Air Launched Vehicle Exergy Analysis During Aircraft Boost Phase

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Abstract

The analysis of air launched vehicles carrying payloads to low earth orbit is complex. The integration of the aircraft flight phase and the launch vehicle flight phase requires the integration of systems functioning from different energy relationships. System exergy balance provides a relationship to integrate the efficiency of the aircraft launcher and the efficiency of the launch vehicle in a single, integrated system assessment. The exergy balance of the aircraft flight phase can be calculated with the launch vehicle included as part of the vehicle mass. As exergy balance allows for separate of the masses, different velocities, and different propulsion systems to continue the mission analysis after separation through payload orbital insertion and aircraft landing. This paper presents the initial assessment of the aircraft launch phase up to separation of the launch vehicle. Showing the method of integration afforded by the system exergy balance relationship.
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Introduction

The power of system exergy as a system integration approach is very apparent in looking at launch vehicles that are launched from an aircraft. The exergy balance allows for the integration of aircraft and launch vehicle terms to produce an integrated balance equation. To determine the exergy efficiency of an air-launch vehicle with an aircraft serving as the booster, a Boeing 747-400 Freighter was chosen as the aircraft booster. The launch vehicle rocket stages are the second and third stages of the integrated aircraft/rocket vehicle. The rocket launches from the aircraft while it is in steady, controlled flight, and then ascends to orbit. The aircraft returns to the landing site. The exergy balance allows both of these flight phases to be considered in the overall balance of the system.

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Nomenclature

α	=	angle of attack for aircraft
Δ	=	general change from one state to another
δQ	=	change in path specific heat transfer
η	=	thermodynamic symbol for efficiency
h_{prop}	=	specific enthalpy for propulsion
H_p	=	Heating value for turbojet fuel
KE	=	Kinetic Energy
$m_{propellant}$	=	mass of propellant
PE	=	Potential Energy
S,s	=	Entropy, Specific entropy
S_{gen}	=	Entropy Generation
T	=	Temperature
T_0	=	Temperature of surrounding in a system
V_e	=	Exit velocity of rocket propellant
X_{des}	=	Exergy destroyed

1. Air Launched System Exergy Balance

Exergy balance provides the relationship between all the thermodynamic properties of a system including kinetic energy, potential energy, mechanical work, electrical work, fluid work, and thermal work. For an aircraft exergy balance is[i],

$$\Delta m_{propellant} H_{total} - \int_{taxi\ and\ take\ off}^{landing\ and\ taxi} T_i\, dS_{total\ irreversibilities} = \Delta\left(m_{vehicle}\frac{V_{vehicle}^2}{2}\right) + \int_{taxi\ and\ take\ off}^{landing\ and\ taxi} m_{vehicle}\, g\, dheight \tag{1}$$

Aircraft propulsion exergy is related to the enthalpy of the propulsion system as seen by the H_{total} term. For a rocket, propulsion is driven by the propellant exhaust velocity, V_e, and the exergy balance is given by[ii],

$$\sum_{stages}\left[\Delta m_{propellant}\left(h_{prop} + \frac{V_e^2}{2}\right)\right] - X_{des} = \sum_{stages}\left[\left(M_{vehicle,final}\frac{V_{vehicle,final}^2}{2} - M_{vehicle,initial}\frac{V_{vehicle,initial}^2}{2}\right) + \left(\frac{GM_E M_{vehicle,initial}}{r_{altitude,initial}} - \frac{GM_E M_{vehicle,final}}{r_{altitude,final}}\right)\right] \tag{2}$$

Combining these equations gives the total balance for the aircraft boosted launch vehicle as,

$$\Delta m_{propellant,aircraft} H_{total,aircraft} + \sum_{stages}\left[\Delta m_{propellant}\left(h_{prop} + \frac{V_e^2}{2}\right)\right] - X_{des} = \sum_{stages}\left[\left(M_{vehicle,final}\frac{V_{vehicle,final}^2}{2} - M_{vehicle,initial}\frac{V_{vehicle,initial}^2}{2}\right) + \left(\frac{GM_E M_{vehicle,initial}}{r_{altitude,initial}} - \frac{GM_E M_{vehicle,final}}{r_{altitude,final}}\right)\right] \tag{3}$$

Where the vehicle mass, velocity, and altitude in the kinetic energy and potential energy term on the right hand side of the equation are for the total integrated system (i.e., aircraft and launch vehicle) during the boost phase.

2. Aircraft Flight Path

Aircraft exergy is calculated over the aircraft taxi and flight path from engines start to engines shut down. A phase specific mission plan (aircraft flight plan and rocket trajectory) must be established to calculate this. For the aircraft, data for the typical flight performance characteristics for the Boeing 747-400F were determined as shown in Table 1.[iii,iv,v] This is visualized in Fig 1.
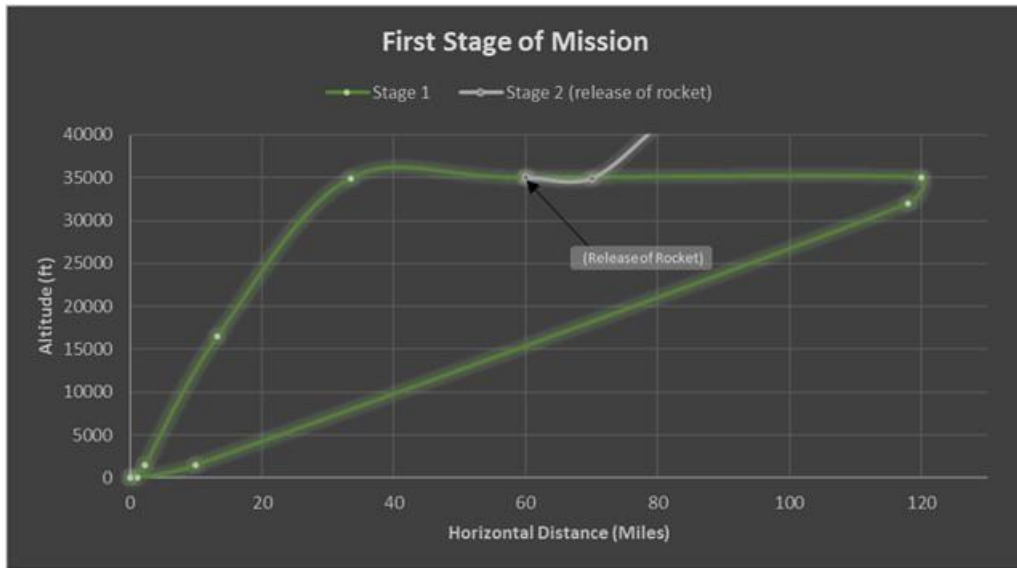

Fig. 1. Visualization chart of first stage for air-launched rocket

The green line in Fig. 1 represents the flight path as the 747 travels along a 2D path to a cruising altitude of around 35,000 feet. When the 747 reaches the launch area 60 miles away from the initial starting point, the rocket is released and ignited. Table 1 provides a specific flight plan for the aircraft. According to the flight plan in Table 1, the aircraft will be at a cruising speed of about 621 miles per hour.

Table 2. Mission Phases for the Boeing 747-400F carrying the air-launched rocket

Flight Phase	Description
1) Engine Start and Taxi	Engines start and taxi to runway
2) Take off	Accelerate to 155 knots (178 mph) to takeoff to minimum ground clearance altitude (35 feet)
3) Initial Climb	Climb to 1500 feet (speed approx. 191 mph)
4) Climb to Cruising Altitude	Climb to 35,000 feet (290 knots or 288 mph) with angle of attach reduced to 10 degrees at 16,500 feet
5) Cruise Flight to Release Point (prelaunch checkout)	Accelerate to and maintain 540 knots (621.4 mph) and perform launch vehicle prelaunch checkout
6) Launch Vehicle Release	Release launch vehicle on clearance from range and launch vehicle control
7) Cruise Flight to Landing Field	Return to airfield (same as departure field in this scenario)
8) Descent Final Approach	Descend to 1500 feet and reduce speed to 250 knots (288 mph)
9) Final Approach and Landing	Decelerate and land at 135 knots (155 mph) slowing to taxi speed
10) Taxi and Engines Shut Down	Taxi to parking ramp and shut down engines

3. Launch vehicle Trajectory

Fig. 2 illustrates the altitude profile of the aircraft trajectory through rocket separation and initial burn of the second stage. The aircraft is the first stage of this system and is represented by the orange track. The launch vehicle is represented by the yellow track. The launch vehicle initially drops upon release and then gains altitude as the second stage burns and the launch vehicle quickly gains altitude.

Fig. 3 illustrates the launch vehicle separation events and the altitude and down range distance gained at each event. The aircraft is shown as the orange track, the second stage burn is the yellow track, and the 3rd stage burn (2nd stage of the rocket) is show as the green track. Note the relative short distance the aircraft transports the launch vehicle in both ground track and altitude as compared with the launch vehicle stages.
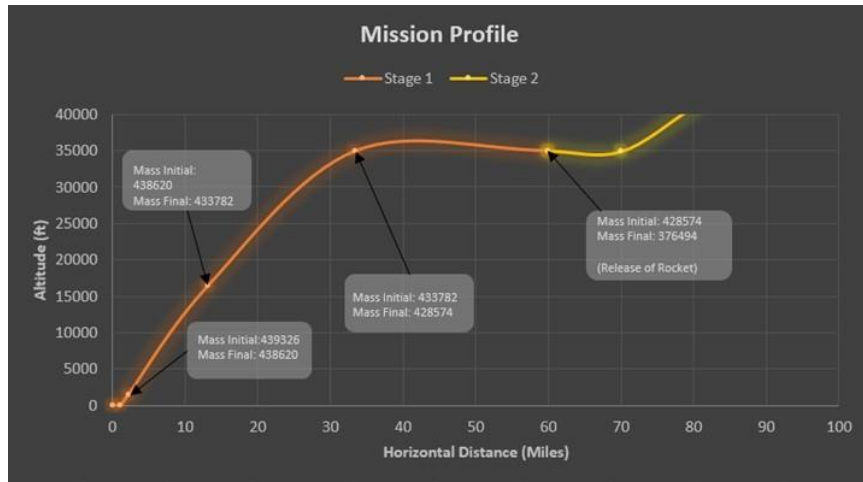

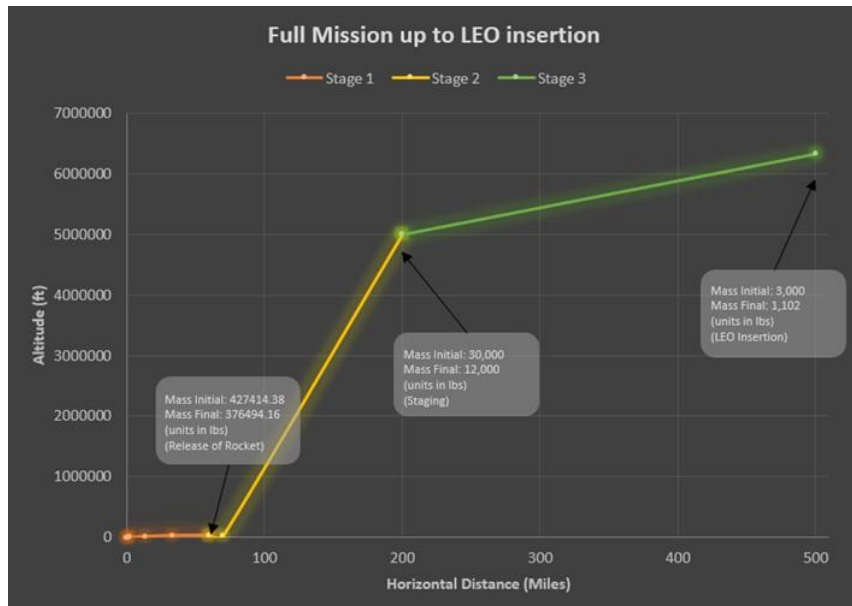Fig. 2. Visualization chart of first and second stage of the air-launched rocket.

Fig. 3. Visualization chart of the entire mission for an air-launched rocket

4. Aircraft Flight Phase Exergy Calculation

Equation 1 is used to calculate the aircraft phase trajectory efficiency. Note, that this is basically Equation 3 with $\Delta m_{propellant} = 0$ before the launch vehicle propulsion is ignited. The top rows in Table 2 provide the data for the aircraft boost phase exergy balance for each portion of the aircraft flight profile. The exergy values were then used to calculate the exergy efficiency for each mission phase. The data in the table shows the change in system mass, Δm, accounting for the fuel consumption in each of the flight phases and the change in aircraft mass with the drop of the launch vehicle. The aircraft kinetic energy, potential energy, and heating values (for JP-4 and JP-5) are also shown. JP-4 is used in this analysis for the 747-400.

Table 4-14: Aircraft Boost Phase Exergy Balance Calculations

Boeing 747-400F	Exergy Destruction Inputs	Please refer to Boeing 747-400F Mission Context for Phase #s. The Boeing 747 is acting as the booster (first) stage of the mission. The exergy destroyed in this table should be added to the final exergy.			
Input Variable:	Change in mass (Δm)	Change in KE (ΔKE)	Change in PE (ΔPE)	Heating Value (JP-4)(Hp)	Heating Value (JP-5)(Hp)
Units:	lb_m	BTU	BTU	BTU/lb_m	BTU/lb_m
Description:	This is the change in mass of propellant	Change in Kinetic Energy of the Vehicle $\Delta KE = \Delta\left(m_{veh}\frac{v^2}{2}\right)$	Change in Potential Energy Across the mission w.r.t. altitude $\Delta PE = \int_{mission} m_{veh} g \, dh$	Used to estimate change in the chemical potential from the freestream air and the propellant in the tanks to the equilibrated wake outflow	Used to estimate change in the chemical potential from the freestream air and the propellant in the tanks to the equilibrated wake outflow
Phase 2:	705.6	67,717.43	816,909.89	18400	18315
Phase 3:	4838.4	644,263.82	8,263,090.25	18400	18315
Phase 4:	5208	428,846.02	9,970,783.24	18400	18315
Phase 5:	1159.62	5,302,369.97	-51,599.81	18400	18315
Phase 6:	2816.22	-835,706.65	-2,265,805.92	18400	18315
Phase 7:	6560.136	-4,933,582.56	-16,047,454.17	18400	18315
Phase 8:	1219.86	-882,552.01	-705,472.24	18400	18315
Phase 9:	614.88	-362,917.19	0.00	18400	18315
-	-	-	-	-	-
Staging will take place at this point, rocket exergy equation may now be used for further analysis					
OUTPUTS:	Total Exergy Destroyed	Exergy Efficiency (By Phase)			
Units:	BTU	*no units*	%		
Phase 2:	12,098,412.69	0.068	6.81	2	
Phase 3:	80,119,205.93	0.100	10.01	3	
Phase 4:	85,427,570.74	0.109	10.85	4	
Phase 5:	16,086,237.84	0.246	24.61	5	
Phase 6:	54,919,960.58	-0.060	-5.99	6	
Phase 7:	141,687,539.13	-0.174	-17.38	7	
Phase 8:	24,033,448.25	-0.071	-7.08	8	
Phase 9:	11,676,709.19	-0.032	-3.21	9	
Final Exergy Efficiency					
Units:	BTU	*no units*	%		
Across Mission	92217618.62	0.10	9.60	Takeoff	
	177645189.4	0.10	10.21		
	193731427.2	0.12	11.61		
	242448362.6	0.11	10.53		
	342173828.3	0.13	12.64		
	363031228	0.12	12.34		
	373982102.8	0.12	12.10	Land	

Table 2 also shows the results of the exergy efficiency calculations. The center of the table shows the exergy destroyed due to system efficiencies for each mission phase defined in Table 1. This section also shows the exergy efficiency in each phase of flight. Note, that the aircraft exergy efficiency increases during acceleration phases and is most efficient during the cruise flight. On return the exergy efficiency decreases (as seen by the negative efficiencies). Separation of the launch vehicle represents a large exergy drop in the aircraft exergy due to the loss of the launch vehicle and payload mass at separation. The energy imparted into the launch vehicle while attached to the aircraft is lost to the aircraft at separation. The exergy efficiency continues to decrease on the return phases as the aircraft slows, losing kinetic energy. This is illustrated in Fig. 4.
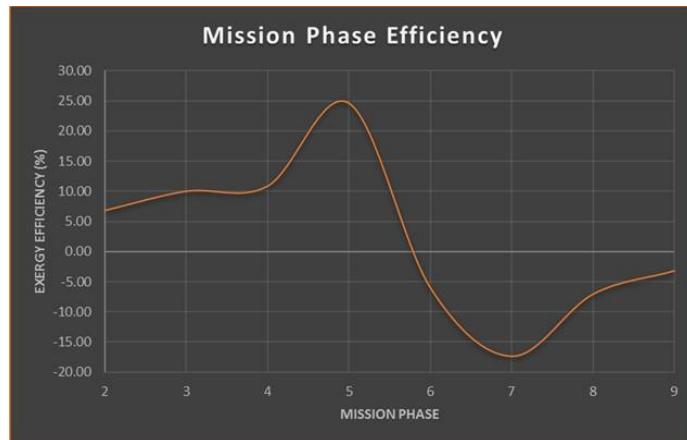

Fig. 4. Exergy Efficiency specific to individual mission phases

The bottom section of Table 2 shows the cumulative exergy destruction and exergy efficiency, summing the efficiency increases and decreases across each phase to obtain the final system efficiency of 12.1%. Note, that the energy expenditures to slow the aircraft are in the opposite direction of the thrust. Therefore, the signs of the kinetic and potential energy are reversed during descent and landing to account for the expenditure of energy in the opposite direction. Fig. 5 illustrates the total exergy efficiency of the aircraft across the flight phases.

Note, the aircraft exergy efficiency drops between phases 5 and 6. This reflects the drop of the rocket from the aircraft where the aircraft loses the exergy contained in the rockets kinetic and potential energy after the drop while the rockets exergy efficiency starts with this kinetic and potential energy. Thus, the launch vehicle starts with much higher kinetic and potential energy than for those vehicles starting from a ground launch pad.
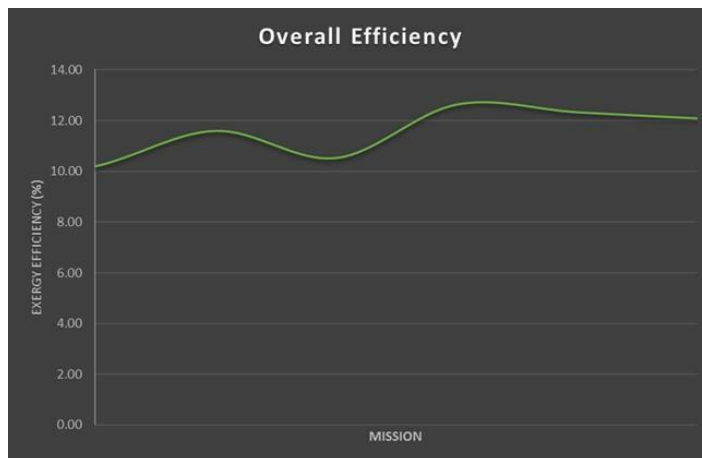

Fig. 5. Overall Exergy Efficiency for the entire first stage flight

5. Aircraft Flight Phase Exergy Calculation

The power of the exergy balance relationship to integrate systems with different a different thermodynamics basis is shown by equation 3. This shows that the integrated aircraft/launch vehicle system can be treated as an integrated unit before separation and then two units after separation. The exergy efficiency of the aircraft phase has been calculated including the separation point of the launch vehicle. This led to an aircraft efficiency of 12.1% for a Boeing 747-400. Future work will add the rocket phases for this integrated system and provide the overall rocket exergy efficiency to orbit and the combined aircraft and rocket exergy efficiency through aircraft landing and rocket orbital insertion.

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