

In the kingdom of Bhutan, high in the Himalayan Mountains, is Paro International Airport. One of the world's most challenging airports, Paro is 7,300 ft (2.23 km) above sea level and surrounded by deep valleys and 18,000-ft (5.48-km) peaks. Here a Boeing 737-700 recently completed successful technical demonstration test flights that proved its performance capabilities and verified procedures for safe takeoff and landing operations in high-elevation, high-terrain environments.

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737-700

TECHNICAL DEMONSTRATION FLIGHTS IN

BHUTAN

Paro International Airport, in the kingdom of Bhutan, is high in the Himalayan Mountains. At 7,300 ft (2.23 km) above sea level, with a runway 6,500 ft (1.99 km) long, surrounded by deep valleys and 18,000-ft (5.48-km) peaks, Paro is one of the world's most difficult airports for takeoffs and landings.

In February 2003, a Boeing 737-700 successfully completed 11 test flights at Paro International Airport. The series included two technical demonstration flights and eight customer relations flights with Druk Air Royal Bhutan Airlines, the national airline of Bhutan. Druk Air, which operates two 72-passenger BAe 146-100 jets from Paro to six cities in five countries, is considering upgrading its fleet and extending its routes. The rigorous test flights proved that the 737-700 is capable of meeting all performance and procedural requirements for safe operations at Paro and other airports in high-elevation, high-terrain environments.

The 737-700 performed flight maneuvers as predicted and met or exceeded performance expectations for simulated one-engine-inoperative maneuvers, which were accomplished by reducing thrust on one engine to idle power. The expected performance levels proved conservative when compared with the demonstrated performance of the 737-700.

Test flight data were verified by flight data recorder (FDR) information, indicating that predicted airplane performance is representative of actual airplane performance as recorded by the FDR.

The test flights verified procedures for takeoff and landing operations at Paro. The 737-700 demonstrated

engine-out takeoff procedures, which is required for Paro operations, engine-out missed approach and go-around procedures, and Druk Air procedures for landing on both directions of the runway at Paro.

This article discusses

1. Technical demonstration test flight airplane.
2. Technical demonstration test flights description.
3. Technical demonstration test flight analysis.

1 TECHNICAL DEMONSTRATION TEST FLIGHT AIRPLANE

The demonstration airplane was a 737-700 Boeing Business Jet (BBJ) configured with blended winglets and a business jet interior (fig. 1 and table 1). The 737-700 BBJ used for the demonstration flights is aerodynamically equivalent to the commercial variant of the 737-700 being offered to Druk Air.

2 TECHNICAL DEMONSTRATION TEST FLIGHTS DESCRIPTION

On February 6, 2003, two technical demonstration test flights were accomplished from runways 33 and 15



The kingdom of Bhutan is located near Nepal, between China in the north and India in the east, south, and west. The kingdom, which is roughly the size of Switzerland, has a population of 750,000 people. The Bhutanese value their rich natural environment and ecosystem, which includes 770 species of birds and 5,500 species of plants.

FIGURE



at Paro International Airport. Boeing pilots Captain Buzz Nelson and Captain Van Chaney flew the 737-700 accompanied by the Druk Air chief pilot on the first flight and a senior first officer on the second flight.

To prove the capability of the 737-700 at Paro, the technical demonstration flights had to show that the airplane could take off following a simulated single engine failure at the most critical point during the takeoff ground roll (V_1) and safely return to the airport on one engine.

Terrain in the valleys surrounding Paro limits takeoff performance. Flight operations into and out of Paro only occur when the visibility in the valley is clear. This visibility is required to allow an airplane to turn around safely within the steep valley walls and reach the minimum safe altitude to depart the valley or return to the airport in the event of an engine failure.

The technical demonstration flight profile consisted of a takeoff with a simulated single engine failure at V_1 , a turnback within the river valley, a missed approach, a go-around,

1

DEMONSTRATION AIRPLANE SPECIFICATIONS

TABLE

Airplane model	Boeing 737-700 BBJ
Registration number	N184QS
Manufacturer's serial number	30884
Maximum taxi weight	171,500 lb (77,791 kg)
Maximum takeoff weight	171,000 lb (77,564 kg)
Maximum landing weight	134,000 lb (60,781 kg)
Maximum zero fuel weight	126,000 lb (57,153 kg)
Fuel capacity	9,700 U.S. gal (36,718 L)
Engines	CFM56-7B

a turnback at the opposite end of the valley, and landing, with one engine remaining at idle (representing the engine failure) throughout the demonstration. One technical flight demonstration was accomplished in each direction from the runway at Paro.

Runway 33 Technical Demonstration Test Flight

The first technical demonstration test flight was performed from runway 33 (fig. 2). After takeoff, a right bank was initiated for a heading change of

approximately 30 deg to avoid terrain that extends from the west valley wall. This maneuver was followed by a left bank to position the airplane along the east wall of the west fork of the river. The climb continued close to the east wall until the turnback initiation point. A teardrop turnback was initiated just after passing abeam the Chhukha village. Here the terrain falls away off the right wing where a stream empties into the river. The turnback was flown with a 30-deg bank while maintaining speed throughout the turn.

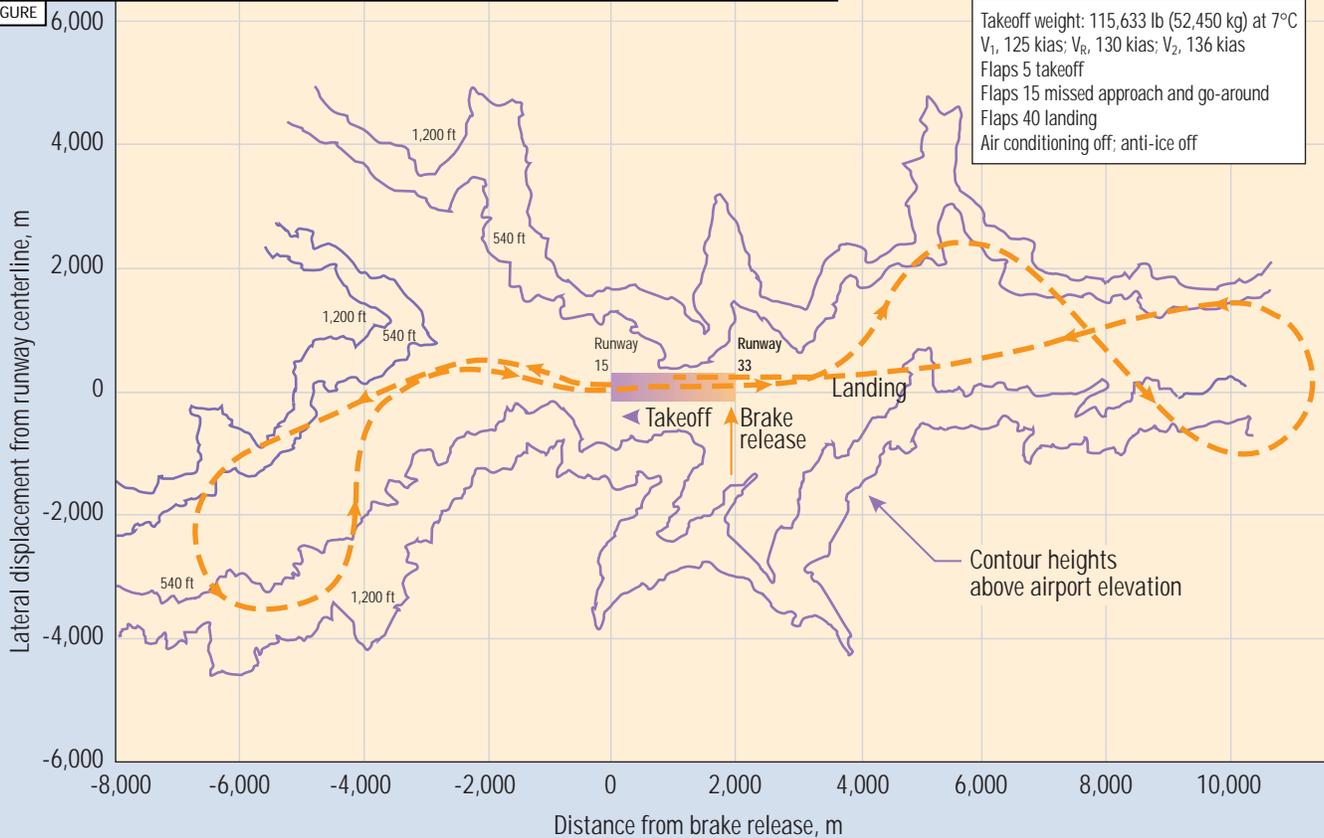
After completing the teardrop maneuver, the pilots performed a flaps 15 (engine-out landing flap) missed approach to runway 15. This was followed by a go-around and a teardrop turnback south of the runway using the Druk Air runway 15 turnback procedure. The condition was completed successfully with a normal flaps 40 landing using the Druk Air straight-in landing procedure.

The takeoff weight for runway 33 is limited by the turning radius required

2

PARO RUNWAY 33 TECHNICAL DEMONSTRATION TEST FLIGHT OVERVIEW

FIGURE



2

DEMONSTRATION AIRCRAFT TAKEOFF GROSS WEIGHT

TABLE		
Runway 33	Zero fuel weight*	100,433 lb (45,556 kg)
	Fuel	15,200 lb (6,895 kg)
	Takeoff weight	115,633 lb (52,450 kg)
Runway 15	Zero fuel weight*	100,433 lb (45,556 kg)
	Fuel	13,900 lb (6,305 kg)
	Takeoff weight	114,333 lb (51,861 kg)

* Includes the weight of three crewmembers, ten passengers, amenities, and potable water.

assuming that the airplane was positioned within 492 ft (150 m) of the valley wall.

The takeoff gross weight for the technical demonstration was calculated based on the airplane empty weight and the weight of the crew, passengers, and fuel on board (table 2). Table 3 lists the airport conditions and airplane configuration and takeoff speeds.

Engine failure was simulated by throttling back the left engine to idle at 125 kias, the V_1 speed for takeoff.

Runway 15 Technical Demonstration Test Flight

The second technical demonstration test flight was performed from runway 15 (fig. 3).

After liftoff, a right bank was performed for a 10-deg heading change, followed by a left bank for a 60-deg

to perform a 30-deg bank turnback. The available turning radius is based on the valley width at the net height achievable while maintaining not less than 492 ft (150 m) of lateral separation to the terrain and all obstacles on either side of the intended track. The limit weight calculations were based on the valley width at the net height for turnback initiation,

3

PARO RUNWAY 33 TEST FLIGHT PARAMETERS

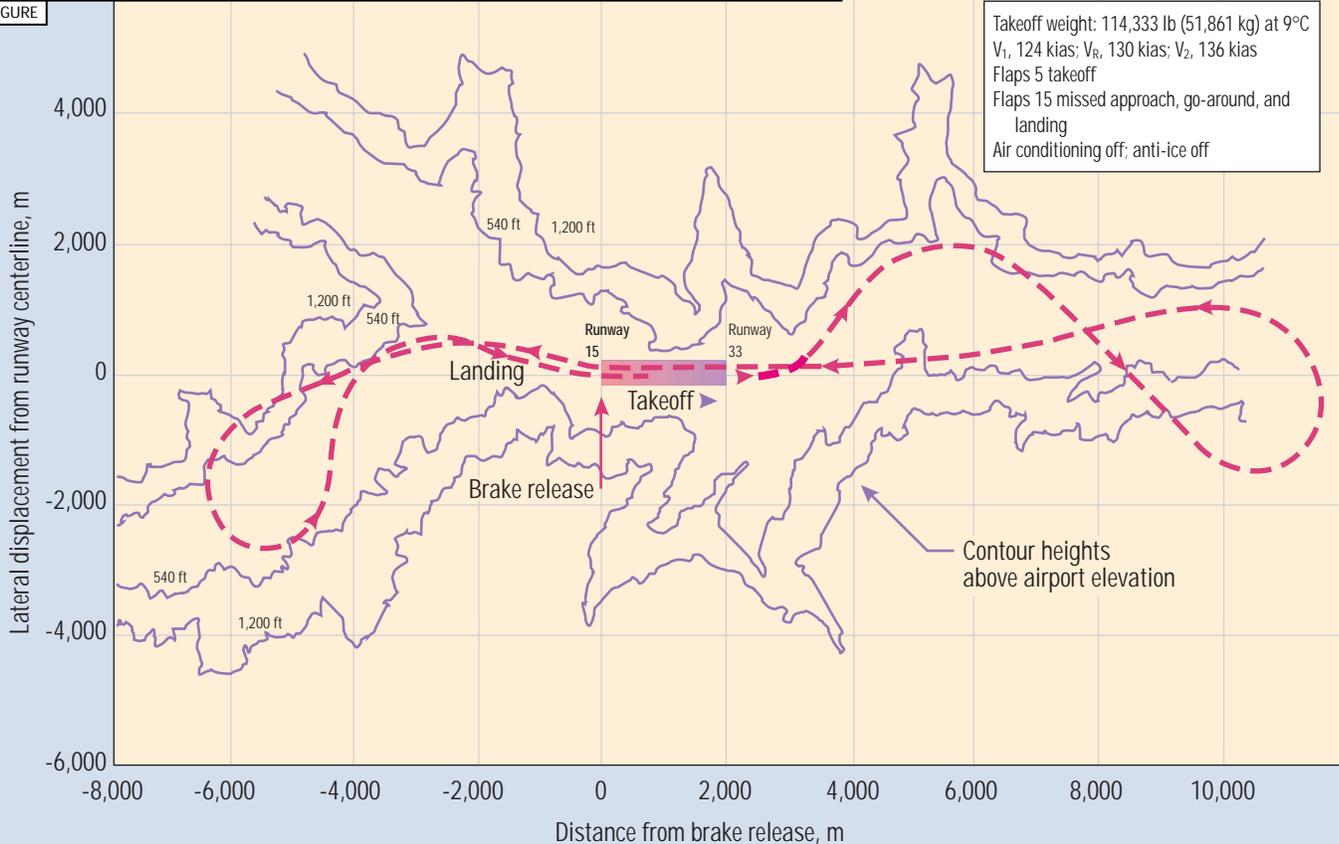
TABLE

Airport conditions	Airplane configuration
Takeoff time: 03:58 Zulu	Takeoff gross weight: 115,633 lb (52,450 kg)
Landing time: 04:10 Zulu	Takeoff thrust rating: CFM56-7B26
Tower-measured temperature: 7°C	Center of gravity: 18.1%MAC
Tower QNH: 1,021 mbar = 7,140 ft pressure altitude	Stab trim: 5.25 units
Tower wind: 190 deg at 6 kn	Flaps 5 takeoff
	Flaps 15 missed approach and go-around
	Flaps 40 landing
	Air conditioning off; anti-ice off
	Left engine pulled to idle at V_1
Airplane takeoff speeds	
V_1 , 125 kias; V_R , 130 kias; V_2 , 136 kias	

3

PARO RUNWAY 15 TECHNICAL DEMONSTRATION TEST FLIGHT OVERVIEW

FIGURE



heading change. The left bank took the airplane across the valley toward the east wall and avoided a hill that extends from the west wall of the valley.

A right bank was then held for an approximate 95-deg heading change, which directed the airplane from the east side of the valley back toward the west side and the Silung Nang village. The airplane flew over Silung Nang and the ridge behind it, which required an altitude of 9,100 ft (2.77 km). After the airplane cleared the ridge, a turnback was initiated with a 30-deg bank while maintaining the designated V_2 speed.

After completing the turnback maneuver, the pilots performed a flaps 15 (engine-out landing flap) missed approach to runway 33, followed by a go-around and a teardrop turnback north of the runway using the runway 33 turnback procedure. The condition was completed

successfully with a normal flaps 15 landing using the Druk Air straight-in landing procedure on runway 15.

The turnback procedure limit for runway 15 originally was determined to be the turning radius required to perform the 30-deg bank turnback. This limit was based on the valley width at the net height achieved while maintaining a minimum 492-ft (150-m) splay outside the intended track.

However, before the technical demonstration flights, Boeing and Druk Air pilots flew practice flights. After these flights, the pilots determined that the critical requirement was clearing the ridge beyond the village of Silung Nang, which requires a net height of 9,100 ft (2.77 km) at the turn initiation point. The limit weight calculations were based on the requirement to achieve this height on the net flight path. The turn radius

4

PARO RUNWAY 15 TEST FLIGHT PARAMETERS

TABLE

Airport conditions
Takeoff time: 04:22 Zulu
Landing time: 04:30 Zulu
Tower-measured temperature: 9°C
Tower QNH: 1,020 mbar = 7,140 ft pressure altitude
Tower wind: 140 deg at 6 kn
Airplane takeoff speeds
V_1 , 124 kias; V_R , 130 kias; V_2 , 136 kias

Airplane configuration

Takeoff gross weight: 114,333 lb (51,861 kg)
Takeoff thrust rating: CFM56-7B26
Center of gravity: 18.1%MAC
Stab trim: 5.25 units
Flaps 5 takeoff
Flaps 15 missed approach, go-around, and landing
Air conditioning off; anti-ice off
Right engine pulled to idle at V_1

was not limiting at this condition, assuming a 30-deg bank.

Table 2 shows the airplane takeoff gross weight for the runway 15 technical demonstration flight. Table 4 lists the airport conditions and airplane configuration and takeoff speeds.

Engine failure was simulated by throttling back the right engine to idle at 124 kias, the V_1 speed for takeoff.

3 TECHNICAL DEMONSTRATION TEST FLIGHT ANALYSIS

FDR Analysis

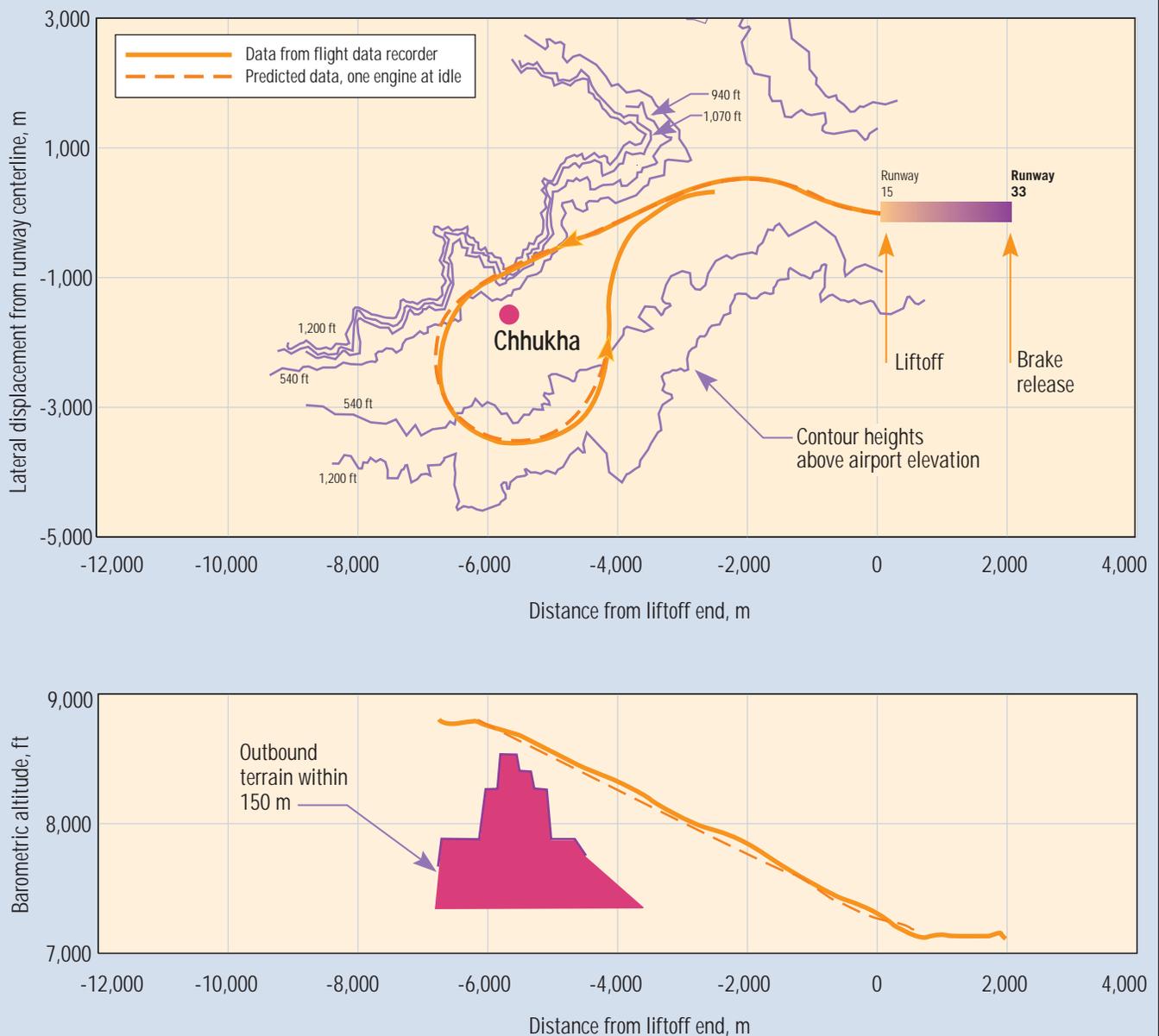
FDR information was downloaded from the airplane after the technical demonstration test flights. The FDR flight paths were compared with profiles of predicted performance to

verify the capability to match actual flight profiles.

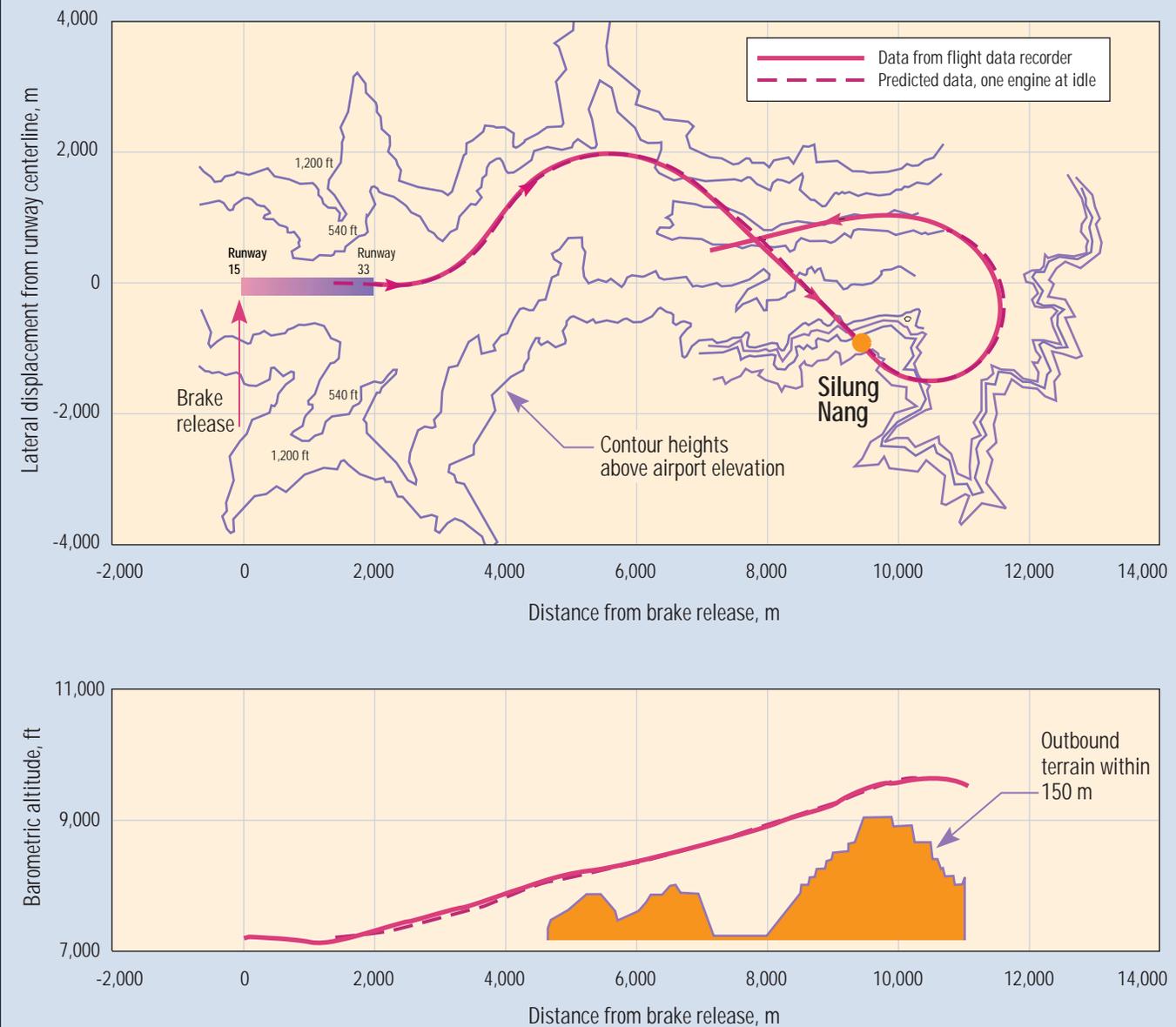
Figures 4 and 5 show the ground tracks and altitude profiles for the demonstration test flights from runways 33 and 15, respectively. The calculated flight paths with one engine pulled back to idle thrust closely match the demonstrated flight paths.

4 PARO RUNWAY 33 TEST FLIGHT GROUND TRACK AND ALTITUDE PROFILE

FIGURE



FIGURE



The calculated altitudes at the turnback initiation points for both flights were within 50 ft (15 m) on the conservative side of the predicted altitudes.

Turn Procedure Optimization

For the technical demonstration test flight from runway 15, takeoff weight was limited by the Druk Air procedural requirement to fly over a ridge after flying south over Silung Nang. To clear the ridge, a net altitude of 9,100 ft (2.77 km) is necessary at

the turn initiation point.

Flying parallel to the valley wall near Silung Nang instead of crossing the ridge removes the requirement to reach 9,100 ft (2.77 km) and allows a greater takeoff weight. The performance then becomes limited by the width of the valley. Through careful selection of the turn initiation point, additional takeoff weight is possible.

The available turn radius as a function of altitude was determined by computing the maximum turn

radius available in the valley at each altitude line on a digitized topography map. Maximum takeoff weight was calculated by plotting the available turn radius and the turn radius required as a function of gross takeoff weight.

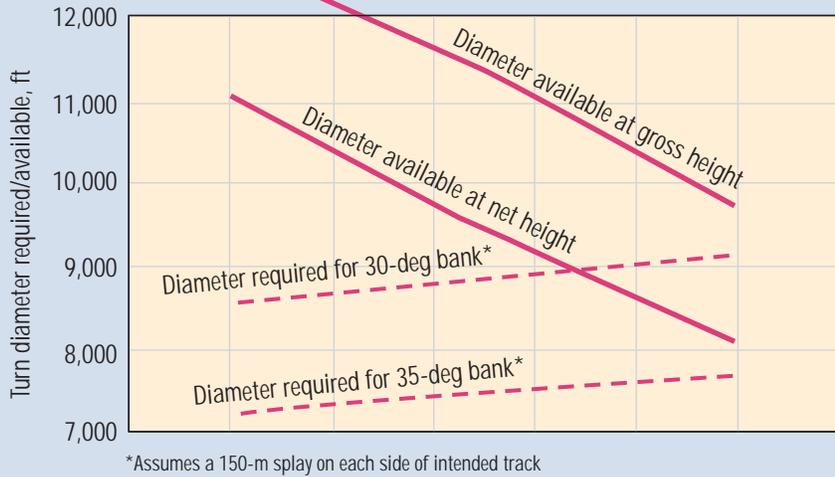
Figure 6 is an example takeoff weight calculation. The bottom plot shows the airplane altitude at the turn initiation point. The middle plot shows the corresponding airspeeds. The top plot shows the turn diameter required for a 30-deg bank, which

6

PARO TAKEOFF WEIGHT CALCULATION

FIGURE

Flaps 5 takeoff
Air conditioning off; anti-ice off
Forward center of gravity
No wind
Engine failure at V_1



is solely a function of true airspeed and bank angle, and the turn diameter available at the corresponding net height.

Boeing continues to investigate product and operational improvements

as part of its commitment to ensure that current and potential customers can maximize payload capability during safe takeoff and landing operations in high-elevation, high-terrain environments.

SUMMARY

The success of rigorous technical demonstration test flights at Paro International Airport in Bhutan validated the capability of the Boeing 737-700 to perform as predicted in a high-elevation, high-terrain environment.

The test flight data demonstrate that the 737-700

- Met or exceeded performance expectations for simulated one-engine-inoperative flight maneuvers, proving that predicted performance is representative of actual performance as recorded by the FDR.
- Verified procedures for safe takeoff and landing operations at Paro, one of the world's most challenging airports.

Editor's note:

Druk Air Royal Bhutan Airlines only operates BAe 146-100 jets at this time; Boeing is not maximizing the payload capability of the BAe jets.

IMPORTANCE OF SPEED DURING TAKEOFF TURNBACK PROCEDURES

Proper speed is essential when flying takeoff turnback procedures. Lower speeds decrease the climb capability and thereby reduce terrain clearance. Higher speeds increase the turn radius and bring the airplane closer to valley walls.

The pilots had the option of overbanking to stick-shaker speed or the initial buffet speed to achieve a smaller turn radius. They also could have combined pitch and roll to trade speed for altitude and reduced turn radius. Although these maneuvers are non-normal and were beyond the scope of this study, the pilots discussed their potential use to avoid terrain in an emergency or in high, unexpected cross-canyon wind conditions.

Optimal performance was achieved during the takeoffs from Paro by accelerating the airplane to a speed that was 10 kias faster than the minimum safety takeoff speed (10 kias of improved climb). This allowed for 30 deg of bank angle and provided the climb gradient necessary to initiate the turnback.

TAKEOFF CAPABILITY REFINEMENT

After the technical demonstrations, several performance options were studied to improve the takeoff weight capability from Paro. These included additional optimization of the turn procedures, increased takeoff thrust, use of alternate forward center of gravity positions, and installation of a weather station to allow use of Druk Air procedures B and C for runway 15. Using these procedures, the 737-700 can take off from Paro with 114 passengers and 4,850 lb (2,200 kg) of payload. Other enhancements that were studied, such as potential runway extensions and the removal of obstacles surrounding the airport, will further improve safe operation at Paro.

INCREASE TAKEOFF GROSS WEIGHT USING CFM56-7B26/B2 THRUST RATING AND ALTERNATE CENTER OF GRAVITY

The technical flight demonstrations were performed using the CFM56-7B26 thrust rating, which currently is the highest thrust rating certified on the 737-700. A new thrust bump rating,

produce at least 2% more thrust than the CFM56-7B26 rating at the Paro International Airport elevation. The additional thrust is worth approximately 2,100 lb (953 kg) of additional takeoff gross weight at Paro.

CFM56-7B26/B2, has been offered to Druk Air as a new product. The CFM56-7B26/B2 thrust rating will

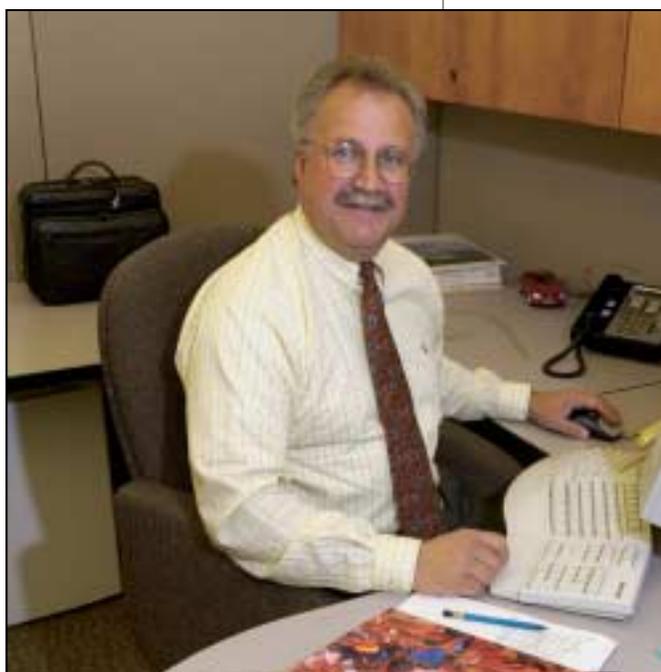
Takeoff gross weight can be increased further by using the optimal airplane takeoff center of gravity (CG) location instead of the conservative forward-limit location specified by the standard airplane flight manual (AFM). The increase is achieved by using the AFM-alternate CG takeoff performance option on the 737-700, which allows the operator to select one of two specified CG locations. Using CG locations aft of the forward limit decreases airplane drag and lowers stalling speeds, thereby increasing takeoff performance. For example, using a 23%MAC CG location instead of the forward-limit location for

runway 15 increases 737-700 takeoff gross weight by 1,200 lb (544 kg).

Airport conditions and terrain constraints limited the demonstration takeoff gross weight to approximately 115,000 lb (52,163 kg). However, by optimizing the turn procedures and using the CFM56-7B26/B2 thrust rating and alternate CG performance, takeoff gross weights in excess of approximately 120,000 lb (54,431 kg) are achievable. This improvement would allow Druk Air to fly a 737-700 with a full passenger payload from Paro to all its current initial destinations.



Miguel Santos is director of international sales for countries in Asia and Africa. During his 24-year career with Boeing, he has held engineering and management positions in advanced engineering, marketing, sales support engineering, marketing management, customer requirements, and sales organizations. Miguel has bachelor's and master's degrees in aerospace engineering and an MBA.



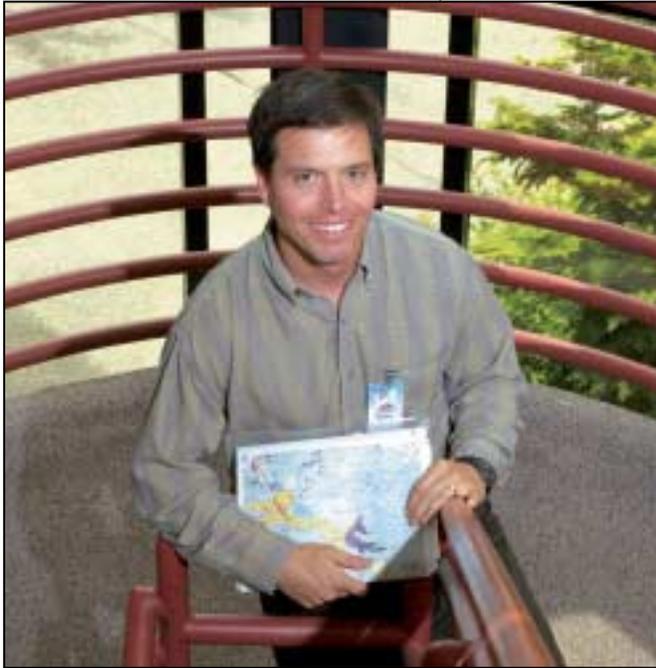
Allen Rohner is regional director of marketing for countries in the Indian Ocean, Indian subcontinent, and Africa. In his 30 years at Boeing, Allen has held technical analyst positions in aerodynamics engineering, working on the 747, 767, and 777 programs in sales and marketing support and product development. Allen was key in facilitating and organizing the effort that made the technical demonstration test flights in Bhutan happen.



Capt. Van Chaney has almost 20 years of aircraft testing experience, both as a test pilot and an aerospace engineer. A 737 and 757 pilot, Van has worked at Boeing for seven years and conducts research in the company's H-295 Helio Courier and Cessna 206. He is a member of the Society of Experimental Test Pilots and has authored several professional papers.

About the Authors

Magaly Cruz is a performance engineer with five years of experience in aerodynamics. Magaly was instrumental in developing takeoff procedures for the Paro technical demonstration flights.



James Wilson, lead engineer, supports the sales of all Boeing airplane models by providing aerodynamic performance information. During his 18 years with Boeing, James has worked in aerodynamics on 747-400 certification, 747 and 767 fleet support, and 747, 767, and 777 fuel mileage.



Capt. Buzz Nelson has flown more than 14,000 flight-hours during his 40-year aviation career. He is qualified on all models of the 737, 747, 757, 767, and 777 and has been involved in their development and certification programs during his 30 years with Boeing. For almost 10 years, Buzz was a member of the Society of Automotive Engineers S-7 committee, which writes design practices for the handling qualities of large commercial airplanes and flight deck designs.