# A historical survey with success and maturity estimates of launch systems with RL10 upper stage engines

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Key Words: reliability, historical survey, upper stage, RL10


*SUMMARY & CONCLUSIONS*

Pratt & Whitney's RL10 engine line has a long and rich history, beginning in 1958 and continuing today. This paper provides a historical summary of launch vehicles using RL10 engine derivatives dating from 1962-2005. The historical launch data is used to derive baseline launch success rates and growth curves for vehicles configured with RL10 engines in the upper stage.

Because it was the first liquid hydrogen fueled rocket engine, the RL10 engine launch history provides a unique opportunity to investigate the maturity trends for revolutionary new complex systems. All of the data used in this survey was acquired through publicly-available sources [1-21]. In all, 190 vehicles configured with RL10 upper stage engines were launched between 1962 and 2005. There were 12 upper stage failures that either failed to reach orbit, or reached a lower, unintended orbit.

The early failures were dominated by knowledge gaps in system interactions and operational flight conditions. There is a clear trend of early development growth with an eventual plateau as system knowledge improved as a result of flight experience and more thorough test programs.

Failures due to process-based issues (fabrication techniques, quality control, etc.), however, do not appear to exhibit maturity growth. Eventually, as the knowledge-based failures are removed, these process-based failures become the dominant risk driver. Vehicles that use mature, highly-reliable components are still vulnerable to process or functional changes, and failures of this type occur fairly uniformly with flight experience.

In order to improve future reliability estimates for such systems, it is important to understand the trends and relationship between the knowledge-based and process-based issues, and determine which class of issues currently dominates. It should be noted that of the 12 upper stage failures, only one was caused by a defective part.


## *1 INTRODUCTION*

The RL10 engine is primarily used to power the Centaur upper stage in either a single engine or double engine configuration (SEC = Single Engine Centaur, DEC = Double Engine Centaur). The Centaur upper stage, in turn, was used on Atlas and Titan launchers. The RL10 engine was also used in the upper stages of the Saturn I in a six-engine cluster and Delta launchers.

The RL10A-5 engine variant was also used for the DC-X (Delta Clipper) experimental vehicle. The DC-X and DC-XA used four RL-l0A-5 rocket engines, each generating 6,100 kgf thrust. Each engine is throttleable from 30% to 100% with a burn time 127 seconds. There were 12 test missions of the DC-X and DC-XA (7 vehicle failures) before the program was cancelled. In all, the RL10 engines performed a total of 48 flight firings (12 flights x 4 engines) and nearly 5,000 seconds of flight time. These missions are not included in the launch success calculations.

## *2 LAUNCH VEHICLE FLIGHT SUCCESS*

Between 1958 and 2005, 190 launch vehicles configured with RL10 engines in the upper stage were launched. Of the 190 launch attempts, twenty-two failures occurred, so launchers with RL10 upper stage engines have a flight success probability of 88.4%. Of the 22 launch failures, 8 were due to the first stage, 12 were due to the upper stage, and 2 were due to the shroud.

## *3 UPPER STAGE FLIGHT SUCCESS*

A summary of the failure effects and root causes are summarized in Figure 1. The first two columns show the final effect of the failure and the intermediate functional fault that occurred, the third column lists whether the launch system failed to reach orbit with all mission objectives met or reached a lower, unintended orbit. The component that failed and its root cause is shown in the next two columns, followed by the launch vehicle number and a short description of the failure.

Of the 12 upper stage failures, all three ignition failures lead to flight termination and vehicle destruction by the range safety officer (RSO). Three structural integrity failures occurred, two of which were caused by higher than expected loads on the vehicle. On the first Atlas Centaur vehicle, AC-1/F-1, the insulation failure was caused by higher than predicted aerodynamic forces, leading to overheating and eventual disintegration of the vehicle at T+55 seconds (before upper stage separation).

The intermediate bulkhead structural failure caused by an anomalously violent staging event resulted in failure at t=288.8 seconds, precluding the second burn. The remaining failures lead to improper upper stage conditions which eventually manifested themselves as either engine restart failures or

| Effect | Functional Failure | Orbit achieved | Cause | Flight experience | LV S/N | Component* | Failure title | Ref. |
|---|---|---|---|---|---|---|---|---|
| Explosion | Structural integrity | Failed | Design failure | 1 | F-1 | Insulation shield | Vehicle overheated and destroyed due to weather shield failure | 2 |
| | | Unintended | Excessive condition | 72 | AC-62 | Intermediate bulkhead | Centaur structural failure during coast phase due to anomalously violent staging event | 2, 8 |
| | | | Manufacturing | 140 | D269 | Combustion chamber | Engine failure at ignition for second burn of Centaur upper stage | 1, 3, 21 |
| No restart | Improper conditions | Unintended | Leak | 12 | AC-8 | Boost pump | Centaur main engine fails to restart due to H2O2 leak | 13, 14, 18 |
| | | | | 21 | AC-17 | Boost pump | Centaur main engines fail to restart due to oxidizer leak on common supply line | 15, 16 |
| | Loss of control | OK, but failed to meet mission objectives | Design failure | 7 | AC-4 | Ullage | Centaur main engines fail to restart due to ullage/propellant management | 11, 12, 18 |
| Shutdown/ short burn | Loss of control | Failed | Design failure | 5 | AC-3 | Hydraulic pump shaft | Centaur loss of control due to hydraulic pump shaft failure | 10, 11, 18 |
| | | | Defective part | 28 | AC-24 | Gyroscope | Centaur loss of control due to inadvertent Centaur electronic signal | 2 |
| | | Unintended | Verification | 139 | 4B-32/ TC-14 | Software | Loss of control due to Centaur software programming error | 3, 9 |
| Flight terminated by RSO | No ignition | Failed | Contaminant | 79 | AC-70 | Turbopump | Centaur main engine failed to start due to turbopump failure caused by changes to ground prechilling activities | 1, 3 |
| | | | | 85 | AC-71 | Turbopump | Centaur main engine failed to start due to turbopump failure caused by changes to ground prechilling activities | 1, 3 |
| | | | Installation | 38 | 23E-1/ TC-1 | Boost pump | Centaur main engine did not ignite on first Titan/Centaur flight | 2 |

* Component where failure was manifested.

*Figure 1: Summary of upper stage failures and effects, 1962-2005.*

premature shutdown failures.

Of the 12 upper stage failures, 6 did not reach orbit while 6 missions still managed to reach an unintended orbit. The missions that did not reach orbit were labeled “catastrophic” failures, while the missions that reached an unintended orbit were labeled “degraded” failures.

- RL10-based upper stage success per engine-mission: 96.8%
- RL10-based upper stage catastrophic: 98.3%
- RL10-based upper stage degraded: 98.3%

## 4 RELIABILITY GROWTH

### 4.1 *Flight History and Failure Breakdown*

Figure 2 shows a timeline of failures for all missions made with launch vehicle configurations using RL10 engines in the upper stage between 1962 and 2005. The line labeled “All launch failures” is the total of all booster, upper stage (i.e. main propulsion system, RL10 engines, and other upper stage components), and shroud failures. These line plots are not “stacked” and include all failures that occurred, including those that resulted in unintended lower orbits. The vertical dotted lines mark 10 years of flight since 1962: 1972, 1982, 1992, and 2002.

The most interesting points to notice in this chart are:

- The two upper stage failures between the 80th and 90th flights circled in red were repeated failures. Changes to the ground prechilling sequence introduced air through a stuck check valve, causing a turbopump startup failure. This was not correctly identified and corrected until the second occurrence the following year,
- All but one of the failures in the first 40 flights (spanning 12 years) were due to the upper stage,
- Upper stage and shroud reliability appear to have reached or is quickly approaching a growth plateau,
- The string of failures around the 140th flight were all unrelated, some due to the booster and some due to the upper stage,
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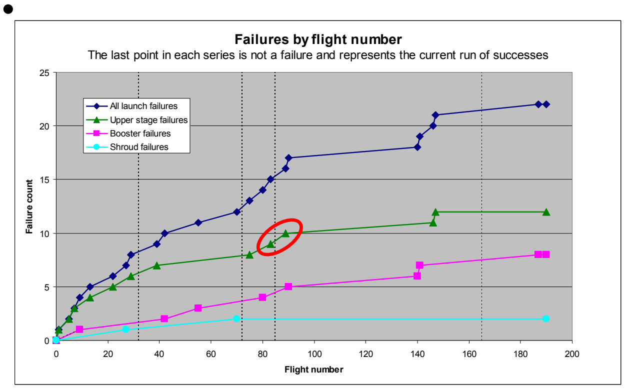


*Figure 2: Launch vehicle failure history, 1962-2005*

- The back-to-back booster failures around the 140th flight were unrelated, one occurring on a Titan 401A (damaged cable) and the other occurring on a Delta 8930 (faulty software), and
- The back-to-back upper stage failures around the 146th flight were also unrelated, one occurring on a Titan 401B (faulty Centaur software) and the other occurring on a Delta 8930 (flawed engine combustion chamber brazing process).

### 4.2 *Reliability growth of upper stages configured with RL10 engines*

Figure 3 shows a growth curve of the upper stage failures using a least squares logarithmic growth curve. An assumption was made by assuming that 0.25 additional failures occur at the end of the dataset. That is, the last data point plotted is not an actual failure but is used for the curve fit. In this plot, the repeated prechilling failure was removed for calculating the growth curve, but is shown for reference as a non-solid diamond. The equation of this curve is given as failure number, F = 2.95*ln(0.233x +1), where x is the flight number. The derivative of the curve gives the instantaneous failure rate, currently around 98.5%.

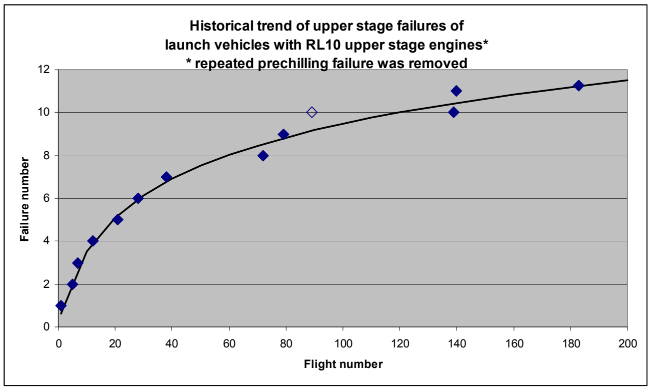


*Figure 3: RL10 powered upper stage growth curve*

A few other growth models were fitted to the data to see how they impacted reliability estimates. The logarithmic, exponential (also known as Musa or Goel-Okumoto), and Pareto models were compared. All of these models are concave growth models, not S-shaped growth models, as the failure history looks more concave than S-shaped. The differences between the concave models are in their assumptions about whether or not faults can be completely removed in the limit. Because space launch system configurations and requirements rarely remain unchanged for long, the asymptotic reliability potential and behavior were considered a secondary effect.

### 4.3 *Grouped estimates*

To account for the non-homogeneity of the system configurations in this historical data set, different curves were fitted for each of major classes of RL10 engine derivatives. The results of this partitioning of the data were inconclusive.

Next, the launch vehicles were grouped into the following 19 vehicle configuration subsets in order to look for a relationship between failures and the introduction of large-scale vehicle changes:

- Atlas family: Atlas Centaur (5), Atlas Centaur D (7), Atlas G Centaur (7), Atlas I (11), Atlas II (10), Atlas IIA (23), Atlas IIAS (30), Atlas 3A (2), Atlas 3B (4), Atlas V (7, includes 400s and 500s), SLV-3C Centaur (17), SLV-3D Centaur (32),
- Saturn family: Saturn I (6),
- Titan family: Titan IIIE, Titan 401A/Centaur (9), Titan 401B/Centaur (7),
- Delta family: Delta 8930 (3), Delta 4M (3, includes M+), Delta 4H (1).

The numbers in parentheses indicate the number of flights for each launch vehicle configuration. This is a completely different partitioning of the data from above since the same engine derivative may be used in more than one launch vehicle configuration.

Failures are clustered in the very early flights after changes are made. The upper stage failures manifest themselves very early in a new launch configuration's flight history. Booster failures appear more distributed over flight experience, and shroud failures even later.

In this partitioning, only 11 out of 19 of the subset series had a flight history of at least 7 missions, which may affect the results. However, this highlights the reality that space launch configurations rarely remain static for long, and offers evidence suggesting that component changes do not impact reliability growth as dramatically as configuration changes. The demand for flexible, interchangeable components that can accommodate a wide range of mission and payload requirements lead to integration changes that often result in new failures being introduced. Configuration changes drive the overall system reliability despite the use of components with long, reliable histories. Thus, it is extremely important to develop reliability estimates that reflect the integration contribution.

In Figure 4, the 11 upper stage failures are partitioned by cause: knowledge-based or process-based. Here again, the repeated prechilling failure (circled) was removed for the curve fits and the last data points are not actual failures. Knowledge-based failures are those due to incomplete understanding of the environmental conditions involved or the behavior of the system under actual flight conditions, and are typically resolved by design changes (either vehicle or trajectory). Knowledge-based failures experienced by the RL10-based upper stage launch vehicles involve incomplete understanding of propellant management in zero gravity (propellant settling, sloshing, etc), the effects of a long-duration coast phase, and the effects of anomalous flight conditions.

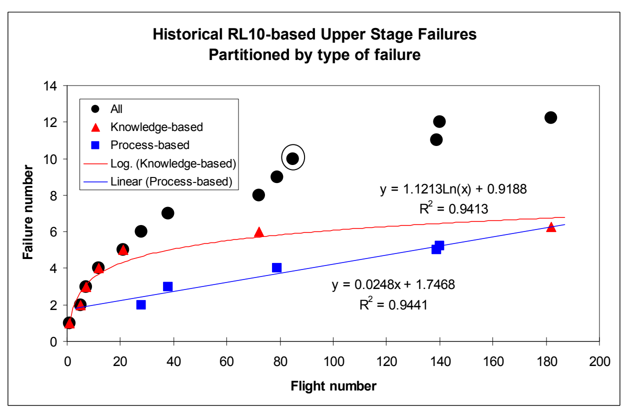


*Figure 4: Upper stage failures by error type*

Process-based failures are those due to fabrication processes, verification and validation processes, or ground processing procedures, and are corrected by procedural changes. Historically, these process-based failures involved misinterpretation of design specifications, ineffective verification and validation methods, or incomplete reporting policies. The RL10 engine pre-chilling failures were classified as process-based failures by this author, but it is recognized that they could also be considered knowledge-based failures.

The choice of a linear curve fit for the process-based errors was made because the failures occur relatively uniformly with experience, suggesting that these types of failures are driven more by random events or constantly changing mission requirements rather than growth.

Not shown in this paper is the slope of the curve in Figure 4. Depending on the particular growth model used, the instantaneous failure probabilities cross around the 30$^{th}$ or 40$^{th}$ flight. Before this cross-over point, knowledge-based errors drive the failures. After this cross-over point, process-based errors dominate the failures. This is an important point to recognize--that the nature of the dominant failures shifts as a system matures.

## *5 CONCLUSIONS*

The Centaur upper stage was America's first attempt at utilizing liquid hydrogen fuel for space flight. Studying the development history of the launch vehicles that used RL10 engines in their upper stages provides a unique perspective in understanding how revolutionary systems tend to evolve. While there were many failures in the beginning, it was an area of rapid growth in knowledge. The main conclusions drawn from this historical survey are:

- The first-order problems involve incomplete understanding of the fundamental physical behavior of the system under actual environmental conditions. Many of the early failures involved leakage of cryogenic hydrogen and incomplete understanding of proper propellant management in zero gravity. These types of problems diminish over time as knowledge of the behavior of the system under typical operating conditions increases.
- The region of rapid learning (i.e. failures) occurred in the first 10-20 flights. Here, first-order problems were quickly identified and addressed. Development of the proper test facilities is a critical part of rapid growth, as was demonstrated by the rate of progress achieved for Centaur after the Plum Brook test facilities were built.
- The processed-based problems tend to involve procedural and integration processes. These faults usually occur as a result of poor quality control, poor verification, and modifications of existing fabrication processes.
- Failures often occur right after major configuration or trajectory changes are made, despite the use of mature, highly-reliable components. Configuration and trajectory changes require modifications to existing processes and expose a system using mature components to new environmental conditions (different or longer in duration) or integration procedures. Thus, both kinds of changes will introduce new processed-based and knowledge-based failure modes.

## *6 FUTURE WORK*

The early development years for liquid hydrogen engines occurred during the time of the space race, when multiple efforts were being pursued simultaneously. The lessons learned from Centaur upper stage failures during this growth period were shared with and quickly leveraged by other space flight programs pursuing the use of liquid hydrogen fueled upper stage engines. Future studies would include understanding the level of acceleration in reliability growth for other similar launchers that were developed during this time period. Characteristic growth curves of other liquid oxygen-liquid hydrogen engine programs and launch systems could be developed to improve understanding of the level of benefit from heritage and application similarities.

This survey did not look at the effect that advanced development and test programs had on maturity. Improved techniques and data to support evaluations of the comprehensiveness of such programs would be of great value.

## *ACKNOWLEDGEMENTS*

The author wishes to thank Joseph Fragola, Donovan Mathias, and Blake Putney for the many stimulating discussions and constant encouragement that lead to the development of this historical survey.

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