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Optimization of ETO Launch Systems for Airplane-like Safety and Reliability

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Achieving airplane-like safety and reliability on ETO launch systems requires fundamental changes in vehicle propulsion and flight trajectories. Current launch systems all have extended regions where catastrophic engine failure means loss-of-vehicle (LOV) either through loss of control or insufficient thrust to weight (T/W < 1.0). These regions have been euphemistically termed "dead zones" for obvious reasons. The most straightforward solution is to supply extra engines to give "engine-out capability", but this approach has limited use because of the additional cost and weight penalties, and the fact that uncontained engine failures will often result in "engine fratricide", which can still reduce T/W < 1. In this paper we examine causes of unreliability, available intact abort options, and a variety of approaches for enhancing the safety of different reusable launch systems. We are focusing on reusable launch systems because reuse has historically resulted in one to two orders of magnitude reduction in vehicle loss rate (after a reasonable flight test program).

Nomenclature

ACES = Air Collection and Enrichment System
ETO = Earth-to-Orbit
HTHL = Horizontal Takeoff Horizontal Landing
LOV = Loss of Vehicle
LOX = Liquid Oxygen
MFBL = Mean Flights Between Losses
MTBF = Mean Time Between Failures
RLS = Reusable Launch System
SCRJ = Supersonic Combustion Ramjet
TBCC = Turbine-Based Combined-Cycle
TSTO = Two-Stage-To-Orbit
T/W = Thrust-to-Weight Ratio
VTHL = Vertical Takeoff Horizontal Landing

Introduction

Three Two Stage to Orbit (TSTO) Reusable Launch System (RLS) concepts in this paper, one vertically launched and two horizontal takeoff configurations. All use rocket engines on one or both stages and all have jet engines for takeoff and/or recovery. The technology exists to build rocket engines with extremely low probability of uncontained failure and these are key to achieving high reliability in our reference TSTO VTHL RLS. An alternate approach to achieving very high safety and reliability is to emulate the airplane (i.e. takeoff from runways using wings, landing gear, jet engines, and standard aircraft design rules). Commercial aircraft using this approach routinely demonstrate mission LOV < $1/10^6$ (four orders of magnitude better than rockets). The addition of wings, gear, and jet engines greatly improve safety, but present a large weight penalty to any launch system. Making this weight penalty affordable is the fundamental challenge to the high safety Horizontal Takeoff, Horizontal Landing (HTHL) TSTO RLS. The best solution for keeping the weight penalty for wings, gear, and jet engines affordable is to collect the oxygen for high-speed flight after takeoff (less takeoff weight, less weight penalty). In this paper we examine two approaches to oxygen collection. One approach is to design the boost stage to use hypersonic airbreathing propulsion and carry only enough Liquid Oxygen (LOX) to accelerate the 2nd stage from Mach 10, or higher, to orbit. This requires advanced propulsion and thermal control technologies, which should be physically realizable sometime in the near future, but funding in this area is fading. The second approach is to use old technology in a new way, namely to use the Alchemist™ Air Collection and Enrichment System (ACES) to generate and store all the LOX for both stages while the booster cruises subsonically to the desired launch position (a position chosen both for operational flexibility and safe abort). Rocket motors on the booster and 2nd stage are then used to accelerate the system from subsonic to hypersonic speeds outside the sensible atmosphere where staging occurs and the 2nd stage proceeds to orbit under its own power. Both the hypersonic airbreathing and Alchemist ACES boosters are sized to abort safety back to base carrying the 2nd stage if for any reason the systems do not separate at staging conditions. This is in contrast to VTHL launch systems, which cannot afford to carry enough wing area on the booster to abort with the 2nd stage.

In this paper we have optimized each of the three RLS concepts for a common mission (9 MT roundtrip to 28.5 degrees LEO) using a variety of engine cycles and derating techniques to improve safety and reliability. Subsystems on each launch system concept were also chosen to improve safety and reliability for reasonable nonrecurring and recurring costs. Sensitivity to alternate design approaches to enhance safety were also included (e.g. engine-out-to-orbit and recovery jet engines on the orbiter). In our results we compare dry weights, propellant weights, reliability, and safety (LOV); across the entire trade space. Finally, we draw conclusions and make recommendations as to where technology development monies could be best spent in order to maximize the safety and reliability of future reusable launch systems.

Reliability and Safety Results

Figure 1 summarizes the results of the RLS Safety/Reliability analyses. The results are based on historic reliability data for individual system elements, operational time lines from optimized ascent trajectories, redundancy levels selected using best engineering practices, and safe abort trajectory simulations. The buildup of each reliability estimate is covered in detail in the remainder of the paper. Note, that the low mean flights between losses (MTBL) for the second stage orbiters is driven by the 1/1000 probability of loss of orbiter during a piloted dead-stick landing (NASA estimate). Improvements in landing L/D and addition of go-around jet propulsion should increase 2nd stage MTBF to be comprable to the first stage LOV. All stages were also penalized by a 1/25,000 probability of LOV during staging (Historical data).

	VTHL with Fly-back Boosters	**TBCC HTHL staging at Mach 10**	**HTHL with Alchemist ACES**	
Number of engines on Stg1	**8**	**5**	**4**	Engines
1st Stg burn time	**151**	**925**	**150**	Seconds
Stg1 Dead zone for loss of one engine	**0**	**0**	**0**	Seconds
Stg1 Dead zone for loss of two engines	**30**	**500**	**0**	Seconds
Stg1 Dead zone for loss of three or more engines	**25**	**800**	**0**	Seconds
Number of engines on Stg2	**3**	**3**	**3**	Engines
2nd Stg Burn Time (Parallel Burn)	**416**	**275**	**404**	Seconds
Stg2 Dead zone for loss of one engine	**0**	**0**	**0**	Seconds
Stg2 Dead zone for loss of Two engines	**75**	**0**	**0**	Seconds
Stg2 Dead zone for loss of Three or more engines	**325**	**60**	**60**	Seconds
1st Stg Engine Contained Shutdown Rate	**750**	**2000**	**1000**	Probably/10^6 cycles
1st Stg Engine Uncontained Shutdown Rate	**40**	**200**	**200**	Probably/10^6 cycles
1st Stg Engine Shutdown w/ Collateral Damage	**25**	**20**	**40**	Probably/10^6 cycles
2nd Stg Engine Contained Shutdown Rate	**1000**	**1000**	**1000**	Probably/10^6 cycles
2nd Stg Engine Uncontained Shutdown Rate	**200**	**150**	**150**	Probably/10^6 cycles
2nd Stg Engine Shutdown w/ Collateral Damage	**40**	**2**	**2**	Probably/10^6 cycles
Mean Flights Between Loss of Stg1 Vehicle	**17,617**	**10,822**	**41,667**	**Based on Main Propulsion Failures Only**
Mean Flights Between Loss of Stg2 Vehicle	**44,200**	**472,996**	**463,728**	
Mean Flights between loss of any vehicle	**12,597**	**10,579**	**38,232**	
Mean Flights Between Loss of Stg1 Vehicle	**232,576**	**233,384**	**112,769**	**Based on Non-Propulsive Failures Only**
Mean Flights Between Loss of Stg2 Vehicle	**20,286**	**20,274**	**20,286**	
Mean Flights between loss of any vehicle	**18,658**	**18,653**	**17,193**	
Mean Flights Between Loss of Stg1 Vehicle	**16,377**	**10,342**	**30,425**	**Based on Probability of Vehicle Loss from All Causes**
Mean Flights Between Loss of Stg2 Vehicle	**13,904**	**19,440**	**19,436**	
Mean Flights between loss of any vehicle	**7,520**	**6,751**	**11,860**	

Figure 1. Summary of RLS safety / reliability analysis

A. Summary of Results

It should be pointed out that usually no one system drives reliability. Reliability is the sum of hundreds of small failure probabilities averaged over individual element operating times. For the systems assumed in this paper, the probability of LOV will be driven by two events, namely stage separation and orbiter landing. This means the design can be further refined, since there are design solutions that can rectify this situation; and they will be described in the conclusions section. Meanwhile, we will continue to define and analyze the three systems described above.

The operating timelines used to analyze system reliabilities are shown below in Figure 2, and the individual propulsion system assumptions follow directly.

	HTHL Mission Phases (hrs)				VTHL Mission Phases (hrs)	
	Mach 10	notes	Gryphon	notes		VTHL
Taxi	0.167	Turbofan	0.167	Turbofan		
Takeoff & Climb	0.097	Turbofan	0.75	Turbofan		
Cruise to Launch Location	0.264	Ram/Scram	2.5	Alchemist		
Full Throttle Pull-up	0.025	Ram/Scram	0.02333	Turbofan		
Boost Phase (Carrier Eng)	0.01458	SCRJ/Rocket	0.04056	TF + Rocket	Boost Phase	0.031525
Separation	0.00833	SRMs	0.00833	Rocket	Booster Separation	0.00833
Carrier RTLS	2 ave.	Turbofans	2 ave.	Turbofan Ops	Booster RTLS	0.5
Orbiter Burn Phase	0.0766	Orb Rocket	0.1178	Orb Rocket	Orbiter Burn	0.12529
Orbiter Coast	0.75		0.75		Drop Tank Jettison	N/A
OMS Orbit Circ	0.01481	ORB OMS	0.01481	ORB OMS	OMS Orbit Circ	0.01481
Phasing Coast Period	12 ave.		12 ave.		Phasing Coast Period	12 ave.
Orbit Raising Burn	0.06185	ORB OMS	0.06185	ORB OMS	Orbit Raising Burn	0.06185
Coast	0.9166		0.9166		Coast	0.9166
Circularization Burn	0.05753	ORB OMS	0.05753	ORB OMS	Circularization Burn	0.05753
ISS Rendezous & Hold	36 ave	ORB RCS	36 ave	ORB RCS	ISS Rendezous & Hold	36 ave
Approach & Dock	6 ave.	ORB RCS	6 ave.	ORB RCS	Approach & Dock	6 ave.
At ISS	192 ave.		192 ave.		At ISS	192 ave.
Desengage & Depart	1 ave.	ORB RCS	1 ave.	ORB RCS	Desengage & Depart	1 ave.
Reentry Phasing	6 ave.		6 ave.		Reentry Phasing	6 ave.
Deorbit Burn	0.073	ORB OMS	0.073	ORB OMS	Deorbit Burn	0.073
Coast to Reentry Interface	0.78		0.78		Coast to Reentry Interface	0.78
Reentry	0.66	ORB RCS	0.66	ORB RCS	Reentry	0.66
Approach & Landing	0.417		0.417		Approach & Landing	0.417

Figure 2. Mission timelines used to calculate safety and reliability

B. Significant Assumptions

- Jet engines fail most of the time with no collateral damage. Disk failures are a 10^{-7} event.
- Jet engine MTBCF is 15,000 hours (Modern high-performance jet engine reference number)
- VTHL Flyback engine MBTF is 10,000 hours (Air-started after exposure to vibration and vacuum)
- High Mach Turbo-ramjet MTBF is 5,000 hours (Working harder, less access for maintenance)
- Ram/Scramjet failure rate projected to be 2/1000 (Heating rates like rockets but twice times the cooled area)
- TPS has one level of redundancy. No single failure will cause loss of vehicle.
- HTHL Orbiter failures during cruise and boost are not flight critical. (Booster returns orbiter to base)
- RTLS abort, Trans-Atlantic Landing (TAL), and Abort Once Around (AOA) use no flight reserves
- Design case aborts were for ISS launches where OMS propellants are available
- Only 30 % of uncontained rocket engine failures result in loss of vehicle
- Only 50% of uncontained rocket engine failures result in loss of two or more adjoining engines
- Only 70% of uncontained rocket engine failures result in loss of one adjoining engines
- 20 % of rocket engine failures occur during first 3 seconds (startup)
- Remaining 80% of rocket engine failures occur randomly during the cycle

C. Non-Rocket Systems Contribution to LOV

Figure 3 below shows how non-rocket component reliability contributes to the overall LOV probability. Similar figures were generated for the two HTHL RLS. Note that Figure 3 does not include stage separation or orbiter landing unreliability's. Those were estimated separately using NASA provided data. With the initial systems elements chosen to provide reasonable levels of redundancy the non-rocket systems elements do not drive LOV probability. However, with the current assumed probabilities for LOV during stage separation and orbiter landing, neither do the rocket elements. See section D for details.

D. Main Propulsion Contribution to LOV

At the start of this study it was assumed that failures in the main propulsion rocket systems would be the largest factor in vehicle unreliability and LOV. We were wrong, but for some very interesting reasons. First of all, rocket engine designs have evolved and margins have improved. This can best be shown in Figures 4a-c, where contained and uncontained shutdown rates for new staged-combustion engines (1st stage) and new expander cycle engines (2nd stage) are shown. This data is from a P&W report published as part of NASA Contract NRA8-27, but Rocketdyne and Aerojet report similar results.

VTHL Systems Reliability (less Rocket Engines)

	MTBCF (hrs)	Ops Time (hrs)	Initial Sys Elements	Required to Recover	System PLOV	Missions between LOV
Flyback Booster					2.99674E-07	3,336,961
Attitude Control	100,000	0.54	3	1	5.66858E-15	176,410,975,115,953
Command, Control, & Data	15,000	0.54	3	1	1.67937E-12	595,459,922,364
Electrical Power	15,000	0.54	3	1	6.99727E-08	14,291,295
Environ Control	15,000	0.54	2	1	5.18381E-09	192,908,179
Propulsion (less Engines)	10,000	0.54	2	1	1.16634E-08	85,738,512
Main Propulsion (jets)	10,000	0.54	2	1	1.16634E-08	85,738,512
Reaction Control System	5,000	0.03667	2	1	2.15149E-10	4,647,949,305
Structure Mechanical Sys	25,000	0.54	2	1	1.8662E-09	535,848,337
Thermal Control	2,500	0.54	2	1	1.86584E-07	5,359,525
Thrust Vector Control	2,500	0.03667	2	1	8.60588E-10	1,161,995,848
Orbiter					8.7991E-07	1,136,479
Attitude Control *	100,000	8	3	1	1.84261E-11	54,270,836,806
Command, Control, & Data *	15,000	8	3	1	5.44969E-09	183,496,615
Electrical Power *	15,000	8	3	1	5.44969E-09	183,496,615
Environ Control *	15,000	8	3	1	5.44969E-09	183,496,615
Propulsion (less Engines)	10,000	0.5	2	1	3.9998E-08	25,001,250
Reaction Control System *	5,000	8	3	1	1.46515E-07	6,825,261
Payload Separation System	25,000	8	2	1	1.02367E-07	9,768,751
Structure Mechanical Sys*	25,000	8	2	1	4.09469E-07	2,442,188
Thermal Control	2,500	0.33	3	1	8.27551E-11	12,083,841,725
Thrust Vector Control	2,500	0.129	2	1	1.65111E-07	6,056,514
Payload Accomodations					4.41555E-06	226,473
Payload Separation Systems	25,000	0.6	2	1	7.67982E-09	130,211,458
Structure/Mechanical	25,000	256	2	1	3.24325E-06	308,333
Thermal Control *	2,500	8	3	1	1.16462E-06	858,649

* Mission terminated if more than one level of redundancy lost
(8 hrs is assumed as the maximum time for return to earth recovery site)

Figure 3. Non-rocket systems reliability and contribution to Loss of Vehicle

Secondly, for HTHL boosters, rocket engines are not needed or are backed up by jet engines, so that uncontained failures prior to staging do not eliminate intact abort options. For second stage orbiters, HTHL boosters allow a launch location to be selected so that after staging abort sites are readily available down-range in case of orbiter rocket engine shutdown. This eliminates all but total loss of thrust from the LOV calculation (see Figures 4 for details). The detailed assumptions used to generate the loss of engine abort time windows in Figure 4 are covered in section E. The details on the abort assumptions used in assessing the LOV options are shown in the next section with additional background material provided in the Appendix.

E. Safe Abort Options

Abort options fall into several categories:

1. ***Category 1- Abort After Staging:*** *Easiest to analyze because there were no failures prior to staging.*

Approach: Work backwards from burnout identifying fail-operational time period, then fail-safe once-around time period, and finally time periods for abort to recovery site. For single engine failures it is likely that RTLS abort time period will overlap the once-around abort period minimizing "dead zones". For VTHL Flyback concepts staging is so far downrange that orbiter RTLS is unlikely. Therefore, we need to look at alternative recovery sites downrange. For the ISS missions out of KSC

CASE:VTHL Launched to ISS from KSC	Input Data	Units		Probability of Loss	LOV frequency
Number of engines on stg1	**8**	Engines	Direct loss of vehicle (Engine Detonation)	4.79995E-05	20,834
1st Stg burn time	**151**	Seconds	Loss of three or more Engines/Vehicle in Liftoff Deadzone(Fractricide)	7.94699E-06	125,834
Stg1 Dead zone for loss of one engine	**0**	Seconds	Loss of Two Engines/Vehicle in Liftoff Deadzone (Shutdown)	8.15107E-07	1,226,833
Stg1 Dead zone for loss of two engines	**30**	Seconds	Loss of Three Engines/Vehicle in Liftoff Deadzone (Shutdown)	3.29741E-10	3.033E+09
Stg1 Dead zone for loss of three or more engines	**25**	Seconds	Engine Shutdown in Stg2 One Engine Dead Zone	0.000E+00	N/A
Number of engines on Stg2	**3**	Engines	Loss of three or more Engines/Vehicle in Stg2 Deadzone(Fractricide)	2.24998E-05	44,445
2nd Stg Burn Time (Parallel Burn)	**416**	Seconds	2 Engines Shutdown in Stg2 2 Engine Dead-Zone	1.248E-07	8,013,585
Stg2 Dead zone for loss of one engine	**0**	Seconds			
Stg2 Dead zone for loss of Two engines	**75**	Seconds			
Stg2 Dead zone for loss of Three or more engines	**325**	Seconds			
1st Stg Engine Contained Shutdown Rate	**750**	Probably/10^6 cycles			
1st Stg Engine Uncontained Shutdown Rate	**40**	Probably/10^6 cycles			
1st Stg Engine Shutdown w/ Collateral Damage	**25**	Probably/10^6 cycles			
2nd Stg Engine Contained Shutdown Rate	**1000**	Probably/10^6 cycles			
2nd Stg Engine Uncontained Shutdown Rate	**200**	Probably/10^6 cycles	Total Propulsion Related Loss Rate & Mean Flts between LOV	7.939E-05	**12,597**
2nd Stg Engine Shutdown w/ Collateral Damage	**40**	Probably/10^6 cycles	NonRocket Systems Catastrophic Failure Rate	5.59513E-06	178,727
Number of Jet Engines	**4**	Engines	Stage Separation Catastrophic Failure Rate (fail-op,fail-safe)	5.00E-05	20,000
Average Operating Cycle	**1**	Hours	Orbiter Landing Related Loss Rate (go-around jet engines)	4.00E-05	25,000
Jet Engine Contained Shutdown Rate	**140**	Probably/10^6 hours	Nominal Probability of Loss	1.750E-04	5,715

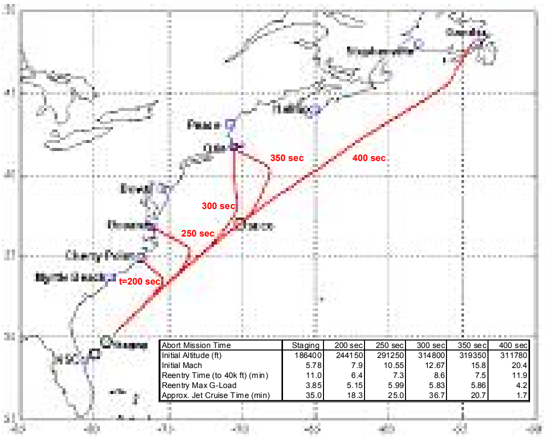
Figure 4a. VTHL rocket engine related probability of Loss of Vehicle

CASE: TBCC HTHL RLS launched from CONUS	Input Data	Units		Probability of Loss	LOV frequency
Number of engines on stg1	**5**	Engines	Direct loss of vehicle (Engine Detonation)	2.99996E-05	33,334
1st Stg burn time	**925**	Seconds	Loss of three or more Engines/Vehicle in Liftoff Deadzone(Fractricide	3.45941E-05	28,907
Stg1 Dead zone for loss of one engine	**0**	Seconds	Loss of Two Engines/Vehicle in Liftoff Deadzone (Shutdown)	2.75811E-05	36,257
Stg1 Dead zone for loss of two engines	**500**	Seconds	Loss of Three Engines/Vehicle in Liftoff Deadzone (Shutdown)	2.33364E-07	4.285E+06
Stg1 Dead zone for loss of three or more engines	**800**	Seconds	Direct loss of vehicle (Engine Detonation)	1.8E-06	555,556
Number of engines on Stg2	**3**	Engines	Engine Shutdown in Stg2 One Engine Dead Zone	0	N/A
2nd Stg Burn Time (Parallel Burn)	**275**	Seconds	Loss of three or more Engines/Vehicle in Stg2 Deadzone(Fractricide)	3.14182E-07	3,182,871
Stg2 Dead zone for loss of one engine	**0**	Seconds	2 Engines Shutdown in Stg2 2 Engine Dead-Zone	0.000E+00	N/A
Stg2 Dead zone for loss of Two engines	**0**	Seconds			
Stg2 Dead zone for loss of Three or more engines	**60**	Seconds			
1st Stg Engine Contained Shutdown Rate	**2000**	Probably/10^6 cycles			
1st Stg Engine Uncontained Shutdown Rate	**200**	Probably/10^6 cycles	Total Propulsion Related Loss Rate & Mean Flts between LOV	9.452E-05	**10,579**
1st Stg Engine Shutdown w/ Collateral Damage	**20**	Probably/10^6 cycles	NonRocket Systems Catastrophic Failure Rate	5.61005E-06	178,252
2nd Stg Engine Contained Shutdown Rate	**1000**	Probably/10^6 cycles	Stage Separation Catastrophic Failure Rate (fail-op,fail-safe)	4.00E-05	25,000
2nd Stg Engine Uncontained Shutdown Rate	**150**	Probably/10^6 cycles	Orbiter Landing Related Loss Rate (go-around jet engines)	4.00E-05	25,000
2nd Stg Engine Shutdown w/ Collateral Damage	**2**	Probably/10^6 cycles	Nominal Probability of Loss	1.801E-04	5,551

Figure 4b. TBCC HTHL SCRJ / rocket engine related probability of Loss of Vehicle

EXAMPLE: ACES HTHL launched up the East co	Input Data	Units		Probability of Loss	LOV frequency
Number of engines on stg1	**4**	Engines	Direct loss of vehicle (Engine Detonation)	2.39998E-05	41,667
1st Stg burn time	**150**	Seconds	Loss of three or more Engines/Vehicle in Liftoff Deadzone(Fractricide	0	N/A
Stg1 Dead zone for loss of one engine	**0**	Seconds	Loss of Two Engines/Vehicle in Liftoff Deadzone (Shutdown)	0	N/A
Stg1 Dead zone for loss of two engines	**0**	Seconds	Loss of Three Engines/Vehicle in Liftoff Deadzone (Shutdown)	0	N/A
Stg1 Dead zone for loss of three or more engines	**0**	Seconds	Direct loss of vehicle (Engine Detonation)	1.8E-06	555,556
Number of engines on Stg2	**3**	Engines	Engine Shutdown in Stg2 One Engine Dead Zone	0	N/A
2nd Stg Burn Time (Parallel Burn)	**404**	Seconds	Loss of three or more Engines/Vehicle in Stg2 Deadzone(Fractricide)	3.56436E-07	2,805,556
Stg2 Dead zone for loss of one engine	**0**	Seconds	2 Engines Shutdown in Stg2 2 Engine Dead-Zone	0.000E+00	N/A
Stg2 Dead zone for loss of Two engines	**0**	Seconds			
Stg2 Dead zone for loss of Three or more engine	**60**	Seconds			
1st Stg Engine Contained Shutdown Rate	**1000**	Probably/10^6 cycles			
1st Stg Engine Uncontained Shutdown Rate	**200**	Probably/10^6 cycles			
1st Stg Engine Shutdown w/ Collateral Damage	**40**	Probably/10^6 cycles	Total Rocket Related Loss Rate & Mean Flts between LOV	2.616E-05	38,232
2nd Stg Engine Contained Shutdown Rate	**1000**	Probably/10^6 cycles	Non-Rocket Systems Catastrophic Failure Rate	1.01631E-05	98,395
2nd Stg Engine Uncontained Shutdown Rate	**150**	Probably/10^6 cycles	Stage Separation Catastrophic Failure Rate (fail-op,fail-safe)	4.00E-05	25,000
2nd Stg Engine Shutdown w/ Collateral Damage	**2**	Probably/10^6 cycles	Orbiter Landing Related Loss Rate (go-around jet engines)	4.00E-05	25,000
Nonengine Catastrophic Failure Rate	**10**	Probably/10^6 cycles	Nominal Probability of Loss	1.163E-04	8,597

Figure 4c. Gryphon ACES HTHL rocket engine related probability of Loss of Vehicle



Abort Mission Time	Staging	200 sec	250 sec	300 sec	350 sec	400 sec
Initial Altitude (ft)	186400	244150	291250	314800	319350	311780
Initial Mach	5.78	7.9	10.55	12.67	15.8	20.4
Reentry Time (to 40k ft) (min)	11.0	6.4	7.3	8.6	7.5	11.9
Reentry Max G-Load	3.85	5.15	5.99	5.83	5.86	4.2
Approx. Jet Cruise Time (min)	35.0	18.3	25.0	36.7	20.7	1.7

Figure 5. Abort to alternate fields vs. loss of engine times

(VTHL) there are two or three good prospects. If we assume jet engines on both the booster and orbiter we can reenter and fly to a downfield abort site as shown in Figure 5.

For the HTHL ISS aborts we can assume we launch up the east coast and use the same recovery sites. This simplifies our task since there are an infinite number of air-launched trajectories. For the polar missions, assume a launch off the California coast with a recovery on the Washington coast. Once we identified the single engine failure time periods we repeated the analysis assuming two engines fail simultaneously. A non-optimized case was generated for the VTHL RLS using the 1200 fps DV of OMS propellants as reserves for completing an Abort Once Around (AOA) after loss of orbiter engines. . The lower limit for once around abort (fail-operational in this case) with single engine out is approximately 197 seconds and with two engines out it's 310 seconds.) This is shown as Figure 6.

*2. **Category 2 – Booster Engine Failure during Boost:** Next easiest to analyze since systems can be fail-operational.*

Approach used (VTHL RLS): Our current VTHL Flyback Booster concept is fail-operational with respect to a single booster engine failure because of a perceived requirement to arrive at the staging point with no propellants in the booster to assure adequate flying qualities. This is straightforward and minimizes loss of missions, but it does penalize performance. This requirement to derate the engines can be relaxed if an adaptive GN&C is assumed to be available. With an adaptive GN&C, if a once-around abort is not possible, the combined vehicles would throttle all engines immediately after engine failure and alter the ascent trajectory to arrive at a new staging condition suitable for separation, which would also assure recovery of the booster(s), and then perform a RTLS abort to recover the orbiter. This is a very complex analysis and requires a tool like OTIS to do branching trajectories. Modeling aborts with an adaptive GN&C is very difficult. This is beyond the scope of this study so we used hand-optimized trajectories. Our approach for Category 2 aborts with the HTHL boosters is to fly back to base carrying the orbiter for any failures prior to separation.

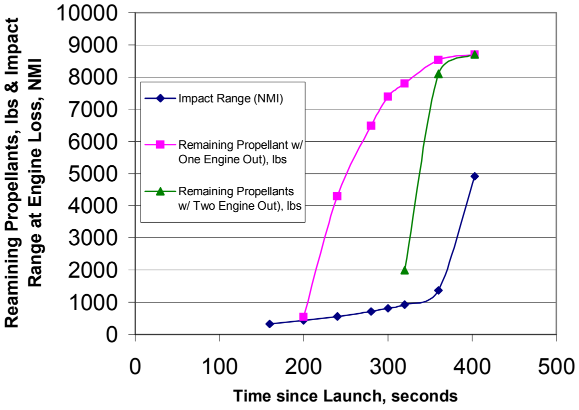


Figure 6. VTHL reserve OMS propellants vs. time of engine loss (Abort Once Around)

*3. **Category 3 – Orbiter Engine Failure during Boost:** Hardest to analyze since RTLS abort is usually involved.*

Approach used (VTHL RLS) Our current VTHL RLS concept is fail-safe with respect to a single orbiter engine failure during boost in that the booster(s) arrive at a slightly lower staging point with no propellants, but the orbiter has no hope for a once-around trajectory so an RTLS or ATRS is necessary every time. This is relatively straightforward and similar to Category 1. If we relax the requirement to derate the engines and assume an adaptive GN&C is available, things get complicated. As before, with an adaptive GN&C, the combined vehicles would throttle all engines immediately after engine failure and alter the ascent trajectory to arrive at a new staging condition suitable for separation, but which would also assure recovery of the booster(s) and the orbiter. This is another very complex analysis and probably requires a tool like OTIS to do branching trajectories. A non-optimized RTLS abort example is shown in Figure 7. The key to a successful RTLS abort is entering the atmosphere at a shallow flight path angle. Booster burnout much above 20 nmi and not near zero flight path angle will result in very high normal force at reentry (8 to 10 gravities).

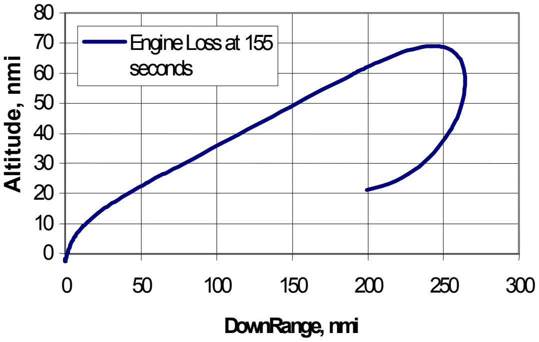


Figure 7. VTHL Return to Launch Site abort

Approach used (HTHL ACES): HTHL ACES can fly back to base for any failures prior to separation. RTLS abort is simple and safe.

Approach used (TBCC HTHL): TBCC HTHL does not start the orbiter engines until after separation (1000 nmi downrange) so a non-start or loss of engine requires an alternate landing site near the flight path. RTLS is only applicable before staging.

Recommendations

A well-crafted RLS design would have every system contribute roughly the same unreliability. Any system or function that dominates unreliability probably needs additional work, and that is the case here. Shuttle orbiter landings are high risk because of the high approach speed and uneven pilot landing abilities. Automatic landings are commonplace in commercial jets and need to be base-lined here. Additional orbiter wing area and go-around jet engine capability could be added for a (steep) price, but this is probably justified if high flight rates are desired. Once orbiter landing has been eliminated as the unreliability tent pole, then the 1/25,000 LOV due to staging becomes the prime consideration. This can be reduced in two ways. First with the HTHL concepts, don't attempt staging unless all conditions are nominal at staging. It's better to refly the mission, rather than risk loss of vehicles. That rule alone should eliminate half the failure reasons (for HTHL RLS). Secondly, disconnect all umbilicals prior to staging and make the separation system elements redundant (can be released from either stage). That should effectively remove staging as the tent pole issue.

Once these two tent pole issues are resolved, we reach LOV ranging from 1/5551 for the TBCC HTHL to 1/8597 for the ACES HTHL. These are acceptable numbers for new commercial ventures including space tourism (acceptable because at 200 flights/year for twenty years there likely will no loss of vehicles).

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Appendix

A. Proposed Abort Ground Rules for Future Abort Trades

There are two needs which drive propellant reserves; 1) launch window requirements, and 2) performance reserves including off-nominal ascent performance (e.g. headwinds, wind gust and shear, mixture ratio variations, and reduced engine performance (thrust and/or Isp)). The launch window OMS propellant is only available for LEO and MEO launches but is available 100% of the time for aborts, while the performance reserve is statistical in nature and the primary issue is to what extent this reserve can be tapped to reduce abort “dead zones”. It makes little sense to carry enough propellants to account for several three-sigma events.

B. Launch Window Requirements

The earth rotates under stationary orbits at exactly 15 degrees per hour. Therefore a 10-minute launch window (plus or minus 5-minutes) involves a 1.25-degree orbital plane change capability. Assuming this plane change is done with OMS in LEO (must occur at nodal intersect) vertical launchers need to carry an additional 564 fps of OMS propellants. GEO launches don’t normally use launch windows so the launch window reserves are not necessary and not available for aborts. Note, that HTHL has a modified launch window since it can follow the orbital plane at 650 to 850 fps. Therefore, the OMS ΔV varies with launch latitude as shown in Figure A1. At launch latitudes above 56 degrees launch windows become infinite (or until a subsonic booster runs out of fuel).

C. Performance Margin

Early in preliminary design we traditionally carry an additional one percent of total ideal velocity for design performance margin. That margin will gradually be used up as the program progresses so we do not propose to use any of that margin for safe abort.

D. Performance Reserves

As a design practice we carry one percent of total ideal delta velocity as performance reserves. This is to account for off-nominal environment (wind gusts and shear, season winds aloft, density variations, etc.) and engine performance shortfall (mixture ratio bias, reduced chamber pressure, etc.). These are statistical variations and can be estimated using shuttle actual propellant consumption data. Once we have completed PDR we have refined our design to the point where we can actually calculate the performance reserves required using six degree of freedom trajectory simulations in dispersed atmospheres with statistical engine performance data. Since we won’t have that capability for this paper, we should use historical shuttle ascent performance, which will plot into a curve like that shown in Figure A2.

That data can be replotted into a reserves available curve versus fraction of total flights as shown in Figure 3. We are primarily concerned with aborts after staging so the atmospheric losses have already taken place, and engine performance will remain constant enough to extrapolate remaining propellants. In this example 80% of all flights will have 60% of performance reserves remaining at SECO and 90% will have more than 50% remaining. For example, we can simulate the abort trajectories using 50% of the reserves plus the Launch Window OMS (assuming the remainder of reserves has been consumed) and report the resulting “dead zones” as 90% probable.

For the purposes of the Future Safety Analysis it is proposed that we assume 50% of the reserve propellants have been consumed prior to engine failure and 50 % are available for abort. For LEO and MEO launches we will carry the appropriate OMS for a ten-minute launch window. The GTO launches have no launch windows and few alternative landing sites so they will provide the worst “dead zones”.

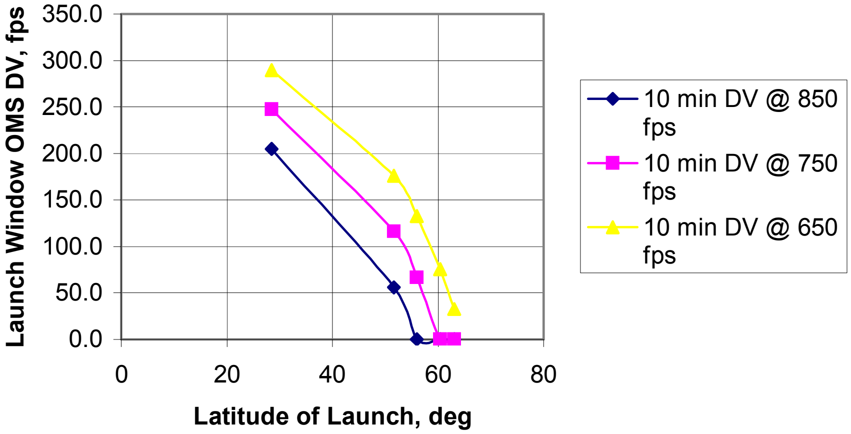

Figure A1. Delta velocity for 10 minute launch window versus cruise speed

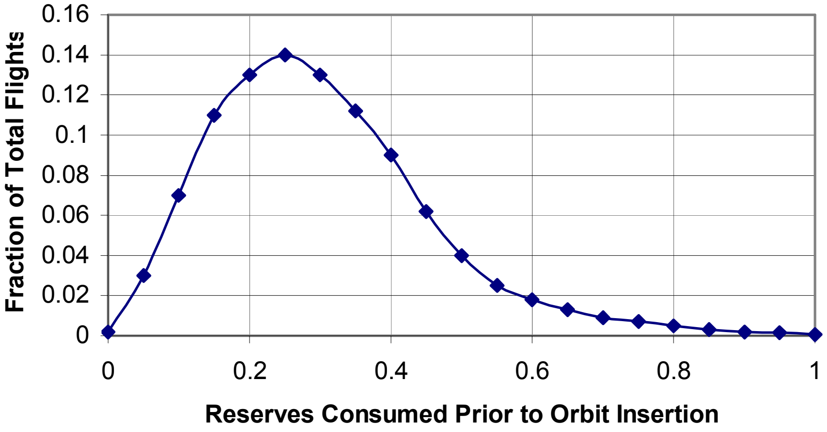

Figure A2. Hypothetical reserves available at orbit insertion

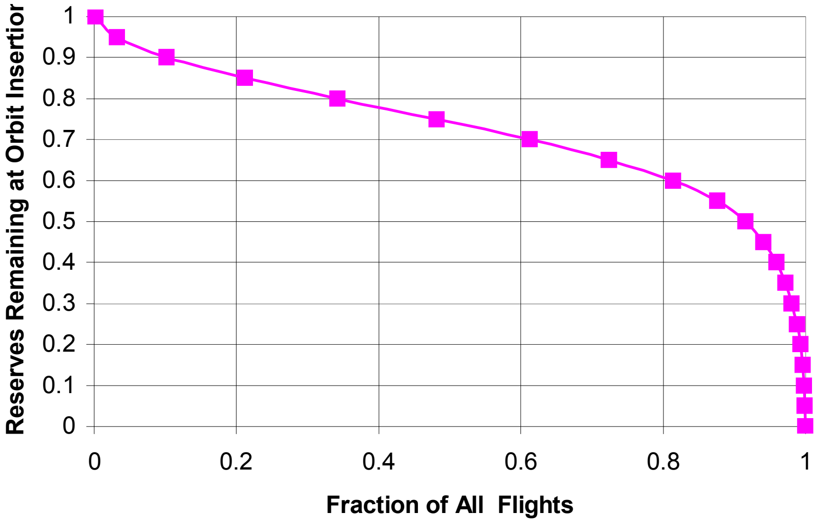

Figure A3. Reserves remaining at orbit insertion