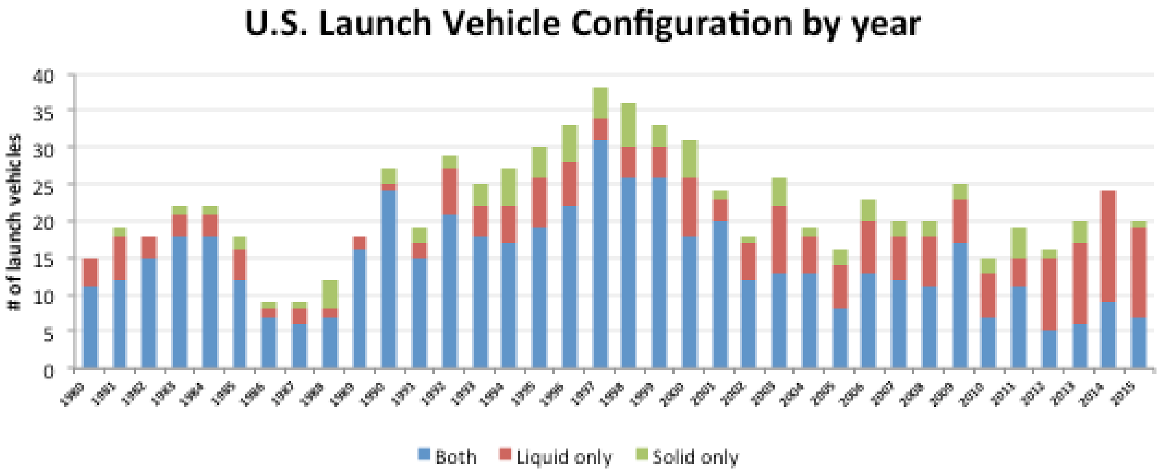


Figure 1. Historical launch vehicle configurations by year.

Table 3 contains the breakdown of launches and launch status by vehicle type and number of stages of a given type. The demonstrated probabilities at the 5th, 50th, and 95th percentiles of fully successful flights are listed for each launch configuration, assuming a beta distribution for the probability of success. Launch vehicles employing both solid and liquid stages appear to be more reliable than vehicles using a single propulsion type. However, this conclusion adds little insight into possible differences between the two propulsion technologies since these vehicles employed both propulsion technologies in almost equal numbers (56% of the total number of stages used in the combined type vehicles were liquid stages and 44% were solid stages). Although the median demonstrated reliability of liquid-only vehicles is greater than the reliability of solid-only vehicles, the demonstrated reliability ranges of liquid-only and solid-only vehicles have significant of overlap.

Table 3. Launch vehicle reliability rates, by vehicle configuration.

Launch Configuration	**Launch Vehicle Errors**	**Total Flights**	**Launch vehicle reliability 5th-50th-95th percentile**	**Total # liquid stages in configuration**	**Total # solid stages in configuration**
Combined	25	527	94-95-97%	891	700
Liquid only	17	191	87-91-94%	436	0
Solid only	10	77	80-87-93%	0	274
Grand Total	**52**	**795**	**92-93-95%**	**1327**	**974**

Figure 2 shows the distribution of launch vehicle errors by failure class. About half of all historical launch vehicle errors can be attributed to process errors, and about a third can be considered design errors. It is unclear if process errors are larger because they are inherently more difficult to manage, or if they are easier to implement as a corrective action than design changes.

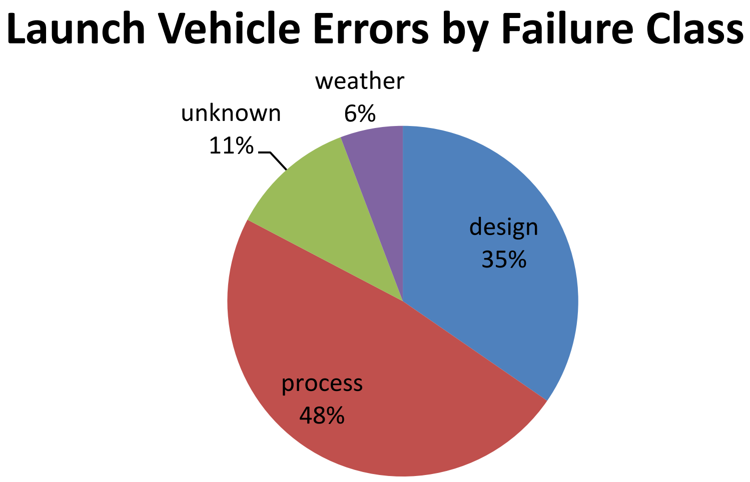


Figure 2. Historical launch vehicle errors by failure class.

Figure 3 plots the same launch vehicle error data as a cumulative trend over time. Unknown failures reached a plateau after 2002, likely due to better investigation reporting and availability of documentation. Weather-related failures plateaued after 1996, likely due to stricter launch commit criteria and improved weather predictions. Process-based errors occurred most often, followed by design-based errors. The design- and process-based errors occurred at a relatively constant rate throughout the survey timeframe. That is, no obvious maturity growth for these root causes was observed. While this constant failure rate is consistent with random failure, it is more likely due to the wide variation of launch vehicles included in the study. The subsystem components and flight profiles of vehicle families received continual updates, essentially rendering the individual vehicles as dissimilar systems. Maturity growth curve analysis requires the isolation of specific vehicles or launch capabilities and falls outside the scope of this report. Launch vehicle maturity growth remains an area of active research [9] [10] [11].

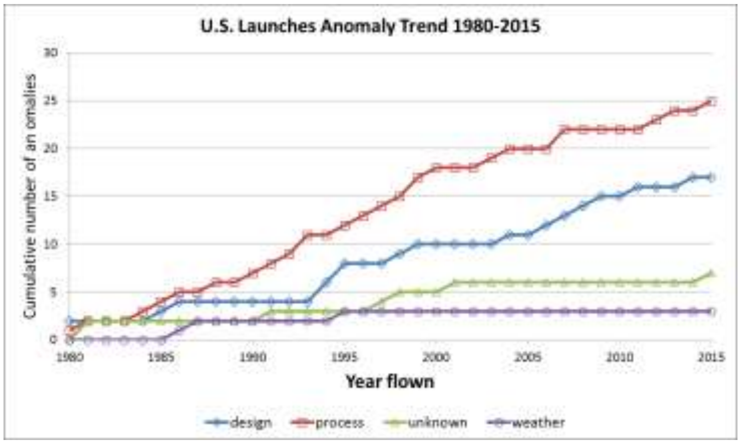


Figure 3. Historical launch vehicle errors by failure class, 1980 – 2015.

1.3 Historical Failure Study: Stage-based Approach

This section describes the present study's examination of flights with launch vehicle errors, in which the stages and the types of propulsion involved in the errors were identified. To facilitate direct comparisons among propulsion technologies, the *stage type* in which the flight error occurred is tracked instead of *vehicle type*. Since staging failures occur at the interface between two vehicle stages, the total number of staging events is assumed to be the sum of all stages and labeled as a "staging/deployment" stage type. Among the 795 flights in the entire launch history, a total of 1,327 liquid stages and 974 solid stages (605 of which were strap-on "stages") were flown, for an overall ratio of 58%/42% liquid/solid stages. Much of the remainder of this report focuses on assessments of reliability at the stage level.

To investigate the relationship between flight errors and the types of propulsion systems involved, stage failure rates of flights with vehicle errors, broken down by payload orbit achieved, are plotted in Figure 4. The staging failure rate is defined as the ratio of staging failures to total staging events (equivalent to the sum of all flight stages, or 2301). Liquid stage failures occur most frequently (2.1e-2 failures per liquid stage), followed by solid stage failures (1.2e-2 failures per solid stage), and staging failures (5.0e-3 failures per staging event).

The results above appear to contradict the results from Table 3, which indicated that liquid-only *vehicles* exhibited a higher demonstrated reliability than solid-only *vehicles*. However, about half of the flight errors occurred on vehicles configured with both types of propulsion stages. Hence, the failed propulsion type is not explicitly identified when using the vehicle-level splitting of the data. Many of the errors on the combination vehicles, in fact, did occur in a liquid stage.

Separation errors between two vehicle stages appear to occur most infrequently, but the total rate of encountering a staging failure is closer to 1.5e-3 failures per flight because a typical flight has multiple staging events.

Figure 4 also shows the percentage of failed stages broken down by payload orbit achieved. The final orbit achieved may be used as a proxy for assessing the severity of a failure or a rough approximation of when the error occurred in a flight. While the total percentage of errors differ by propulsion stage type, the percentage of stages that do not reach any orbit is about equal (1%) for liquid and solid stage types.

About half of the flights with liquid stage failures delivered payloads that still reached some orbit. Solid stage failures, on the other hand, often led to payloads that failed to reach orbit. This result suggests that liquid stage failures tend to occur later in flight, or are more benign and mitigable than solid stage failures. Because most of the missions involved satellite or cargo deliveries, many of the launches involving solid stage failures were intentionally terminated for safety reasons, further supporting the suggestion that these failures tend to happen earlier in flight or are more catastrophic. The low orbital success rate following solid stage failures suggests certain implications for the safety of crewed vehicles, if one may extrapolate the results of this analysis primarily expendable launch vehicles. The implications of the ultimate demise of the failed flights on the safety of crewed vehicles versus cargo vehicles are described later in this document.

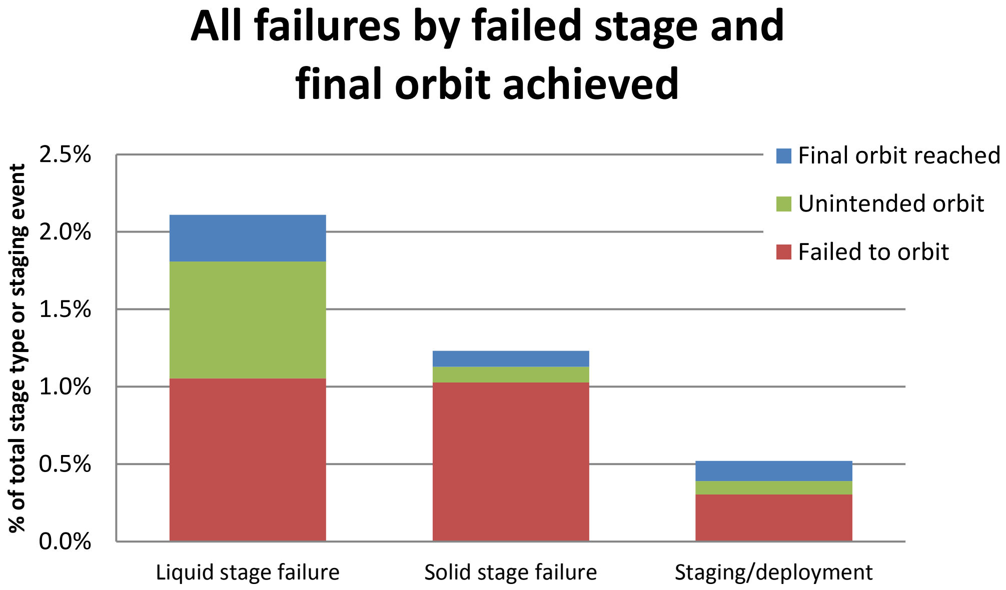


Figure 4. Stage-wise failure percentages for U.S. launches between 1980-2015.

The stages and failed stage types of the 52 flights with errors are summarized in Figure 5. Each launch vehicle configuration is represented by a column of stacked bars: blue for solid stages, red bars for liquid stages, and green for air-launched stages. The stacked bars start with "Stage 0" for strap-on boosters or aircraft and increase up through all stages. The launch vehicle family and launch date are listed on the horizontal axis, and are grouped by vehicle type. The failed stage is marked by a diamond. If a payload failure occurred during or after deployment, the diamond is placed in "Stage 5." If a staging failure occurred (including fairing jettison errors occurring near other stage separation events), the diamond is placed between the appropriate stages. The manifestation class of the failure is indicated by the shading of the diamonds: black for uncontained, grey for loss of control, and white for contained failures. Propulsion system failures (motor/engine or MPS) are marked by diamonds outlined in yellow.

The interpretation of a few launches in the flight error data of Figure 5 are as follows. For example, the Atlas failure that occurred on 12/9/1980 was configured with one liquid and one solid stage and no strap-on boosters. A propulsion failure occurred during the first stage burn and resulted in a loss of control failure. In another example, the Taurus launch on 2/10/1998 has conflicting and sparse details surrounding the flight. For this case, the diamond is placed on the horizontal axis, marking no particular failed stage or staging event. Little information on the incidents surrounding the 8/1/1997 Pegasus and 11/3/2015 Super Strypi flights was found at the time of writing, therefore the manifestation class for these flights are "unknown" and marked with an asterisk.

A number of observations can be drawn from Figure 5. Five flights encountered issues with the strap-on boosters (all solid motors), 19 flights encountered issues during the first stage burn (4 on solid stages, 15 on liquid stages), and 14 others after the first stage burn (2 on solid stages, 12 on liquid stages). Just over half (52%) of the liquid stage failures occurred during the first stage burn, while the majority (82%) of the solid failures occurred during first stage burn, which includes Stage 0 strap-on boosters, where solids are commonly employed. Consistent with an earlier observation, solid stage errors are found to occur earlier in flight than liquid stage errors. Of the 12 staging event failures, one occurred during SRB jettison and three during payload deployment. Of the remaining 8 staging event failures, 6 (75%) occurred between two solid stages and 2 (25%) occurred between two liquid stages.

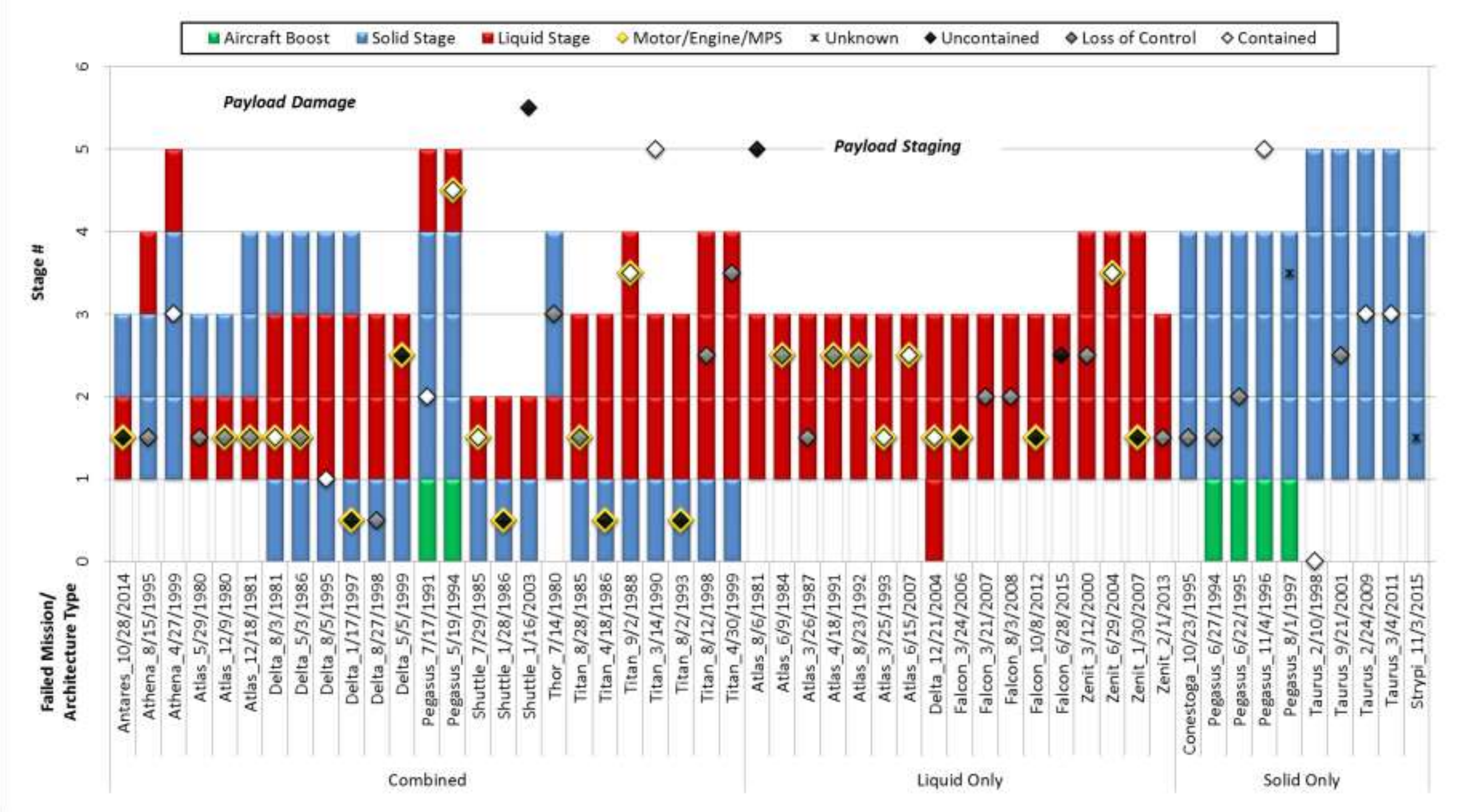
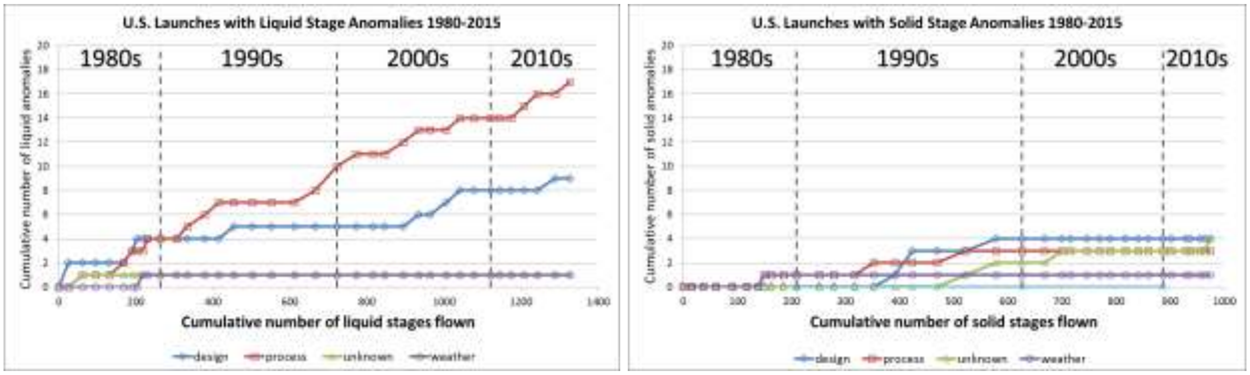


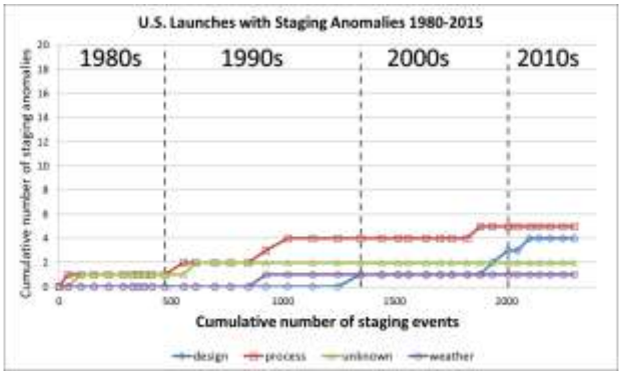
Figure 5. Summary of launch vehicle errors.

1.4 Stage-based Error Trends by Failure Class

Figure 6 shows the historical trend of all flight anomalies by failure class, similar to Figure 3, but separated by failed stage type. Stages and staging events were counted each year so that the rates of solid, liquid, and staging anomalies could be compared as functions of *stage experience* rather than as functions of the year flown for developing safety and reliability trends. The vertical dotted lines separate the decades, just as a point of reference.



a) Liquid stages *b) Solid stages*



c) Staging events

Figure 6. Failure class trends by failed stage type.

Figure 6a shows that liquid stage anomalies stemming from design and process errors have not reached a plateau and that process-related causes dominate the observed flight anomalies. The constant growth of the process-related errors may indicate that either the complexity of liquid propulsion stages continues to be difficult to manage or that these stages are more frequently used to meet higher, more challenging mission demands. Design-related errors exhibit a similar trend, with anomalies continuing to occur throughout the liquid stage experience, but with some plateauing occurring in the 1990s and early 2000s. Unknown and weather-related errors comprise only a very small fraction of liquid stage anomalies.

Figure 6b shows that solid stage anomalies appear to have reached a plateau with only one error since 2001. Unknown error classifications, which arise generally from a lack of launch failure documentation, were observed more often in solid stage failures than liquid stage or staging failures.

Figure 6c shows that staging/deployment event anomaly trends resemble solid stage anomaly trends in all areas except recent (post-2007) design errors.

1.5 Vulnerabilities and System-System Interactions

All Failures

The results of the current survey are consistent with previous studies [12] [13], which have shown that that most launch vehicle failures manifest in a propulsion system. Figure 7 categorizes the flights with launch vehicle errors by the manifesting subsystem of each failure. Propulsion failures, which include both engine/motor failures and MPS failures, were responsible for 46% of the failed flights.

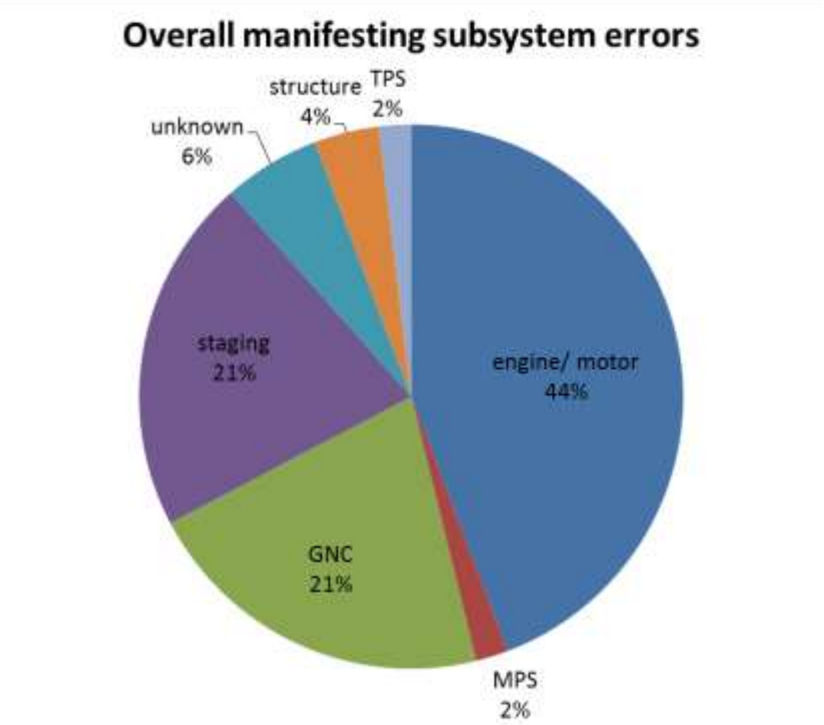
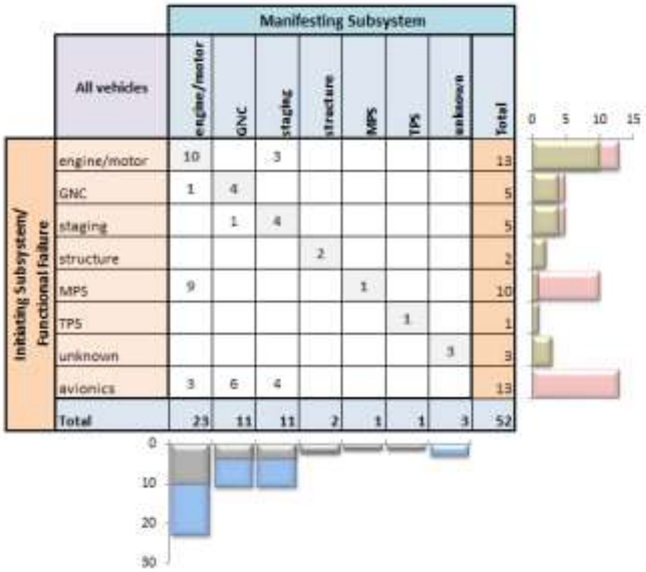


Figure 7. Manifesting subsystem failures over all launches.

To understand how problems develop in launch vehicles, it is useful to know where the first signs of off-nominal behavior begin and how these problems propagate through the launch vehicle. Figure 8 shows the relationship between the initiating and manifesting subsystems in the flights with launch vehicle errors. A given cell contains the number of launches with that combination of initiating-to-manifesting subsystems. For example, of the 23 engine and motor manifesting failures (column 1), 10 originated within the engine or motor itself and 14 originated elsewhere (9 in the MPS, 3 in avionics, and 1 in GNC).

Stacked bar charts in Figure 8 illustrate the relationship between initiating and manifesting subsystems in the launch failures using the failure tallies in the figure matrix. The stacked bars to the right the figure matrix show the number of launch failures *by initiating subsystem* in which the manifesting and initiating subsystem are the same (on matrix diagonal) in tan and different (off-diagonal) in pink. The stacked bars below the figure matrix show the number of launch failures *by manifesting subsystem* in which the manifesting and initiating subsystem are the same (on matrix diagonal) in grey and different (off-diagonal) in blue.

The stacked bar charts show that while most vehicle failures do evolve into propulsion failures, the initiating subsystems leading to the failure are not limited to issues within the engine/motor itself, but rather also stem from propellant management (MPS), avionics, and GNC initiators. This suggests that an engine/motor subsystem tends to be tightly coupled to other subsystems, rendering it prone to causing launch failures at rates higher than the rate its inherent subsystem reliability would indicate. The tightly-coupled interactive relationships between the subsystems in the launch vehicles play a large role in the overall failures of the vehicles, as demonstrated by the relatively large number of failures that are not initiated and manifested in the same subsystem (i.e., given the sizes of the pink and blue bars relative to the tan and grey bars, respectively). Among all of the initiating subsystem errors, avionics, and MPS errors propagate to and manifest failures in the most other subsystems. Engine/motor, GNC, and staging functions are relatively sensitive to failures in other subsystems.

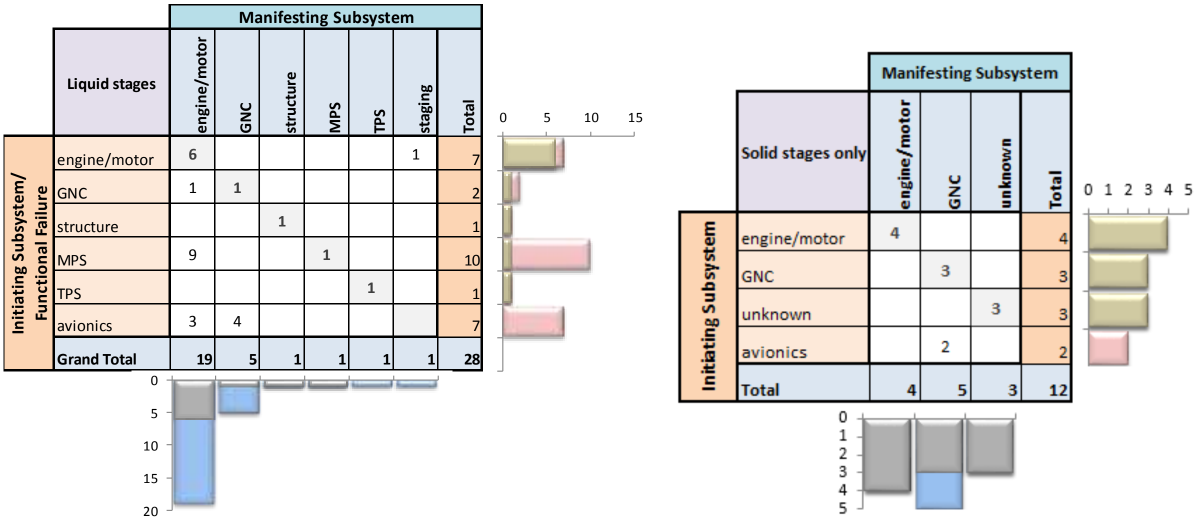


All vehicles	engine/motor	GNC	staging	structure	MPS	TPS	unknown	Total
engine/motor	10		3					13
GNC	1	4						5
staging		1	4					5
structure				2				2
MPS	9				1			10
TPS						1		1
unknown							3	3
avionics	3	6	4					13
Total	23	11	11	2	1	1	3	52

Figure 8. System interactions matrix for all failed flights.

By Failed Stage Type

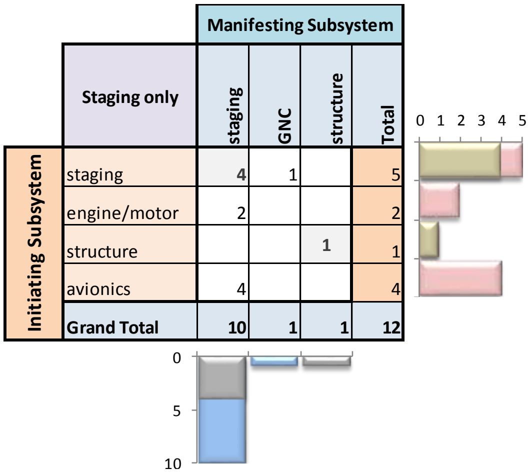
Similar dependency matrices for flight failures grouped by failed stage type reveal differences between the interactive subsystem dependencies of liquid and solid stages (Figure 9). The failures associated with staging, isolated in Figure 9c, show that over half of the staging errors originated in other subsystems (engine and motor or avionics). For flight failures involving liquid engine stages (Figure 9a), two-thirds of the flight errors were manifested in the engine, with the primary initiators occurring in three different subsystems (engine/motor, MPS, and avionics). Nearly half of the engine-manifesting failures originated in the MPS. For solid stages (Figure 9b), the failures remained localized to the error source, rather than propagated to other subsystems. This dominance in subsystem failure propagation by liquid propellant stages reflects a complex interdependence among liquid stage subsystems, especially between engine and propellant management systems, and is consistent with the prevalence of process-based anomalies in liquid propulsion stages (Figure 6).



		Manifesting Subsystem						
	Liquid stages	**engine/motor**	**GNC**	**structure**	**MPS**	**TPS**	**staging**	**Total**
Initiating Subsystem/ Functional Failure	engine/motor	6					1	7
	GNC	1	1					2
	structure			1				1
	MPS	9			1			10
	TPS					1		1
	avionics	3	4					7
	Grand Total	**19**	**5**	**1**	**1**	**1**	**1**	**28**

		Manifesting Subsystem			
	Solid stages only	**engine/motor**	**GNC**	**unknown**	**Total**
Initiating Subsystem	engine/motor	4			4
	GNC		3		3
	unknown			3	3
	avionics		2		2
	Total	**4**	**5**	**3**	**12**

a) Liquid stages *b) Solid stages*



		Manifesting Subsystem			
	Staging only	**staging**	**GNC**	**structure**	**Total**
Initiating Subsystem	staging	4	1		5
	engine/motor	2			2
	structure			1	1
	avionics	4			4
	Grand Total	**10**	**1**	**1**	**12**

c) Staging events

Figure 9. Interactions matrix by failed stage types.

Section 2: Historical Safety Study

Vehicle safety implications from the historical launch vehicle survey data presented in the previous section are assessed in this section. Because the historical data contains only one vehicle designed for human spaceflight, namely, the Space Shuttle, limited data exists which may be used directly for safety and ascent abort assessments. However, data relevant to crew safety may still be inferred by examining the much larger set of accidents of cargo flights. Ascent failures of all launch vehicles, whether crewed or cargo, can be characterized with a small set of attributes, such as the extent of the propagation of the failure, the initial manifestation of the failure, and the ultimate demise of the launch vehicle during ascent. These characteristics provide insight into the types of failure environments to which an abort system for a crewed vehicle would be subjected. Using the historical data to extrapolate for categorical differences in vehicle demise leads to an understanding of the timeframes typically encountered immediately after an ascent failure and offers qualitative guidance to the amount of time in which an abort system would be required to respond. This section extends the historical launch vehicle failure data and discusses the distinction between reliability and safety, the key factors that would affect crew safety, and the manifestations of failures.

2.1 Reliability vs. Safety

The assessment of a launch system's safety begins with the launch system's reliability, which is obtained from a system-wide consolidation of component reliabilities, and continues with the analysis of the consequences of the system's failures. One might intuitively expect that a more reliable vehicle would also be a safer vehicle and, were there sufficient data, there would likely be a strong correlation between reliability and safety. The presence of an abort system designed to safely return the crew in the event of failure, however, makes such a correlation less than perfect. That is, one could conceive a situation in which one launch vehicle tends to experience infrequent failures but failures of types that create difficulties for the abort system, relative to another vehicle that fails more frequently but more benignly. Essentially, the distinction between reliability and safety assessments then lies in the additional attention paid, in the case of a safety assessment, to failure consequences and their impact on the ability of the abort system to perform its mission.

In most cases, the effects of a failure early in its propagation will not directly threaten the crew. In cases when the crew is not threatened by the environment directly produced by the localized manifestation of the failure, a crew-threatening environment may still result from the subsequent propagation of the failure through the vehicle via the transfer of material and/or energy until a vehicle-level energy release is produced, i.e., energy release directly causing demise of the vehicle or a vehicle stage. A safety assessment involves characterizing the types of environments that could be created by the various failure modes, and quantifying the impact of the end state environments on the ability of a crew module to successfully abort. Essentially, one would like to answer the following questions:

- What type of end-state environments (e.g., explosion) will be generated, given a specific type of failure?
- Will the crew be able to survive the end-state environments?

The historical launch survey data cannot directly address the second question due to the lack of U.S. launch failures involving crewed flights with launch abort systems. To some extent, the historical launch failure data can address the first question pertaining to failure propagation, although the use of flight termination systems to destroy failing launch vehicles complicates the analysis. Engineering judgment is used to fill in the gaps and extrapolate, as necessary, to provide a crude assessment of failure propagation patterns in the launch vehicle failure historical record. The accident information is interpreted in a manner to best characterize the vehicle state at loss of mission (LOM) and the way in which this state evolves to vehicle demise. These two failure propagation states provide an important framework for analyzing crew safety.

A brief overview of the factors affecting crew safety is provided, followed by results of the historical safety study.

2.2 Factors Impacting Crew Safety

A complete assessment of the crew safety for a launch vehicle would need to consider the crew's exposure to risks in three main phases of an abort:

1. **Near-field** – Immediately before and after abort initiation, the crew module and escape system must survive any environment generated by the launch vehicle failure. For example, a launch vehicle explosion will generate a blast overpressure wave, a debris field, and radiant heating or a fireball environment. The relative risks of these environments are dependent upon the launch vehicle design, especially the types of propulsion systems employed.

2. **Mid-field** – Depending on the ascent trajectory and mission elapsed time of the failure, the abort system may be subject to dynamic pressure regimes in which maneuverability may be limited. Under these conditions, relative ballistics of the launch vehicle and abort system may also allow the launch vehicle (or its debris field) to catch up to the crew module following its successful escape from the near-field failure environments.

3. **Far-field** – During high-altitude service module aborts in which parts of the abort trajectory are exo-atmospheric, the crew may be exposed to risks associated with: a) high g-loading and/or heating associated with off-nominal entry conditions, b) insufficient time-of-freefall prior to atmospheric entry in which to perform any pre-entry maneuvers and maintain separation between potential collision hazards, and c) inability to reach a landing location from which the crew can be reliably rescued.

The present study is limited to consideration of the risks in the near-field phase, due to dependence of these risks on the specific launch vehicle architecture and type of propulsion systems employed.

Near-Field Environments from Solid Stages

Solid stages are generally Class 1.3 detonation hazards, which means that they will not detonate unless subjected to extreme impact pressure. Therefore, risks to crew during flight are due to the overpressure wave associated with the rapid release of contained pressure and a debris field comprised of the stage hardware and propellant. These risks will tend to increase with MET as the internal empty volume (i.e., the volume not occupied by propellant) increases, but vehicle velocity and altitude tend to mitigate the propagation of these types of blasts. Evidence from observations of failures of solid propellant stages indicate that the debris field generated is of sufficient density and energy to endanger a nearby crew module.

Near-Field Environments from Liquid Stages

Liquid stages can produce near-field overpressure waves from detonation of propellant mixtures within the confines of the stage (defined as a confined-by-missile explosion), deflagration of propellants released into the atmosphere, or detonation of clouds of propellants partially contained by the ground in the case of pad explosions. Detonation pressures can be orders of magnitude larger than deflagration pressures near the center of the explosion. The specificity of the conditions required for a detonation to occur makes these events fairly unlikely; however, they must be considered given the severity of the environments they create.

Internally generated explosions (or confined-by-missile explosions) will likely create a debris field that can pose a risk to the crew. There are no known occurrences in the historical record involving confined explosions of this type, but data from designed tests [14] indicate the potential for high velocity fragments from such events. Pressurized tank bursts and explosion of propellants released following structural failure, in combination with aerodynamic forces, will likely produce fragments, but with lower imparted velocities than those produced by the high detonation pressures and extreme strain rates from confined explosions.

Liquid stage failures while the vehicle is on the launch pad will produce fireballs capable of generating a high heating environment hundreds of meters from the launch site. This heating environment is unlikely to pose a risk to the metallic structure of the crew module during abort, but may cause failure of deployed parachutes, creating risk to the crew.

Other Factors

Another factor affecting overall probability of abort success, especially from loss-of-control scenarios, is the vehicle’s structural limitations. The ability of the structure to withstand off-nominal attitudes and rates, in combination with other design parameters such as trajectory, dynamic pressure, vehicle mass properties, and gimbal authority, is an important determinant in the amount of time the abort system may be given to escape prior to breakup (assuming an effective vehicle stability monitoring system). While these sub-systems are not part of the propulsion system per se, structural requirements will clearly depend on the type of propulsion system selected. Characterization of the details of this dependence, however, is beyond the scope of the present study.

Finally, failure of any launch vehicle flying in proximity to populated areas will require a range safety destruct system to ensure termination of thrust and prevent debris impacts that could be a threat to public safety. The degree to which the flight termination system, installed to protect the public, can produce hazardous environments to the crew has historically depended on the type of propulsion system employed. Solid motors have been required to be fitted with explosive destruct systems for termination of thrust regardless of the nature of the failure (assuming the failure has not already done so). The destruct system designs within the U.S. historical failure record have been observed to generate debris that would have posed potential risk to crew safety had a crew been on board. The degree to which this potential risk would be realized for a specific architecture is strongly dependent on details of the architecture, ascent trajectory, and abort system.

2.3 U.S. Failure Initial Manifestation Types and Classes

Descriptions of the initial failure manifestations are specified as a set of “initial manifestation types” that have occurred in the U.S. launch vehicle historical record. Table 4 lists these types with a brief description of their meaning as well as a “manifestation class.” The “manifestation class” is a broader classification intended to give a high-level indication of the risk of the failure in terms of its ability to propagate into a full conflagration, greatly increasing the safety risk to a crewed vehicle. Each launch failure was assigned a *Manifestation Class* and *Initial Manifestation Type* based on available information pertaining to that failure. The intent is to assign a type and class based on the state of the vehicle at the time of the initial failure manifestation and the potential for propagation of the failure beyond the initiating subsystem. This is clearly a challenging exercise, one requiring a fair amount of judgment and expected uncertainty.

Table 4. Initial manifestation types and classes observed in U.S. launch vehicle failure history.

Manifestation Class	***Initial Manifestation Type***	***Brief Description***
Contained	Low Performance	Payload delivered to wrong orbit. Nominal entry.
	Benign failure/false positive	Engine shutdown prior to safe orbit. Immediate abort required.
	Propellant leak - low performance	Leakage of liquid propellant leading to premature engine shutdown through propellant depletion or insufficient tank pressure.
	Staging - payload fails to separate	Failure of payload to properly separate from launch vehicle. Contained failure, but would be safety threat on crewed vehicle.
	Staging - low performance	Problem during staging which manifests as loss of performance (retained mass, impeded nozzle extension, etc.)
	Vehicle Over-performance – Off-Nominal Ascent	Payload delivered to wrong orbit due to excessive thrust.
Loss of Control	Loss of control	Failure to maintain controlled attitudes and rates.
	Loss of control (asymmetric thrust)	Special case for 2+ engine systems in which one shuts down prematurely.
	Propellant leak - loss of control	Leakage of liquid propellant leading to a loss of control through side forces and/or movements.
	Staging - loss of control	Problem during staging which manifests as loss of control (re-contact, impeded nozzle gimbaling, etc.)
	Tank Burst – Loss of Control	Pressurized tank rupture leading to loss of control through side forces.
Uncontained	Case breach	Slow developing opening in a solid motor case, e.g., due to burn-through of case or seal.
	Case burst	Rapid release of solid motor internal pressure through structural failure.
	LRE Uncontained	Liquid engine failure to contain energy during shutdown, e.g. MCC burst, turbine burst, or gas leak.
	Launch explosion	Failure on the pad leading to release of propellant with ground confined explosion.
	Nominal ascent – Damage to payload	Payload is delivered to correct orbital conditions but has been damaged by the vehicle in the process.
	Tank Burst – Loss of Vehicle	Pressurized tank rupture leading to rapid, uncontained structural failure and explosion.
Unknown	Unknown	Investigation on this flight was either inconclusive or unavailable.

Generally, an uncontained failure is associated with the release of matter or energy outside the bounds of its intended container. However, in a few cases this definition is considered too rigid and doesn't capture the true level of danger associated with the type, e.g., propellant leak that leads to depletion and premature engine shutdown is classified as uncontained but may not be an explosion risk. Another example to note is the "Nominal ascent – damage to payload" type, which has been categorized as an "uncontained" manifestation class because of the potentially serious crew safety consequences of incurring damage to the crew module during ascent—the Columbia accident is the obvious example. The classification of the "case breach" manifestation type is particularly difficult because of the strong sensitivity to the specific architecture, i.e., the consequences can vary from no impact (no LOM) to catastrophic impact (e.g., the Challenger accident). The classification assignments in this study are based on the worst-case outcome. To view the initial manifestation types for each flight, see Table B-2 in Appendix B.

All Failures

The failed flights were classified based upon written descriptions of the events during the flight, analysis of the failures, and the root cause/corrective action recommendations. Figure 10 shows the percentage of failed flights assigned to each manifestation class and type. The *Manifestation Classes* are plotted in the inner pie chart while the *Manifestation Types* corresponding to each class are plotted in the outer ring within each class slice. For example, the "Contained" *Manifestation Class* represents 31% of the failed launches and is comprised of the types listed in the outer ring between "Benign Failure/False Positive" and "Vehicle over-performance – Off-nominal ascent."

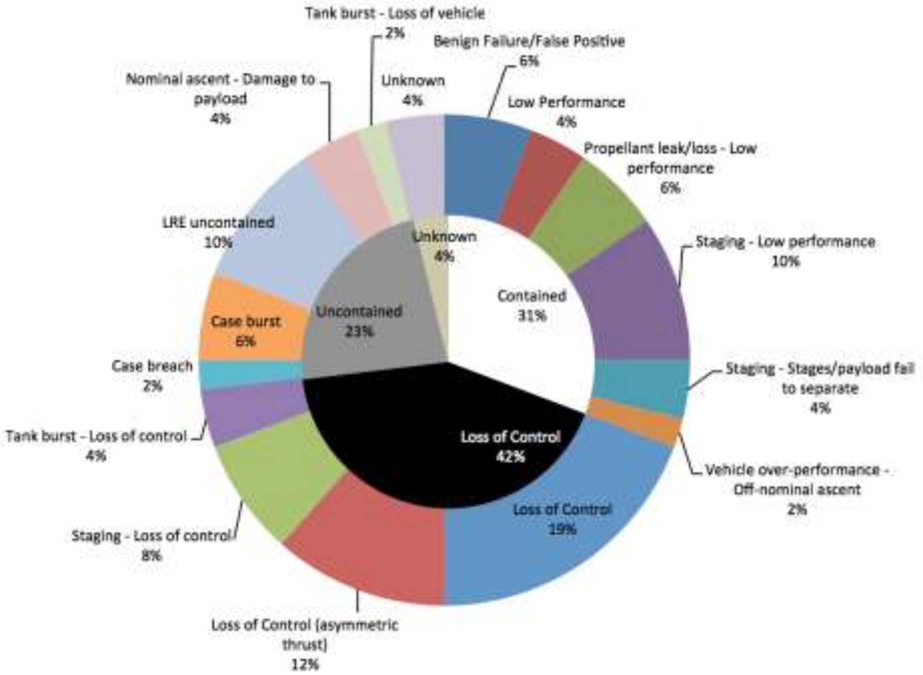


Figure 10. Breakdown of all historical failures by manifestation type and class.

The “Loss of Control” *Manifestation Class* makes up 42% of the failures. Cases where this occurs at high dynamic pressure will ultimately lead to structural breakup and some type of explosion involving any liquid propellants on board. However, the explosions resulting from this manifestation class are generally considered more survivable than confined-by-missile explosions for two reasons:

1. Unconfined (free-air) mixtures, even assuming an ignition source is available, are considered not detonable, so any resulting explosion would be in the form of a vapor cloud deflagration. Although such explosions can generate blast waves with considerable peak overpressures, these peak pressure values are significantly lower in the near-field than detonation-generated peak overpressures and are less able to overcome vehicle velocity effects. Lower overpressures produce weaker blast waves, which travel at slower speeds.
2. An abort system can be used to increase the separation distance between the crew module and launch vehicle prior to vehicle breakup and explosion. Activation of the abort system would depend upon the vehicle data available and the abort trigger rules applied. The warning time, which depends on the launch vehicle design (mass properties, failure limits, on-board propellant mass and type, escape system performance, etc.), is typically sufficient to provide a fairly high level of abort effectiveness against these failures.

The “Uncontained” *Manifestation Class* makes up 23% of the failures. This manifestation class is intended to capture failures that arise in such a way as to make abort difficult, usually through rapid release of energy with the potential to propagate into a severe environment. Typically, this class is dominated by failures manifesting in the propulsion system (i.e., engine, motor, or propellant feed system). This class also includes failures that lead directly to payload damage without necessarily developing any dramatic failure environment, and often not even preventing the launch vehicle from reaching its intended orbit.

By Failed Stage Type

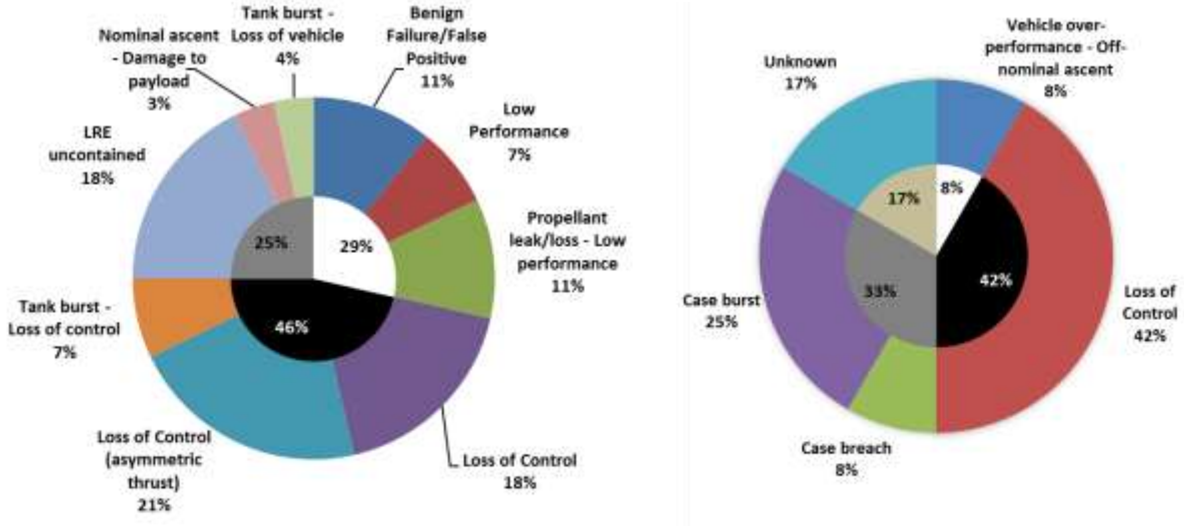
The failed launches were separated according to the failed stage type of each flight in Figure 11, where the same plot style and shading scheme as in Figure 10 is used. Except for one failure caused by low first stage engine performance leading to staging at off-nominal dynamic pressure, staging failures were not considered the fault of the propulsion system. The plots were then assessed to determine the effects of stage type on the initial failure manifestation and potential for failure propagation.

A larger fraction of the solid stage failures was observed to have been manifested as uncontained failures compared to those of liquid stages (33% versus 25%). The percentage of uncontained liquid stage failures includes missions characterized as failures due to payload damage. This classification is justified in the case of Space Shuttle Columbia because the liquid stage insulation initiated the accident; however, the root cause of the other payload damage case (August 6, 1981 Atlas flight) is unknown.

Nearly 30% of liquid stage failures manifested as premature shutdowns which, depending on the mission elapsed time of the failure, are categorized as a “benign failure” with immediate reentry, or as “low performance” with off-nominal orbit. By comparison, the fraction of solid stage failures that are considered contained failures is only 8%.

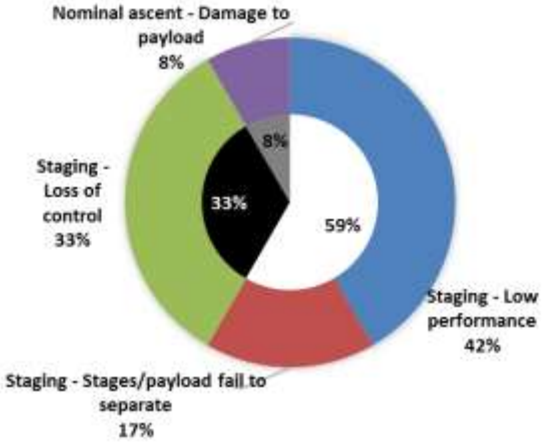
For solid stages, 42% of the failures manifested as “loss of control” failures, comparing similarly with 46% of liquid stage failures. Three of the solid stage loss of control failures involved exhausting the hydraulic fluid required to drive the stage’s thrust vector control (TVC) system, whereas liquid stages tend to use on-board propellant to drive the TVC hydraulics and are therefore less prone to loss of hydraulic fluid.

Finally, 12 staging failures are shown in Figure 11c. These failures were manifested as loss of control in 33% of the observed cases, either through gimbal limitation, re-contact, or asymmetric separation. Another 42% of the cases led to low performance, either because nozzle extensions were impeded or because mass that was intended to be shed separated late or not at all. Two cases (17%) were failures of the satellites to separate at the correct conditions.



a) Liquid stages

b) Solid stages



c) Staging events

Figure 11. Manifestation types broken down by type of stage in which failure was manifested.

By Propulsion System Failures

The flight failure data discussed above was filtered to consider only failures that originated in the propulsion system (engine, motor, and MPS) and is shown in Figure 12. A total of 24 failures were identified as directly propulsion-related: 20 liquid engine failures and 4 solid motor failures. All solid motor-related failures were classified as “uncontained” manifestations. The liquid engine failures break down in a manner in which, relative to the overall liquid stage failure distribution, a contained failure is more likely than an uncontained failure. Loss of control failures represent roughly one third of liquid engine failure outcomes, a somewhat lower fraction than observed that for all liquid stage failures.

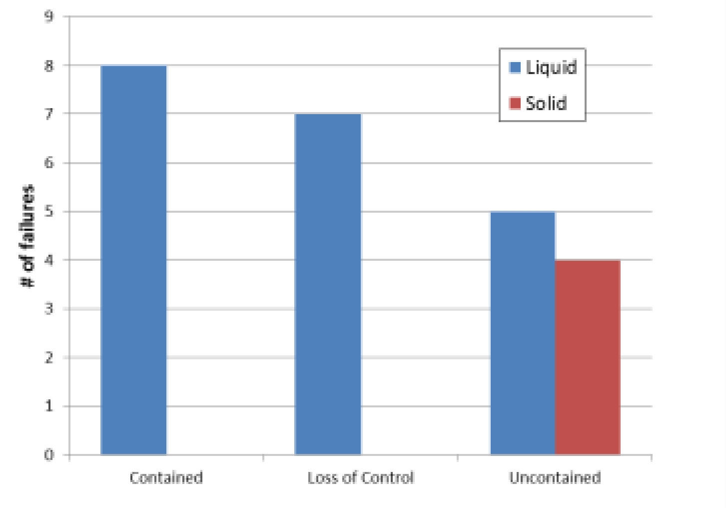


Figure 12. Propulsion related failures by manifestation and propulsion type.

2.4 Ultimate Mode of Demise

The failure history was assessed in terms of the ultimate mode of launch vehicle demise for more insight into the potential for sufficient warning time to initiate an abort. The mode of demise represents the end of the propagation process that begins with the manifestation types discussed in the previous section. Tracking the ultimate demise allows an assessment of the degree to which the observed initial manifestation propagated to catastrophic demise of the vehicle. The cases are categorized according to the mode by which the vehicle was ultimately destroyed:

- *Environment* – The release of energy, either as a direct result of the initial failure manifestation or from a propagation of failures through the vehicle, results in the immediate breakup of the vehicle. For example, engine fire causes burn-through or over-pressurization of aft propellant tank.
- *Loss of function* – The immediate manifestation does not directly lead to vehicle breakup, but the loss of critical functionality causes the vehicle to be subjected to extreme loads or to be a threat to public safety. For example, engine failure causes loss of thrust leading to ground impact (near pad), loss of control (high dynamic pressure), and/or range violations and FTS activation.

- *None* – Launches whose payloads achieved orbit, including unintended orbits, or whose payloads failed to achieve orbit but for which the vehicle failure occurred outside the detectible atmosphere and did not suffer its demise prior to reentry.

This classification differentiates failures that cause vehicle demise by internal failure propagation from those that lead to demise by external forces/environments because the vehicle has lost the capability of resisting or avoiding those forces/environments. This classification approach is valuable because failures in which the demise was experienced through loss of function are perhaps more likely to be detected in advance of vehicle breakup relative to those in which the initial environment propagates directly to breakup.

Twenty-eight flights placed payloads into some type of orbit or where the launch vehicle did not suffer demise before reaching orbit altitude and were categorized with the demise type “None.” Table 5 excludes these flights and provides a summary for the remaining 24 flights with their demise types.

Table 5. Failures not reaching orbit, grouped by method of destruction with manifestation and demise classifications.

Launch	Failed Stage	Failed Stage Type	Manifestation Class	Launch Vehicle Demise
Antares_10/28/2014	1	Liquid	Uncontained	Environment
Athena_8/15/1995	1	Solid	Loss of Control	Loss of Function
Atlas_12/18/1981	1	Liquid	Loss of Control	Loss of Function
Atlas_12/9/1980	1	Liquid	Loss of Control	Loss of Function
Atlas_3/26/1987	1	Liquid	Loss of Control	Loss of Function
Atlas_4/18/1991	2	Liquid	Loss of Control	Loss of Function
Atlas_8/23/1992	2	Liquid	Loss of Control	Loss of Function
Conestoga_10/23/1995	1	Solid	Loss of Control	Loss of Function
Delta_1/17/1997	0	Solid	Uncontained	Environment
Delta_5/3/1986	1	Liquid	Loss of Control	Loss of Function
Delta_8/27/1998	0	Solid	Loss of Control	Loss of Function
Falcon_3/24/2006	1	Liquid	Uncontained	Loss of Function
Falcon_6/28/2015	2	Liquid	Uncontained	Environment
Pegasus_6/22/1995	2	Staging	Loss of Control	Loss of Function
Pegasus_6/27/1994	1	Solid	Loss of Control	Loss of Function
Shuttle_1/28/1986	0	Solid	Uncontained	Environment
Strypi_11/3/2015	1	Solid	Unknown	Environment
Titan_4/18/1986	0	Solid	Uncontained	Environment
Titan_8/12/1998	2	Liquid	Loss of Control	Loss of Function
Titan_8/2/1993	0	Solid	Uncontained	Environment
Titan_8/28/1985	1	Liquid	Loss of Control	Loss of Function
Zenit_1/30/2007	1	Liquid	Uncontained	Loss of Function
Zenit_2/1/2013	1	Liquid	Loss of Control	Loss of Function
Zenit_3/12/2000	2	Liquid	Loss of Control	Loss of Function

Seventeen flights (over 70%) were categorized as a "Loss of Function" vehicle demise. These cases could be further divided into those for which demise was produced by aerodynamic breakup versus those for which the FTS system was activated. The former would typically evolve more rapidly to vehicle failure than the latter and these are important cases in the design of abort and detection systems.

The vehicles in seven of the failure cases (nearly 30%) were destroyed by neither range safety nor environments produced by loss of functionality. Instead, these vehicles are classified as having been destroyed directly by the failure environment (demise category "Environment"). In some of these cases, especially those with strap-on boosters, detection might have been possible using break wires to indicate component separation. Predicting the effectiveness of such systems is difficult; however, video evidence of some of these failures indicate that sufficient warning might have been available.

The launch vehicle demise data are grouped according to stage type, manifestation class, and launch vehicle demise and are graphed in Figure 13. The figure leads one to the obvious conclusion that only uncontained failures can propagate directly to vehicle-level explosion. The manifestation type and class of the 11/3/2015 Strypi failure could not be determined based on the currently available information. However, given the demise class appears to be spontaneous explosion, it is reasonable to infer that the manifestation class is "Uncontained". Relatively high fractions of uncontained failures propagated to vehicle demise for both solid and liquid stage failures. All uncontained failures of solid stages propagated to demise by failure environment. Uncontained failures of liquid stages propagated to demise by environment in 50% of the cases. Caution is recommended in accepting these statistics beyond the current observations, given the small sample size.

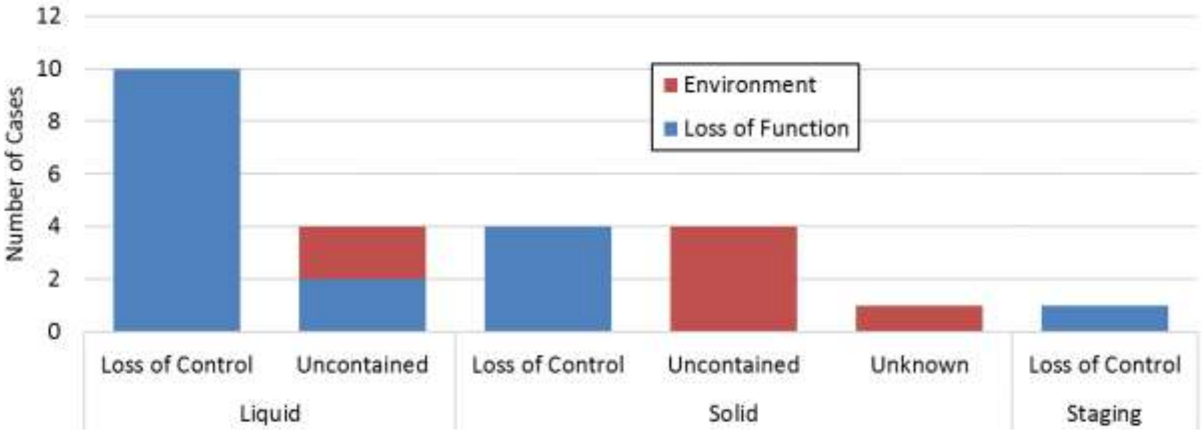


Figure 13. Failures not reaching orbit by launch vehicle demise and manifestation class.

Given a reliable abort system and vehicle health monitoring system, one would expect a high likelihood of survival from launch failures not classified as uncontained. Survival rates for those uncontained failures that propagate directly to vehicle explosion would depend on factors that are difficult to quantify from the available data in a general way. These factors include the ability to detect conditions early in the failure propagation process and the severity of the explosive environments created at vehicle demise.

Section 3: Safety and Reliability Summary

This historical review was conducted to identify trends in launch vehicle failures as they pertain to safety and reliability of liquid and solid propellant propulsion technologies. While launch vehicles over the history of space flight have come in a variety of distinct architectures, a combined analysis across all architectures assessed at the vehicle stage level more readily identifies vulnerabilities, root causes, and interactions that impact mission success and crew safety. The key findings of this study are:

- Mission success statistics are strongly dependent on the accounting approach used. Conclusions vary significantly depending on how the data is parsed.
- When considering failures by launch vehicle configuration, vehicles configured with both liquid and solid stages have the highest median demonstrated reliability, followed by liquid-only and then solid-only vehicles.
- When considering failures by the type of stage (liquid or solid) which failed, liquid systems experienced more mission-limiting failures than solid stages, while solid stage failures showed a higher likelihood of being uncontained than liquid stage failures (33% vs. 25%, respectively).
- Most liquid engine failures were associated with interactions between systems, and were dominated by process control issues. The majority of solid motor failure initiators did not migrate to other systems.
- Classification of historical failure manifestations indicated that a large majority of U.S. launch vehicle failures led to contained shutdown or loss of control, with only 23% leading to uncontained failure.
- Assessment of the ultimate mode of vehicle demise showed that, of the 52 launch failures included, only about 13% appear to have experienced demise by failure environment directly, without first experiencing a loss of functionality. All others either did not end in demise or broke up through the action of environments produced by the loss of functionality. This indicates a fairly high level of potential survivability if one assumes these environments (e.g., attitudes and rates from loss of control) are more predictable and reliably detectable than those produced by internal failure propagation.
- Failures producing local environments that evolve directly to vehicle demise/explosion are of special concern for crew safety because of the potential for explosion to occur prior to activation of an abort system. Assessment of uncontained failures indicates a large majority of uncontained failures propagated to vehicle demise by way of the failure environments. All uncontained failures (and one of unknown class) of solid stages have propagated directly to vehicle demise and half of uncontained failures of liquid stages led directly to breakup.

Appendix A: Relevant Exceptions

Table A-1 lists the flights with post-separation or minor errors that are not included in the failure database because they do not fit the definitions of launch vehicle error used in this report. Most of the flights in this list are classified as spacecraft failures or partial failures in other sources.

Four of the flights in this table (boldfaced and labeled with an *) may appear to conflict with other sources so a short rationale for how they were eventually processed in our database is provided below. Details for three other flights categorized as successes in our database are provided below because anomalous events have been documented or they may appear to conflict with some sources. A brief description of these seven flights is included below since they present scenarios that may be relevant to specific risk studies.

Table A-1. Flights between 1980-2015 with post-separation or minor errors not covered in the failure data.

Date	Vehicle Family	Launch Status
4/10/1982	Thor/Delta	Post-separation error
4/4/1983	Space Shuttle	Post-separation error
2/3/1984	Space Shuttle	Post-separation error
6/17/1985	Space Shuttle	Post-separation error
8/27/1985	Space Shuttle	Post-separation error
9/6/1989	Titan	Post-separation error
6/23/1990	Titan	Post-separation error
12/1/1990	Atlas	Post-separation error
12/2/1992	Space Shuttle	Post-separation error
4/25/1993	Pegasus	Post-separation error
10/5/1993	Titan	Post-separation error
4/13/1994	Atlas	Post-separation error
11/21/1996	Atlas	Post-separation error
10/22/1997	Pegasus	Post-separation error
3/5/1999	Pegasus	Post-separation error
4/9/1999	**Titan***	**Post-separation error**
7/23/1999	**Space Shuttle***	**Minor error**
8/23/2000	**Thor/Delta***	**Minor error**
3/8/2002	Atlas	Post-separation error
11/23/2002	**Space Shuttle***	**Minor error**
1/11/2004	Zenit-3	Post-separation error
4/16/2004	Atlas	Post-separation error
12/14/2006	Thor/Delta	Post-separation error

1. **Titan 34B 4/24/1981 (success) –** This flight is listed as a partial failure in multiple sources [15] [16] [17], but very little additional information about the sequence of events was found. Jumpseat 6, did not separate and only achieved an apogee of 708 km (instead of the 39377 km planned). It is not clear if this error was caused by the launch vehicle or the payload, thus, our survey follows reference [4] and treats this flight as a success.
2. **Titan 34D 4/9/1999 (post-separation error)** – The two-stage Inertial Upper Stage (IUS) failed to operate properly and left the payload tumbling after it attempted a second stage burn. The IUS not considered a part of the launch vehicle itself in reference [4] and this definition was adopted for this survey. Therefore, this incident is treated as a post-separation error in our survey.
3. **STS-93, Columbia 7/23/1999 (minor error) –** This mission was considered a success by many sources as it fell within the +/- 18km limit of its intended orbit and fulfilled all mission objectives. However, Columbia experienced an early SSME shutdown due to a small hydrogen leak. A gold pin used to plug an oxidizer post caused the leak after it was violently ejected and struck the inner nozzle surface, tearing open 3 hydrogen cooling tubes. At T+5s an electrical short disabled the center SSME's primary digital control unit (DCU) and the right SSME's DCU. The engines continued running on their remaining DCU for the rest of the flight. Without the redundant set of DCUs, Columbia would have experienced two SSME shutdowns that would have resulted in a very risky abort. Poorly routed wiring that rubbed through on an exposed screw head caused the electrical short [18] [19]. This flight is labeled as having a "minor" error in our survey.
4. **Delta-8930 8/23/2000 (minor error) –** The launch vehicle missed its intended target by over a thousand nautical miles, but the mission was still considered a complete success by Boeing. The company launched a demonstration satellite in an attempt to prove the reliability of their Delta III rocket after two earlier failures. The desired apogee was 12,637 miles, but the vehicle inserted the dummy payload with an apogee of 11,174 miles. This fell within their determined margin of error but was still rumored as a failure throughout the aerospace industry [20]. This flight is labeled as having a "minor" error in our survey.
5. **STS-113, Endeavour 11/23/2002 (minor error) –** After many launch scrubs, STS-113 finally took off and successfully achieved all mission objectives. However, during an OMS (Orbital Maneuvering System) assist burn during the early part of ascent to orbit, a valve in the right OMS engine failed to open completely. It was decided to only use the left OMS engine for later burns [7]. This flight is labeled as having a "minor" error in our survey.
6. **Falcon 9 12/9/2010 (success) –** This mission's primary goals were to demonstrate the orbital maneuvering and reentry of the Dragon capsule and it became the first commercially built and operated spacecraft to be successfully recovered from orbit. In 2011, Space Exploration Technologies (SpaceX) Corp. acknowledged that its Falcon 9 rocket experienced an engine anomaly during its December launch of the company's reusable Dragon space capsule [21]. Despite the anomaly, the mission was considered a complete success [22]. Two of the nine liquid-fueled Merlin engines that power the rocket's first stage ran low on kerosene during the cutoff sequence, resulting in a potentially problematic situation that a senior SpaceX official described as "an oxidizer-rich shutdown." Such a shutdown could change mixture ratios, which could cause temperatures to increase inside the gas generator and damage the turbines in the

turbopumps. As a result, more fuel was loaded on the following flight to avoid a repeat of the oxidizer-rich engine shutdown [23]. Despite the documented anomaly, this flight follows most other sources and is considered a success in our survey.

7. **Delta IV 10/4/2012 (success) –** This mission was considered a success to both the United Launch Alliance (ULA) and their client, the U.S. Air Force, despite a fuel leak in the RL10B-2 upper stage engine that prompted an anomaly investigation and a hold on Atlas V and Delta IV flights configured with RL10 engines. The leak started during the first engine start sequence of the launch [24]. The mission included three planned upper-stage burns that would eventually move the payload to a circular orbit in line with the GPS network. However, the engine produced less thrust than expected and as a result, the launch vehicle extended each of the burns 20-36 seconds longer than nominal predictions to compensate. The success of the mission was attributed to the satellite's light weight, which allowed the Delta IV to burn longer than planned with plenty of fuel left over [25]. Detailed information on the cause of the anomaly is not immediately available, thus this flight is considered a success in our survey.

Appendix B: Additional Data for Flights with Launch Vehicle Errors

Table B-1. Stage and Vehicle Information.

Date	Vehicle Model	Vehicle Type	Stage 0 Type	Stage 1 Type	Stage 2 Type	Stage 3 Type	Stage 4 Type	Failed Stage #	Failed Stage Type
5/29/80	Atlas-E/F-Star-37-ISS	Combined	None	Liquid	Solid	None	None	1	Liquid
7/14/80	Thor-LV2F Burner-2A	Combined	None	Liquid	Solid	Solid	None	3	Staging
12/9/80	Atlas-E/F MSD	Combined	None	Liquid	Solid	None	None	1	Liquid
8/3/81	Delta-3913	Combined	Solid	Liquid	Liquid	Solid	None	1	Liquid
8/6/81	Atlas-SLV3D Centaur-D1AR	Liquid Only	None	Liquid	Liquid	None	None	5	Staging
12/18/81	Atlas-E/F SGS-1 (Atlas-E/F SVS-1)	Combined	None	Liquid	Solid	Solid	None	1	Liquid
6/9/84	Atlas-G Centaur-D1AR	Liquid Only	None	Liquid	Liquid	None	None	2	Liquid
7/29/85	Shuttle (STS)	Combined	Solid	Liquid	None	None	None	1	Liquid
8/28/85	Titan-34D	Combined	Solid	Liquid	Liquid	None	None	1	Liquid
1/28/86	Shuttle (STS)	Combined	Solid	Liquid	None	None	None	0	Solid
4/18/86	Titan-34D	Combined	Solid	Liquid	Liquid	None	None	0	Solid
5/3/86	Delta-3914	Combined	Solid	Liquid	Liquid	Solid	None	1	Liquid
3/26/87	Atlas-G Centaur-D1AR	Liquid Only	None	Liquid	Liquid	None	None	1	Liquid
9/2/88	Titan-34D Transtage	Combined	Solid	Liquid	Liquid	Liquid	None	3	Liquid
3/14/90	Commercial Titan-3	Combined	Solid	Liquid	Liquid	None	None	5	Staging
4/18/91	Atlas-1	Liquid Only	None	Liquid	Liquid	None	None	2	Liquid
7/17/91	Pegasus-H	Combined	Aircraft	Solid	Solid	Solid	Liquid	2	Staging
8/23/92	Atlas-1	Liquid Only	None	Liquid	Liquid	None	None	2	Liquid
3/25/93	Atlas-1	Liquid Only	None	Liquid	Liquid	None	None	1	Liquid
8/2/93	Titan-403A, 404A, 405A	Combined	Solid	Liquid	Liquid	None	None	0	Solid
5/19/94	Pegasus HAPS	Combined	Aircraft	Solid	Solid	Solid	Liquid	4	Liquid
6/27/94	Pegasus-XL	Solid Only	Aircraft	Solid	Solid	Solid	None	1	Solid
6/22/95	Pegasus-XL	Solid Only	Aircraft	Solid	Solid	Solid	None	2	Staging
8/5/95	Delta-7925 (Delta-2925)	Combined	Solid	Liquid	Liquid	Solid	None	0	Staging

Date	Vehicle Model	Vehicle Type	Stage 0 Type	Stage 1 Type	Stage 2 Type	Stage 3 Type	Stage 4 Type	Failed Stage #	Failed Stage Type
8/15/95	Athena-1	Combined	None	Solid	Solid	Liquid	None	1	Solid
10/23/95	CONESTOGA 1620	Solid Only	None	Solid	Solid	Solid	Solid	1	Solid
11/4/96	Pegasus-XL	Solid Only	Aircraft	Solid	Solid	Solid	None	5	Staging
1/17/97	Delta-7925 (Delta-2925)	Combined	Solid	Liquid	Liquid	Solid	None	0	Solid
8/1/97	PEGASUS XL\L.1011	Solid Only	Aircraft	Solid	Solid	Solid	None	3	Solid
2/10/98	Taurus-2210	Solid Only	None	Solid	Solid	Solid	Solid	Unknown	Solid
8/12/98	Titan-401A Centaur-T	Combined	Solid	Liquid	Liquid	Liquid	None	2	Liquid
8/27/98	Delta-8930 (Delta-3940)	Combined	Solid	Liquid	Liquid	None	None	0	Solid
4/27/99	Athena-2	Combined	None	Solid	Solid	Solid	Liquid	3	Staging
4/30/99	Titan-401B Centaur-T	Combined	Solid	Liquid	Liquid	Liquid	None	3	Liquid
5/5/99	Delta-8930 (Delta-3940)	Combined	Solid	Liquid	Liquid	None	None	2	Liquid
3/12/00	Zenit-3SL	Liquid Only	None	Liquid	Liquid	Liquid	None	2	Liquid
9/21/01	Taurus-2110 (Commercial-Taurus)	Solid Only	None	Solid	Solid	Solid	Solid	2	Solid
1/16/03	Shuttle (STS)	Combined	Solid	Liquid	None	None	None	1	Liquid
6/29/04	Zenit-3SL	Liquid Only	None	Liquid	Liquid	Liquid	None	3	Liquid
12/21/04	Delta-4H (Delta-4050H)	Liquid Only	Liquid	Liquid	Liquid	None	None	1	Liquid
3/24/06	Falcon-1	Liquid Only	None	Liquid	Liquid	None	None	1	Liquid
1/30/07	Zenit-3SL	Liquid Only	None	Liquid	Liquid	Liquid	None	1	Liquid
3/21/07	Falcon-1	Liquid Only	None	Liquid	Liquid	None	None	1	Staging
6/15/07	ATLAS V 401	Liquid Only	None	Liquid	Liquid	None	None	2	Liquid
8/3/08	Falcon-1	Liquid Only	None	Liquid	Liquid	None	None	2	Staging
2/24/09	TAURUS (CASTOR 120) XL 3110	Solid Only	None	Solid	Solid	Solid	Solid	3	Staging
3/4/11	TAURUS (CASTOR 120) XL 3110	Solid Only	None	Solid	Solid	Solid	Solid	3	Staging
10/8/12	FALCON 9 V1	Liquid Only	None	Liquid	Liquid	None	None	1	Liquid
2/1/13	ZENIT 3 SL (SEA LAUNCH)BLOK DM-SL	Liquid Only	None	Liquid	Liquid	Liquid	None	1	Liquid
10/28/14	ANTARES-130	Combined	None	Liquid	Solid	None	None	1	Liquid
6/28/15	FALCON 9 V1	Liquid Only	None	Liquid	Liquid	None	None	2	Liquid
11/3/15	SPARK	Solid Only	None	Solid	Solid	Solid	None	1	Solid

Table B-2. Failure Details.

Date	Vehicle Model	Payload Orbit Achieved	Failure Class	Initiating Subsystem	Manifesting Subsystem	Manifestation Class	Initial Manifestation Type	Launch Vehicle Demise
5/29/80	Atlas-E/F-Star-37-ISS	Unintended orbit	design	engine/motor	staging	Loss of Control	Tank burst - Loss of control	None
7/14/80	Thor-LV2F Burner-2A	Failed to orbit	process	avionics	staging	Loss of Control	Staging - Loss of control	None
12/9/80	Atlas-E/F MSD	Failed to orbit	design	engine/motor	engine/motor	Loss of Control	Loss of Control (asymmetric thrust)	Loss of Function
8/3/81	Delta-3913	Unintended orbit	unknown	MPS	engine/motor	Contained	Propellant leak/loss - Low performance	None
8/6/81	Atlas-SLV3D Centaur-D1AR	Final orbit reached	unknown	structure	structure	Uncontained	Nominal ascent - Damage to payload	None
12/18/81	Atlas-E/F SGS-1 (Atlas-E/F SVS-1)	Failed to orbit	process	engine/motor	engine/motor	Loss of Control	Loss of Control (asymmetric thrust)	Loss of Function
6/9/84	Atlas-G Centaur-D1AR	Unintended orbit	process	MPS	MPS	Loss of Control	Tank burst - Loss of control	None
7/29/85	Shuttle (STS)	Unintended orbit	design	avionics	engine/motor	Contained	Benign Failure/False Positive	None
8/28/85	Titan-34D	Failed to orbit	process	MPS	engine/motor	Loss of Control	Loss of Control (asymmetric thrust)	Loss of Function
1/28/86	Shuttle (STS)	Failed to orbit	weather	engine/motor	engine/motor	Uncontained	Case breach	Environment
4/18/86	Titan-34D	Failed to orbit	process	engine/motor	engine/motor	Uncontained	Case burst	Environment
5/3/86	Delta-3914	Failed to orbit	design	avionics	engine/motor	Loss of Control	Loss of Control (asymmetric thrust)	Loss of Function
3/26/87	Atlas-G Centaur-D1AR	Failed to orbit	weather	avionics	GNC	Loss of Control	Loss of Control	Loss of Function
9/2/88	Titan-34D Transtage	Unintended orbit	process	MPS	engine/motor	Contained	Propellant leak/loss - Low performance	None
3/14/90	Commercial Titan-3	Final orbit reached	process	avionics	staging	Contained	Staging - Stages/payload fail to separate	None
4/18/91	Atlas-1	Failed to orbit	process	MPS	engine/motor	Loss of Control	Loss of Control (asymmetric thrust)	Loss of Function
7/17/91	Pegasus-H	Unintended orbit	unknown	staging	staging	Contained	Staging - Low performance	None
8/23/92	Atlas-1	Failed to orbit	process	MPS	engine/motor	Loss of Control	Loss of Control (asymmetric thrust)	Loss of Function
3/25/93	Atlas-1	Unintended orbit	process	MPS	engine/motor	Contained	Low Performance	None
8/2/93	Titan-403A, 404A, 405A	Failed to orbit	process	engine/motor	engine/motor	Uncontained	Case burst	Environment

Date	Vehicle Model	Payload Orbit Achieved	Failure Class	Initiating Subsystem	Manifesting Subsystem	Manifestation Class	Initial Manifestation Type	Launch Vehicle Demise
5/19/94	Pegasus HAPS	Unintended orbit	design	GNC	engine/motor	Contained	Benign Failure/False Positive	None
6/27/94	Pegasus-XL	Failed to orbit	design	avionics	GNC	Loss of Control	Loss of Control	Loss of Function
6/22/95	Pegasus-XL	Failed to orbit	process	staging	GNC	Loss of Control	Staging - Loss of control	Loss of Function
8/5/95	Delta-7925 (Delta-2925)	Final orbit reached	weather	staging	staging	Contained	Staging - Low performance	None
8/15/95	Athena-1	Failed to orbit	design	GNC	GNC	Loss of Control	Loss of Control	Loss of Function
10/23/95	CONESTOGA 1620	Failed to orbit	design	avionics	GNC	Loss of Control	Loss of Control	Loss of Function
11/4/96	Pegasus-XL	Unintended orbit	process	avionics	staging	Contained	Staging - Stages/payload fail to separate	None
1/17/97	Delta-7925 (Delta-2925)	Failed to orbit	process	engine/motor	engine/motor	Uncontained	Case burst	Environment
8/1/97	PEGASUS XL\L.1011	Final orbit reached	unknown	unknown	unknown	Unknown	Unknown	None
2/10/98	Taurus-2210	Unintended orbit	unknown	unknown	unknown	Contained	Vehicle over-performance - Off-nominal ascent	None
8/12/98	Titan-401A Centaur-T	Failed to orbit	process	avionics	GNC	Loss of Control	Loss of Control	Loss of Function
8/27/98	Delta-8930 (Delta-3940)	Failed to orbit	design	GNC	GNC	Loss of Control	Loss of Control	Loss of Function
4/27/99	Athena-2	Failed to orbit	design	avionics	staging	Contained	Staging - Low performance	None
4/30/99	Titan-401B Centaur-T	Unintended orbit	process	avionics	GNC	Loss of Control	Loss of Control	None
5/5/99	Delta-8930 (Delta-3940)	Unintended orbit	process	engine/motor	engine/motor	Uncontained	LRE uncontained	None
3/12/00	Zenit-3SL	Failed to orbit	process	avionics	GNC	Loss of Control	Loss of Control	Loss of Function
9/21/01	Taurus-2110 (Commercial-Taurus)	Failed to orbit	unknown	GNC	GNC	Loss of Control	Loss of Control	None
1/16/03	Shuttle (STS)	Final orbit reached	process	TPS	TPS	Uncontained	Nominal ascent - Damage to payload	None
6/29/04	Zenit-3SL	Final orbit reached	process	avionics	engine/motor	Contained	Low Performance	None
12/21/04	Delta-4H (Delta-4050H)	Unintended orbit	design	MPS	engine/motor	Contained	Benign Failure/False Positive	None
3/24/06	Falcon-1	Failed to orbit	design	MPS	engine/motor	Uncontained	LRE uncontained	Loss of Function
1/30/07	Zenit-3SL	Failed to orbit	process	engine/motor	engine/motor	Uncontained	LRE uncontained	Loss of Function
3/21/07	Falcon-1	Failed to orbit	process	engine/motor	staging	Loss of Control	Staging - Loss of control	None

Date	Vehicle Model	Payload Orbit Achieved	Failure Class	Initiating Subsystem	Manifesting Subsystem	Manifestation Class	Initial Manifestation Type	Launch Vehicle Demise
6/15/07	ATLAS V 401	Final orbit reached	design	MPS	engine/motor	Contained	Propellant leak/loss - Low performance	None
8/3/08	Falcon-1	Failed to orbit	design	engine/motor	staging	Loss of Control	Staging - Loss of control	None
2/24/09	TAURUS (CASTOR 120) XL 3110	Failed to orbit	design	staging	staging	Contained	Staging - Low performance	None
3/4/11	TAURUS (CASTOR 120) XL 3110	Failed to orbit	design	staging	staging	Contained	Staging - Low performance	None
10/8/12	FALCON 9 V1	Final orbit reached	process	engine/motor	engine/motor	Uncontained	LRE uncontained	None
2/1/13	ZENIT 3 SL (SEA LAUNCH)BLOK DM-SL	Failed to orbit	process	GNC	GNC	Loss of Control	Loss of Control	Loss of Function
10/28/14	ANTARES-130	Failed to orbit	design	engine/motor	engine/motor	Uncontained	LRE uncontained	Environment
6/28/15	FALCON 9 V1	Failed to orbit	process	structure	structure	Uncontained	Tank burst - Loss of vehicle	Environment
11/3/15	SPARK	Failed to orbit	unknown	unknown	unknown	Unknown	Unknown	Environment

Appendix C: Descriptions of Flights with Launch Vehicle Errors

This appendix provides a brief discussion of each flight in the historical failure set organized alphabetically by launch vehicle family and then by launch date. Headings for each flight summarize the launch date, the propellant types used in the launch vehicle, the stage number and type in which the failure initiated ("0" indicates a strap-on booster), the initial failure manifestation type, and the manner in which the vehicle was destroyed.

Antares

Vehicle/Flight: Antares-130					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
10/28/2014	Combined	1	Liquid	LRE Uncontained	Environment

This was the fifth and last flight of the Antares 100 series, the first flight of the upgraded Antares 130 (with upgraded second stage). The first stage used two Russian NK-33 engines built in the 1970s that had been purchased and refurbished by Aerojet and renamed AJ-26. This vehicle had two AJ26-62s.

The vehicle behaved erratically right after launch. At just over T+15s, an explosion occurred in engine 1 of the Main Engine System (MES-1) and propagated to MES-2. The vehicle lost thrust and began to fall back to the launch pad. The Range Safety Officer (RSO) issued the destruct command just before the vehicle struck the ground in order to minimize the potential damage from the expected ground impact and subsequent explosion. A large explosion ensued and the vehicle and payload were lost. The launch pad and some nearby buildings were damaged.

Aerojet Rocketdyne, Orbital Sciences and NASA conducted separate investigations after the accident with differing conclusions [26]. Orbital's investigation report identified the likely source of the failure as a machining defect in the turbine assembly of the turbopump during manufacturing while Aerojet's suggested the failure source was foreign object debris. The NASA Independent Review Team (IRT) identified three possible technical root causes of the failure: inadequate design of the AJ-26 liquid oxygen (LO2) hydraulic balance assembly (HBA) and turbine-end bearing, foreign object debris introduced into the LO2 turbopump, and a machining defect in the liquid oxygen turbopump. The IRT eventually concluded that the most likely cause of the MES-1 explosion was due to loss of radial positioning in the LO2 turbopump 1, which caused friction due to rubbing between rotating and stationary components in the turbopump Hydraulic Balance Assembly (HBA) seal package, leading to ignition and fire [27].

In December 2014, Orbital Sciences announced that the RD-181—a modified version of the RD-191—would replace the AJ26 on the Antares 200-series.

Figure C-1. Explosion in the Antares MES. Credit: NASA

Figure C-2. Antares explodes just before hitting the launch pad. Credit: NASA

Athena

Vehicle/Flight: Athena-1					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/15/1995	Combined	1	Solid	Loss of control	Loss of Function

At T+79s into Athena's debut flight, an anomalous pitch was detected by tracking cameras that resulted in uncontrolled oscillations. After the first stage shut down as planned at T+82s, the coning motion dislodged the shroud at T+121s. Six seconds later, the inertial measurement unit failed followed by second stage ignition. Although the second stage rapidly stabilized itself, the vehicle was already thrown off course, prompting the RSO to destroy it at T+160s [28].

Two independent failures were discovered, either of which would have led to a loss of the vehicle on their own: expended hydraulic fluid burned in the aft section of the first stage that damaged nozzle feedback cables and caused a loss of gimbal control and tumbling, and arcing in the Inertial Measurement Unit (IMU) high-voltage power supply that caused a loss of attitude reference.

Vehicle/Flight: Athena-2					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
4/27/1999	Combined	3	Staging	Staging – low performance	None

Athena launched carrying the Ikonos 1 high-resolution commercial imaging satellite. During the third stage, the shroud snagged and the payload fairing failed to separate. The extra weight prevented the satellite from reaching orbit and the third stage fell into the atmosphere over the South Pacific.

The cause was determined to be an electrical failure caused by a design flaw. The shroud was designed in two pieces with pyrotechnic charges at its base to circumferentially split the shroud and charges inside the shroud to split it longitudinally. After the charges at the base fired, the others failed to follow. The initial shock of charges at the base had disconnected the cables for the charges inside of the shroud [28].

Atlas

Vehicle/Flight: Atlas-19F					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
5/29/1980	Combined	1	Liquid	Tank Burst – Loss of Control	None

The vehicle was running low on velocity and heavy on propellant for most of its flight, running almost a minute past its nominal burn time. The failure was caused by a rare but known failure mode when a seal was jostled loose by the rapid-fire pyrotechnic cartridge ignition system used in the Atlas E/F missiles, flooding the B-1 turbopump with fuel and slowing down its rotation speed. As a result, thrust levels in the engine were cut to 80% and booster velocity and fuel consumption were considerably reduced. The Atlas's onboard computer tried to compensate first by extending the booster engine burn time, but eventually a backup command forced a booster shutdown and jettison before the correct velocity could be achieved. After booster engine cutoff, the computer still tried to compensate by extending sustainer burn time until it went 50 seconds past what would have been normal cutoff. Following SECO, the booster also had to execute vernier solo mode for another 11 seconds [28].

For simplicity and to reduce the launch readiness time by removing the need to test an interface between the booster and the spacecraft, the NOAA satellite had no electrical interface with the Atlas [29]. Lacking communication with the booster, the satellite used its own accelerometer to determine when to separate and its solid rocket kick motor was designed to activate at a preset separation time in the event the accelerometer malfunctioned. The Atlas was consequently still running when the preset time occurred, causing the kick motor to rupture the LOX tank dome, which registered on telemetry readouts as an immediate loss of tank pressure. The spacecraft was unable to properly separate and perform the required pitch-down maneuvers, and the satellite reached a useless orbit and had to be abandoned [30].

Vehicle/Flight: Atlas-68E					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
12/9/1980	Combined	1	Liquid	Loss of Control (asymmetric thrust)	Loss of Function

A few hundred milliseconds before the planned commanded shutdown, one booster engine prematurely lost thrust. The asymmetric thrust cause the vehicle to rapidly spin 180 degrees before it stabilized in a retrofire attitude, lost velocity, and started descending back to Earth. The vehicle exploded high above the Earth’s surface. The cause was determined to be corrosion in a piece of ducting that resulted in the loss of lubricant to the turbopump.

The mishap investigation revealed that the cause of the engine failure was loss of engine gearbox lubrication, which occurred at around T+100s. The conclusion reached by the U.S. Air Force Mishap Board was that a section of the lubrication feed line failed. Portions of the feed line were made of a material that was susceptible to stress corrosion. This fact had been known for years, but with the plans underway to replace all U.S. expendable launch vehicles (ELVs) with the Space Shuttle, there was little interest in spending any unnecessary funding on the old boosters [31].

Vehicle/Flight: Atlas-Centaur (AC-59)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/6/1981	Liquid	5	Staging	Damage to Payload	None

Damage to the payload was sustained during ascent and the satellite did not become operational. The damage was ultimately attributed to explosive delamination of the fiberglass honeycomb fairing during flight. Specifically, the inside wall of the fairing damaged one of the solar arrays and bent the transmit antenna mast, preventing the antenna from fully deploying. The satellite was also placed in a lower orbit than anticipated and was eventually moved by ground controllers to a satisfactory orbit [32]. It is unclear when the fairing failed, so the failed stage number was assigned a 5 (payload deployment) rather than a particular vehicle stage number. The fairing used an unvented honeycomb sandwich structure, which was later shown to explode at high altitude in a proof test at 90,000 feet [33], making it possible that this failure occurred early during the flight, before booster engine cutoff (BECO).

Vehicle/Flight: Atlas E/F SVS-1 (76E)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
12/19/1981	Combined	1	Liquid	Loss of Control (asymmetric thrust)	Loss of Function

Atlas suffered an early engine shutdown 6 seconds after launch. By T+7.4s the MA-3 booster had lost all thrust and the vehicle began to lose control. It pitched over sharply and began to roll. At T+19.8s, the vehicle exploded before hitting the ground only 500 feet from the launch pad.

After examining the debris, the cause of the failure was clear. During inspection of the B-2 engine before installation on the booster, a metal O-ring seal was found to have slipped out of place. This issue had been seen many times before and the standard repair procedure was followed. The new seal was coated with Plastiseal, a sealant designed for that particular application, and the standard repair procedure indicated that “no excess globs of Plastiseal material to be applied to the seal." Those instructions were followed, but there was still just enough sealant to flow over and plug up three coolant holes around the gas generator injector [34]. When Atlas was ignited, it only took 4 seconds for temperatures in the gas generator to melt the stainless steel casing [35]. The engine overheated and burned through its gas generator, severing an oxidizer line and shutting down the engine.

Vehicle/Flight: Atlas G					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
6/9/1984	Liquid	2	Liquid	Tank burst – Loss of control	None

After the payload reached low earth orbit, the upper Centaur stage of the Atlas G exploded during the coast phase, prior to the second Centaur burn, as a result of a large oxygen tank leak. The Centaur and Intelsat tumbled end-over-end and reentered the atmosphere 4 months later.

A minor fatigue crack developed in the LOX tank during an anomalously violent staging and orbital injection when sulfur oxide collected in the interstage area and amplified the charge firing enough to crack the LOX tank.

Propellant boost pumps were deleted on this version of Centaur to save weight, and the LOX tank pressure was increased 25% to compensate. The leak had gone undetected during pre-flight inspection procedures. Although the tank had been designed to accommodate higher pressure, the technicians at Convair failed to check Centaur for leaks before shipping it to Cape Canaveral [36].

Vehicle/Flight: Atlas-G Centaur-D1AR					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
3/26/1987	Liquid	1	Liquid	Loss of control	Loss of Function

Although Atlas was launched into rain, it was reported that this launch did not violate the rules set for launch in rainy conditions as there were no reported thunderstorms within 5 miles of the pad and no anvil clouds within 3 miles of the pad. However, At T+48s, unknown to the ground crew, the vehicle was struck by lightning, damaging the guidance computer. As a result, an erroneous pitch down command was sent that caused the vehicle to yaw and lose control. At T+51s, the vehicle strayed off course and the RSO destroyed it. A piece of the recovered aerodynamic shroud was found with a number of burn-through pinhole punctures, confirming that Atlas had been struck by lightning several times. The digital computer unit sent the erroneous command to gimbal hard to the right and the vehicle began to break up at T+50.7s [37].

Vehicle/Flight: Atlas-1 (AC-70)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
4/18/1991	Liquid	2	Liquid	Loss of control (asymmetric thrust)	Loss of Function

This was the first of two Atlas-Centaur upper stage failures (AC-70 and AC-71) due to a stuck valve. When the Centaur stage ignited at T+361s, one of the two engines did not achieve full thrust due to the ice plug and the vehicle tumbled, prompting the RSO to destroy it at T+441s.

The privately led investigation incorrectly concluded that "perhaps a nut or a bolt" was introduced during cleaning for propellant ducts, causing the turbopump failure. Changes to the cleaning process and software were instituted. In addition, the Centaur was modified to yield extra torque in order to overcome a 'slow start' in a turbopump, and software was rewritten to shut down and rerun the startup cycle in the event of an engine start failure [28].

The true cause of this failure was not discovered until 1992 when another AC-71 suffered the same error. The investigation following the second failure found that one of the valves used was prone to leaks, and that this had likely existed for a long time as a latent issue. However, the valve did not cause any issues until General Dynamic's engineers found a way to increase engine performance with a more efficient pre-chilling process. Atmospheric nitrogen entered the Centaur C-1 engine after pre-chilling through a stuck check valve and, upon contact with the hydrogen, froze in the LH2 turbopump and gearbox. The new pre-chilling process allowed the ice plug to form [38].

Vehicle/Flight: Atlas-1 (AC-71)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/23/1992	Liquid	2	Liquid	Loss of control (asymmetric thrust)	Loss of Function

This launch vehicle failed due to the same error that occurred during the April 18, 1991, Atlas-1 AC-70 launch. At Centaur ignition, the engine did not achieve full thrust, causing the stage to tumble. The vehicle was destroyed by RSO about 8 minutes after launch [39].

The increased torque added after the AC-70 failure should have produced a successful start, and the new software did order a second startup cycle, but neither provision worked. The investigation board for this accident included government participation and correctly hypothesized that during the pre-launch chill-down procedure, moisture from the ambient air entered the Centaur C-1 engine through a stuck check valve and froze in LH2 turbopump and gearbox. A solenoid valve was added to prevent air from entering the turbopump and freezing on its blades [38].

Vehicle/Flight: Atlas-I (AC-74)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
3/25/1993	Liquid	1	Liquid	Low performance	None

At T+24s the Atlas' two auxiliary engines began to lose thrust, eventually leveling off at 65% power. Although the Centaur upper stage computer tried to compensate for the thrust loss by extending the first burn by 24 seconds, the stage exhausted its propellant prior to completing the burn. The launch vehicle inserted the Hughes UHF 1 follow-on spacecraft into a lower orbit than anticipated. The satellite maintained functionality, but was considered a loss due to the unacceptable orbit. An improperly torqued set screw in the first stage sustainer engine precision regulator caused reduced power and an early shut down [38].

Figure C-3. An Atlas I rocket awaits lift-off. Credit: NASA

Vehicle/Flight: Atlas V					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
6/15/2007	Liquid	2	Liquid	Propellant leak/loss - Low performance	None

The Centaur upper stage shut down four seconds earlier than planned due to a fuel leak in the engine system cryogenic liquid hydrogen valve. The leak continued during the nearly one hour coast phase between the two Centaur main engine burns. Some real-time indications of an anomaly occurred during the mission. Several parameters suggested that the temperature was off-nominal, but the effects of the difference on the performance of the engine were unknown until the premature shutdown due to fuel depletion. Although the payload was placed in a lower orbit than planned, a proper orbit was eventually achieved using the spacecraft's on-board propulsion system.

The failed LH2 fuel valve in the RL10 was a new design used in only a half-dozen previous flights (the manufacturer was phasing the old valve out of their product line). Future Atlas 5 and Delta 4 rocket launches -- both rocket families use versions of RL10 engines to power their upper stages – planned to revert the previous fuel inlet valve design that officials fully trusted. Subsequent testing during the investigation showed that the heritage valve design had larger closing force margins. This mission also experienced a longer than average first burn, which increased valve exposure to cryogenic hydrogen and elevated valve friction. As a result, the valve did not close completely and leaked fuel during the coast phase [40].

Figure C-4. An Atlas V rocket lifts off from Launch Complex 41. Credit: NASA

Conestoga

Vehicle/Flight: Conestoga-1620					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
10/23/1995	Solid	1	Solid	Loss of control	Loss of Function

At T+44.4s the launch vehicle began to turn and then pitched down. The RSO sent the self-destruct command, but the FTS failed to operate on two of the Castor 4 stage 1 motors. The third stage Castor 4B and fourth stage Star 48 were not destroyed by range safety and landed in the ocean. Noise in the guidance control system led to excessive steering of one stage-1 booster motor and depleted the motor's hydraulic fluid [7]. The vehicle completely lost control and broke up at T+46s [41].

Delta

Vehicle/Flight: Delta-3913					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/3/1981	Combined	1	Liquid	Propellant leak/loss - Low performance	None

Delta-3913 failed when a malfunction in the booster rocket caused the main engine to shut off early. This caused the DE-2 satellite (co-launched with DE-1) to be placed in a lower orbit than anticipated. This issue was not considered serious and the satellite lasted its intended lifespan. It reentered the atmosphere in 1983. DE-1 was placed in a higher orbit and retired in 1991.

The underperformance of the main engine was caused by a propellant loading error that was the result of an instrumentation error [30].

Vehicle/Flight: Delta-3914					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
5/3/1986	Combined	1	Liquid	Loss of control – Asymmetric thrust	Loss of Function

Delta-3914 failed when the first stage engine shut down prematurely at T+71s of a planned 223s firing. Without attitude control and the 3 air-started strap-on motors burning, sufficient yaw had developed by T+77s to over-stress the shroud and shear it off. The payload was destroyed. The vehicle had completed a full 360-degree rotation before the RSO commanded its destruction.

According to the launch vehicle telemetry, there had been two power surges at T+70s before the engine shut down. These two surges caused a reduction in voltage to the relays that held the propellant valves open, supplying fuel to the engines. Once voltage to keep those relay coils energized was lost, even momentarily (6 and 13ms), they could no longer be re-actuated, killing the power to the vehicle's rocket engine relay box and shutting the engine down. Years earlier, the wiring insulation was changed from polyvinyl chloride (PVC) to Teflon. The shape of the harness caused it to chafe and expose the wires as the launch vehicle vibrated on ascent. The vehicle was carrying the GOES-G weather satellite, designed to replace GOES-5 and provide continuous vertical profiles of atmospheric temperature and moisture [28].

Vehicle/Flight: Delta-7925					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/5/1995	Combined	0	Staging	Staging - low performance	None

At T+66s the three strap-on Graphite-Epoxy Motors (GEMs) ignited while the other six motors used to augment launch jettisoned normally. At T+130s, two of the air-started motors jettisoned normally, but one failed to jettison and remained attached to the vehicle. The explosive lines used to separate the motor were damaged due to exposure to excessively high temperatures caused by a failure of the insulation to protect the rocket's booster separation circuits [42]. The added weight of the motor resulted in a significant loss of velocity after the first stage shut down. The second stage computer attempted to correct this error by extending the initial burn an extra 35 seconds, but the tanks ran dry after just 10 seconds during the follow-on burn. The payload eventually achieved geostationary orbit at the expense of over half of its orbital life expectancy [4].

Figure C-5. Delta 7925 at Launch Pad 17-B. Credit: NASA

Vehicle/Flight: Delta-7925 (D241)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
1/17/1997	Combined	0	Solid	Case Burst	Environment

At T+13 seconds and a height of 1600 feet, the launch vehicle exploded and rained 250 tons of propellant and hardware on and around the launch pad. Photographs showed black smoke venting from the side of one of the six Graphite Epoxy Motors (GEMs) about T+6 seconds after ignition, indicating a case breach [28]. At T+7.2 seconds after ignition, GEM number 2 developed a 71-inch-long split in its casing. The split grew to 254 inches before the motor failed at T+12.6 seconds [43]. Telemetry showed that the self-destruct system detected a vehicle distortion at T+13 seconds, immediately after the explosion of GEM number 2 [28]. Mission Control sent destruct commands at T+ 22.3 seconds to destroy the largely intact second and third stages, releasing the payload and fairing. As a result, the payload exploded on impact with the ground [43].

Vehicle/Flight: Delta-8930					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/27/1998	Combined	0	Solid	Loss of control	Loss of Function

At T+55s the rocket began a 4 Hz roll oscillation that the control software design had not accounted for [44]. As a result, the TVC system tried to correct the roll, but over-compensated and actually exacerbated the instability. Once the TVC system depleted the hydraulic fluid, the oscillation diminished, but the gimbals, without fluid for control, pitched the vehicle over. At T+72s attitude control was lost, and the vehicle began to break up. The initial roll oscillations were found to be caused by the air-lit SRMs gaining significant control influence as the other ground-lit SRMs depleted their propellant. The significance of this roll mode was overlooked and not incorporated into the design of the control system [28].

Vehicle/Flight: Delta-8930 (D3-2)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
5/5/1999	Combined	2	Liquid	LRE Uncontained	None

Two shock events occurred during the second stage RL-10B-2 failure. The first occurred 4.5 seconds after the second stage's first ignition, and the second, larger shock occurred 3.5 seconds after the second ignition, which was to inject the satellite into a transfer orbit. There was an increase in temperature around the engine, followed by a sudden decrease. This rapid thermal variation was believed to have been caused initially by hot gases escaping from a breach in the combustion chamber, followed by cold propellant flowing out from a ruptured cryogenic propellant line. The venting of the hot gases already in the chamber put the stage/spacecraft assembly into an uncontrollable tumble, during which the engine shut down. The satellite separated from the stage according to the preset programming.

Analysis found a 67 square inch diamond-shaped breach of the engine's combustion chamber. The investigation found the breach at a seam that leaked during static firing and had been repaired. The flawed brazing left air pockets that allowed the joint to split. The repaired seam survived a dozen later tests and its first in-flight firing, prompting Pratt & Whitney to argue that there must have been some other unexpected torsional stress. Boeing disagreed. After this incident, seams were plated in place instead of brazed, and each unit placed into an oven and baked. Pratt & Whitney's corrective actions included: 1) immediate ultrasonic inspection of 25 existing RL10 engines to reveal bonding weaknesses and 2) use of a "slightly different technique" to braze combustion chamber reinforcing bands on new RL10s.

In their previous 36-year-long history, the RL10s had never experienced a combustion chamber rupture. In this instance, however, the investigation determined that brazing coverage was "a factor of four" below design requirements. In some areas, the brazing was as low as 20% per linear inch. Drawings had called for a minimum of 80% coverage per linear inch, but product inspectors reinterpreted the standard to mean 80% coverage averaged over the entire length of the reinforcement strip. Since the offending brazing technique was a relatively recent innovation, many of the 25 existing engines tested out well – they had been built using the older technique [4] [28] [45].

Vehicle/Flight: Delta-IV Heavy					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
12/21/2004	Liquid	1	Liquid	Benign Failure/ False Positive	None

This was the first (demonstration) launch of the Heavy variant of the Delta IV, carrying a DemoSat and a NanoSat2 (a set of two very small satellites). A main engine early shutdown was triggered by an empty tank signal from the fuel sensor during the first stage. Cavitation that initiated around the entrance to the propellant feed line is believed to be the cause of the failure. The vehicle was carrying two payloads, one of which was separated at a very low orbit and subsequently burned up in the atmosphere. The second payload was released at a lower orbit than anticipated, but achieved its primary flight objectives [7].

As a result of the early shutdown, the upper stage was left with a 1500 foot-per-second speed deficit and attempted to compensate. The upper stage had three planned burns over the 6-hour mission to geosynchronous orbit. The first burn of the upper stage was designed with propellant margin in case of any Common Core Booster shortfalls, and burned much longer than the planned 7-minute first burn, but still could not reach a stable orbit, releasing its payload too low. The second stage made its second burn and coasted for 5 hours before its final burn. The final (third) circularization burn was to last 3 minutes, but the stage shut down two-thirds of the way in, having spent all of its fuel.

This same configuration worked without a problem in previous Delta IV incarnations. However, the acceleration profile, combined with the liquid levels and flow rate of the new mission, resulted in the cavitation phenomena. Cavitation margin adjustments were taken into consideration for subsequent fights, with throttling schedules and ullage pressurization management strategies [46].

Figure C-6. A Delta-IV Heavy rocket lifts off from Launch Complex 37. Credit: NASA

Falcon

Vehicle/Flight: Falcon-1					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
3/24/2006	Liquid	1	Liquid	LRE Uncontained	Loss of Function

At T+34s, the main engine shut down after a fire broke out just above the engine and damaged the first stage pneumatic helium system. The vehicle rolled and pitched over before falling back to the ground and landing onto a dead reef about 250 feet from the launch site. A kerosene fuel leak began at T–400s when the propellant pre-valves were opened; the fuel was ignited when the main engine started at liftoff. Over time, the fire resulted in a loss of pneumatic pressure, causing the RP-1 and liquid oxygen pre-valves to close, terminating engine thrust 34 seconds after ignition.

A corroded fuel line nut was determined to have been the cause of the failure. The nut actually broke sometime in the 18 hours prior to launch [47]. SpaceX implemented numerous changes to the rocket design and software to prevent this type of failure from recurring, including replacing aluminum hardware white stainless steel (which is less expensive, but heavier) and increasing pre-liftoff computer checks by a factor of thirty [48].

Vehicle/Flight: Falcon-1					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
3/21/2007	Liquid	1	Staging	Staging - Loss of control	None

The interstage fairing on the top of the first stage contacted the second stage engine bell during staging due to a higher than expected rotation rate. The stages separated at a lower altitude than planned, causing high rotation rates due to aerodynamic forces that would have otherwise been negligible at the planned staging altitude. The fuel mixture ratios were slightly off-nominal as a result of an incorrect propellant utilization file that was loaded onto the engine computer, resulting in a lower first stage trajectory. At T+260s, a circular coning oscillation began and video was lost. At T+301s the vehicle started to roll and telemetry was lost. The second stage engine shut down at T+450s due to a roll control issue. The increased oscillation was the result of sloshing propellant in the LOX tank. The fuel in the second stage centrifuged, exposing fuel inlets, and caused the second stage engine to flame out at T+660s. Baffles were added to the second stage tanks in future flights to reduce possible sloshing. The Thrust Vector Control system in the second stage would have normally dampened the oscillation, but the bump to the second stage engine bell caused overcompensation in the correction [47].

Vehicle/Flight: Falcon-1					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/3/2008	Liquid	2	Staging	Staging - Loss of control	None

This launch debuted the new Merlin 1C engine, meant to increase Falcon’s payload size and provide higher thrust. Stage separation went as intended, but residual fuel in the new engine evaporated and provided additional transient thrust. The first stage re-contacted the second stage and damaged the engine, resulting in the vehicle failing to reach orbit.

This was the first flight with a new regeneratively cooled engine. A longer than expected thrust transient that occurred after engine shutdown caused the first stage to be pushed toward the second stage after separation. The gap between engine cutoff and staging was too short (1.5 s) for the new engine (it was fine for the ablatively cooled engine used prior to this flight). Testing the new engine at sea level rather than at vacuum level masked the thrust transient and the need for a longer gap. During re-contact, the second stage firing of a (damaged) pressure-fed Kestrel engine burned the parachutes in the first stage. As a result, neither stage was recovered.

Vehicle/Flight: Falcon 9					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
10/8/2012	Liquid	1	Liquid	LRE Uncontained	None

The vehicle performed nominally until T+80s when one of the nine Merlin 1C first stage engines shut off and appeared to expel debris. The vehicle continued on its trajectory with the other eight engines and the second stage burning slightly longer to make up for the loss of thrust. The primary payload, cargo for the first NASA Commercial Resupply Services mission, was inserted into orbit and completed its mission. However, due to the first stage engine anomaly, there was not enough fuel left to insert the secondary payload into its required orbit. The secondary payload reentered the atmosphere and broke up.

An undetected material flaw in the engine chamber jacket, likely introduced during engine production, ultimately developed into a breach in the main combustion chamber during flight. This breach released a jet of hot gas and fuel in the direction of the main fuel line causing a secondary leak and ultimately a rapid drop in engine pressure and engine failure (either a shutdown or explosion) that did not propagate beyond the initiating engine but did cause the fairing that protects the engine from aerodynamic loads to rupture and fall away from the vehicle. As a result, the on-board guidance system successfully compensated for the loss of thrust by commanding longer burns using a modified flight profile. The remaining eight first stage engines burned 12-13 seconds longer and the second stage burned 15-16 seconds longer. Because the longer second stage burn consumed some of the reserve fuel required by ISS policy, delivery of the secondary payload, an Orbcomm communications satellite, to its proper orbit was not attempted. The secondary payload reentered Earth two days later [49] [50].

Vehicle/Flight: Falcon 9					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
6/28/2015	Liquid	2	Liquid	Tank Burst – Loss of vehicle	Environment

The first stage of the launch vehicle operated nominally until T+139s when an overpressure event occurred in the upper stage LOX tank. The first stage of the vehicle continued to power through the overpressure event for several seconds before it disintegrated. The Dragon spacecraft on board the launch vehicle survived and continued to communicate until it fell below the horizon. The time from first indication of trouble to loss of all data was 0.893 seconds. A steel strut holding a high-pressure helium tank was later discovered to have snapped during ascent under the combination of g-forces and cryogenic temperatures, ultimately leading to helium tank rupture within the LOX tank or impact with, and puncture of, the LOX tank wall. In either case, the LOX tank experienced an overpressure event and ruptured catastrophically. The helium tank is located inside the cryogenic oxygen tank for temperature regulation [51].

Figure C-7. A Falcon 9 launch vehicle lifts off from Cape Canaveral. Credit: NASA

Pegasus

Vehicle/Flight: Pegasus HAPS					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
7/17/1991	Combined	2	Staging	Staging – low performance	None

Pegasus suffered a stage separation malfunction between the first and second stage. The pyrotechnic separation system caused the vehicle to veer off course. At T+102.8s the second stage burn started in a nose-down attitude followed by incomplete payload fairing separation at T+214s. Course corrections during second and third stage burns allowed the vehicle to reach orbit, but the loss of velocity placed the satellites in a low orbit, cutting their lifespans down by 2.5 years [4] [52].

Vehicle/Flight: Pegasus HAPS					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
5/19/1994	Combined	4	Liquid	Benign failure/false positive	None

The HAPS liquid upper stage shut down about 25 seconds early due to a software navigation error, resulting in a lower-than-specified orbit. The payload was still able to provide useful data [4].

Vehicle/Flight: Pegasus-XL					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
6/27/1994	Solid	1	Solid	Loss of control	Loss of Function

Several seconds after first-stage ignition, Pegasus veered off course and lost speed, prompting RSO to destroy it. The investigation revealed that the vehicle experienced an anomalous roll due to a ‘phantom yaw’ caused by an improper aerodynamics model used in the control system autopilot design [4] [28].

Vehicle/Flight: Pegasus-XL					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
6/22/1995	Solid	2	Staging	Staging – loss of control	Loss of Function

The second stage nozzle gimbal became constrained when the interstage ring between the first and second stages failed to separate. Control authority was greatly reduced and the vehicle began to tumble out of control during the second stage. After two and a half loops, the interstage was eventually shaken off and the second stage re-stabilized, but the IMU was overwhelmed and the vehicle veered off course, prompting range safety to destroy it [4] [28].

Vehicle/Flight: Pegasus-XL					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
11/4/1996	Solid	5	Staging	Staging – payload fails to separate	None

The launch vehicle reached the correct orbit but failed to separate from the payload. A rapid decrease in voltage from the transient battery prior to the payload separation pyro event resulted in the failure of the separation system. Investigators found that the shock of third-stage separation caused damage to a power bus at T+460s, leaving the stage without enough voltage to activate the pyrotechnic separation device [53].

Vehicle/Flight: Pegasus-XL					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/1/1997	Solid	3	Solid	Unknown	None

The payload was delivered to an orbit 98km lower than planned and required additional propulsive maneuvers to reach the desired orbit for operation [54].

Space Shuttle

Vehicle/Flight: Space Shuttle (STS-51-F Challenger)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
7/29/1985	Combined	1	Liquid	Benign Failure/False Positive	None

The number one main engine experienced a premature shut down at T+345s (the only in-flight main engine shutdown of the entire shuttle program) due to a faulty fuel turbine discharge temperature sensor. The crew was instructed to Abort to Orbit (ATO). Approximately 8 minutes into the flight, after the ATO order, one of the same temperature sensors in the right engine failed and the remaining sensor displayed values close to the redline, which would have prompted a second engine shutdown. The systems engineer commanded the crew to inhibit any further automatic engine shutdowns based on readings from the remaining sensors. STS-51-F completed the mission objectives at a much lower orbit than originally planned. This quick action prevented the loss of another engine and a possible abort scenario far riskier or far worse than the already in-progress ATO [55].

Figure C-8. STS-51-F launches from Kennedy Space Center, Florida. Credit: NASA

Vehicle/Flight: Space Shuttle (51-L Challenger)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
1/28/1986	Combined	0	Solid	Case Breach	Environment

STS Challenger was launched at an ambient temperature of 38°F (3.3°C) instead of the minimum 53°F (11.7°C) derived from the previous temperature experience of the STS program. The cold temperatures led to loss of resiliency in the motor case joint rubber O-rings. The combustion flame leaked through the O-rings and case joint, and impinged on the motor's aft attach-struts and the external tank. Failure of the aft struts caused the aft end of the motor to move outward and forced the nose of the SRM into the upper portion of the external tank.

Initially, many individuals believed the Challenger broke apart in a massive explosion of the propellants because of a large circular cloud seen at the bottom of the liquid oxygen tank area at 73.282 seconds MET. The Explosion Working Group (EWG) assembled in the wake of both the Challenger and Titan 34D-9 accidents concluded, however, that no significant explosion was generated during the failure evolution. Analysis of the dynamics of the cloud that resulted from the disaster, and examination of the photography led the EWG to conclude that the percentage of hydrogen consumed in a rapid burn was between 6% and 19%. Experts from Marshall Space Flight Center concluded that the bright spot initially thought to be an explosion was in fact a result of reflected sunlight from liquid hydrogen and oxygen droplets spread by flash vaporization. These findings were supported by lack of evidence of exposure to intense heat, e.g., melted aluminum, in any of the recovered debris, other than that caused by the exhaust of the errant right Solid Rocket Booster (SRB) exhaust. Finally, no evidence of significant shrapnel damage was observed on the External Tank (ET) or Orbiter surfaces.

The EWG determined that the breakup of the ET primarily resulted from the errant, gyrating right SRB distorting the ET intertank area and tearing open both the liquid oxygen and liquid hydrogen tanks. The right SRB also contacted the Challenger spacecraft's right wing, which, together with minor explosions in the intertank area, helped release the orbiter and expose it to the destructive aerodynamic forces that ultimately tore the vehicle apart.

The EWG report also states that, based on photographic evidence, the IUS rocket booster for the TDRS-B exited the payload bay intact during the Challenger breakup. Other payloads in the bay could not be positively tracked in the photographic evidence; however, it is believed, based on examination of the recovered debris, that the major damage was sustained from impact with the water. It is also believed that the Challenger crew compartment was intact during the descent following the explosion but that the crew died on impact with the sea [28] [56].

Ultimately, the propagation of the failure was enabled by the proximity of critical structural, load bearing, and propellant containment components to the initial case breach, a failure that might have had relatively benign consequences within a different architecture.

Figure C-9. A puff of black smoke is seen coming from the lower portion of the right SRB. Credit: NASA

Vehicle/Flight: Space Shuttle (STS-107 Columbia)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
1/16/2003	Combined	1	Liquid	Damage to Payload	None (Orbiter reached intended orbit and destroyed during reentry)

At T+81.7s one large piece and at least two smaller pieces of insulation foam separated from the External Tank (ET) left bipod ramp. At T+81.9s the larger piece struck the underside of the left wing, striking between Reinforced Carbon Carbon (RCC) panels 5 through 9. The larger piece of foam was determined to be 21 to 27 inches long and 12 to 18 inches wide. It was moving at a relative velocity to the Shuttle of 625 to 840 feet per second at the time of impact. The impact was of sufficient force to crack the RCC that provided the thermal protective barrier to the internal wing structure. On entry, the extreme temperatures generated in the vehicle flow-field were thus able to penetrate to the internal wing structure, causing structural failure, loss of control, and complete vehicle breakup [57].

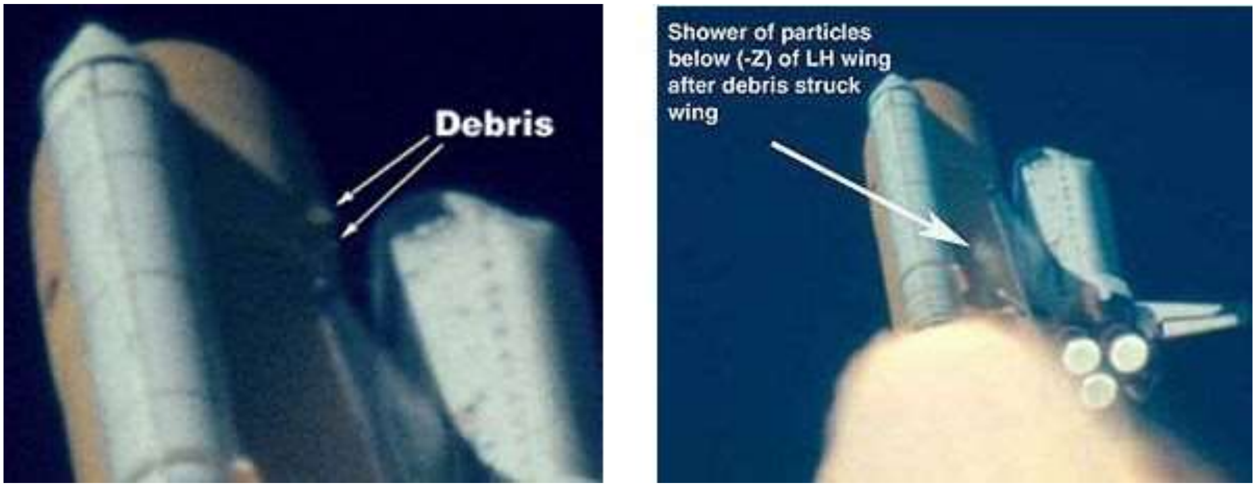


Figure C-10. Columbia debris particles and wing strike. Credit: NASA

Super Strypi

Vehicle/Flight: SPARK					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
11/3/2015	Solid	1	Solid	Unknown	Environment

This launch vehicle was designed to carry small satellites to a sun-synchronous orbit and serve as a relatively inexpensive, easy-to-operate satellite launcher. The first and only launch of the vehicle was experimental and meant to test the rocket at its full payload capacity. It carried many cubesats and a small imaging satellite (HiakaSat), but broke up due to tumbling shortly after lift-off. Air Force officials admitted they accepted “elevated risk” over concerns that hot gas inside the LEO-46 first stage motor could burn through insulation lining the composite casing. However, the root cause of the failure has yet to be released [58] [59].

Taurus

Vehicle/Flight: Taurus-2210					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
2/10/1998	Solid	Unknown	Solid	Vehicle over-performance - Off-nominal ascent	None

The payload was delivered 91km higher than planned, and despite the error, mission objectives were met [4].

Vehicle/Flight: Taurus-2110					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
9/21/2001	Solid	2	Solid	Loss of control	None

At T+83s the second stage Orion 50S ignited but the driveshaft of the actuator for the thrust-vectoring system seized for about 5 seconds, causing the vehicle to veer off course. The Taurus suddenly turned to the left and then right, with gyrations continuing for several seconds before the rocket appeared to regain control. The system recovered and continued its launch profile, but because of a velocity shortfall, the vehicle did not reach a sufficient orbit and reentered the atmosphere over the Indian Ocean [60].

Vehicle/Flight: Taurus XL 3110					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
2/24/2009	Solid	3	Staging	Staging – Low performance	None

The launch vehicle performed as planned until 7 seconds after the second stage burn (note: Taurus vehicle stages are numbered starting with zero to remain consistent with Pegasus upper stage numbering, but because we use "zero" to denote strap-on boosters, the failed stage listed here is "3" rather than "2"), when the command for payload fairing separation was sent. The fairing separation indicators showed no change, prompting the ground team to rapidly assess the situation. The payload had separated from the upper stage, but was still encased within the payload fairing. The mission was lost and the payload reentered the atmosphere, breaking up over the Pacific Ocean near Antarctica.

This was the first of two consecutive payload separation failures by the Taurus XL, the second of which occurred on T9 carrying the Glory spacecraft in 2011. Both failures resulted in payload reentry.

The executive summary on the NASA website cites 4 possible causes of the fairing separation failure: a frangible joint subsystem failure that failed to provide separation, an electrical subsystem failure that did not provide current needed to initiate the explosives, a pneumatic system failure that did not supply enough pressure to separate the fairing, or a snagged cord on a frangible join side rail nut [61]. Full details of the report were not disclosed for proprietary reasons. The executive summary states that whereas the Mishap Investigation Board (MIB) was unable to determine which component or subcomponent was the direct cause for the fairing not to separate, the snagged cord was a remote possibility. Rather than suppress the report until further testing was complete, the MIB opted to release the report with these intermediate findings.

Space News reported that the cause was a faulty pressure initiator in a gas-generator component. In the report, the COO of Orbital was quoted to have said that their investigation concluded that failure was a faulty pressure initiator and the defective fairing-separation system was "a supplier issue and dealt with some lot-acceptance testing of the pressure initiator." He referred to "lower shock margins in these lot-acceptance tests" for the pressure initiators as being partly to blame, and said the initiator design would be modified [62] [63].

Vehicle/Flight: Taurus XL 3110					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
3/4/2011	Solid	3	Staging	Staging – Low performance	None

Similar to the Taurus XL failure in 2009 (T8), this launch vehicle (T9) also performed nominally until just after the second stage ignition burn (note: Taurus vehicle stages are numbered starting with zero to remain consistent with Pegasus upper stage numbering, but because we use “zero” to denote strap-on boosters, the failed stage listed here is “3” rather than “2”). Payload fairing separation was scheduled for 176.98 seconds after liftoff. Telemetry indicated that the subsequent stage 2 burn and separation, stage 3 ignition and burn, and spacecraft separation all occurred as planned. However, the payload fairing remained partially attached and the payload was not able to reach a stable orbit. It reentered the atmosphere and likely broke and/or burned up because of reentry loads and aerodynamic heating.

Although both missions involved payload fairing separation failures, with both payloads reentering, the root causes appear to be associated with different components. In the previous failure, a faulty pressure initiator was to blame. Here, the frangible joint did not fracture completely when detonated.

As a result of the T8 accident, an extra pressure sensor was added to the cold gas pressurization system in place of the hot gas generator system. This sensor ultimately provided valuable data to the T9 MIB. The sensor data verified that the cold gas pressurization system performance was satisfactory and that the T9 payload fairing’s base ring indeed had separated. As a result, the T9 MIB could eliminate the cold gas pressurization system and the base ring as root causes and focus on the scenario in which the forward end of the payload fairing side rail failed to fracture.

In the end, a root cause could not be definitively established, due mostly to lack of flight data and hardware to examine (it all burned up on reentry), but also due to sparse reporting of changes and testing during vehicle and trajectory redesign: the evolution of the base ring since its development for the Pegasus vehicle was insufficiently documented. For the frangible joint, the investigation board recommended improved system manufacturing process controls, a detailed design failure analysis, and a qualification and test activity [64].

Thor

Vehicle/Flight: Thor-LV2F Star-37XE Star-37S-ISS					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
7/14/1980	Combined	3	Staging	Staging - loss of control	None

The last Thor Burner 2A mission status was nominal through its second stage burn when telemetry was lost. The wiring harness between the second and third stages was misaligned and did not disconnect as intended. When the Star 37S-ISS third stage ignited its engine, its wiring harness catastrophically displaced, causing short circuits that disabled the flight control system. The stage pitched down and failed to achieve orbit [65].

Titan

Vehicle/Flight: Titan-34D					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/28/1985	Combined	1	Liquid	Loss of Control (asymmetric thrust)	Loss of Function

During the first stage burn, engine 1 began experiencing low performance at T+102s. At T+117s, after SRM jettison, engine 1 shut down completely. Because both engines were needed to maintain a controlled flight, the vehicle lost attitude control and began tumbling. The on-board computer shut down engine 2 and began premature separation and ignition of stage 2. The vehicle tumbled and was destroyed by range safety at T+272s.

An oxidizer leak in the first stage caused a turbopump failure when the pump's pinion gear broke due to the loss of cooling or lubrication. This caused a premature engine shutdown in one of the two main core stage engines [66].

Vehicle/Flight: Titan 34D (34D-9)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
4/18/1986	Combined	0	Solid	Case Burst	Environment

The solid rocket motor case insulation in SRM-2 de-bonded during ignition. This led to burn-through of the case at the butt-joint between segments 1 and 2. At 8.5 seconds into the flight, a 12-ft diameter ball of fire erupted from the side of SRM-2. At 8.7 seconds, the SRM exploded, and the vehicle and its payload were automatically destroyed 800 feet above the launch pad at Vandenberg AFB. Debris was scattered, causing major damage to the launch complex. The other SRM (SRM-1 on the west side of stack) was destroyed by the Inadvertent Separation Destruct System (ISDS) approximately 0.3 seconds after the SRM-2 initial burn through. Engine shutdown was commanded at T+15.5s, followed by a self-destruct command at T+16.3s. The vehicle impacted the ground at T+28.4s [67].

Reconstruction of recovered fragments from both SRMs indicated a case burst of the lower segments of SRM-2 followed by a tearing open of the upper segments. Discussion in the "Propellant Explosive Hazards Study Volume II" report by E. J. Tomei notes that "Using 0.5 psi as damage threshold, the explosive yield from the liquid propellant only can be enveloped at no greater than 4.7% TNT (surface burst) or 3% TNT (air burst) [68]".

Vehicle/Flight: Titan 34D Transtage					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
9/2/1988	Combined	3	Liquid	Propellant leak – low performance	None

When the Transtage reached geosynchronous transfer orbit and attempted its circularization burn, its engine misfired. Hydrazine and helium leaks damaged the Transtage, which apparently lost pressure through a small hole in the fuel tank feed system. The hole was believed to be the result of repair activities during prelaunch or from shrapnel impact during payload fairing release. The investigators concluded that there had been enough pressure for the Transtage's first burn, but not enough pressure for its second burn. The Chalet-Vortex electronic intelligence-gathering satellite was stranded in transfer orbit [32].

Vehicle/Flight: Commercial Titan 3					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
3/14/1990	Combined	5	Staging	Staging – payload failed to separate	None

The Intelsat 603 became stranded in a low orbit when it failed to separate from the Titan second stage. In order to keep the satellite from falling back into the atmosphere, it was ordered to separate from the Orbus perigee kick motor and use its own thrusters to achieve a slightly higher orbit. The Titan launch vehicle had been wired in a configuration meant for two payloads. Because the vehicle was only carrying one payload, it did not separate when the signal to fire the pyro-cable was sent to the wrong system. The Space Shuttle (STS-49) later rescued the satellite in May of 1992 [7] [69].

Vehicle/Flight: Titan IV (K-11)					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/2/1993	Combined	0	Solid	Case Burst	Environment

During the SRM's burn, video imagery showed that a light colored ring enveloped and quickly expanded from the Titan IV K-11 vehicle. The puff of the doughnut-shaped ring was immediately followed by an explosion of one of the SRMs T+101.2 seconds into the flight, while the vehicle was beginning to pitch over to a more horizontal attitude and accelerate downrange to place its payload in a polar orbit. After the explosion occurred, Range Safety issued destruct commands at 90 miles (145 km) downrange and an altitude of 110,000 feet (33,528 m). The designed nominal burn time of the SRM is 127 seconds.

The propellant in one of the Titan IVA-11 solid rocket segments was cut approximately 0.25 in. (0.625 cm) deep and extended 34 in. (86.36 cm) in the radial direction from the bore during repair of a damaged restrictor. The repair was more extensive than had ever been attempted on such a motor segment. At motor ignition, the face of the cut was pressurized and open, allowing the flame to propagate along the cut insulation, ultimately leading to the motor case burn-through at 101.2 seconds [70].

Vehicle/Flight: Titan-401A Centaur-T					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
8/12/1998	Combined	2	Liquid	Loss of control	Loss of Function

At T+40s the launch vehicle pitched over and was subsequently destroyed by aerodynamic forces and range safety. When the course of the rocket deviated to an angle of attack approximately 11 to 13 degrees from its planned path, aerodynamic stresses on the vehicle exceeded its structural design and the SRM separated from the core booster, initiating the Inadvertent Separation Destruct System. At T+45.529s, approximately 3 seconds after the automatic destruct sequence, Mission Flight Control Officers sent command destruct signals to the vehicle.

Intermittent power shorts from a damaged wire in the second stage wiring harness caused the inertial guidance unit to lose its reference attitude and begin generating improper steering commands. The Accident Investigation Board concluded that pre-launch wire insulation damage existed in the Vehicle Power Supply somewhere in Stage II, which left at least one powered conductor with exposed wire that was not detected during the pre-launch inspections and tests. This particular Titan vehicle was noted to have 44 wiring defects with shorting potential recorded over its lifetime [71] .

Vehicle/Flight: Titan IV B Centaur					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
4/30/1999	Combined	3	Liquid	Loss of control	None

This Titan IV B launch vehicle was equipped with a Centaur upper stage intended to deliver a Milstar satellite into geosynchronous orbit. After the Centaur separated from the Titan IV B, the vehicle began to experience anomalous rolls. The reaction control system eventually stabilized the vehicle during the transfer orbit coast phase, but used 85% of its hydrazine fuel in the process. When the vehicle attempted its second burn, it became unstable again and continued into its third burn tumbling. The vehicle did not reach its intended velocity or orbit. The Milstar satellite was permanently shut down 10 days later and declared dead in orbit.

Failed software development, testing, and quality assurance was ultimately the cause of the failure. During development of the Centaur computer software, a decimal point was misplaced while manually entering the roll rate filter constant in the Inertial Measurement System flight software file. This error was detected pre-flight but was not properly recognized or understood. Although it was not needed, the software had been kept in for “consistency” [28] [72].

Zenit

Vehicle/Flight: Zenit-3SL					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
3/12/2000	Liquid	2	Liquid	Loss of control	Loss of Function

Sea Launch’s first failure occurred after the Zenit-3SL’s second stage shut down 80 seconds early into its planned 6.5-minute burn. A software error contributed to an improperly set control pressure valve that caused the second stage to lose control. The rocket’s control system automatically shut down the engine at T+450s when it lost control, and the vehicle fell into the ocean. The ICO F-1 communications satellite was lost.

It is believed that a software error on the ground failed to command a pressure valve to close in a pneumatic system that performed several functions, including vectoring the engine. Telemetry showed that this system lost 60% of its pressure, leading to a significant deviation in altitude, triggering the self-destruct system [28].

Vehicle/Flight: Zenit-3SL					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
6/29/2004	Liquid	3	Liquid	Low performance	None

Zenit's 14th flight ended in failure when the DMSL stage shut down 54 seconds early due to a loose wiring connection. The payload was left in a much lower orbit than planned, but was able to use its own propulsion system to reach geosynchronous orbit.

A wiring problem on the Block-DM upper stage caused an electrical short that distorted propellant flow rate data to the engine control system. The engine mistakenly used more fuel than planned, depleting the fuel tank 54 seconds too early during its second burn and releasing its payload short of its target, stranding it in a transfer orbit with an apogee 14,000 km short of its geosynchronous altitude. The satellite had enough onboard propellant to mitigate the error and reach its proper position without shortening its lifespan [28].

Vehicle/Flight: Zenit-3SL					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
1/30/2007	Liquid	1	Liquid	LRE Uncontained	Loss of Function

The RD-171 engine of the first stage had just ignited, followed by a tilt of the rocket and then immediately followed with a fireball and explosion on the launch pad. The investigation revealed that there had been disruption in the first stage main engine liquid oxygen pump, caused by a stray metal particle entering it due to a manufacturing fault. The metallic object became lodged between the pump's moving and stationary components, ignited, and burned as a result of friction-induced heat. This caused a loss of oxidizer pressurization and the main engine thrust to rapidly drop 3.9 seconds after ignition, with the rocket only about 0.1m off the pad. The rocket fell back onto the pad and exploded [73].

The Zenit contained 400,000 kg of liquid propellant (RP-1 + LOX). Long-range video of the explosion did not give indication of detonation explosion, and the relative lack of damage to the pad would seem to support that conclusion. The pad was in fact damaged but repairable—the flame deflector was blown off, and the blast doors unhinged.

Vehicle/Flight: Zenit-3SL					
Date	***Vehicle Type***	***Failed Stage #***	***Failed Stage Type***	***Initial Manifestation Type***	***Launch Vehicle Demise***
2/1/2013	Liquid	1	Liquid	Loss of control	Loss of Function

About 40 seconds into the flight, the vehicle's on-board computer detected that the vehicle was veering off course, prompting an emergency engine shutdown. The vehicle began to fall back down to the Earth, crashing into the Pacific Ocean just a few miles from the launch platform [74]. A BIM *(Bortovoi Istochnik Moshnosti* - Onboard Power Source) hydraulic pump failed just before liftoff, causing the loss of engine gimballing capability. The BIM system failure was due to a defect in the pump that escaped detection during hardware review. The flight control system and engines were functioning properly. A summary of the sequence of events [75]:

- Monitoring data shows pump turbine quickly slowed down its rotation and then completely stopped. The BIM hydraulic pump failed 4.5 sec after engines were ready (~0.5 sec before liftoff). Engine gimballing function was lost.
- Planned pitch maneuvers were not performed, and around T+16 sec, the vehicle exceeded the allowable limit of 30 degrees for deviation in its rolling motion (its pitch and course at that moment had not yet exceeded the allowable 15 degrees).
- Safety algorithm issued a commanded engine shutdown as a result of the violation, but vehicle thrust termination was delayed until time exceeded T+20 sec for safety reasons.
- Vehicle crashes into the ocean T+56 sec.

The BIM hydraulic system's turbopump is driven initially by high-pressure helium (started 10 sec before liftoff) and then switched over to kerosene by the main engine. The turbopump of the BIM can be tested with helium, but not with kerosene (which requires the main engine to be firing to operational thrust levels). As a result, full testing of the BIM unit was not possible. Corrective actions did not involve hardware changes, only increased testing and manufacturing process changes.

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