PILOT CONTROL OF THE X-20/TITAN III BOOST PROFILE

by

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From the beginning of rocket booster flight, there has been considerable doubt as to the pilot's ability to do any meaningful task during the boost phase, primarily because of the acceleration environment and the difficult flight control task during the high dynamic pressure region. In addition, vehicle constraint from a structural and heating standpoint and the performance requirements at boost burnout appeared to dictate an automated system. Several generalized studies, both from fixed and moving base (centrifuge) simulations have shown that the concept of some pilot control during the boost phase was feasible. In addition, the X-15 flights, though of a short duration, have demonstrated that pilot control is practical in a "g" environment similar to those imposed on the X-20 by the Titan III booster. Since it was felt by the X-20 pilots that they would contribute to mission success by backing up the booster guidance and flight control system, and since it was believed that the glider and pilot provided an available but unused redundant system, recommendations were made to the 620/A (Dyna-Soar) SPO to include pilot control of the booster as a joint objective of the X-20/T-III program. To determine the feasibility of this concept, a fixed base, 6 degree of freedom simulation of the X-20/T-II air vehicle (assuming the then programmed T-II booster constraints and a rigid booster) was conducted at the Boeing Company between February and May 1962. This served as base line information for the dynamic simulation at the Johnsville NADC centrifuge in the summer of 1962. This simulation used T-II constraints but with T-III acceleration values and verified that no significant performance degradation was suffered by the pilot under the T-III "g" environment.

Figure 1 shows the X-20 instrument panel, controller, rudder pedals, and integrated seat/suit restraint system mounted in the gondola at the end of the arm of the Johnsville centrifuge. By varying the position of the gondola and the speed of the centrifuge arm, the exact "g" profile expected to be encountered in the boost program was simulated. In addition, the gondola was "rocked" at frequencies designed to give the vibration profile the pilot would experience during boost. Results from this program proved that fixed base simulations could substitute for the more complex and expensive dynamic simulations. As a result of these simulationss the X-20 SPO directed The Boeing Company to conduct a complete study and simulation using the latest T-III constraints and characteristics to determine if pilot control during the boost phase was feasible, what modificotions would be required to the air vehicle, and exactly how the pilot should fly the boost phase.

Figure 2 shows the general configuration of the Titan III/X-20 air vehicle used in the simulation. Stage "0" includes the two 5 segment "strap on" solids and the modified Titan II, Stage I is the basic Titan II, Stage II the upper stage of Titan II, and Stage III the transtage, a new upper stage and control module. Note that no fins were used for air vehicle stabilization.

Figure 3 shows the Pilot In The Booster Loop (PIBOL) simulation description. The booster was the standard T-III launch vehicle with booster flexibility caused from 2 pitch and 1 yaw bending modes, a 6 degree of freedom simulation (3 degrees of translation and 3 degrees of rotation), and was a complete simulation starting at lift-off and continuing in real time to burnout. The trajectory was that resulting from maximum dynamic pressure and random winds. In addition, variations in booster thrust of ± 10 percent was introduced in Stage 0, and ± 3 percent in Stages 1, 2, and 3. Several flight control systems ond guidance systems were studied; however, only the recommended systems that resulted from this study will be discussed.

The PIBOL boost constraints are shown in Figure 4. The air vehicle limits were the load limits, temperature limits, and staging limit rates of 3 degrees/second in pitch, roll, and yaw. These rates were the maximum that could be imposed on the air vehicle without causing staging interference at separation. The abort limits were the malfunction detection system rates of 3 degrees per second in Stage 0. Any vehicle rates greater than these triggered the automatic abort system and caused the glider to be separated from the booster. The other abort limit was the glider recovery ceiling, above which the glider (if aborted) could not recover without exceeding the structural or heating limits. The burnout performance limits are the injection limits which must be met to allow the glider to reach Edwards. A nominal mission is defined as one in which the glider re-enters over the instrumentation sites, thereby assuring good telemetry data, and calls for a tolerance of ± 9 feet per second in velocity at booster cut-off. The velocity tolerance of ± 40 feet per second allows the glider to make a successful landing at Edwards, but without a re-entry over the instrumentation sites.

Figure 5 shows the boost primary control regions. This is for a once around trajectory, with the shaded regions showing the areas of maximum pilot work load. At lift-off, the pilot rolls the air vehicle to align his heading with his desired track and starts his tip-over. During the maximum q and wind shear regions, the pilot minimizes his angle of attack and side slip excursions to reduce the bending moments on the glider. At staging, he holds his attitude rates to essentially zero to reduce the possibility of interference between stages at separation. At the end of the first staging, he begins to get back on the guidance path, since the wind, in the Stage 0 operation, has probably drifted him off his track. His task from here on is to hold staging rates to a minimum, keep away from the temperature and abort recovery ceiling limits, and arrive at the burnout window at the proper conditions.

Figure 6 shows the present X-20 cockpit. Slight modifications (which will be described later) were all that were necessary to use this same cockpit configuration for the boost phase. The standard X-20 instruments used for boost control were: (1) The all attitude indicator; (2) the yaw (heading) error indicotor; (3) the rate of climb; (4) the inertial altimeter; and (5) the inertial velocity indicator. The two axis side arm controller and rudder pedals (6) were used for vehicle control, and the abort handle (7) was used for thrust termination. In addition, sub-system instruments and malfunction indicators (10) were monitored during boost, and in event of malfunctions, corrective action taken by switching to alternate systems or aborting. Additional instruments necessary for control during boost were: (8) lateral and normal booster accelerations displayed at the bottom and left side of the all attitude indicator, and a burnout display for manual thrust termination, located at (9).

This burnout display (Figure 7) allows the pilot to terminate the booster thrust within ± 2-3 feet/second tolerances when using the transtage. This display uses two (2) moving needles, the vertical one driven by inertial velocity and the horizontal one by rate of climb, moving across the face of an instrument, on which altitude lines are displayed. Nominal injection conditions require that the pilot cut off using an exact altitude, velocity, and rate of climb. However, by making corrections in these three parameters prior to burnout, the pilot could achieve normal injection conditions with varying values of these parameters. For example, if the pilot noted he was low in altitude, he could allow the velocity to increase slightly, and conversely, if high in altitude, could terminate thrust early.

Figure 8 shows the guidance systems studied. The current system, with no inputs from the pilot or glider across the glider-booster interface, has the glider inertial system (GIGS) driving the displays (both attitude and displacement) with the emergency re-entry system (a simple 2 axes gyro platform) as a standby for the attitude display. The booster inertial guidance system (BIGS) is used to drive the booster auto pilot. This system was used as a baseline for evaluating pilot capabilities. The GIGS system had the pilot (by reference to his attitude and displacement displays) making inputs to the booster auto pilot and shutdown circuit, thereby by-passing the booster inertial guidance system. The GCB system (short for Ground Control Boost) assumed that the GIGS had failed and the pilot had only attitude displays from his ERS. To get displacement and shut-down information, he relied on ground voice commands.

The guidance program that the pilot used is shown in Figure 9. Stage 0 was an open loop program where the pilot's principal task was to minimize the loads on the glider and booster and still stay within the guidance constraints. A schedule of pitch program versus time was flown until the air vehicle had been pitched over to approximately 60 degrees. During the first ten seconds of vertical rise, the air vehicle was rolled to the launch heading. At 15,000 feet the booster lateral and normal accelerations (as displayed on the bottom and left side of the attitude indicator) were held to minimum values to reduce the loads on the booster/glider interface until the maximum dynamic pressure region had been safely transversed. He then flew a time versus pitch program until first staging. After staging, he used a program of time, rate of climb, and altitude to check his guidance progress. If these values did not agree, he would modify the nominal pitch program and hold this correction until the next check point. If he was back on the climb schedule, he would again assume the nominal pitch attitude. This pitch program was flown using the all attitude indicator, the clock, inertial altimeter and rate of climb indicator. Heading error was displayed on a separate instrument (as computed from the glider inertial guidance system), and roll was displayed on the attitude indicator. The pilot "leveled off" slightly below the injection altitude, and at 7 minutes and 15 seconds of elapsed time, flew a pitch angle of approximately 10 degrees until a desired rate of climb had been reached. At this time, he held this rate of climb constant by modulating pitch attitude, and by reference to the shut down meter (as described above) terminated thrust at the proper injection conditions by placing the abort handle in the rearward position.

The ground control boost (GCB) guidance mode (Figure 10) was flown similarly by the pilot as far as attitude indications was concerned. Since the glider inertial system was assumed to have failed, no rate of climb altitude, heading error, or cut-off information was available from on on-board source. This information was given to the pilot by voice command every 30 seconds until approximately one minute prior to thrust termination, and continually from that point until proper burnout conditions were met. Studies show this information would be available through radar tracking information fed into a 7090 computer and then to performance displays for the test conductors information.

Figure 11 shows a comparison between the pilots and the automatic system for Stage O guidance. The top figure is a plot of maximum angle of attack dispersions at the wind spike as flown by all six of the X-20 pilots compared to the excursions experienced by the automatic system. The hatched lines show the air vehicle load constraints. The lower figure shows a similar plot of side slip excursions at the wind spike. The pilots used the technique of nulling A_y and A_z (normal and lateral accelerations) from 15,000 to 60,000 feet and did not exceed vehicle constraints in either the pitch or yaw axis; the automatic system did not exceed constraints in pitch, but did exceed the maximum allowable side slip.

Figure 12 shows the pilot performance for the remainder of the profile. Note that the pilot does not fly as exact a profile as the automatic system, but still arrives at the final injection condition without exceeding constraints, using either the pitch attitude program and glider inertial or by using the GCB.

The final configuration for the PIBOL guidance and control integration is shown in figure 13. The ERS drives the attitude displays, the GIGS, the displacement displays, while the acceleration displays are driven by accelerometers located on the booster. Ground communications provides a third source of information of velocity, altitude, rate of climb, and heading, which can be used as a third or deciding source of information, or in the event of failure of both booster and inertial guidance systems, could be used for GCB to an injection which would allow a safe landing at Edwards.

In the automatic system, the BIGS makes the attitude inputs to the summing amplifier, while acceleration and pitch rate feed back are fed into the amplifier from the booster flight control system. When the pilot switches over, he provides the attitude inputs and the booster flight control system the acceleration and rate feed back. The pilot then is replacing the BIGS and using the same booster flight control system as the automatic guidance system.

A safety and reliability study by The Boeing Company showed that with this system, the pilot could save approximately 85 percent of the guidance system failures by monitoring the booster flight path on his glider instruments, and, with ground assistance from the GCB concept, take over in case of booster inertial guidance system failure.

As a result of this simulation, the X-20 SPO has recommended to AFSC that pilot control of the boost phase be incorporated with the manned X-20/Titan III missions as a backup capability with a further objective of proving this concept during the X-20/Titan III program by programming flights using pilot control from liftoff. At the present time, a joint X-20/Titan III committee is studying the problems associated with this concept and will make a joint presentation to AFSC on feasibility, modifications, and cost and schedule impact at a later date.

DISCUSSION

CROSSFIELD: I'd like to know why the decision was that you might use the pilot for the back-up. Why don't you use the GIGS for the back-up?

WOOD: Well, it's always an interesting one as to how you evolve the original design. I think if you had started with the idea that the pilot would be primary, you would design, for instance, the flight control system differently. However, I think we have to remember that, in Titan III, we have what is known as a standard launch vehicle that already has a standard flight control system which is designed for the automatic mode. Now we're having to use this, then, as the prime mode and show thot the pilot can be used as the back-up mode.

CROSSFIELD: If we believe our statistics, we have right now, with the supposedly-developed Titan vehicles, about 70% reliability or possibility of mission success. So you start out with about a 30% requirement for the pilot, anyway.

WOOD: I can't argue with the figures.

CROSSFIELD: They're approximate.

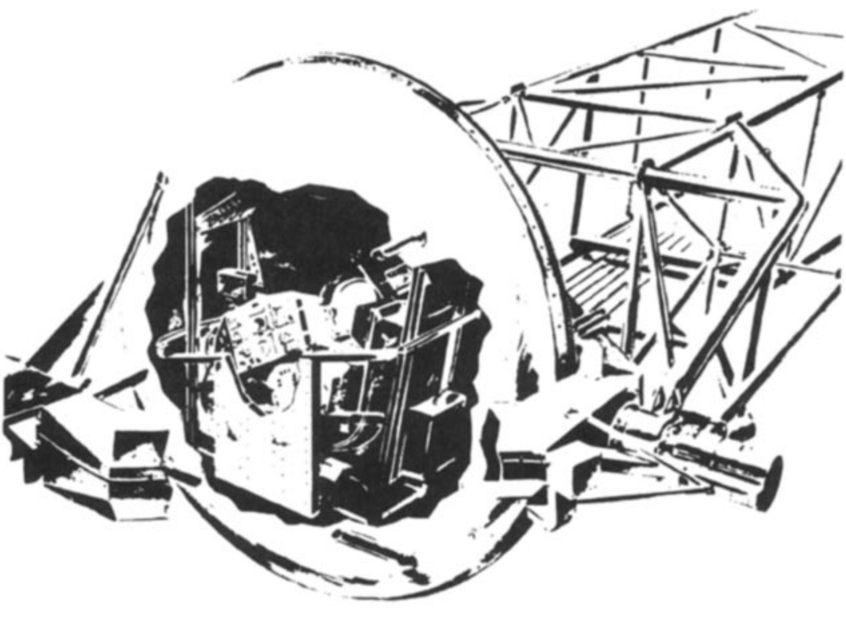


FIGURE 1

BOOSTER DESCRIPTION

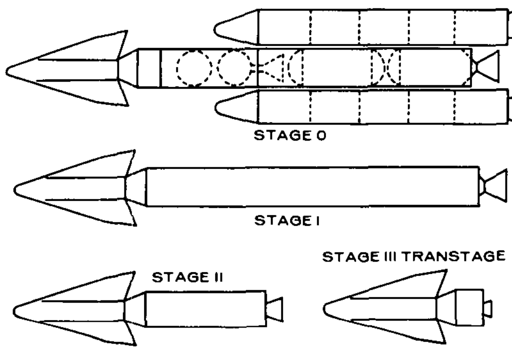


FIGURE 2

PIBOL SIMULATION DESCRIPTION

BOOSTER

- FLEXABILITY - 2 PITCH & 1 YAW MODES
- 6-DEGREE OF FREEDOM SIMULATION
- COMPLETE SIMULATION LIFT-OFF THRU BURNOUT

TRAJECTORY

- MAX q TRAJECTORY
- RANDOM WINDS
- ±10% STAGE 0 THRUST, ±3% STAGE 1, 2 & 3

FLIGHT CONTROL SYSTEMS

- PILOT & SEVERAL BOOSTER SYSTEMS

GUIDANCE SYSTEMS

- SEVERAL PILOTED SYSTEMS USING GLIDER & GROUND DATA

FIGURE 3

PIBOL BOOST CONSTRAINTS

AIR VEHICLE LIMITS
- AIR VEHICLE LOAD LIMITS
- TEMPERATURE LIMITS
- STAGING LIMITS PIBOL USED 3°/SEC RATE

ABORT LIMITS
- MDS RATE SENSOR THRESHOLDS - PIBOL USED 3°/SEC ST O
- GLIDER RECOVERY CEILING

BURNOUT PERFORMANCE LIMITS
- VELOCITY TOLERANCE 9 FPS FOR NOMINAL MISSION
- VELOCITY TOLERANCE 40 FPS FOR EDWARDS LANDING

FIGURE 4

BOOST PRIMARY CONTROL REGIONS

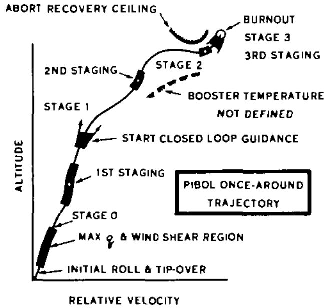


FIGURE 5

FIGURE 6

BURNOUT CAPABILITY

USING BURNOUT DISPLAY & MANUAL CUTOFF

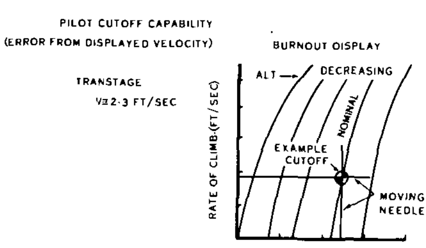


FIGURE 7

GUIDANCE SYSTEMS STUDIED

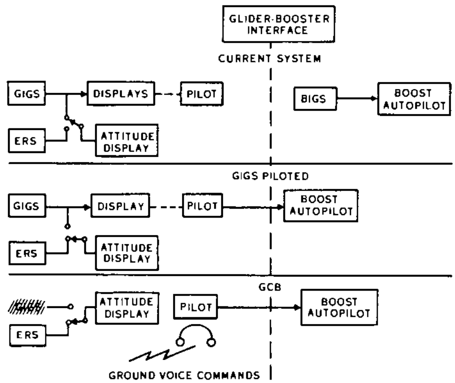
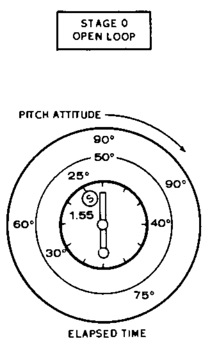


FIGURE 8

PILOT GUIDANCE PROGRAM



STAGE 1. 2. 3
CLOSED LOOP

TIME	RATE OF CLIMB FPS	ALTITUDE 1000 FT	PITCH ATT-DEG
I (S) 30 SEC INTERVALS	FOR CORRES-PONDING TIME INTERVAL	FOR CORRES-PONDING TIME INTERVAL	25 15 ↓ 30
II (S) 30 SEC INTERVALS			↓ 15 ↓ 10 @ 7:15
III (S) 30 SEC INTERVALS	↓	↓	TO $\dot{h}$ = DESIRED VALUE. THEN HOLD $\dot{h}$ CONST.

FIGURE 9

GROUND CONTROLLED BOOST (GCB)

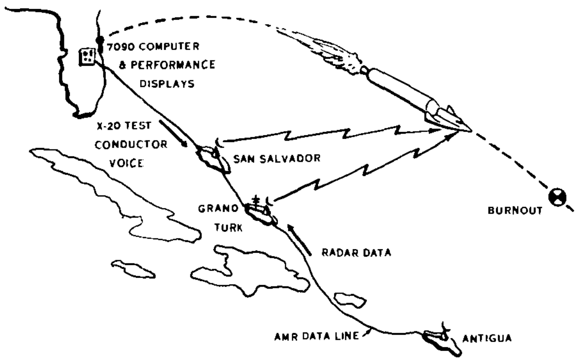


FIGURE 10

STAGE 0 GUIDANCE COMPARISON

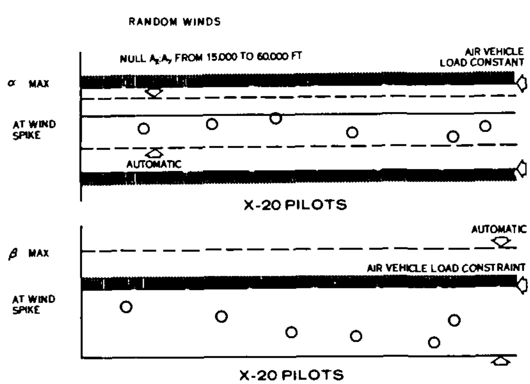


FIGURE 11

PIBOL PERFORMANCE SUMMARY

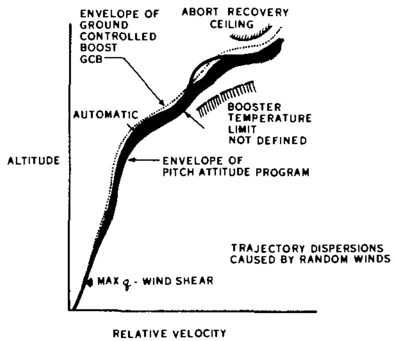


FIGURE 12

PIBOL GUIDANCE AND CONTROL INTEGRATION

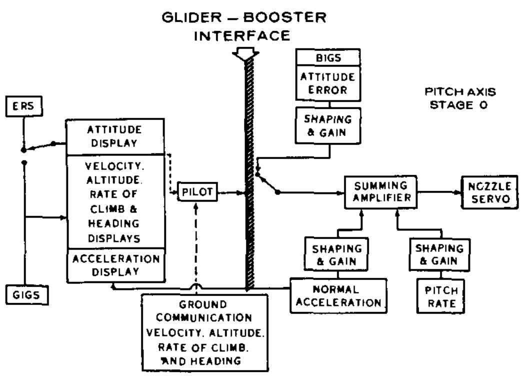


FIGURE 13