# Launch Pad Abort of the HL-20 Lifting Body

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The capability of the HL-20 lifting-body spacecraft to perform an abort maneuver from the launch pad to a horizontal landing was studied. This study involved both piloted and batch simulation models of the vehicle. A point-mass model of the vehicle was used for trajectory optimization studies. The piloted simulation was performed in a fixed-base simulator. A candidate maneuver was developed and refined for the worst-case launch-pad-to-landing-site geometry using an iterative procedure of off-line maneuver analysis followed by piloted evaluations and heuristic improvements to the candidate maneuver. The resulting maneuver demonstrates the launch site abort capability of the HL-20 and dictates requirements for nominal abort motor performance. The sensitivity of the maneuver to variations in several design parameters was documented.

# Introduction

T HE HL-20 has been proposed as a crew transport vehicle for the Personnel Launch System. The current baseline design is a 20,000-lb lifting body with a maximum subsonic lift-to-drag ratio of 4.3 (see Fig. 1) capable of being launched vertically into low Earth orbit with a crew of two and up to eight passengers using an expendable launch vehicle and of being landed horizontally following re-entry. Both manual and automatic landing capabilities are planned.<sup>1</sup>

An adapter module will be used to mate the HL-20 to the launch vehicle (see Fig. 2). This adapter design will include a launch escape system intended to thrust the HL-20 away from the booster in the case of a malfunction either during the actual launch or on the pad prior to launch (on-pad abort). Acceleration levels on the order of 8 g would be required to propel the vehicle a safe distance away from a malfunctioning booster. After a specified time, the abort motor thrust would drop down to provide approximately 1 g thrust for an additional specified amount of time. The adapter module would be jettisoned following abort motor burnout.

The capabilities of the HL-20 to successfully abort during the ascent phase of a launch have been treated in a separate study by Naftel and Taley<sup>2</sup>; the on-pad-abort maneuver, performed in an emergency prior to ignition, is the subject of this paper.

Since the initial lift-to-drag ratio precluded a glide to a nearby runway, original launch pad abort scenarios were similar to those used for earlier manned capsules, i.e., an abort to an ocean landing using a recovery parachute.<sup>3</sup> Additional aerodynamic refinements of the HL-20 configuration led to increased subsonic lift-to-drag ratios and a higher performance launch escape system abort motor was specified.<sup>4</sup> These improvements raised the possibility of performing a conventional horizontal landing following a launch pad abort (pad abort to landing).

An earlier manned space project, the X-20 Dyna-Soar, envisioned a pad-abort-to-runway option from the launch pad. To verify the feasibility of this abort option, an in-flight simulation study was performed in a delta-wing interceptor aircraft.<sup>5</sup> The trajectory flown in the aircraft consisted of a low-level, high-speed entry into a vertical pull-up at a predetermined location to simulate abort initiation. This was followed by a pullover to the horizon, a roll maneuver to an upright wings level attitude, and a 180 deg turn to landing. The relationship between the pad and the runway in the X-20 launch scenario was somewhat different than that proposed for the HL-20.

A study was initiated to determine if the HL-20 vehicle could successfully be maneuvered to a runway landing in the event of an on-pad abort and to determine what design parameters would improve the feasibility of such a maneuver. The results of the study are presented below.

# **Simulation Models**

To evaluate the pad-abort-to-landing scenario, a candidate maneuver was developed and analyzed with both off-line and real-time simulation tools. The real-time piloted simulation was used to explore possible abort maneuvers; the off-line simulation was used to arrive at a numerically optimal trajectory. The piloted simulation was then used to validate the optimal trajectory and to suggest simplifications to the maneuver to make it easier to perform. The piloted simulation tests were performed in a generic transport-type cockpit with a left-hand sidestick, a hydraulic control loader, forward and left-side out-the-window displays, head-down instrumentation and displays, and a simulated wide-field-of-view head-up display. The motion cueing system was not employed for these tests due to motion performance limitations.

The math model used in the piloted simulation was derived from an existing HL-20 approach and landing simulation model.<sup>6,7</sup> Modifications included adding a steerable abort motor model with thrust and pitch/roll torques specified as a function of time, modeling the orbital maneuvering system (OMS) rocket motors, and increasing the vehicle mass properties appropriately. Modifications to the flight director/autopilot control laws, the control law mode switching logic, and simulation initialization logic were required. Flight displays, both head up and head down, were modified to assist in pilot orientation during the maneuver.

The off-line simulation employed a point-mass model using optimal-trajectory simulation software.<sup>8</sup> The fairly simple aerodynamics of this model consisted of lift and drag coefficients as

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Fig. 2 HL-20 launch escape system adapter with abort motors.

a function of Mach number and angle of attack. Control deflection, landing gear, and ground effects were not modeled. Some performance differences between the off-line and piloted simulations are apparent; however, the optimal maneuvers developed using the off-line simulation provided insight into a practical and efficient abort maneuver for manual or automatic flight control.

The optimal-trajectory simulation software is based on a direct method for obtaining the solution of a trajectory optimization problem that uses collocation and nonlinear programming. More information concerning this method is found in Refs. 8 and 9.

# **Abort Trajectory Design**

A set of probable launch pad/runway geometries, vehicle orientations, and abort maneuvers was initially considered. The set included simulated aborts from Kennedy Space Center launch pads 39A, 40, and 41 with simulated landings at both the Shuttle Landing Facility and the Cape Canaveral Air Force Station skid strip (see Fig. 3). Candidate abort scenarios included various orientations of the launch stack in which the vertical fin of the HL-20 was pointed due east, slightly south of east, or slightly north of west or was allowed to be pointed in an optimal direction. These vehicle orientations were dictated by launch pad constraints.

Nominal touchdown speed for the abort cases was increased from 200 knots equivalent airspeed (KEAS) (the nominal end-of-mission value) to 230 KEAS due to the heavier weight of the vehicle with all consumables still aboard (25,800 lb vs 19,100 lb). This mandated a higher minimum speed at the beginning of the preflare maneuver (275 KEAS instead of 250 KEAS).

As a starting point in this investigation, an optimized trajectory was generated for one of the abort situations (pad 40 to skid strip 13) using angle of attack and bank angle as the control variables.



Fig. 3 Possible launch-pad-abort-to-runway geometries.

The starting point for the maneuver was 100 ft above launch pad 40 with an initial velocity of 50 ft/s (to avoid numerical problems). Final conditions were specified to be a trimmed glide at 450 ft/s (266 knots) over the approach end of runway 13, aligned with the runway heading. Bank angle was constrained to  $\pm 30$  deg and roll rate to  $\pm 28.6$  deg/s ( $\pm 0.5$  rad/s). Angle of attack was constrained to be between 0 and 30 deg and angle-of-attack rate to  $\pm 5.7$  deg/s ( $\pm 0.1$  rad/s). The optimization program was free to pick an initial flight path angle and heading as well as angle-of-attack and bank angle control trajectories. A 3-s, 8-g abort motor thrust pulse at the start of the maneuver, followed by a constant 1500 lb thrust from the simulated OMS engines, was modeled as the only energy addition to the problem. The optimizer was asked to maximize the altitude over the runway threshold (threshold crossing height).

The resulting trial trajectory (Fig. 4) indicated an initial flight path angle of approximately 45 deg was preferred; this corresponds with the launch angle of ballistic projectiles to achieve theoretical maximum range in a vacuum. The optimal turn to final was shown to be a gradually increasing bank angle that reached the bank angle



Fig. 4 Optimal trajectory for launch pad 40 to runway 13 abort.

limit just prior to intercepting the runway extended centerline. The altitude achieved over the runway threshold was predicted to be 1193 ft. This initial trajectory indicated the benefit of steerable abort motors that would allow rapid modification of the vehicle orientation at the beginning of the maneuver to obtain optimal heading and flight path angles as soon as possible. It also indicated that the optimal trajectory would be difficult for a pilot to follow due to the continuous variation in flight conditions, and the inevitable deviation from the preplanned trajectory would require recomputation of a new optimal trajectory from the new vehicle state.

In addition to the pad 40 to skid strip 13 abort situation, a candidate trajectory for each of the other situations was developed in the piloted simulation. Early abort maneuver candidates included a half Cuban eight (for head-down aborts), pushovers (for head-up abort), and a modified "sliceback" or wingover maneuver for abort orientations requiring a heading change. (In this context, the term head up or head down refers to the attitude of the crew during the initial portion of the abort.) The improvement in maneuver performance gained by immediately rolling and pitching the vehicle to an optimal heading and attitude led to the addition of steerable abort motors. Aborts both with and without firing the OMS and with modified abort motor thrust profiles were studied.

From these preliminary investigations the worst-case launch-padto-runway geometry was selected for further study. This worst-case geometry involved an abort from the most northern launch site (of those under consideration), pad 39A, to the skid strip runway 13, a straight-line distance of 8.3 nautical miles. This geometry involved the longest glide and was thus designated the worst-case scenario. The vertical fin of the HL-20 on the launch pad was assumed to be pointed 100 deg true (clockwise from north), corresponding to an eastward head-down launch configuration. This required an immediate right roll to orient the vehicle for a head-up abort. Winds were assumed to be steady at 22 knots, coming directly from the runway to the launch pad, and no OMS thrust was assumed.

The focus of the research then shifted to the development of a simplified abort maneuver that was as efficient as possible, yet could be flown repeatedly by a pilot. It is anticipated that, given the suddenness of the abort maneuver and the rapid rotation of the vehicle, automatic control of the vehicle will be required for at least the initial part of the maneuver; however, the simplified maneuver was developed using a pilot and demonstrated by both the pilot and an automatic flight control system, allowing manual takeover at any point.

#### **Initial Steering**

The abort maneuver from pad 39A was begun with a 3.5-s, 248,800-lb burn of the abort motors. The abort motors were assumed to be steerable and were used to rapidly roll the vehicle to a 182 deg heading to begin a head-up maneuver to the runway. The motors then pitched the vehicle down to a 45-deg pitch attitude. These maneuvers were completed in the first second of the abort. Figure 5 shows the abort motor thrust and torque time histories used in the simulation. After 3.5 s, the abort motor thrust was decreased to 33,000 lb, providing a nearly 1-g sustainer thrust level for the next 11.5 s. (This value for the duration of the sustainer motor burn was determined after several piloted simulation runs.) The pilot was asked to hold a 45-deg flight path angle using the heads-up display (HUD) pitch ladder and velocity vector until abort motor burnout, at which time the adapter module was jettisoned.

## **Pushover Maneuver**

Following abort motor burnout a zero angle-of-attack (zeroalpha) pushover maneuver was executed. The pilot performed this maneuver by moving the boresight marker to coincide with the velocity vector on the HUD. Nominal apogee conditions were 10,633 ft and 228 KEAS and a distance of 13,240 ft downrange from the launch pad at 28 s after initiation of the abort. The zero-alpha flight condition was maintained until a specified negative flight path angle was reached.

#### **Pullout Maneuver**

A pullout maneuver was then performed to achieve the nominal glide condition (300 KEAS at -14 deg flight path angle), which was maintained until beginning the turn to final. The details of the maneuver were developed heuristically in the piloted simulation and consisted of remaining in the zero-alpha flight condition until an approximate -28-deg flight path condition is reached at approximately 240 KEAS. Angle of attack was then increased over the next 25 s to simultaneously achieve the nominal glide speed (300 KEAS) and flight path angle (-14 deg) conditions that were maintained until starting the final-turn maneuver. The rate at which the velocity vector was raised was limited by the requirement not to exceed the best lift-to-drag angle of attack (13 deg). Angles of attack above 13 deg resulted in rapid energy dissipation.



Fig. 5 Abort motor thrust and moment profiles for pad 39A to runway 13 abort.



Fig. 6 Steady glide trim conditions: abort configurations.

#### **Steady Glide**

To determine the best glide conditions, a set of trim cases were generated using the full nonlinear model for steady-heading glide conditions at constant equivalent airspeed for various levels of OMS thrust (see Fig. 6). The nominal glide speed used in the simulation for the zero OMS thrust worst-case situation (300 KEAS and -14deg flight path) was higher than the best glide speed for the vehicle (265 KEAS) at the heavy abort weight of 25,800 lb. This higher speed was chosen to improve penetration into the headwind as well as to match the entry speed of the final-turn maneuver.

#### **Final-Turn Maneuver**

The initial optimal point-mass solution (Fig. 4) included a constantly varying bank angle in the turn to final. This was judged as difficult for the pilot to perform consistently, and a nonoptimal, constant bank angle turn was deemed more acceptable. A set of steep gliding turn trim cases were generated off-line for the full nonlinear vehicle model both with and without OMS thrust augmentation. This resulted in a set of curves demonstrating that a bank angle of 49 deg could be sustained at 300 KEAS and 1.4 load factor. During the 8000-ft-radius turn the HL-20 would lose approximately 65 ft of altitude per degree of heading change while maintaining sufficient speed to complete the flare and landing maneuver (see Fig. 7). Turns performed at slower speeds could yield a slight improvement in turn efficiency (a 42 deg bank turn at 250 knots, for example, loses only 50 ft/deg), but insufficient altitude remains after the turn to accelerate for the landing flare maneuver. Thus, the 300-knotairspeed, 49 deg-bank-angle, and 8000-ft-radius turn was chosen for the final-turn maneuver. In practice, given the limitations on the roll performance of the lifting body, the pilot rarely stabilized the vehicle at the nominal-turn conditions and instead flew the final-turn maneuver visually.

After the turn to final approach a flare and landing maneuver followed shortly. Touchdown occurred at a nominal distance of 1931 ft down the runway.



Fig. 7 Steady turn performance vs airspeed: abort configuration.

# **Worst-Case Maneuver Comparisons**

A typical heuristic abort trajectory is shown as long dashed curves in Fig. 8. This condition includes 22 knots wind from 181 deg true (clockwise from north) and the abort motor performance history given in Fig. 5. This trajectory was flown manually following the method described above. The threshold crossing height was 25.3 ft.

A fully automatic abort trajectory is shown as short dashed curves in Fig. 8 for the same conditions as the manual trajectory. This control strategy employed the same heuristic rules as the manual strategy, with the exception of holding a constant angle of attack from apogee to extended glideslope intercept; this difference in control strategy accounts for the slight variations in the steady- glide portion of the trajectory. Threshold crossing height was nearly the same as the manual case (24.8 ft).

Following the development of the heuristic trajectory in the piloted simulation, an optimal trajectory for the worst-case geometry was generated for comparison. The optimal trajectory is plotted as solid curves in Fig. 8 along with the manual and automatic abort trajectories. It is apparent that the optimal trajectory outperformed the heuristic trajectory; however, the optimal trajectory was generated with a simplified math model of the aircraft without control surface deflection or pitch dynamics and was therefore a somewhat more optimistic prediction of vehicle performance. In addition, the goal of the optimization algorithm was to end up with the highest possible threshold crossing height, subject to the constraints described previously. Threshold crossing height for the optimal trajectory was 3794 ft.

## **Parametric Variations**

Modifications to the launch escape system and vehicle design parameters were explored to determine the sensitivity of the abort maneuver to changes in design parameters. Parametric variations in vehicle weight, steady winds, maximum lift-to-drag ratio, abort motor thrust levels, and the effect of firing the OMS thrusters were

Table 1	Parametric sensitivities for launch pad 39A abort to runway 13
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Varied parameter	Variation amount	Estimated TCH, ft	TCH difference, ft	TCH sensitivity
Baseline		104		
Sustainer duration	-1.5 s	-1035	-1139	759 ft/s
	+1.5 s	1321	1217	811 ft/s
Vehicle weight	+3,000 lb	-2451	-2555	0.85 ft/lb
-	-3,000 lb	2799	2696	0.90 ft/lb
L/D ratio	-0.5 L/D	-1340	1444	289 ft/0.1 L/D
	+0.5 L/D	1787	1684	337 ft/0.1 L/D
Abort motor duration	+0.2 s	1415	1311	656 ft/0.1 s
Abort motor thrust	-15,000 lb	-1283	-1386	92.4 ft/1000 lb
	+15,000 lb	1411	1307	87.1 ft/1000 lb
OMS thrust	1,000 lb	2027	1923	1.9 ft/lb
Headwind from 181 deg	11 knots	-141	-245	22.3 ft/knot
Headwind from 181 deg	22 knots	-207	-311	14.1 ft/knot

TCH = threshold crossing height. L/D = lift to drag.



Fig. 8 Comparison of optimal, manual, and automatic abort maneuver for pad 39A to runway 13.

studied and benefits were calculated. Numerical results of the parametric study, which was performed in the piloted simulation, are given in Table 1.

#### Conclusions

As a result of this study, it was concluded that a successful launchpad-abort-to-runway landing could be performed both manually and automatically for worst-case conditions with some margin for error. A candidate abort maneuver was developed through analysis and pilot experimentation, and sensitivity of the maneuver to design parameter variation was determined. A guidance and control law to automatically perform the abort was developed that was successful in providing a safe landing in the case of crew incapacitation.

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