the thickness of the composite and hence reduce the shear stress at the bonded interface.

Applications

Several large aircraft and missile components have been fabricated at Convair Aerospace using metal-matrix composites as one of the key structural materials. These include a large payload adapter, an F-106 access door, and a portion of an F-111 fuselage bulkhead. The success of these programs depended to a large degree on the composite joints developed.

The payload adapter (Fig. 12) built in 1968 was the first major metal-matrix structure and is the largest such structure built to date: 4 ft in diameter and 7 ft high. The resistance welded, riveted construction of unidirectional stringers and crossply reinforced skins offered a 45% weight saving over the existing 2024 aluminum design. The stringers failed at approximately 200% of design limit load during testing.

The access door (Fig. 13) built in 1969 was the first B/Al structure to be flight tested. The door, $11\frac{3}{8}$ in. high and 11 in. wide, contoured to a 43 in. radius, is approximately 20% lighter than the original design in aluminum. A duplicate test of the adhesively bonded door panel (attached by Camloc fasteners) failed at 160% of the design limit load. The flight article is still in service and about to undergo a new series of flight tests.

The bulkhead (Fig. 14), measuring 48 in. high by 30 in. wide, consists of Borsic/6061-T6 Al with a titanium frame. The crossplied skin is stiffened with unidirectionally reinforced zees, angles, and straight and joggled tees. Joints were made by spot welding, adhesive bonding, and lockbolts. The bulkhead represented a 26% weight saving, and during structural testing failure occurred at 130% design limit load.

FEBRUARY 1973 J. AIRCRAFT VOL. 10, NO. 2

Pilot Control of Shuttle Orbiter during Approach and Landing

Henry A. Streb Jr.*
Lockheed Missiles & Space Company Inc., Sunnyvale, Calif.

Using a fixed base, six degree-of-freedom piloted simulation of a Shuttle Delta Body Orbiter, a simplified unpowered orbiter energy management technique has been developed and demonstrated from 100,000 ft altitude to touchdown. The results indicate that satisfactory unpowered orbiter landings from random initial conditions and with unknown winds can be accomplished by the pilot, utilizing conventional TACAN distance and heading information for energy management. The effective use of man's skill in this important area can reduce system complexity, enhance system reliability, and reduce over-all program costs.

I. Introduction

THE development of an economical, reusable Space Shuttle that can transport personnel and cargo to and from low Earth orbit is an essential first step in NASA's future space exploration program. A key element in achieving this objective is the development of both manual and automatic modes of recovery from orbit, including standard approach procedures for accomplishing unpowered landings on a routine basis.

As long as the requirement for piloted re-entry and landing exists, it is essential that the piloting techniques and procedures be developed prior to the development of the guidance software. By first developing a simple, reliable technique for a piloted, manual mode of re-entry and landing and then implementing this technique in the guidance equations for the automatic mode, several significant advantages are realized: 1) Complete compatibility between automatic and manual modes. This is required for ease of transition from one mode to the other and to ensure that an automatic mode failure would not present the crew with an insoluable piloting problem. 2) Definition of realistic automatic mode design requirements. 3) Definition of minimum cockpit display and navaid requirements for the manual mode of recovery. 4) Minimum cost to develop an effective (simple, reliable) re-entry GC&N system.

This paper presents the results of a piloted simulation study conducted by Lockheed for NASA/MSC during the first half of 1971.[4] For the purpose of the study a high crossrange delta lifting body configuration was programmed and flight controls loops were designed to yield acceptable handling qualities throughout the aerodynamic operating range.

The energy management technique uses lift to drag (L/D) ratio modulation for flight-path angle control and maximizes the conservation of potential energy until the runway is "made". At this time, the flight-path angle is increased so that final approach may be flown with sufficient kinetic energy to allow a precise flare and landing. Using this technique, touchdown dispersion of 1250 ± 550 ft of runway length and 180 ± 8 knots airspeed were realized.

II. Simulation Systems Description

A. Simulated Vehicle Characteristics

The Space Shuttle Orbiter used in this simulation is a lifting body concept with a delta planform shape (see Fig. 1). With the c.g. at 75% of vehicle reference length, longi-

Presented as Paper 72-227 at the AIAA Man's Role in Space Conference, Cocoa Beach, Fla., March 27–28, 1972; submitted March 31, 1972; revision received November 2, 1972.

Index categories: Entry Vehicles and Landers; Post-Entry Deceleration Systems and Flight Mechanics; Spacecraft Navigation, Guidance, and Flight-Path Control Systems.

*Manager, Space Shuttle Piloted Simulation Programs. Member AIAA.

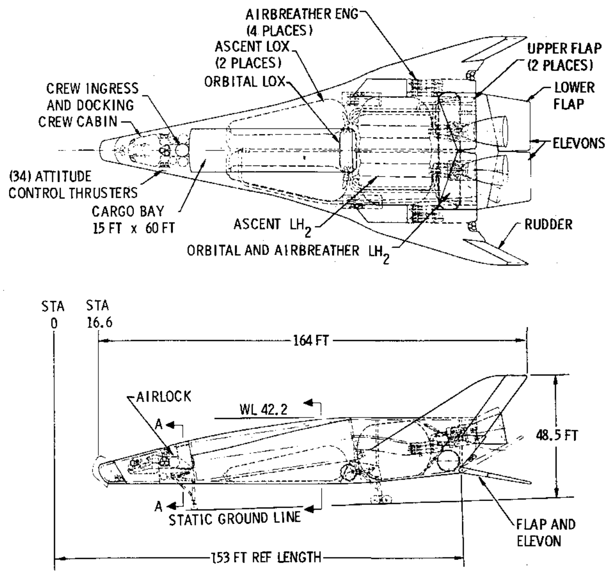


Fig. 1 Delta body orbiter.

tudinal static margin of 3% subsonically and 2% hypersonically is realized. Directional stability is acquired with two vertical fins (canted at 30° from vertical). Pertinent vehicle physical characteristics include: 1) Gross Landing Weight = 216,500 lb (payload in.), 2) c.g.—75% reference length, 3) Reference Length—153 ft, 4) Reference Area—5060 ft^2, and 5) Wing Loading, W/S—42.75 lb/ft^2.

The vehicle develops a maximum trimmed lift/drag ratio of 4.9 subsonically ($\alpha = 17°$) and 2.0 supersonically ($\alpha = 19°$).

B. General Arrangement and Capabilities

Figure 2 is a block diagram illustrating the schematic layout of the simulation system major components. The digital computer is programmed to solve the six degree-of-freedom vehicle equations of motions, all aerodynamic equations, navigational equations, visual system drive equations, and other auxiliary equations, all in realtime. The primary flight controls, secondary flight controls, stability augmentation system, and autopilot are mechanized on the analog computer. The analog computer also provides scale, bias, and buffer amplifiers for cab instruments, controls, and strip chart recorders. The hybrid interface unit provides analog-to-digital conversion, digital-to-analog conversion, discrete input/output and mode control, and also serves to interface the analog computer with the digital computer.

The visual system consists of a close circuit television camera which moves in six degrees-of-freedom relative to

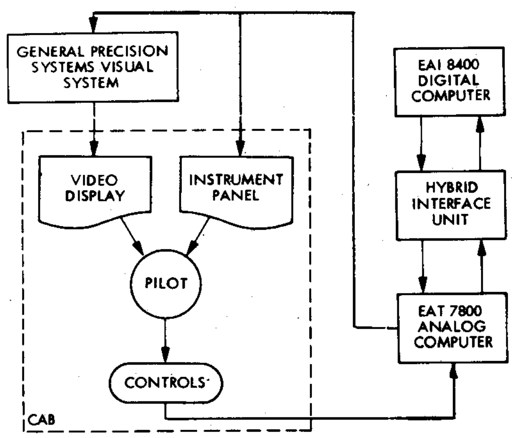


Fig. 2 Space shuttle simulation block diagram.

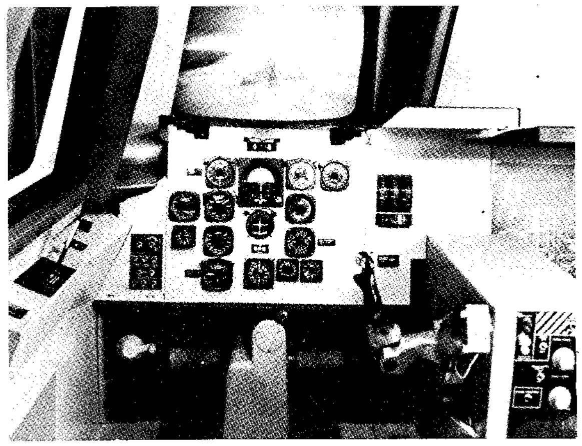


Fig. 3 Cockpit arrangement.

a three-dimensional terrain model. The camera moves in response to the computed position and attitude of the vehicle. The video output is displayed to the pilot on one of two TV monitors, depending on whether the pilot selects a forward window view or a side window view. The pilot then moves the controls in the cab as a function of the instrument and video display.

C. Cockpit Arrangement

Although the instrument panel (see Fig. 3) included Inertial Velocity and Altitude, Mach No., Radar Altitude, Rate of Descent, Normal Acceleration, Turn Rate, Roll Rate, Yaw Angle, and Dynamic Pressure (all of which were used during the simulation development), the basic flight instruments required to fly the entire energy management solution consist of only a) Three-axis Vehicle Attitude Indicator, b) Equivalent Airspeed, c) Angle-of-Attack, and d) Altimeter.

To perform the navigation task during the flight, only the following is needed: 1) Remote Magnetic Indicator (RMI) (gives magnetic heading and magnetic bearings to TACAN stations); 2) DME (gives horizontal range in miles and tenths to either of the TACAN stations selectively); 3) ILS Indicator—localizer and glideslope (for VFR approaches, this is not needed).

Primary Flight Controls consist of a two-axis side-arm controller for pitch and roll axis control and rudder pedals for yaw and axis control. Additional controls included a landing gear actuation switch, speed brake handle, and longitudinal trim selection and actuation switches.

D. Navigational Aids

Minimum navigational aids have been incorporated to allow the pilot to fix his position at any time and to define the final approach glideslope and groundtrack. Two TACAN stations with DME are available (one is actually sufficient) to aid the pilot in solving the energy management problem of entering the final approach window. These aids are located in line with the active runway for the problem solution.

An ILS indicator with localizer and glideslope crossbars indicates the horizontal and vertical angular displacement from the glideslope. The localizer transmitter is located at the far end of the landing runway and the glideslope transmitter is located approximately 3000 ft short of the runway threshold where the glideslope would intersect the ground surface without flare maneuver. In order to be able to try various gliding approach speeds and flare techniques, the threshold distance of the glideslope transmitter and the transmitted glideslope angle are easily adjusted.

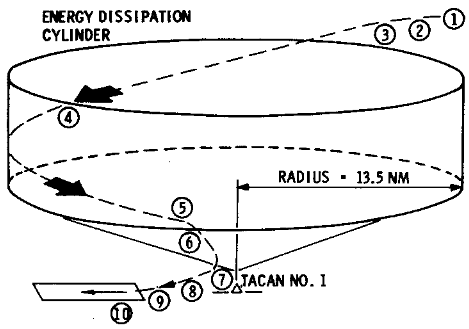


Fig. 4a Terminal area energy management.

POINT	DESCRIPTION	α (DEG)	KEAS	γ (DEG)	ALTITUDE
①	INITIAL POSITION	18	200	-9	100K
②	INITIAL COURSE ADJUSTMENT, $\phi = 45^\circ$, $V_{EAS} = 200$ KTS				
③ → ④	MAXIMUM L/D FLIGHT (FLY CONST PITCH ATTITUDE OF $\theta = 9^\circ$ UNTIL SUPERSONIC FUGOID DAMPENS)	17	170	-9	
④	INTERCEPT ENERGY DISSIPATION CYLINDER; PUSH OVER TO	13	200	-14	
⑤	45 DEG BANKED TURN-IN TO INITIAL APPROACH				38K
⑥ → ⑦	INITIAL APPROACH-FLY COURSE TANGENT TO LOW ALTITUDE TURN CIRCLE	13	200	-14	33 → 12K
⑦	30 DEG BANKED TURN TO FINAL; PUSH OVER TO		255*		
⑧	KEYPOINT ALTITUDE, MINIMUM FINAL APPROACH ENTRY				12K
⑧ → ⑨	FINAL APPROACH	9.5	255	-19.7	12K → 800 FT
⑨ → ⑩	FLARE/FLOAT (1.3g FLARE MANEUVER)		255 → 180		800 FT – S.L.
⑩	TOUCHDOWN, 1500 FT BEYOND RUNWAY THRESHOLD	14	180	-1	S.L.

* SPEED BRAKES 1/2 DEPLOYED AT 255 KEAS; THEN MODULATED AS REQUIRED TO MAINTAIN AIRSPEED.

III. Piloted Simulation Development

During the development phase of the piloted simulation, subtask effort was concentrated in two categories, flight controls and handling qualities development, and flight performance and energy management procedures development.

A. Flight Controls and Handling Qualities Development

Flight controls development was dictated by typical aircraft handling qualities criteria and pilot opinion. Starting with simple rate command loops with fixed gains on all three control axes, the flight control system evolved to incorporate modified rate command control loops on all three axes with moderate gain scheduling as functions of Mach number, angle-of-attack, and dynamic pressure.

By proper compensation in the lateral/directional axes for turn coordination, the system is designed to be flown essentially "feet-off" (with the exception of intentional sideslip). This is accomplished through the use of lateral acceleration feedback and roll-yaw crossfeed, which limit induced sideslip.

Supersonically the pitch channel is a pure rate command concept, while subsonically and transonically a washout filter has been added which modifies the rate command concept to essentially a rate damping one. The pilot thus has more positive control over normal acceleration, while still retaining the desirable damping features of the pure rate command system.

Handling qualities for the augmented vehicle exceed the requirements of MIL-F-8785B for Class III airplanes for Category B and C flight with the possible exception of maximum roll rate capability during low airspeed, high angle-of-attack landings.

B. Flight Performance and Energy Management Procedures

A building block approach was used to develop the flight procedures and key flight parameters of the energy management solution. After determining wings level and maneuvering flight performance as functions of Mach number, altitude, angle-of-attack, bank angle, and aerodynamic pressure, the "energy window" (range vs crossrange vs vehicle heading) for 100,000-ft altitude was determined and then check-flown. Also, special attention was

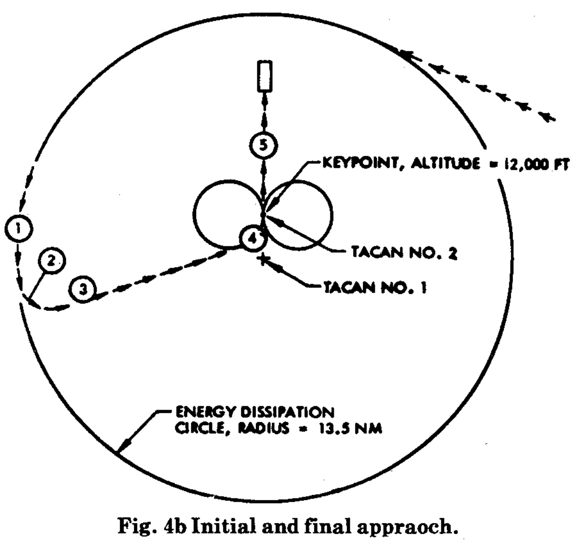
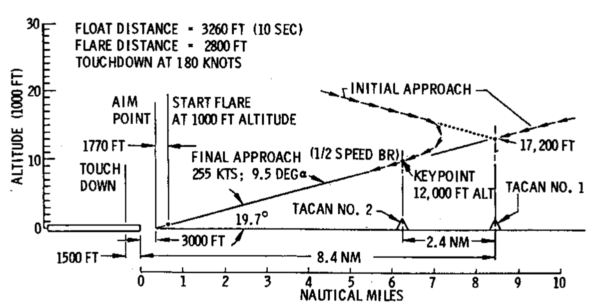


Fig. 4b Initial and final appraoch.



NOMINAL FINAL APPROACH AND LANDING

Fig. 4c Nominal final approach and landing.

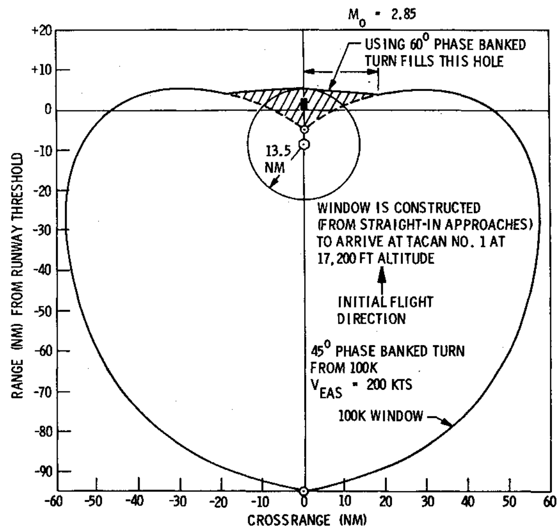


Fig. 5 100,000 ft energy window.

given to flight techniques for the final approach and flare maneuver. Examining off-nominal final approach conditions at 6 naut miles from the end of the runway (range of the final approach "KEY POINT"), it was found that the glideslope could be captured and a successful landing made with lateral offsets of ± 2 naut miles from the localizer, and vertical offsets from 7,000 ft altitude to 18,000-ft altitude.

Total energy management problems (i.e., from 100,000 ft to touchdown) were flown with the initial conditions both picked at random, within the "energy window," and picked to yield initial approaches to the final approach "key point" from a variety of directions.

The energy management technique and flight procedures are so simple and easy to fly that successful approaches were made on all total energy management flights, both with and without unknown winds. (The wind model used contained a 100-knot jetstream and a 180° reversal in wind direction while on final approach. The model was programmed so that the entire wind profile could be rotated in azimuth between flights to yield a variety of problems.) A wind gust model satisfying MIL 8785B was flown on final approach with little adverse effect.

C. Energy Management Procedures

The basic energy management concept presented here is a set of relatively simple navigational procedures for the pilot to fly while the craft is maintained on the front (or fast) side of the L/D vs α curve during unpowered gliding flight. This technique is an adaptation of the basic lifting body and F-111 IFR power-off approach technique developed at the NASA Flight Research Center and the Air Force Flight Test Center at Edwards AFB, Calif.[1]

Precision power-off approaches to landings may easily be made under both instrument flight and visual flight conditions. The technique is illustrated in Figs. 4a, b, and c.

The following piloting techniques are very fundamental and are quickly learned with little practice. Throughout the procedure, the objective is to maximize the conservation of potential energy until the final approach is "made" and then to fly final with sufficient kinetic energy to allow a precise flare and landing.

a. Maximum L/D glide flight to the energy dissipation cylinder

At the start of the problem, note the relative bearing and range to the TACAN No. 1 using the RMI and DME indicators. Deciding to proceed to the energy dissipation cylinder (vs a straight-in-approach), turn to the nearer tangent course to the energy dissipation cylinder. (The nearer tangent is the one requiring the least degrees of heading change; i.e., if the station bearing is to the left of the nose, the nearer tangent is the right (vs left) one, which would result in circling the station in a left decending turn.) Maintaining low $\bar{q}$, $V_{EAS} \approx 200$ knots, in all turns, track the tangent course and fly at $L/D_{\max}$ until arrival at the point of tangency. (Cues for identifying tangent course: the 13.5-naut miles radius subtends a 20° angle between the station bearing and the tangent course line at 40-naut mile range, and a 30° angle at 27-naut miles range.)

b. Energy dissipation flight

Upon capturing the cylindrical surface, accelerate to and maintain 200 knots, allowing altitude to bleed off while staying in the surface of the cylinder (requires about a 15° bank angle at higher altitudes and approximately an 8° bank angle at lower altitudes).

c. Initial approach

At 38,000-ft altitude, initiate turn towards TACAN No. 1 (simply put RMI bearing needle on nose). If not at 13.5 naut miles from TACAN as turn is anticipated, allow 2000-ft altitude for 1.5-naut miles deviation; i.e., if at 15 naut miles, turn early at 40,000 ft; and, if at 12 naut miles, delay turn to 36,000 ft. At 11-naut mile range, inbound to TACAN No. 1, altitude should be 31,000 ft. Observe initial approach course (bearing to TACAN No. 1). If course is between 260° and 110° (through North), continue heading toward TACAN No. 1, anticipating final approach turn to capture localizer at approximately 3 naut miles from TACAN No. 1. If initial approach is from the remaining sector of the compass rose (from behind the landing field), the course tangent to the final approach turn circle is offset from the TACAN No. 1 bearing. This offset is a maximum of 25° (approaching from due North of the field), decreasing to zero on courses of 110° or 260°.

d. Final approach

Completing the final approach turn, capture the localizer and glideslope at 12,000-ft altitude (over TACAN No. 2). Maintain glideslope allowing airspeed buildup at 255 knots. Deploy ½ speed brakes and modulate to maintain 255 knots while flying final. Switch trim to manual.

e. Flare and landing

Initiate 1.3–1.5g flare at approximately 1000-ft altitude. To stop rotation and ballooning tendency after flare, forward stick is needed. Complete flare close to the ground over runway threshold and land approximately 1500 ft down the runway at 180 knots.

Notes:

1) During the entire procedure (a through e), only three airspeeds and two principal bank angles are used. Until dissipation cylinder is captured, fly $L/D_{\max}$, $V_{EAS} = 170$ knots. Then fly 200 knots all the way to final approach, and then 255 knots. For final approach turn, use a 30° bank angle turn; and, for all other sizable heading changes, use 45° bank angle turns, with the following minor exception: the forward indentation in the 100,000-ft altitude energy window (see Fig. 5) is filled if a low $\bar{q}$ 60° bank angle turn is used instead of a 45° bank angle. This is due to the short downrange distance required to complete a 180° turn for the 60° bank angle turn, as compared

to the 45° bank angle, even though the altitude loss in the turn is greater.

2) Speed brakes are nominally used on final approach, only, to control airspeed while maintaining a constant glideslope. The only other place where speed brakes may possibly be required would be on initial approach with a significant tailwind. In this case, they would be used to dissipate excess altitude while maintaining a constant airspeed, $V_{EAS} = 200$ knots.

3) These procedures (*a* through *e*) apply generally, to all cases within the energy window at 100,000-ft (Fig. 5), which are far enough inside the window-limiting boundary not to require proceeding directly to the station. Even in "close-in" cases, where overshooting the energy dissipation cylinder is unavoidable because of the poor turning performance at altitude, the procedures apply. *Never* apply speed brakes prior to initial approach. Since all maneuvering to capture the energy dissipation cylinder is done at low $\bar{q}$, $V_{EAS} \approx 200$ knots, the use of speed brakes at this time would merely dissipate potential energy (altitude) without improving turn performance.

Anticipating a requirement for cockpit aids for the pilot, Figs. 6 and 7 were generated to aid his visualization of his status at all times. Figure 6 is a plot of minimum altitude vs distance to TACAN No. 1. If the craft is pointed toward the station and inside of a range of 70 naut miles at 100,000-ft altitude, the circling energy dissipation approach should be used. Outside of that range, fly directly toward the station so as to arrive there at approximately 17,200 ft. This should place the craft on initial approach as it crosses the 13.5-naut miles radius conical surface. In fact, any time the craft is more than 17 naut miles inside of the maximum range line, pointed towards the station, at any altitude down to 38,000-ft proceed on a heading tangent to the cylinder. Figure 7 is merely an enlargement of Fig. 4 with range circles drawn for every mile radius from TACAN No. 1 and inbound course radii for every 10°.

After flying several complete energy management problems, the pilot finds that these two aids are unnecessary and that he can visualize his status entirely from instrument panel interpretation and memory. With very little practice, it is possible to consistently arrive at the final approach key point with less than ½-naut miles lateral offset and within 1000 ft of the nominal 12,000-ft altitude.

IV. Pilots' Evaluation Phase

Four different NASA evaluation pilots flew the simulation for an average of 6½ hr each. These flights included actual wind profiles, including a gust model which satisfied MIL Spec. 8785B, and crosswinds on landing of 30 knots. The morning periods were primarily involved in familiarization with the simulator and the vehicle handling qualities. The afternoon sessions were used with energy management flights with a multitude of different navigational problems.

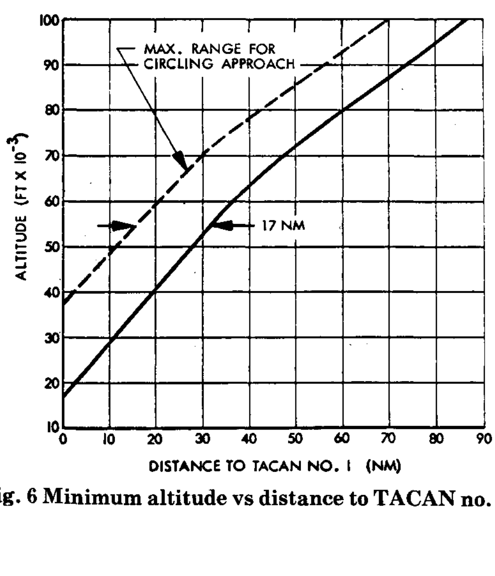


Fig. 6 Minimum altitude vs distance to TACAN no. 1.

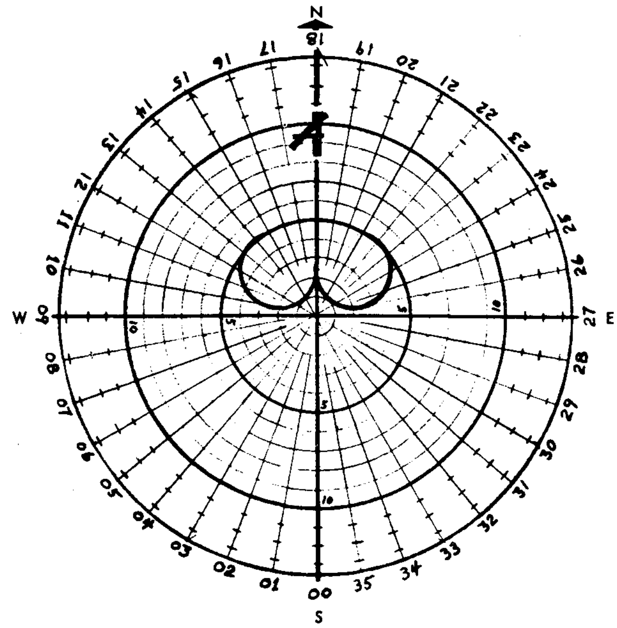


Fig. 7 Space shuttle energy management NAVAID.

Considering the fact that the pilots had no previous experience with this simulator, the vehicle being simulated, nor the energy management techniques involved, the results were very successful. Averaging eight to nine complete energy management flights each, from 100,000-ft altitude to touchdown, none of the four pilots, in any case, failed to make the runway threshold with proper airspeed for landing. Even though an occasional navigational error was made, ample time and energy capability existed to correct the error and complete the approach and landing successfully. For this reason, the pilots felt that the energy management technique employed was easy to fly and was extremely forgiving. The pilots generally agreed that "the most important thing to be learned from this simulation is that with conventional navigation aids a shuttle-like vehicle can be flown to a safe approach for landing using a simple energy management technique."

The flight evaluation program flown by the NASA pilots may best be described by summarizing the results of the energy management flights. These flights were flown from a number of positions on various headings. Figures 8a–e present *x-y* traces of trajectories flown by the four NASA evaluation pilots from 100,000 ft to touchdown. These results demonstrate the ability to perform successful flights from diverse positions within the 100,000-ft energy window using the recommended energy management technique. With the traces of all four pilot's flights for each of the cases superimposed, the energy regulating feature of the technique is demonstrated. Note that, if a pilot was particularly proficient in conserving energy during the $L/D_{\max}$ portion of the flight (Figs. 8a and b), by acquiring the tangent to the cylinder earlier (or cutting slightly inside of it), he is left with more energy to dissipate in the cylinder and, thus, traverses a longer arc around the cylindrical surface before reaching the initial approach turn-in altitude. Conversely, if he is late acquiring the cylinder, more energy is spent, and he reaches the turn-in altitude sooner.

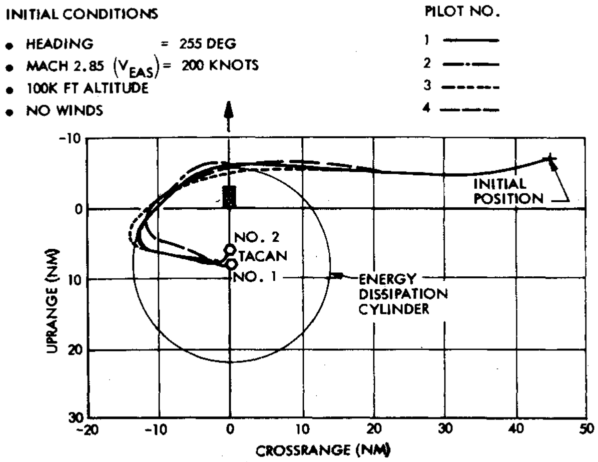


Fig. 8a Energy management/navigation, case 1.

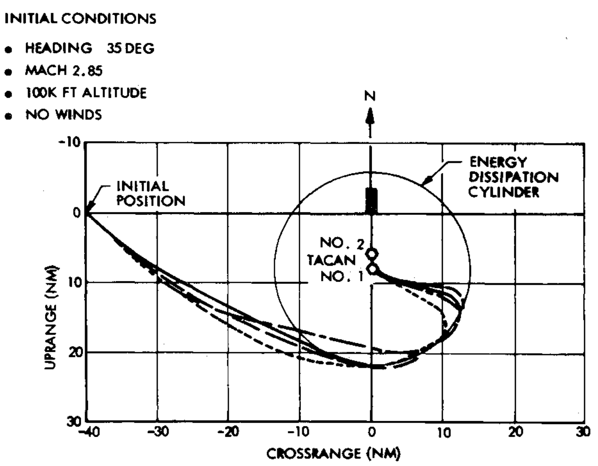


Fig. 8b Energy management/navigation, case 2.

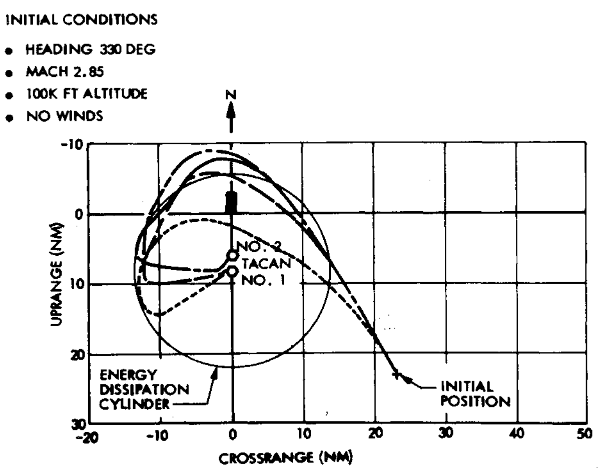


Fig. 8c Energy management/navigation, case 3.

Figure 8c presents traces of flights from an initial position close in to the dissipation cylinder. This case shows the greatest divergence in the ground traces for the different pilots and, again, demonstrates the self-compensating nature of the technique. The initial overshoot of the cylinder by pilots 1, 2, and 4 is due to the reduced turn performance at higher altitude after the cylinder tangent point was acquired. Pilot 3 was advised of this and elected to start his turn early. As a result, he flew through the cylinder and acquired the cylinder from the inside. As it

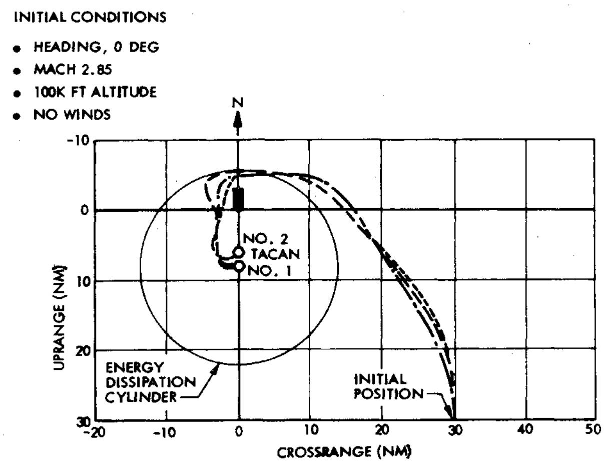


Fig. 8d Energy management/navigation, case 4.

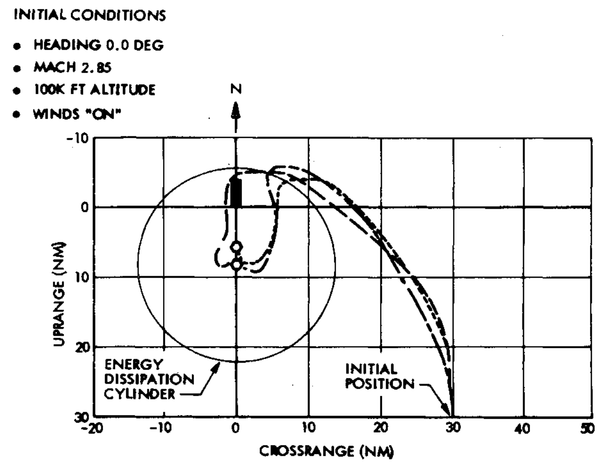


Fig. 8e Energy management/navigation, case 5.

worked out, this put him further around the cylinder by initial approach turn-in altitude, resulting in an initial approach which gave him an easier turn to final approach.

The most difficult of the trajectories flown was the "back door" approach, in which the initial approach turn-in altitude was acquired behind the runway (Fig. 8d). Approaching the final turn from this direction obviously requires more pilot judgment in the execution of the final approach turn. However, the technique is well within the capability of the evaluation pilots, even on their first attempt.

The NAVAID, (Fig. 7), is of help on early flights; and, after a minimum of practice, the pilot remembers enough of the significant reference information to be able to interpret the entire problem and solution from the instrument panel alone.

Although the procedure may be accomplished successfully using bearings and range information from TACAN No. 1 alone, information from TACAN No. 2 proves useful when approaching the final turn from the North. Since the final approach turn radius averages approximately 2 naut. miles, TACAN No. 2 should be approximately 4 naut miles on the wingtip at the initiation of the turn.

Since the backdoor approach is considered the most difficult to fly, it was chosen as the case to fly with winds turned on. At altitude, the winds are predominately out of the west with a jetstream of 100 knots between 40–50k ft altitude. The results are quite interesting. Since pilot No. 4 did a better job of holding the tangent to the cylinder in the face of a strong left crosswind, he made it farther around the dissipation cylinder, resulting in an initial approach to a left bank final turn. Pilots 2 and 3 reached their turn-in altitude sooner and flew initial approaches leading to right banked final approach turns, again demonstrating the flexibility and self-compensating nature of the energy management technique. (Pilot 1 successfully flew a different wind problem case, which is not presented.)

Runway Touchdown Dispersion

Because of scaling in the visual simulation, apparent lateral perturbations of the TV camera were magnified to the pilot. During flare and float, these lateral step inputs elicited lateral maneuver corrections by the evaluation pilots. Holding the craft off until realigned with the runway centerline, plus the difficulty of estimating the imminence of touchdown, quite frequently caused the touchdown point to be beyond the nominal aim touchdown point, i.e., 2000 ft down the runway. It was noticed that, when this occurred, the touchdown speed would be on the slow side of the nominal 180 knots.

Examining the data further, it was found that all flights cross the runway threshold at essentially the same energy level. Reducing the data to the nominal touchdown speed of 180 knots, it was found that all touchdown points would occur in the range of 1250 ± 550 ft. Also, if the pilot uses the technique of landing at a 1250-ft aim point (from the threshold), he can expect an airspeed dispersion of 180 ± 8 knots.

Both of the landing techniques, 1) landing at a given point and accepting an airspeed dispersion, or 2) landing at a nominal airspeed and accepting a touchdown point dispersion, are acceptable proven techniques. Of the two techniques, the former is probably the easier; and, the latter technique has been proven with tandem landing gear aircraft, such as the B-47 where touchdown attitude was so critical that touchdown airspeed had to be controlled to within a few knots.

V. Conclusions and Recommendations

Based on the results of this simulation program, definite conclusions are reached: 1) Satisfactory unpowered orbiter landing from random initial conditions and with unknown winds can be accomplished by the pilot utilizing conventional navigational aids for energy management; 2) The energy management technique utilized can be easily learned and used by the pilot; 3) Delta body orbiter handling qualities as presented to the pilot were satisfactory (Cooper-Harper Rating ≥ 3).

Of equal and far reaching significance are the added conclusions which are inferred by the results of this simulation program and from actual piloted experience gained on the X-15 aircraft and lifting body flight programs flown by a multitude of pilots.

The ability of man to utilize his multiple and integrated skills has been well documented.[2,3] "By utilizing man's capabilities, the X-15 systems were made much simpler than automatic operations would have been, notably for launching, maneuvering, and landing. Also the X-15 program achieved a significant first in analyzing to what degree the pilot contributed to mission success. Significantly, the X-15 record of mission success on 92% of its flights has been achieved with individual system and subsystem reliabilities as low as 80%. While the use of component redundance overcame some of the shortcomings in critical systems, a more important contribution to safety and success has been the capability of the pilot to bypass failed systems or change to alternate modes of operation."

As a case in point, on the 184th flight of the X-15, the engine and APUs were lost during exit flight (resulting in a complete loss of guidance and all computed flight data). For re-entry, the pilot, Maj. William Knight, managed to restart one APU to power the flight control system; and, with just out-the-window visibility and basic air data, he was able to convert catastrophe and performed a successful re-entry and landing at Mud Lake.

In conculusion, I would like to leave you with one thought. Good system design of a manned system requires—no, demands!—that the system be so designed that the man be given access to his own capabilities at the lowest level within the system at which his capabilities are usable.

References

[1]"Therminal Area Energy Management, Approach and Landing Investigation for Maneuvering Reentry Vehicles Using F-111A and NB-52B Aircraft," FTC-TC-70-2, June 1970, Flight Test Center, Edwards Air Force Base, Calif.

[2]Nagel, R. G. and Smith, R. E., "X-15 Pilot-in-The-Loop and Redundant/Emergency Systems Evaluation," ASTIA AD 285943, TDR 62-60, Oct. 1962, Air Force Flight Test Center, Edwards Air Force Base, Calif.

[3]Stillwell, W. H., "X-15 Research Results with a Selected Bibliography," NASA SP-60, 1965.

[4]"Space Shuttle Flight Simulation Study Final Report," NASA MSC-03754, May 7, 1971, Contract NAS9-11459, Lockheed Missiles and Space Co., Sunnyvale, Calif.