UCRL-ID-103497

Plutonium Air Transport Certification (PATC) Program

Phase One Final Report

Project 2:

Development of Draft Criteria for Package Drop and Aircraft Crash Tests and Feasibility Review

July 17, 1990

Carl E. Walter, Editor

Prepared for
U.S. Nuclear Regulatory Commission

This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

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ABSTRACT

Recent U.S. legislation imposes new requirements for certification of Plutonium Air Transport Certification (PAT) packages. Public Law 100-203 establishes the manner in which the Nuclear Regulatory Commission (NRC) may approve and certify the safety of packages intended for transport of plutonium through the airspace of the United States while en route from one foreign country to another foreign country. One of the provisions of the law requires that a package-drop test from aircraft cruising altitude be performed. Another provision requires, as an option, that an aircraft-crash test be conducted.

In response to a tentative request from the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan for certification of a PAT package of PNC design, NRC requested LLNL to develop draft criteria for the package-drop test and the aircraft-crash test and to review the feasibility of performing the tests.

Assumptions with respect to the PAT package design, cargo aircraft, and loading arrangement were made to focus the work and permit quantitative analyses. However, both the draft test criteria which resulted and the conclusions that conducting the tests is feasible are not strongly dependent on these assumptions.

The Law requires that a "worst-case" aircraft accident be considered to the maximum extent practicable as the basis for the aircraft-crash test. NRC specified that the crash of PSA Flight 1771 on December 7, 1987, represented the worst-case accident. The pertinent parameters of the accident were established on the basis of geotechnical investigations of the crash site and flight data recorder analysis so that comparable test conditions could be specified. Additional sources of information were used to support the conclusions that the aircraft impacted on moderately hard, severely weathered and fractured shale and sandstone at 282 m/s at a trajectory angle of 60° with the hillside surface of the crash. The British Aerospace 146-200 aircraft remained intact until impact even though it exceeded its certificated flutter-free speed. As a result of the high-speed impact, remaining fuel on the aircraft was rapidly ejected, burned briefly in the air above the crash point, and contributed no significant damage.

Draft criteria were developed and published for both the package-drop and aircraft-crash tests. Criteria for the package-drop test are based on aerodynamic analysis of free-falling objects. The criteria provide for consideration of arbitrary drop test altitude as long as the impact velocity exceeds specified requirements. An impact-point accuracy analysis was performed to show the size of impact area required to insure that the package would land within it. A conceptual method for dropping the package is described and used to demonstrate that: the test is feasible; suitable test ranges are available in the U.S.; and there are various options for a drop platform.

Specified draft criteria for the aircraft-crash test are consistent with the conditions encountered in the basis accident. The criteria include provisions for consideration of alternative test aircraft because it was found that aircraft alternatives are available that could considerably lower the cost of the test without compromising test results.

Integrity of the test aircraft prior to impact is an issue that must be addressed, since the aircraft may need to fly outside its design envelope to achieve the required impact speed. It may be possible to choose the elevation of the test range in such a way that the test aircraft equivalent-airspeed is within its design range. A review of remote control of aircraft indicates substantial experience, including aircraft having more than one engine. The issue of remote pilot or autonomous control is addressed; it is recommended that an autonomous control system be used. The high airspeeds that must be achieved to meet the specified impact conditions will bring into question the control authority and structural capability of the control surfaces. Nevertheless, it appears that a suitable test range is available and a test aircraft can be modified to fly as required. Thus the aircraft-crash test is considered to be feasible.

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APPENDIXES

ACKNOWLEDGMENTS

This report summarizes the work of many individuals at LLNL and other organizations. We have freely extracted material from their reports and incorporated their ideas. The resulting narrative is intended to provide a consistent summary of the work that was accomplished under Phase I, Project 2 of the Plutonium Air Transport Certification (PATC) program. Readers are urged to read the cited references for additional information.

In particular, we acknowledge edited material provided by authors in specific sections, listed below.

Section	Title	Author(s)
2.3	*Crash Site Geotechnical Properties*	D. W. Carpenter, J. C. Chen, S. C. Blair
2.5	*Flight Simulator Study*	R. E. Wells (BAe),[*] J. C. Geering (BAe)
2.6	*Aircraft Debris*	R. J. Sherwood, B. W. Davis
2.9	*Seismic Signature of Impact*	W. V. Savage (PG&E)[†]
2.10	*Cockpit Voice Recorder Analysis*	R. B. Burdick
4.	*Package-Drop Test*	J. H. VanSant, R. E. Glazer
5.2.2	*Equivalence of Crash Environment*	M. C. Witte, M. Eli
5.3	*Remote Operation Feasibility*	C. J. Herget
5.4	*Candidate Test Ranges*	J. C. Chen
5.6	*Aircraft Crash Test Feasibility Assessment*	J. H. VanSant

Completion of Project 2 was accomplished under the able guidance of C. K. Chou, PATC Program Manager, who kept us focused while encouraging our technical initiatives. Lisa Hensel worked diligently to provide the necessary publishing services. We also enjoyed the support of our NRC sponsors Robert Burnett, Charles MacDonald, John Cook, and the John Jankovich.

There are many persons at LLNL and at organizations such as National Aeronautics and Space Administration (Langley, Ames Research Centers), National Transportation Safety Board, and Federal Aviation Administration who participated directly in the project or furnished useful information to us. We are grateful for their assistance.

Carl E. Walter, Editor
PATC Project 2 Manager

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[*] British Aerospace.

[†] Pacific Gas and Electric Company.

GLOSSARY

AFB—Air Force Base
ARTCC—Air Route Traffic Control Center
BAe—British Aerospace (the "e" is added to distinguish it from British Airways)
CAM—cockpit area microphone
CAS—calibrated airspeed
CBR—California Bearing Ratio
CFR—Code of Federal Regulations
C.G.—center-of-gravity
CID—controlled impact demonstration
CVR—cockpit voice recorder
EAS—equivalent airspeed
FAA—Federal Aviation Administration
FDR—flight data recorder
IAS—indicated airspeed
ILS—instrument landing system.
LLNL—Lawrence Livermore National Laboratory
MSL—(above) mean sea level
NASA—National Aeronautics and Space Administration
NIST—National Institute of Science and Technology
NRC—Nuclear Regulatory Commission
NTSB—National Transportation Safety Board
NUREG—Nuclear Regulatory Report
PAT—plutonium air transport
PNC—Power Reactor and Nuclear Fuel Development Corporation
PPP—parachute/pallet/package (assembly)
PSA—Pacific Southwest Airlines
PST—Pacific standard time.
RPV—remotely piloted vehicle
SI—Systeme International d' Unites.
TAS—True airspeed
UTC—Universal time, coordinated
UTTR—Utah Test and Training Range
VHF—very high frequency
VHS—video home system
WSMR—White Sands Missile Range

1. PROJECT BACKGROUND

To date, the NRC has certified two package designs for transporting plutonium by air. These PAT packages, PAT-1 and PAT-2, were certified in 1978 and 1981, respectively, on the basis of extensive analyses and development tests as prescribed in 10 CFR 71 (Ref. 1) and NUREG 0360 (Ref. 2). The capacity of the PAT-1 package is limited to a maximum of 2 kg of plutonium oxide powder (Ref. 3), while the capacity of the PAT-2 package is one or two orders of magnitude lower (Ref. 4).

During 1988, the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan initiated negotiations with NRC for certification of a PAT package of PNC design. PNC's tentative application for certification of a PAT package is governed by U.S. legislation enacted in December 1987 that imposes new requirements for certification. As a result of these negotiations, NRC agreed (Ref. 5) to develop draft criteria for tests of PAT packages as required by the legislation, Section 5062 of Public Law 100-203 (see Appendix 1). This section of the law establishes the manner in which the NRC may approve and certify the safety of packages intended for transport of plutonium through the airspace of the United States while en route from one foreign country to another foreign country. One of the provisions of the law requires that a package-drop test from aircraft cruising altitude be performed. Another provision requires, as an option, that an aircraft-crash test be conducted. The law also specifies that all costs associated with the application for certification shall be reimbursed to the NRC by the applicant.

The NRC/PNC agreement establishes Phase I of a four-phase program. As part of Phase I, cost and schedule estimates (excluding the cost of the tests themselves) were developed for the remaining phases (see Ref. 6). The four phases are:

Phase I	Develop draft test criteria.
Phase II	Obtain public comment and finalize criteria for package-drop and aircraft-crash tests.
Phase III	Conduct package-drop and aircraft-crash tests.
Phase IV	Perform certification review.

NRC requested LLNL to provide the technical effort required for Phase I. The tasks to be conducted in support of Phase I were subsequently grouped into two projects. Project 1 is directed toward establishment of suitable criteria for developmental tests that would impose an environment on the PAT package at least as severe as would be present in a worst-case accident. A companion report (to be published) summarizes the results from Project 1.

This report summarizes the work of Project 2, which includes:

- Development of draft criteria for the package-drop and aircraft-crash tests that may be required.
- Review of the feasibility of performing the tests.

We made several assumptions in Project 2 with respect to the cargo aircraft, a generic PAT package design, and loading arrangement. These assumptions, stated in Section 3, are based on general considerations of our own. The assumptions we made focused our work and made possible quantitative analyses. However, both the draft criteria that resulted (Ref. 7) and the conclusions that conducting the tests is feasible are not affected even by large departures from these assumptions, as demonstrated in Sections 4 and 5.

Section 5062 of Public Law 100-203 requires that a "worst-case" aircraft accident be considered to the maximum extent practicable as the basis for the aircraft-crash test. Based on general information available, the NRC specified that the crash of PSA Flight 1771 on December 7, 1987 represented the worst-case accident and was suitable for use as the basis accident (Ref. 8). A considerable technical effort was necessary to quantify the pertinent parameters of the accident so that comparable test conditions could be specified on a sound basis.

2. BASIS ACCIDENT DESCRIPTION

Shortly after the crash of Pacific Southwest Airlines (PSA) Flight 1771, it was established that the crash resulted from a criminal act and not a safety deficiency in flight equipment or operations. At that time, the National Transportation Safety Board (NTSB), which had already deployed its investigation teams to the crash site, discontinued their involvement without completing their investigation. Consequently, NTSB did not prepare a final report of the accident, and the separate reports of their individual investigating groups did not include the scope and detail that is customary. NTSB assigned Accident Identification Number DCA-88-M-A008 to the crash of PSA Flight 1771.

Because of the criminal aspect of the accident, an official report addressing the technical details of the crash is not available. As a result, the only information on the accident was obtained and promulgated to a limited audience by local law enforcement agencies and the FBI as a result of their emergency search and rescue functions and criminal investigations. We believe that the report of our investigation of the PSA Flight 1771 crash (Ref. 9) is the most complete and technically correct account that is currently available. We have summarized Ref. 9 in this section. Additional references, which are the basis of Ref. 9, are cited in that document.

2.1 Accident Conditions

On December 7, 1987, PSA Flight 1771 departed from Los Angeles at 15:30 Pacific standard time (PST) with a scheduled arrival in San Francisco at 16:43 PST (00:43:00 UTC, December 8). Half an hour before scheduled arrival, at 00:13:03 UTC, the Federal Aviation Administration's (FAA) Oakland Air Route Traffic Control Center (ARTCC) recorded radio messages from the crew indicating that a gun had been fired on board and that an emergency was being declared by means of their transponder code. The last radar return was recorded at 00:14:36* UTC, at latitude and longitude coordinates 512 m northeast of the impact location. The altitudes corresponding to the last two radar returns were not recorded.

The British Aerospace (BAe) 146-200 aircraft used on PSA Flight 1771 remained intact until it crashed, nose first, on a hillside of the Santa Rita Range in San Luis Obispo County. None of the 43 persons on board survived. Only minor ground

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* Radar times reported by FAA are 4 s fast as discussed in Ref. 9.

fires resulted from the approximately 3200 kg* (1000 gallons) of fuel estimated to be on board at the time of the crash. A dense black smoke cloud was observed at the time of the crash, indicating that some of the fuel apparently burned in the air above the impact point. The aircraft and its contents fragmented into many small pieces, mostly dispersed south of the impact point within a radius of about 100 m (see the white specks in Fig. 2.1-1). The most distant aircraft piece was found 265 m from the impact point, and some paper debris was found as far away as 2 km.

The crash produced an irregularly shaped depression about 3.5 m deep by 6 m wide by 12 m long. These dimensions are estimated from eyewitness reports, photographs, and geophysical surveys. The volume of soil displaced is estimated to have been about 74 m^3, with a corresponding mass of about 175 Mg.

We studied available radar-tracking data and data from the aircraft flight data recorder in considerable detail to establish the impact angle and velocity of the aircraft. Also, BAe performed simulation studies based on the specific aircraft configuration that crashed. We believe that the flight data recorder provides the best estimates of impact conditions. The FDR data is consistent with the studies by BAe. Data from the flight recorder and additional information are summarized in Table 2.1-1.

Fig. 2.1-1. Photo of PSA Flight 1771 crash site.

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* Units of Measurement. We have used Système International d' Unités (SI) units in most of our original work reported here. In some cases we have converted values from some of the references to SI units. In other cases we have used the hybrid systems of units used by the British and the flying industry. In some cases, we used British units in our analysis for ease of comparison. We apologize for these inconsistencies.

Table 2.1-1. Summary of approximate impact conditions for the basis accident.

Flight number	PSA 1771
Date	December 7, 1987
Aircraft type BAe 146-200	
Flight altitude (initial)	6.7 km (22,000 ft)
Elevation of crash site	402 m (1320 ft)
Surface inclination:	
Maximum slope	24°
In vertical plane containing trajectory[a]	16°
Surface material[a]	Intensely weathered and fractured shale and sandstone
Aircraft status at impact:	
Velocity (true airspeed)[a]	282 m/s (925 ft/s)
Mach number	0.83
Surface impact angles (see Fig. 2.3-1b)[a]:	
Fuselage	57° (sum of pitch and surface inclination angles)
Trajectory	60° (sum of trajectory and surface inclination angles)
Direction (heading)	210° true
Pitch angle	41° down
Trajectory angle	44° down
Mass	29,300 kg

[a] Important parameters for crash test.

2.2 Aircraft Description

The BAe 146-200 is a high-wing, 4-engine, jet-powered aircraft designed for short-range (2000-km) intercity flights. As configured, it could carry 83 passengers and a crew of 4. The series 200, shown in Fig. 2.2-1, has an overall length of 28.6 m and a wing span of 26.3 m. Fuselage diameter is 3.6 m. Maximum takeoff weight is 42,200 kg. The design cruise Mach number is 0.7. At the time of the PSA Flight 1771 crash, the estimated total weight was 29,300 kg. The aircraft was flying at 6.7 km (22,000 ft) altitude, where the design true airspeed is 218 m/s (425 kt). The true airspeed and Mach number of PSA Flight 1771 just prior to the shooting as determined from our analysis of radar data were 178 m/s (349 kt) and 0.56, respectively.

Fig. 2.2-1. British Aerospace (BAe) 146-200 aircraft.

2.3 Crash Site Geotechnical Properties

Figure 2.3-1 shows a topographic sketch of the crash site and a depiction of the attitude of the aircraft at impact as determined by our studies.

The characteristics and geotechnical properties of the PSA Flight 1771 crash site were studied on the basis of data from extensive field investigations and measurements as well as laboratory tests. Field investigations consisted of topography surveys, exploratory borings, seismic refraction measurements, and dynamic penetration tests. Laboratory tests measured the basic engineering properties, compressibility characteristics, and stress-strain behavior of the soil/rock samples.

Based on our detailed geological engineering evaluation of the crash site, the impact point is located near the top of a hill at an approximate elevation of 402 m mean sea level (MSL) at 35°31'21" north latitude and 120°51'22" west longitude. The slope gradients of the hill vary from 20 to 40% (11.3 to 21.8°) in the vicinity of the impact point. We estimated the slope in the plane of the aircraft trajectory to be 16°. The crash site is covered with dark-brown, root-bearing, clayey silt colluvial soil that contains a variable amount of sand and weathered rock fragments. The thickness of the soil layer varies from approximately 0.15 m, in the vicinity of the impact point, to 2 m downslope to the southeast at the foot of the hill. The site is underlain by marine sedimentary rocks of the late Mesozoic Toro Formation. The rock near ground surface of the impact point consists mainly of intensely weathered and fractured sandstones interbedded by shales or siltstones.

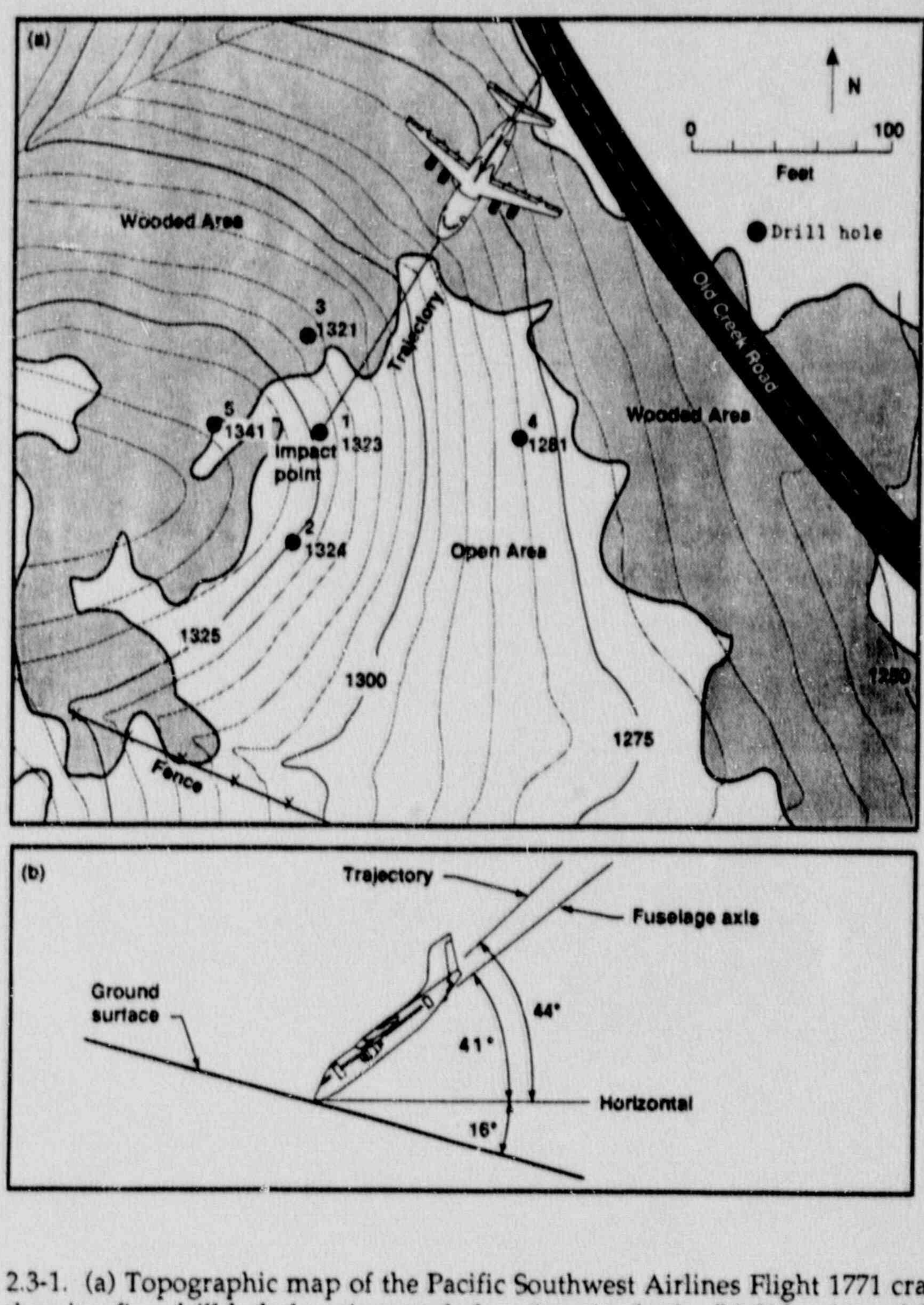

Fig. 2.3-1. (a) Topographic map of the Pacific Southwest Airlines Flight 1771 crash site showing five drill hole locations and elevations (in feet). (b) Side view of final trajectory showing pertinent angles.

Geotechnical properties of the rocks at the site were determined from a variety of laboratory tests and measurements on drill core and outcrop samples. Pressure-volume tests to determine bulk modulus were conducted on cylindrical specimens 2.5 and 5.1 cm in diameter at pressures up to 480 MPa. The uniaxial compressive strengths for both sizes of specimens were also measured. Triaxial compression tests were conducted at pressures between 25 and 500 MPa to investigate the effect of confining pressure on stress-strain behavior. At higher confining pressure, strength increases and material response changes from brittle fracture to ductile, strain-hardening behavior. Strain-rate effect was investigated at confining pressures of 25 and 50 MPa for strain rates between 10^{-4}/s and 20/s. We observed an increase in ultimate strength and Young's modulus with increasing strain rate. Dry density and porosity of some specimens were also measured. Table 2.3-1 summarizes the measured properties.

The engineering properties of the soil were determined from laboratory tests of relatively undisturbed samples obtained from exploratory borings. The testing program consisted of measurements of general properties and tests of volumetric compressibility, as well as stress-strain characteristics. These data are also summarized in Table 2.3-1.

Dynamic penetration tests were conducted at the crash site to determine the penetrability of the soil/rock. The average penetrability constant (*S*-number) is about 2.5 for rock and about 3.4 for the topsoil layer.

As a result of our geotechnical investigations, we determined that the best way to describe the properties of the impact location for the aircraft-crash test was a qualitative one. Accordingly, we prescribed (Ref. 7) that the geotechnical properties of the test site have the relative quality given in Table 2.3-2.

All methods of measurement that we used at the PSA Flight 1771 crash site can be used to establish the relative position of a candidate test location among the materials listed in Table 2.3-2.

Table 2.3-1. Geotechnical properties of the Pacific Southwest Airlines Flight 1771 crash site.

	Best estimate or average
Penetrability constant (S-number):	
Intensely weathered rock	2.5 ± 0.5
Soil	3.4 ± 0.3
Rock quality designation (%):	
Intensely weathered rock	15
Unconfined compressive strength (MPa):	
Weathered rock	22
Unweathered rock	102
Weathered and unweathered rock	53
Unconsolidated undrained strength (MPa):	
Soil	0.76 ± 0.35
Seismic wave velocities in upper 5 m (m/s):	
Shear wave velocity	610
Compression wave velocity	1220
Bulk density (kg/m^3):	
Rock	2370
Soil	2090
Water content, soil (%)	16.2
Porosity (%):	
Rock	8
Soil	32
Poisson ratio	
Rock	0.28
Soil	0.45
Unloading bulk modulus (MPa)	
Rock	
First cycle (0 to 8 MPa)	2180
Up to 4 cycles (8 to 250 MPa)	5100
Soil (varies with mean effective stress)	130
Shear modulus (MPa)	
Rock (defined at 50% stress level)	
Unconfined	1307
Confined (25 to 250 MPa)	3394
Soil (defined at 50% stress level)	11.6

Table 2.3-2. Examples of geologic materials harder or softer than those at the Pacific Southwest Airlines Flight 1771 crash site.

Geologic material	Qualitative hardness
Gabbro	
Basalt	
Granite	
Welded tuff	
Conglomerate	
Cemented sandstone	
Caliche-cemented claystone	Harder
Unweathered shale and sandstone	↑
Intensely weathered, and fractured shale and sandstone	Site material has moderate hardness.
Volcanic ash	↓
Decomposed granite	Softer
Stiff clay	
Sand	
Bay mud	
Peat	

2.4 Radar Data

Table 2.4-1 provides a listing of the radar data recorded at the FAA's Oakland ARTCC, as well as a transcript of recorded radio communications between ARTCC and PSA Flight 1771. We grouped the radar data into three approximately descriptive time periods representing 3.0 min of *pre-upset* operation, 1.2 min of *trouble-awareness* operation, and an overlapping period of 0.8 min of *dive* operation. Only <u>overall average</u> aircraft velocities calculated from these radar data for the first two time periods are considered to be meaningful. The overall average aircraft velocity (inertial speed) calculated for the *pre-upset* period is 178 m/s (349 kt). During the *trouble-awareness* period, from 00:13:00 to 00:14:12 UTC, the average aircraft velocity calculated is 173 m/s (340 kt).

An accurate estimate of aircraft velocity at impact could not be obtained from analysis of the radar data during the *dive* period. The difficulty results from two factors: (1) the characteristics of the normal radar data and (2) the lack of altitude information for at least one of the radar coordinates (at 00:14:24 UTC) and the time of impact. A horizontal representation of the flight path based on the terminal radar data and our topological survey is shown in Fig. 2.4-1. Estimates of aircraft speed based on these data and assumed altitudes are also indicated in Fig. 2.4-1.

We tried several unsuccessful approaches to circumvent the limitations on velocity estimates derived from the radar data. We conclude that average velocity over a period of time may be determined with some confidence, but instantaneous values of velocity cannot be estimated accurately.

Table 2.4-1. Radar data and pertinent radio communications recorded by Federal Aviation Administration's Oakland Air Route Traffic Control Center for Pacific Southwest Airlines Flight 1771.

Time (UTC)[a]		Latitude deg min sec	Longitude deg min sec	Altitude (ft)
00:09:48		35 : 12 : 22	120 : 32 : 04	22,000
00:10:00		35 : 13 : 15	120 : 32 : 58	22,000
00:10:12		35 : 14 : 08	120 : 33 : 52	22,000
00:10:24		35 : 15 : 01	120 : 34 : 47	22,000
00:10:36		35 : 15 : 53	120 : 35 : 42	22,000
00:10:48		35 : 16 : 40	120 : 36 : 46	22,000
00:11:00	*Pre-upset*	35 : 17 : 32	120 : 37 : 31	22,000
00:11:12		35 : 18 : 24	120 : 38 : 36	22,000
00:11:24		35 : 19 : 10	120 : 39 : 30	22,000
00:11:36		35 : 20 : 02	120 : 40 : 25	22,000
00:11:48		35 : 20 : 48	120 : 41 : 19	22,000
00:12:00		35 : 21 : 41	120 : 42 : 14	22,000
00:12:12		35 : 22 : 33	120 : 43 : 28	22,000
00:12:24		35 : 23 : 19	120 : 44 : 14	22,000
00:12:36		35 : 24 : 11	120 : 45 : 08	22,000
00:12:48		35 : 25 : 03	120 : 46 : 03	22,000
00:13:00		35 : 25 : 56	120 : 46 : 58	22,000
00:13:03		Radio communication to Oakland ARTCC "... we've got a problem ... gun fired aboard ..."		
00:13:11		Radio communication repeated "... gun fired aboard ... squawking 7700 ... "		
	Trouble-awareness	(No further radio communications)		
00:13:12		35 : 26 : 42	120 : 47 : 43	22,000
00:13:24		35 : 27 : 34	120 : 48 : 38	22,000
00:13:36		35 : 28 : 20	120 : 49 : 33	22,000
00:13:48		35 : 29 : 13	120 : 50 : 38	22,000
00:14:00		35 : 29 : 58	120 : 51 : 23	21,900
00:14:12	*Dive*	35 : 31 : 06	120 : 51 : 42	21,000
00:14:24		35 : 31 : 43	120 : 51 : 42	- - -
00:14:36		35 : 31 : 36	120 : 51 : 14	- - -

[a] Universal time, coordinated (UTC) on December 8, 1987.

Point	Time (s)	Lat. (35°+)	Long. (120°+)	Coordinates[a] E-W (ft)	N-S (ft)
0	0	29' 13"	50' 38"	0	0
1	12	29' 58"	51' 23"	3,710 W	4,636 N
2	24	31' 6"	51' 42"	1,565 W	7,001 N
3	36	31' 43"	51' 42"	0	3,809 N
4	48	31' 36"	51' 14"	2,306 E	722 S
5	50[b]	31' 21"	51' 22"	659 W	1,542 S

Point	Altitude (ft)	Altitude diff. (ft)	Linear horiz. dist. (ft)	Est. slant dist. (ft)	Est. speed (ft/s)
0	22,000	- - -	- - -	- - -	- - -
1	21,900	100	5,935	5,935	495
2	21,000	900	7,172	7,228	602
3	12,000[b]	9,000	3,809	9,773	814
4	2,000[b]	10,000	2,418	10,288	857
5	1,320	680	1,680	1,812	906
		TOTAL	21,014		

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[a] Coordinates are measured from the preceding point.

- - Linear horizontal distance between coordinates.

— Probable curved horizontal between coordinates.

[b] Assumed

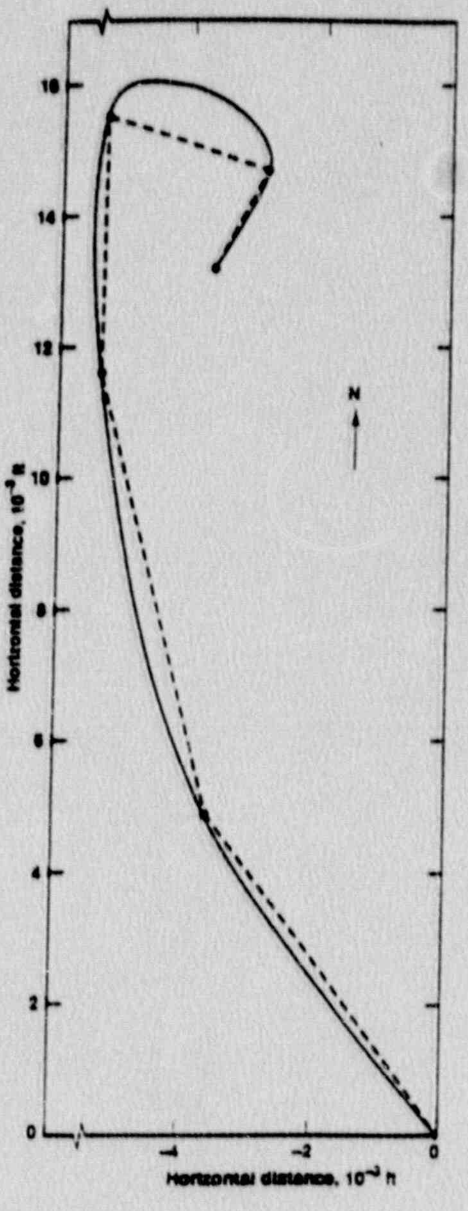

Fig. 2.4-1. Horizontal representation of the terminal flight coordinates based on radar data and our topological survey. Approximate aircraft speed between adjacent points is estimated on the basis of slant distance.

2.5 Flight Simulator Study

Very early in our investigation of the PSA Flight 1771 crash, we determined that the Flight Data Recorder (FDR) had been badly damaged. National Transportation Safety Board (NTSB) indicated that it would be difficult if not impossible to extract useful data from the broken tape. Accordingly, we requested British Aerospace (BAe) to perform flight simulator analyses, and also to review and comment on the structural capability of the BAe 146-200 to remain intact prior to impact at airspeeds clearly in excess of design airspeed. The results of the aerodynamic analyses on the simulator were subsequently reviewed for structural implications.

The purpose of the aerodynamic analyses was to assess, as well as possible, the final velocity and dive angle before impact of PSA Flight 1771. The simulation was started from the known steady flight cruise condition at 22,000 ft and terminated at the known impact elevation of 1320 ft. The analyses were restricted to the pitch axis: i. e., the simulation was constrained in a vertical plane, although the radar data indicated that the trajectory had a "hooked" footprint (as shown in Fig. 2.4-1). The strong increase in drag with increasing Mach number limits the maximum speed, and thus the impact speed, to a narrow range. The terminal Mach number reached before impact is 0.858, and the impact velocity is 935 ft/s true airspeed (TAS) or 545 kt equivalent airspeed (EAS). These speeds do not vary significantly with engine thrust or dive angle.

The results obtained on the simulator were compared with the radar and crash site survey data given in Fig. 2.4-1 by "unwinding the turn". The comparison, with respect to both horizontal distance and time, was not as close as desired.

On the basis of the aerodynamic analysis results from the simulator, radar data used to determine location and speed at the time of the upset, and a survey of the impact site, it is estimated that the ultimate dive speed was 551 kt (930 ft/s) TAS, or 540 kt (911 ft/s) EAS, and the Mach number was 0.835, which is considerably in excess of the aircraft design airspeed. It is also greater than the certificated flutter-free speed, and it must be considered a strong possibility that flutter could have occurred in the later stages of the dive.

British Aerospace reviewed the structural implications of flying the BAe 146-200 aircraft in the most likely manner indicated by the simulator study. They found it not surprising that the structure remained intact until impact with the predicted speeds from the simulator study. Because the speeds were outside the design envelope, data are not available, and therefore additional assurance could not be given that the structure should not have failed.

2.6 Aircraft Debris

We studied the aircraft debris from the PSA Flight 1771 crash in an attempt to better define the impact phenomena that occurred. The extensive fragmentation of the aircraft was not easily explainable. Indeed, the fragmentation was so great that we investigated whether an explosion might also have occurred. We conclude that this was not the case.

Examination of aerial photographs of the crash site taken by the San Luis Obispo County Sheriff's Office shortly after the crash of PSA Flight 1771 reveals a generally uniform distribution of debris in a relatively localized area. The photographs also show that the aircraft broke into a large number of very small pieces. None of the debris is recognizable by a casual observer as a section of fuselage or wing of an aircraft. To pursue the question of debris size and position distribution, a representative aerial photograph of the crash site was processed using a digital image enhancement technique. The objective of this investigation was to establish that the aircraft was intact at impact. Because of uncertainties in several factors affecting the observed debris area, application of the image processing technique did not allow a determination that all debris could be observed. At best, 28% of the estimated outer surface area of the BAe 146-200 could be observed in the photographs. Crash witnesses generally reported that most of the aircraft debris was within view of the aerial photographs that we examined.

To attempt to understand the extensive fragmentation of the aircraft, we performed a short series of high-impact tests on scale models of the fuselage. The objective of these exploratory high impact tests was to discover the mechanism for aircraft fragmentation. A test consisted of firing a plastic projectile at the end of a lightly supported, thin-walled, 25-mm-diam aluminum tube. The length-to-diam ratio was chosen to match the fuselage ratio of the BAe 146-200. Although the thinnest commercially available tubing was used, the wall thickness was six to nine times thicker than required for proper scaling of the BAe 146-200. Projectile velocity was 290 m/s or higher in each test.

Five fragmentation mechanisms were considered to be candidates: (1) high strain rate; (2) high deformation rate; (3) air pressure buildup in fuselage at impact; (4) shrapnel from breakup of rigid/semi-rigid objects inside the fuselage; and (5) eruption of liquid present inside the fuselage. The tests established that "shattering" of the fuselage (and wing) which was observed at the crash of PSA Flight 1771 could be replicated to some extent in a laboratory environment. All five mechanisms were found to contribute to fragmentation of the scale fuselages. The presence of rigid, semirigid, and liquid mass inside the fuselage contributed most significantly to catastrophic fragmentation.

2.7 Fire/Explosion Phenomena

The extensive fragmentation that occurred on impact of PSA Flight 1771 raised the question of the possibility of an accompanying chemical explosion. Witness accounts of voluminous smoke at the time of the impact and accounts of fire fighters standing-by all night following the late afternoon crash to quench "spot fires" suggested that a large fire may have attended the crash. We conclude that there was no extensive fuel explosion; rather, there was a short-duration air-borne fire that rapidly self-extinguished, and the consequences of fire were not significant in the overall damage assessment. The rationale for these conclusions is given in Ref. 9.

2.8 Flight Data Recorder (FDR) Analysis

Both the FDR and cockpit voice recorder (CVR) units used on PSA Flight 1771 sustained extensive damage. Although the FDR (Lockheed Model 209F) was the more severely damaged of the two recorders, it nevertheless provided definitive terminal flight data.

Pieces of the tape are shown in Fig. 2.8-1. Only the piece at the top of the photograph was analyzed. Approximately 80 mm long, this piece of tape contained recorded flight data for the final 7 s of flight. The last altitude measurement that could be read was 179 m above the impact elevation. Thus, only a small amount of extrapolation was required to determine impact conditions.

Most data of interest on the terminal tape segment were successfully recovered. Two methods of data reduction were used to recover flight parameter data of primary interest: (1) automatic data playback; and (2) manual waveform interpretation.

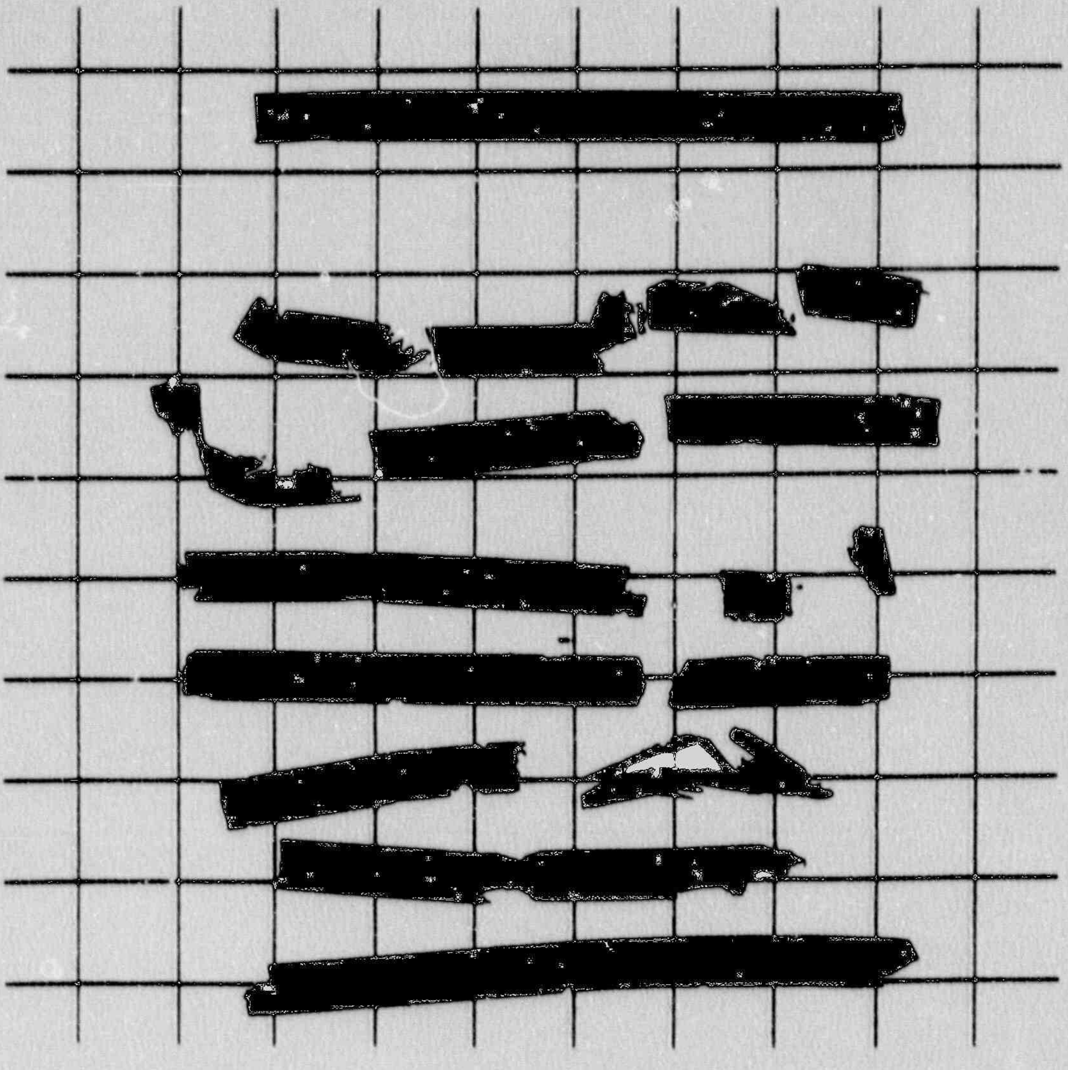

Fig. 2.8-1. Photograph of tape fragments removed from the Pacific Southwest Airlines Flight 1771 flight data recorder (FDR) (approximately full scale).

A partial listing of the reduced data is shown in Table 2.8-1. A data subframe consists of 64 twelve-bit words recorded each second. A data frame consists of four subframes.

Our primary interest in the reduced data from the FDR was establishment of the impact speed and angle. Our analysis yielded the following correlations for altitude, h_i (ft); pitch, p_i (deg); and aircraft inertial speed, V_t (kt) with respect to time before impact, t_i (s).

$h = 1320 - 758.2\ t_i$ for: $-4 < t_i < 0$

$p = -35.639 + 3.955\ t_i$ for: $-4.5 < t_i < 0$

$V_t = 548.5 - 6.8\ t_i - t_i^2$ for: $-4 < t_i < 0$

The altitude calculated from the true airspeed and pitch angle correlations is lower than the altitude calculated from the altitude correlation at the same value of t_i. This is to be expected because the fuselage datum axis is most likely at a small angle of incidence (slightly less steep) with respect to the aircraft inertial trajectory. We attempted to reconcile this discrepancy by postulating a constant angle of incidence that brings the two calculations into close agreement. We found, however, that an unreasonably large incidence angle (about 10°) was required. BAe estimated that the angle of incidence at the time of impact was about 3° and that any greater difference must be due to errors in the recorded pitch, altitude, and speed.

We resolved this issue by considering the average terminal trajectory angle, -53.8°, as given by the altitude and velocity correlations to be an upper bound. A lower bound is provided by the pitch angle at impact, -35.6°, as given by the pitch angle correlation. The average of these bounding values is -44.7°. For convenience, we round the latter value to -44° which, when combined with the impact surface slope, 16° (see Table 2.1-1), results in a total impact angle of 60°.

We accept the BAe estimate of 3° as the incidence angle of the fuselage at impact (i.e., a pitch angle of -41°). Its precise value, for angles less than 15 to 20°, does not significantly affect the impact load on the aircraft or its contents. Because of this insensitivity to incidence angle, we did not attempt to reconcile the discrepancies between altitude, pitch, and velocity correlations as derived from the FDR.

On the basis of information available to us, our analyses, and the work of BAe, we conclude that the best estimates are: impact speed was 282 m/s (925 ft/s, 548 kt), flight trajectory angle was 44°, and aircraft pitch angle was 41°.

We conclude that all four engines were operating nominally at cruise thrust. The aircraft appeared to be straightening from a roll in its terminal flight period, as seen in Table 2.8-1. The final recorded value was under 9°, and further extrapolation of the decreasing roll angle trend yields a roll angle at impact of less than 8°. It is clear, therefore, that the aircraft nose impacted before the wing made contact with the ground.

Table 2.8-1. Partial listing of reduced data obtained from the flight data recorder (FDR) on Pacific Southwest Airlines Flight 1771.

	Fine altitude (ft)	Radio altitude (ft)	Airspeed (CAS)[b] (kt)	Magnetic heading (deg)	Engine speed (N1, %)	Outside air temp (°C)
Data word	32	16	31	17	63	33
Subframe						
2.2	6426	- - -	498	193.6	#2 86	- - -
2.3	5562	- - -	507	193.6	#3 93	42.4
2.4	4741	- - -	512	194.0	#4 94	- - -
3.1	4203[a]	- - -	516	193.2	#1 95	- - -
3.2	3369	- - -	521	194.0	#2 79	- - -
3.3	2669	- - -	524	194.5	#3 90	- - -
3.4	1909	1880	526	194.9	#4 84	- - -

	1 pitch (deg)	2 pitch (deg)	3 pitch (deg)	4 pitch (deg)	1 roll (deg)	2 roll (deg)
Data word	5	21	37	53	14	46
Subframe						
2.2	-62.3	-61.5	-60.6	-59.2	18.4	18.8
2.3	-59.7	-58.3	-57.0	-56.1	20.6	21.1
2.4	-55.2	-54.8	-53.9	-53.0	16.3	18.4
3.1	-52.0	-51.3	-50.4	-49.5	18.4	17.2
3.2	-48.2	-47.3	-46.1	-45.2	16.0	16.0
3.3	-44.1	-43.5	-42.2	-41.4	15.1	13.4
3.4	-40.3	-39.4	-38.3	-37.5	11.0	8.9

	1 Vert. accel. (g)	2 Vert. accel. (g)	3 Vert. accel. (g)	4 Vert. accel. (g)	5 Vert. accel. (g)	6 Vert. accel. (g)	7 Vert. accel. (g)	8 Vert. accel. (g)
Data word	2	10	18	26	34	42	50	58
Subframe								
2.2	2.10	2.09	2.08	2.03	2.00	2.13	2.34	2.28
2.3	2.21	2.10	2.06	2.02	1.96	2.17	2.52	2.58
2.4	2.56	2.52	2.50	2.39	2.28	2.21	2.28	2.48
3.1	2.53	2.60	2.58	- - -	- - -	- - -	- - -	- - -
3.2	2.57	2.53	2.58	2.52	2.44	2.49	2.37	2.38
3.3							2.6	2.7
3.4	2.56	2.61	2.57	- - -	2.74	2.75	2.63	2.63

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[a] Underlined data values were extracted by manual methods.

[b] Calibrated airspeed.

2.9 Seismic Signature of Impact

Pacific Gas and Electric Company (PG&E) operates the Diablo Canyon nuclear electric power plant located about 32 km from the crash site. PG&E recorded the impact of the PSA Flight 1771 crash on December 7, 1987 on their multistation network surrounding the plant that is used to monitor seismic activity. One of their stations is 4.75 km from the crash site. A "paper and ink" drum recording of the event was obtained because a maintenance check of the system was being conducted at the time of the crash. The recording is reproduced in Fig. 2.9-1.

An accurate time signal based on National Institute of Science and Technology (NIST) absolute time is used to correlate the signals from each station in the PG&E network. At the upper left of Fig. 2.9-1, there is a small but impulsive seismic event that was recorded at 00:14:36 UTC on December 8, 1987 (i.e., 16:14:36 PST on December 7, 1987). The time marks on each trace represent one minute from the leading edge of one mark to the leading edge of the next one. Although the first motion is very difficult to see due to the high frequency of the event, it is concluded that the motion is from the ground up, which is consistent with the first motion expected for a surface explosion or impact. There does not appear to be a clear S-wave. The duration of the event (time from first arrival to end of the coda) is about 11 s, which corresponds to a magnitude of near 1.0. We conclude that this signal corresponds to the impact of PSA Flight 1771.

Shock waves produced by the impact reach a surface sensor much more quickly by following a curved path deep into the earth than might be inferred from our measurements of surface compression wave velocity (see Table 2.3-1). PG&E also provided an estimate of travel time of about 1 s for the signal from the crash site to their seismic station. Using this estimate of signal arrival time, we establish the absolute impact time of PSA Flight 1771 as 00:14:35 UTC on December 8, 1987.

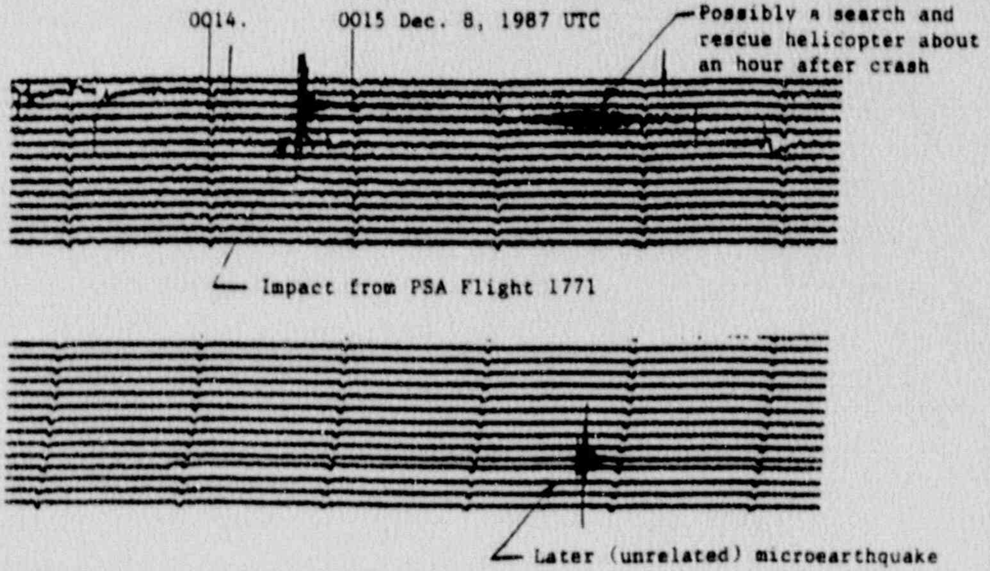

Fig. 2.9-1. Seismic signal detected at Pacific Gas and Electric Company's seismic station located near the Pacific Southwest Airlines Flight 1771 crash site.

2.10 Cockpit Voice Recorder (CVR) Analysis

The CVR unit used on PSA Flight 1771, Fairchild Model A100A, was severely damaged, but it survived the crash in considerably better fashion than the FDR. The Federal Bureau of Investigation (FBI) assumed custody of the tape at the crash site, and the tape was not analyzed by the National Transportation Safety Board (NTSB). For the FBI to utilize the tape, however, it was necessary to reattach the broken tape in several places, and this was done by NTSB at the request of the FBI.

Our early interest in the information available in the CVR was motivated by reports that the aircraft speed was supersonic (it was not), and that this could be inferred from a sound change in the cockpit. We were also hopeful that we could establish the time of impact to aid in interpretation of the radar data. Both issues were eventually resolved in other ways. Nevertheless, our analysis of the CVR tape serves to confirm the timing of the crash scenario.

The procedure we used for the data reduction and analysis was as follows. First, a high quality video home system (VHS) format magnetic tape was generated in our sound studio using several bandpass equalizing filters. This accomplished two objectives: (1) enhancement of the voices and events region of the sound spectrum while diminishing the background (hiss) noise; and (2) creation of a tape in a format more suitable to our digitization and processing techniques. Next, various frequency domains, filters, and voltage settings were explored in order to establish the best set of parameters from which to base the analysis. The third step in the procedure was to digitize the time domain data and to download the results to a computer for post-processing. The fourth step involved correcting the time base to account for changes in the CVR tape recording speed because the tape does not record an absolute time reference. A recorded spike generated by the 400 Hz CVR power supply at approximately 402 Hz provided a correction factor of 402/400. Finally, the corrected time values were plotted and various events annotated.

The end of recording on the CVR is clearly defined. This discrete point in time could have resulted from: (1) interruption of power or audio signal to the CVR due to excessive shaking on the aircraft in flight; or (2) aircraft destruction on impact with the ground. We believe the latter assumption is reasonable. With this assumption our analysis indicates that duration of the flight between the first shot and inferred impact is 106.7 s. Table 2.10-1 lists selected events with zero time referenced to the first shot. Elapsed times from the first shot derived from the FBI transcript are also listed in Table 2.10-1 for comparison. There is generally good agreement. Two exceptions are noted: (1) the time of the sixth shot according to the FBI transcript is 31 s later than the value we derived; and (2) the elapsed time between the two radio communications from the aircraft to the Oakland ARTCC is 10 s according to the FBI transcript, while our value is ~8 s.

There are only three events listed in Table 2.10-1 that can be cross-referenced to an absolute time scale: (1) the first aircraft-to-ARTCC communication; (2) the second aircraft-to-ARTCC communication; and (3) assumed impact. From the elapsed times given in Table 2.10-1, we may infer several values of absolute impact time. In each case we assume that impact is coincident with the end of recording. The reference absolute times are: (1) first radio transmission, designated ARTCC1 at 00:13:03 UTC (see Table 2.4-1); (2) second radio transmission, designated ARTCC 2 at 00:13:11 UTC (see Table 2.4-1); and (3) seismic signal sensed at 00:14:36 UTC as reported by PG&E. Inferred impact times based on these reference times and consideration of seismic signal delay are listed in Table 2.10-2. We conclude that the best estimate of absolute time of impact is that based on its seismic detection. Thus, impact occurred at 00:14:35 UTC on December 8, 1987.

Table 2.10-1. Elapsed times from first shot for key events during the terminal flight period.

	Elapsed time (s)	
Event	LLNL analysis	FBI analysis
First shot	0	0
Second shot	2.5	2
First radio comm. (ARTCC 1)	14.3	11
Second radio comm. (ARTCC 2)	22.3	21
Third shot	34.0	33
Fourth shot	35.0	34
Fifth shot	41.2	40
Door open/close	55.8	55
Sixth shot (uncertain in LLNL analysis)	55.8	87
Begin whistle	73.0	
Recorder vibration	87.0	
End of recording (assumed impact)	106.7	105

Table 2.10-2. Inferred absolute time of impact (UTC, December 8, 1987).

Event	LLNL analysis	FBI analysis
ARTCC 1	00:14:35	00:14:37
ARTCC 2	00:14:35	00:14:35
PG&E seismic signal	00:14:35	

A corollary of this conclusion is that the Oakland ARTCC timing signal for radar data was fast by 4 s. The latter part of this corollary is necessary because the last radar position was stated to be recorded at 00:14:36 UTC, which is after the seismic-derived impact time (considered to be highly accurate) and therefore not possible. The correlations for altitude, pitch, and true airspeed derived from analysis of the FDR data (Section 2.8) and the horizontal distance between the last radar coordinates and the impact point coordinates are best satisfied for $t_i = -2.7$ s. Therefore, the correct absolute time for the last radar data should be 00:14:32 UTC December 8, 1987 instead of 00:14:36 UTC.

The indicated error in ARTCC timing is not surprising. Much greater discrepancies have been observed in other incidents investigated by NTSB. We note that a shorter time difference between radio communications, 8 s versus 10 s, allows consistent estimates of absolute impact time from both radio communications if applied to the FBI data. If the shorter time difference is obtained by delaying the first radio communication by 2 s, then the estimates of absolute impact time derived from FBI data are not only internally consistent, but also consistent with the estimate derived from seismic signal detection.

3. SHIPMENT CONFIGURATION

Three basic assumptions are needed in order to assess the feasibility of conducting the package-drop and aircraft-crash tests that are required by Section 5062 of Public Law 100-203. These assumptions are: (1) the type of cargo aircraft used to transport plutonium; (2) the general design features of the package; and (3) the package arrangement on the cargo aircraft. The impact of these basic assumptions on the feasibility assessment is minor; that is, large departures from them will not compromise the validity of our assessment. By making a consistent set of assumptions, however, we are able to quantify transport scenarios.

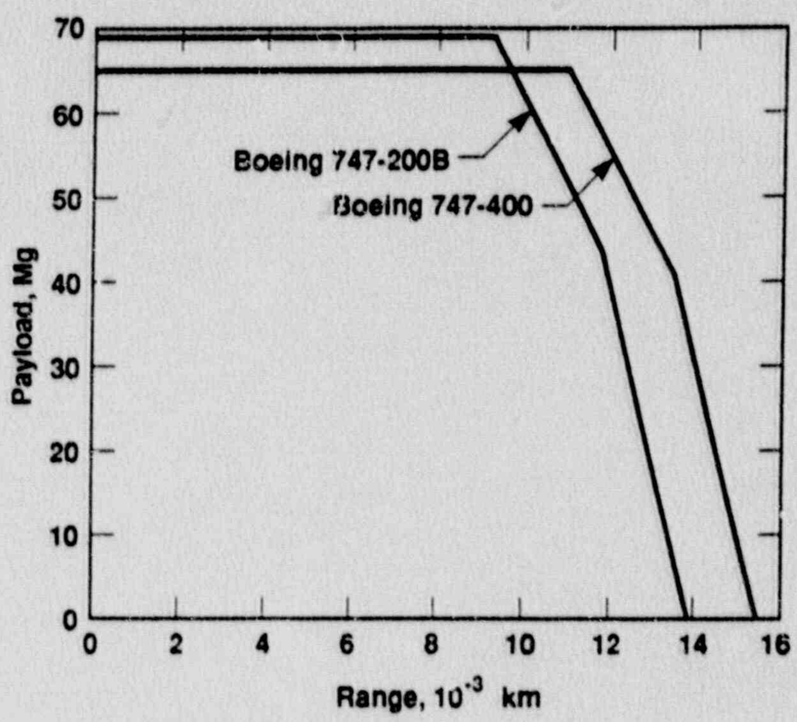

Fig. 3.1-1. Payload/range capability for passenger aircraft with three-class interiors, Pratt and Whitney engines, typical international rules. (Adapted from Boeing Commercial Airplane Company literature.)

3.1 Cargo Aircraft

The Boeing 747 is capable of delivering substantial payloads over considerable distances as shown in Fig. 3.1-1. Currently, only passenger and "Combi" (combined passenger and cargo) types of the Boeing 747-400 are available, but Boeing has recently initiated production of an all-cargo version for initial delivery in 1992 (Ref. 10). The Boeing 767-200 ER (extended range) passenger aircraft recently established a distance record for a commercial twinjet transport aircraft of 16,500 km (Ref. 11). If freighter versions are produced in the future, its endurance might also make the Boeing 767-200 ER a candidate for this application in the future.

Undoubtedly, future versions of the Aerospatiale Airbus series will have substantial payload/range capability (e.g., the A340 could carry 20 Mg a distance of 12,000 km). Nevertheless, we assume in our assessment of feasibility that the cargo aircraft is a Boeing 747.

We also evaluated the ability of a Boeing 747-400 to crash at the maximum speed achieved by the BAe 146-200 in PSA Flight 1771. We conclude that this is plausible as discussed in Section 5. The subsequent generation of subsonic transport planes (e.g. Boeing 767) has lower design speeds (Ref. 12) and may be more susceptible to flutter and less likely to remain intact until impact at the required speed. Thus, by assuming the cargo aircraft to be a Boeing 747-400, there is consistency in the cargo aircraft range, payload, and speed capability with the impact speed required (Ref. 7) for the aircraft-crash test.

3.2 Basis PAT Package

The PAT-1 package (Ref. 3) has been certified to be safe by the NRC, and it is exempted from meeting the requirements of Section 5062 of Public Law 100-203. Also, the PAT-1 package is in Fissile Class I (defined in Ref. 1), which means that: (1) it may be transported in unlimited numbers; and (2) assignment of a transport index to assure nuclear criticality safety is not required. The approximate external dimensions of the PAT-1 package are: diameter 0.6 m and height 1.1 m. The PAT-1 package weighs 225 kg and has a maximum capacity of 2 kg of PuO_2.

We selected as the basis PAT package, for feasibility studies, a design that, in comparison to the PAT-1 package, has its dimensions increased by a factor of 2 (approximately).

Although one might expect the resulting package to weigh eight times as much, we modified this outcome for the basis package. We assume that the total package mass is further increased by a factor of 1.5 to account for the heavier structure that may be needed to withstand the higher impact speed of the aircraft-crash test. We also assume that the plutonium capacity is reduced by a factor of two (i.e. increased by a factor of four, not eight over the PAT-1 capacity) to meet the criticality criterion. Thus, our basis PAT package is cylindrical with these dimensions and capacities: diameter 1.2 m, height 2.4 m, total mass 2.7 Mg, and plutonium oxide powder capacity 8 kg.

The basis package has a specific gravity of just under one and thus would be expected to float in water. Floatation is not an NRC requirement, however survival of the package subjected to deep water immersion is required (Ref. 2).

3.3 Loading Arrangement

The number of basis PAT packages that could be carried would depend on the trip distance. An additional mass allowance of about 20% for the package tiedown system should be included. The number of packages carried could be further limited by considerations of aircraft center-of-gravity. We attempted to evaluate criticality implications on the number of packages that could be carried, and we conclude that, if sufficient neutron absorption material is included with the plutonium container, the basis package may qualify for Fissile Class I (Ref. 1), and therefore criticality considerations would not limit the number of packages that could be carried.

Although the package undoubtedly would be designed for similar end-on and side-on impact resistance, the stronger orientation is intuitively end-on. Therefore, we choose to arrange the packages with their cylindrical axes aligned with the fuselage axis. For general analyses, we considered an arrangement of two parallel strings of five packages each. As shown in Section 5, the most seriously affected package at impact is the one most forward, and its impact resistance is not reduced by the number of packages behind it. The implications of this arrangement on package environment at impact are discussed further in Section 5.

4. PACKAGE-DROP TEST

Section 5062 of Public Law 100-203 (see Appendix 1) requires in paragraph (b)(2)(A) that certification testing of a proposed PAT package must include dropping a full-scale model of the package containing test materials from maximum cruising altitude. We identify the maximum cruising altitude as that of the designated cargo aircraft in which the proposed PAT package would be used, and we infer that "test materials" mean simulated plutonium.

We believe that the package-drop test criteria (see Ref. 7) which we developed satisfy the requirement as stated in the Law. In this section, we describe supporting analysis for the drop test criteria and discuss the feasibility of conducting the package-drop test using these criteria.

4.1 Aerodynamic Analysis of Free-Falling Objects

The criteria specified in Ref. 7 for drop-testing a PAT test package are based, in part, on aerodynamic analyses of packages having the nominal characteristics of the basis PAT package* (see Section 3.2). The method and results of these supporting analyses are given in Ref. 13 and reproduced in part below.

At the beginning of this project, we recognized the need to analyze the PAT package trajectory characteristics when dropped from very high altitude. The operational ceiling for the Boeing 747-400 is 13,750 m (45,100 ft, per Ref. 14). Because the characteristics of free-fall from sufficient height in the earth's atmosphere is such that a maximum velocity (this would be terminal velocity in a constant density fluid) is reached long before the surface, we reasoned that the objectives of the Law could be completely satisfied by conducting the drop test from a lower altitude. Without compromising the impact velocity in any way, the advantages of dropping from a lower altitude are: (1) increased test operation safety; (2) more predictable impact location, thus facilitating recovery and package evaluation; and (3) better instrumentation for documenting the impact.

The aerodynamic analysis uses a numerical computing method that determines package velocity, altitude, and horizontal displacement after the release of the package under specified conditions. The effects of altitude-dependent air density, wind velocity, and compressibility are included. Also considered are side and axial fall orientations of the package.

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* The mass of the basis PAT package in the aerodynamic analyses was 2.6 Mg versus 2.7 Mg, as stated in Section 3. The 4% difference in mass does not significantly alter the results or the conclusions of the analyses.

The surface of the basis PAT package is assumed to be a smooth cylinder. Test packages with irregular contours or rough surface characteristics would cause a higher aerodynamic drag resulting in a lower impact velocity and slightly higher miss distance from the intended impact location if a strong wind is present. Published drag coefficients usually apply only to regular geometries having smooth surfaces. The drag characteristics of the test package should be measured prior to the drop test.

Our analysis indicates that packages released from high-altitude aircraft can have a large horizontal displacement at ground impact. This displacement adversely influences the accuracy of the impact location. Consequently, it appears desirable to use a modified drop method that uses drag parachutes to reduce the package velocity before it is allowed to fall freely. An aerodynamic analysis of this drop method is also included in Ref. 13.

As a result of this analysis, we included in Ref. 7 a provision that allows the test package to be dropped from a lower altitude if the resulting ground impact velocity is not less than sea level velocity for a drop from maximum cruising altitude. Our aerodynamic analysis indicates that most PAT packages that are to be transported in jet cargo aircraft would benefit from this provision. The maximum cruising altitude of these aircraft is usually above 10,000 m, and packages dropped at those altitudes reach their maximum velocity long before impacting the ground at normal elevations.

4.1.1 Methodology

The methodology for the aerodynamic computations is described in Ref. 13 and summarized below. A numerical finite-difference computing method is used to calculate time-dependent values of velocity and altitude. The equations are derived from a balance of forces on a free-falling package in both the vertical and horizontal directions. This allows the trajectory to be described in two dimensions and to include the influence of wind and an initial horizontal velocity (from a non-stationary drop platform).

We used a published synthetic wind velocity profile to model the wind and altitude relationship. The model has a jet stream with a maximum wind speed of 45 m/s occurring at 10.7 km altitude. To allow a more accurate estimate of the package trajectory, and hence the location of impact, wind profile data should be obtained for the drop test area and used in aerodynamic calculations prior to the drop test.

4.1.2 Parameter Values

As discussed in Ref. 13, we reviewed the literature to obtain appropriate values of drag coefficients. Coefficients for cylinders are published for Reynolds numbers up to approximately 2×10^6. Reynolds numbers for the basis PAT package free-fall velocity exceed 10^7, but the literature indicates that drag coefficient changes relatively little for Reynolds numbers above 10^6. As a result of this review, we selected a Reynolds drag coefficient for the basis PAT package of 0.85 for air flow parallel to the cylinder axis (axial) and 0.35 for air flow normal to the axis (side).

In the literature, we did not find drag coefficients for finite cylinders at other than side or axial orientations. Therefore, only these orientations were considered in the calculations. Drag coefficient values for other steady orientations are expected to be between the side and axial drag coefficients. Also, we found no data in the published literature for the effect of tumbling. We expect that the effective drag coefficient for a package that is tumbling would be bounded by the side and axial orientation coefficients.

Mach number influence on the overall drag coefficient is included in the calculation. This influence is significant (~50% increase) in the transonic range that is experienced by the basis package when dropped from a high altitude.

Our computational method is validated by comparing calculated velocities for selected conditions to velocities from corresponding theoretical closed-form solutions. We selected three conditions for the comparisons: (1) free-fall velocity of an object in vacuum; (2) terminal velocity of an object in a constant density fluid; and (3) free-fall velocity (time-dependent) of an object in a constant-density fluid. When velocities from the numerical method are compared to velocities from the closed-form theoretical solutions, they are found to be essentially equal.

4.1.3 Results

The relationship of altitude to velocity for several release altitudes of the basis PAT package is shown in Fig. 4.1-1. The release velocity is zero, and the influence of the model wind profile is included. The package axis orientation is vertical (axial), except for the two noted curves for side orientation. There is little difference in velocity for the two orientations because the product of profile area and drag coefficient of the basis package is nearly equal for the two orientations.

For release altitudes greater than 6 km, the impact velocity is nearly constant. This is the result of the package achieving its maximum velocity before impact. A velocity decrease after the maximum velocity occurs is the result of increasing air density as altitude decreases.

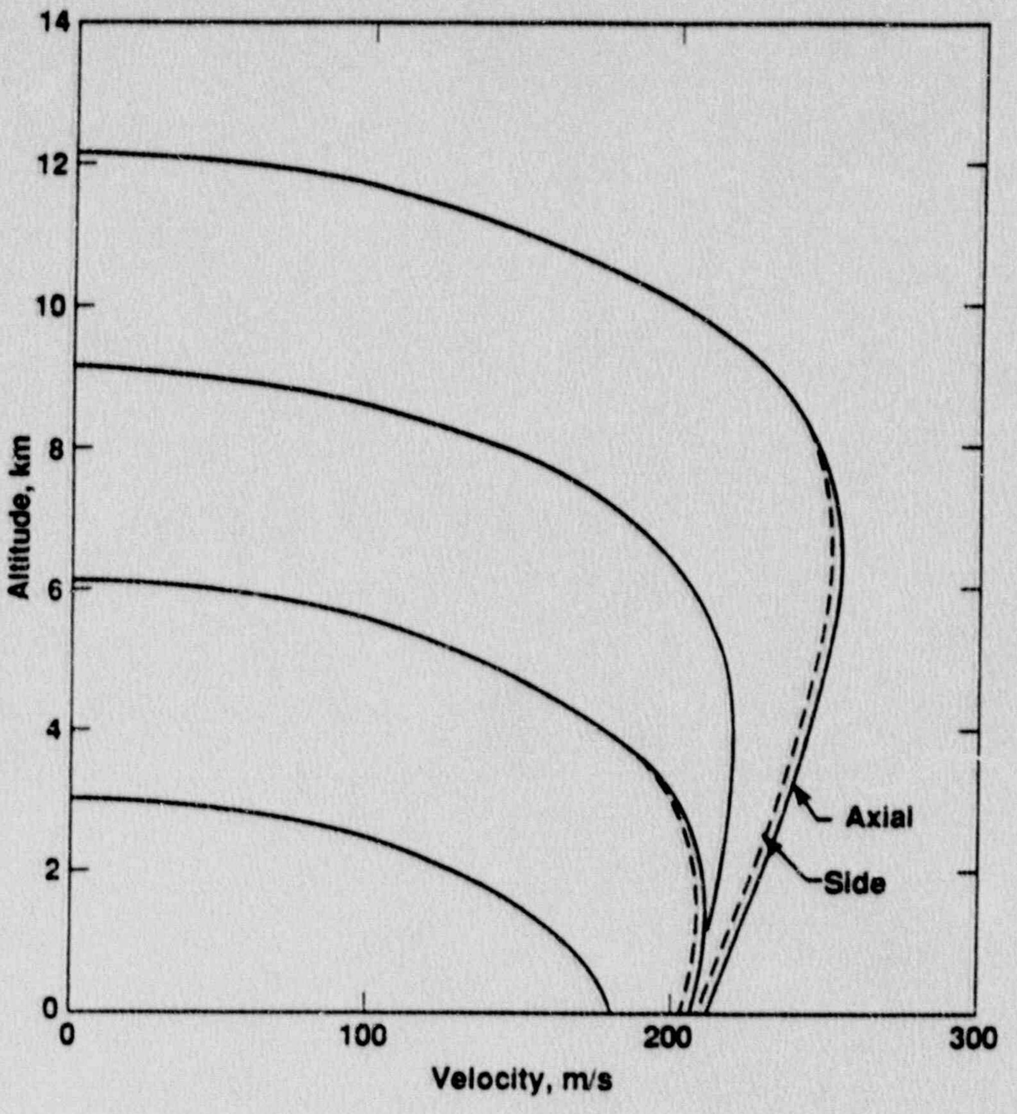

Fig. 4.1-1. Free-fall velocity of the basis PAT package released from selected altitudes.

A horizontal velocity component of the package can be expected due to the velocity of the drop aircraft. The resulting trajectory is illustrated in Fig. 4.1-2, which shows the horizontal displacement and altitude relationship for a package released at 12.2 km at several release velocities. The release velocity is in the same direction as the wind. Note that when the release velocity is 250 m/s (typical for a jet transport aircraft), the horizontal displacement of the package at sea level is almost 11 km from its release position. The impact velocity for this condition is approximately 15 m/s more than when the release velocity is zero.

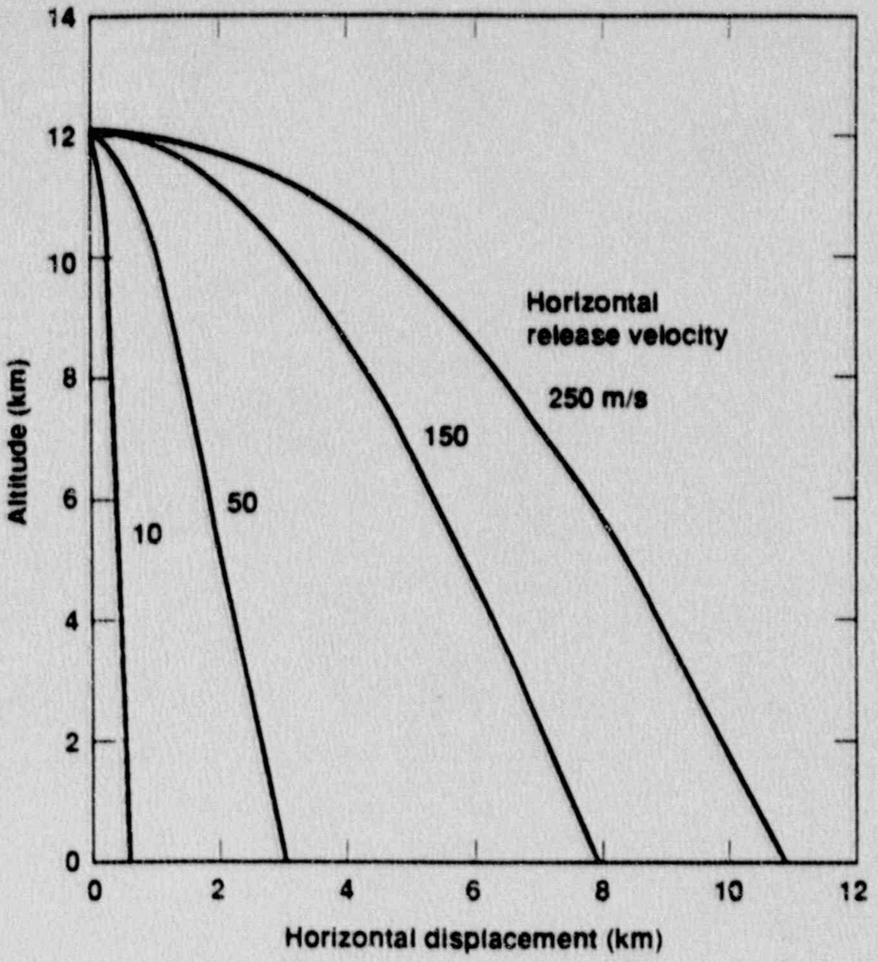

Fig. 4.1-2. Horizontal displacement of the basis PAT package released at 12.2 km and at selected horizontal release velocities.

For the case of zero release velocity (not shown in Fig. 4.1-2), the horizontal displacement at sea level is approximately 200 m. This indicates that the model wind imparts only approximately 200 m horizontal displacement when the package is released at 12.2 km. Packages released at lower altitudes would have a smaller displacement caused by wind. These results suggest that when performing a package-drop test, the preferred conditions are a lower release altitude and a minimum release velocity.

To further develop an understanding of the basis package free-fall behavior, we examined the relationship between package release altitude and its maximum and sea level velocities. The applied conditions are: zero horizontal release velocity, model wind profile, and axial orientation. These results are shown in Fig. 4.1-3. Note that the sea level velocity is nearly constant for release altitudes above 6 km. Note also that the sea level and maximum velocities are approximately equal for release altitudes below 6 km.

If the maximum cruising altitude of the designated cargo aircraft for the basis PAT package is 13.75 km, its sea level impact velocity, according to Fig. 4.1-3, is 205 m/s. The same impact velocity can be achieved if the package is released at lower altitudes, providing the impact elevation is above sea level. This relationship is shown in Fig. 4.1-4. The curve shows, for example, that the 205 m/s impact velocity could be achieved at an impact elevation of 1.0 km if the basis package is released at 6.5 km altitude. These conditions would be more appropriate for a drop test.

Also considered were packages with geometry similar to that of the basis package but differing in mass and dimensions. In the analysis, the package is described by a group of package/drag parameters that combine to form the "ballistic number", B_n. A higher value of the ballistic number results in higher package velocity. Figure 4.1-5 illustrates this relationship. There is also a relationship between the sea level velocity and B_n values for packages that have achieved their maximum free-fall velocity, as shown by the curve in Fig. 4.1-6.

The results given above indicate that, in performing the PAT package-drop test, release altitudes as low as 6 km may be acceptable. Also, a low release velocity is desirable to reduce the horizontal displacement of the package.

The ballistic number of the package has a strong influence on its ground impact velocity. Consequently, design features of the package that reduce this number will significantly reduce its impact velocity and thereby enhance its probability of survival. We note that our basis PAT package will exceed the nominal free-fall velocity (129 m/s) specified in Ref. 2. If it is desired to limit the impact velocity of a PAT package to less than 129 m/s, our results show that the ballistic number must be less than 1.0.

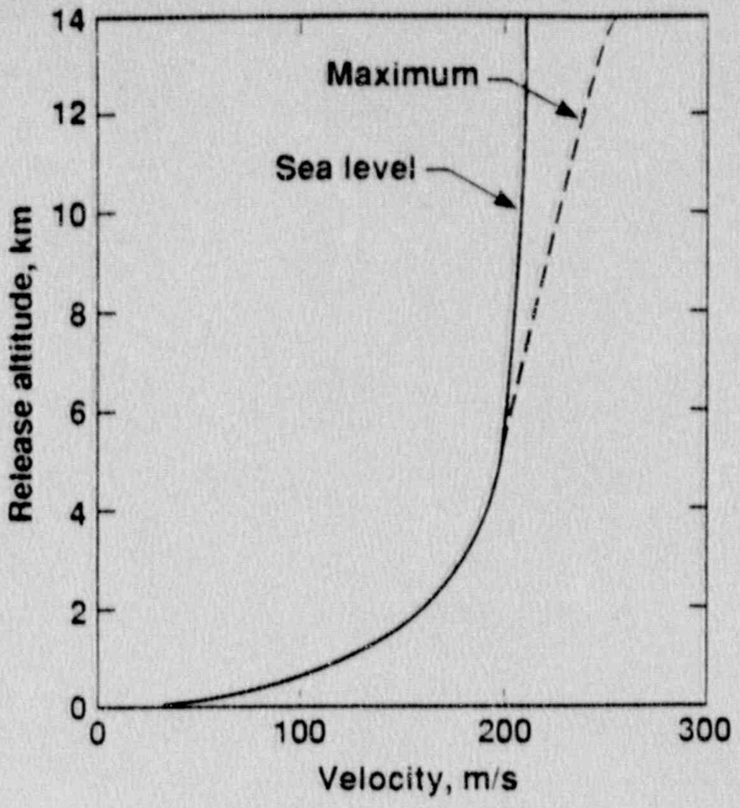

Fig. 4.1-3. Maximum and sea level velocity with respect to release altitude for the basis PAT package.

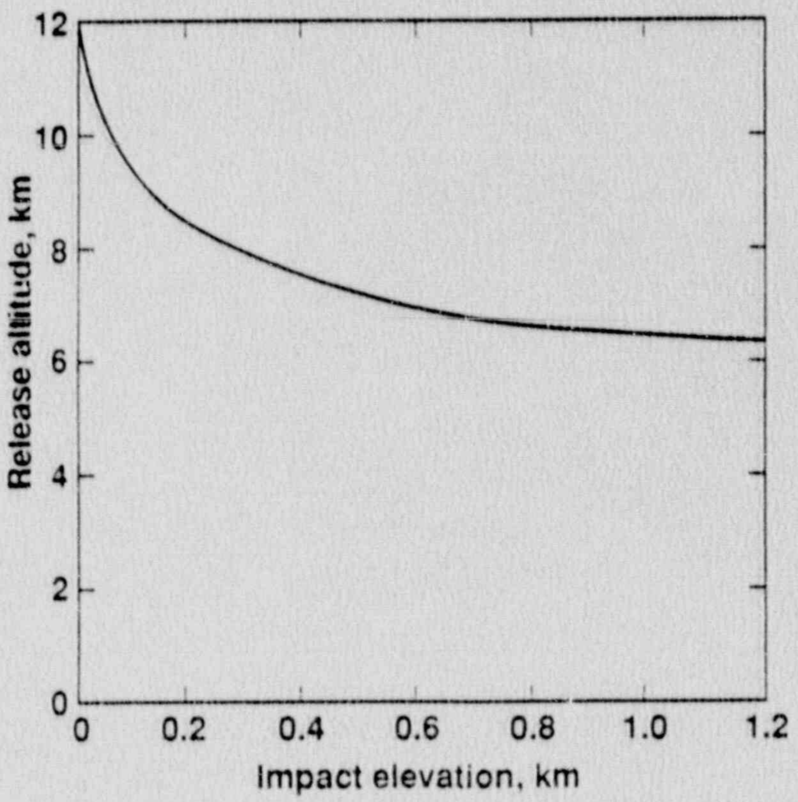

Fig. 4.1-4. Release altitude and impact elevation for 205 m/s impact velocity of the basis PAT package.

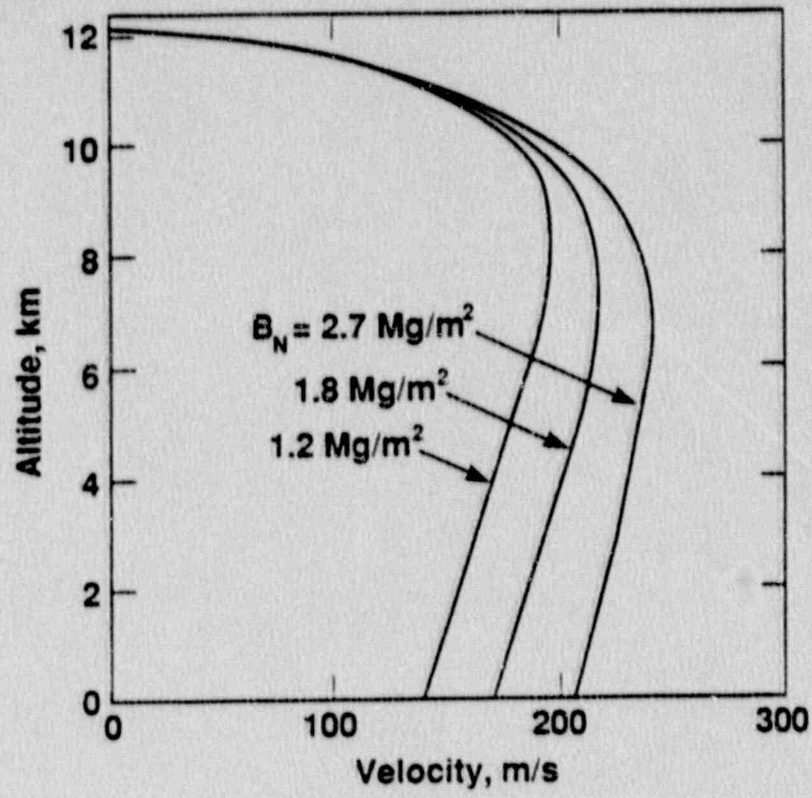

Fig. 4.1-5. Free-fall velocity from 12.2 km for three ballistic numbers, B_n.

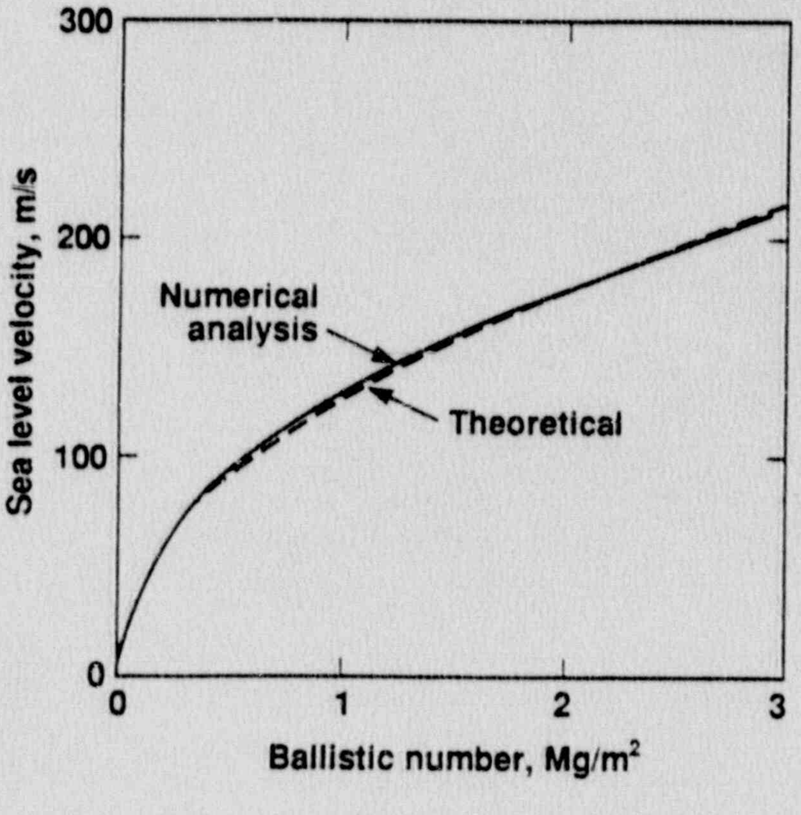

Fig. 4.1-6. Sea level velocity and ballistic number relationship for nonaccelerating packages.

4.2 Drop Test Methods

Several methods are available for conducting the package-drop test. Key parameters are drop altitude and package mass. In general, there appear to be various means of lifting packages, such as our basis PAT package, to various altitudes. The aircraft types that can accomplish this are schematically represented in Fig. 4.2-1. A U.S. Air Force B-52 (one is owned by NASA) has been used to carry much heavier loads than the basis PAT package to altitudes over 15 km.

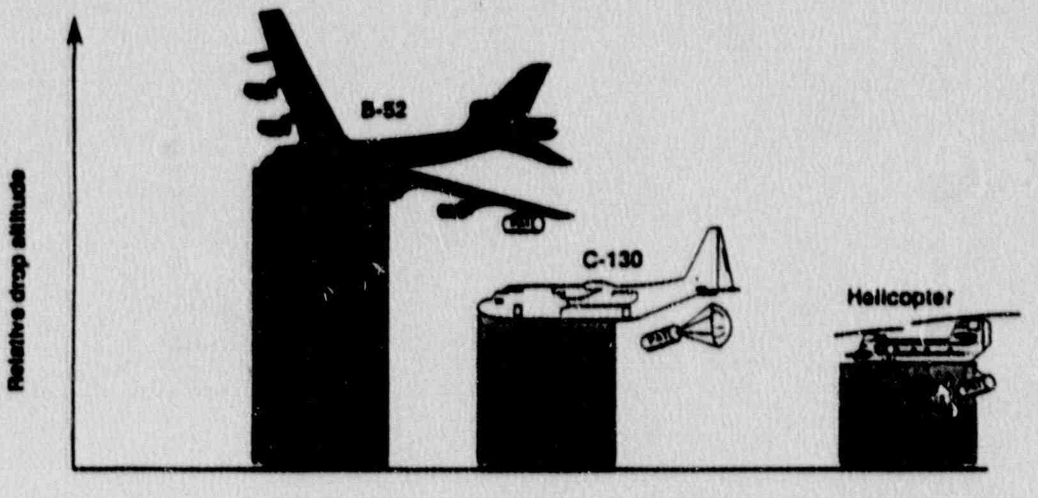

Fig. 4.2-1. Schematic representation of means of raising package to drop altitude.

For drop altitudes below about 3 km, a CH-47D (Chinook) army helicopter would have adequate hover capacity for dropping a package weighing 7 Mg. The Hercules C-130 cargo transport aircraft, used extensively by the Air Force, offers an attractive package-drop platform. It has a rear door which is designed to be opened in flight for dropping cargo from altitudes below about 8 km. We concentrated on the C-130 as the drop platform in order to establish feasibility (see Section 4.6).

The object released from the C-130 would be a parachute/pallet/package (PPP) assembly as described in Ref. 15 and shown in the sketches of Fig. 4.2-2. The PPP assembly could use a number of parachutes; we selected two 5-m parachutes having a drag coefficient of 1.35. The PPP assembly we analyzed had a mass of 2.8 Mg (for a PAT package mass of 2.6 Mg). At a predetermined altitude, the parachute/pallet combination is disconnected from the package and the package free-falls, with a reduced horizontal velocity, away from the parachute/pallet.

The PPP assembly would be released from a C-130 aircraft flying into the wind to achieve a minimum ground velocity. Shown in Fig. 4.2-3 are velocity versus altitude curves for a PPP assembly released at 7.6 km from an aircraft flying at 100 m/s ground speed. The curves are for one, two, and three 5-m diameter attached parachutes and a windless condition. The curves indicate that after descending about 500 m, the PPP assembly horizontal velocity changes slowly.

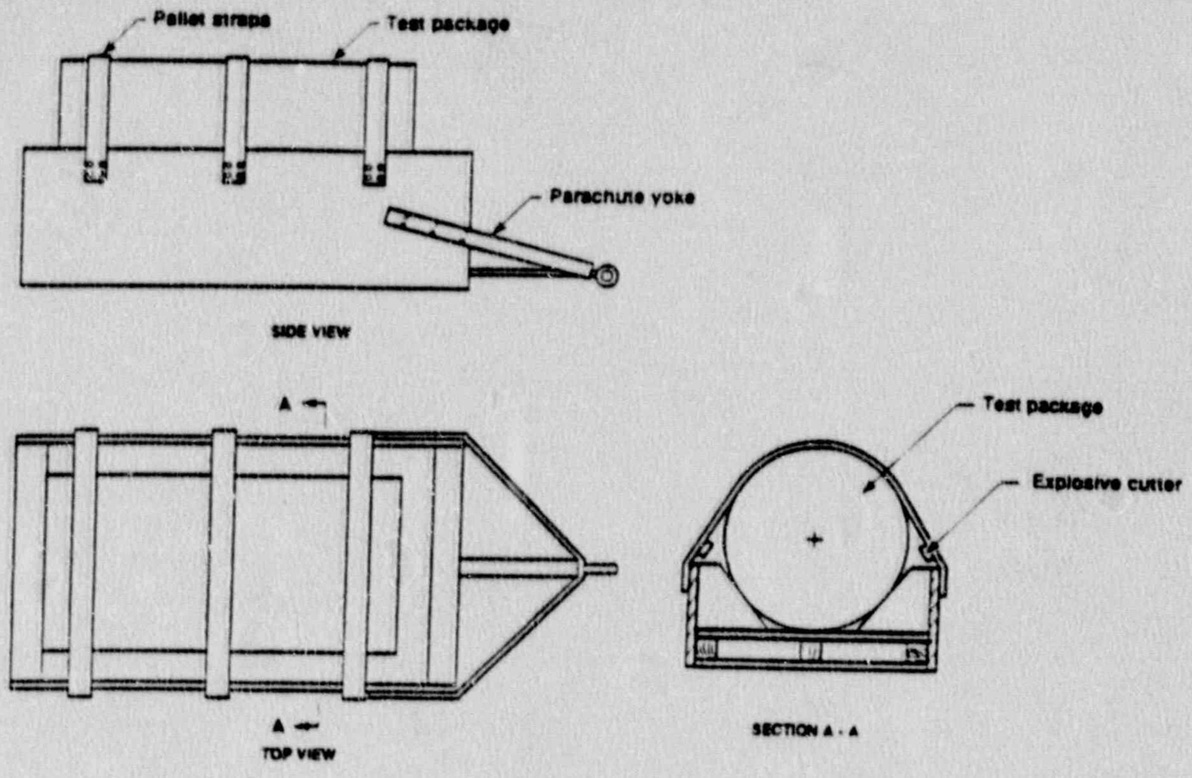

Fig. 4.2-2. Conceptual sketches of a PPP assembly.

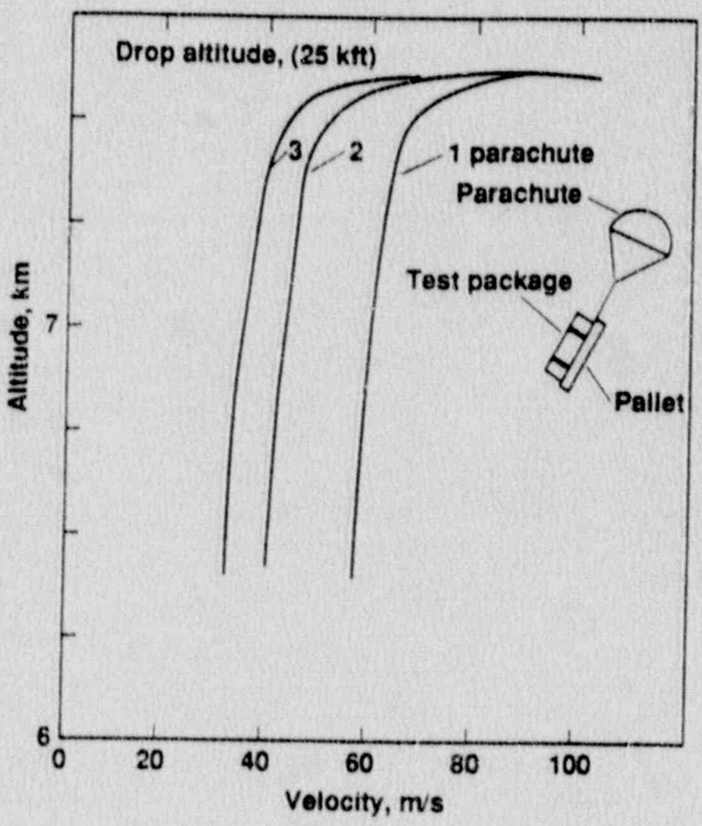

Fig. 4.2-3. Velocity of parachute/pallet/package (PPP) assembly. Aircraft ground speed is 100 m/s.

We considered the case of releasing a PPP assembly from an aircraft flying into the model wind at 77.7 m/s ground speed. (This corresponds to an indicated airspeed of 130 kt, which is reasonably low and achievable with a C-130 aircraft.) In this case, the PPP assembly is released at 7.6 km with two 5-m parachutes attached, and the package is dropped at 7.0 km. Figure 4.2-4 shows the horizontal displacement for this case to be about 1 km. Note that the wind causes the package to be displaced in a direction opposite to the aircraft flight direction. If the package were dropped from the aircraft without the benefit of the drag parachutes, its horizontal displacement would be about 3 km.

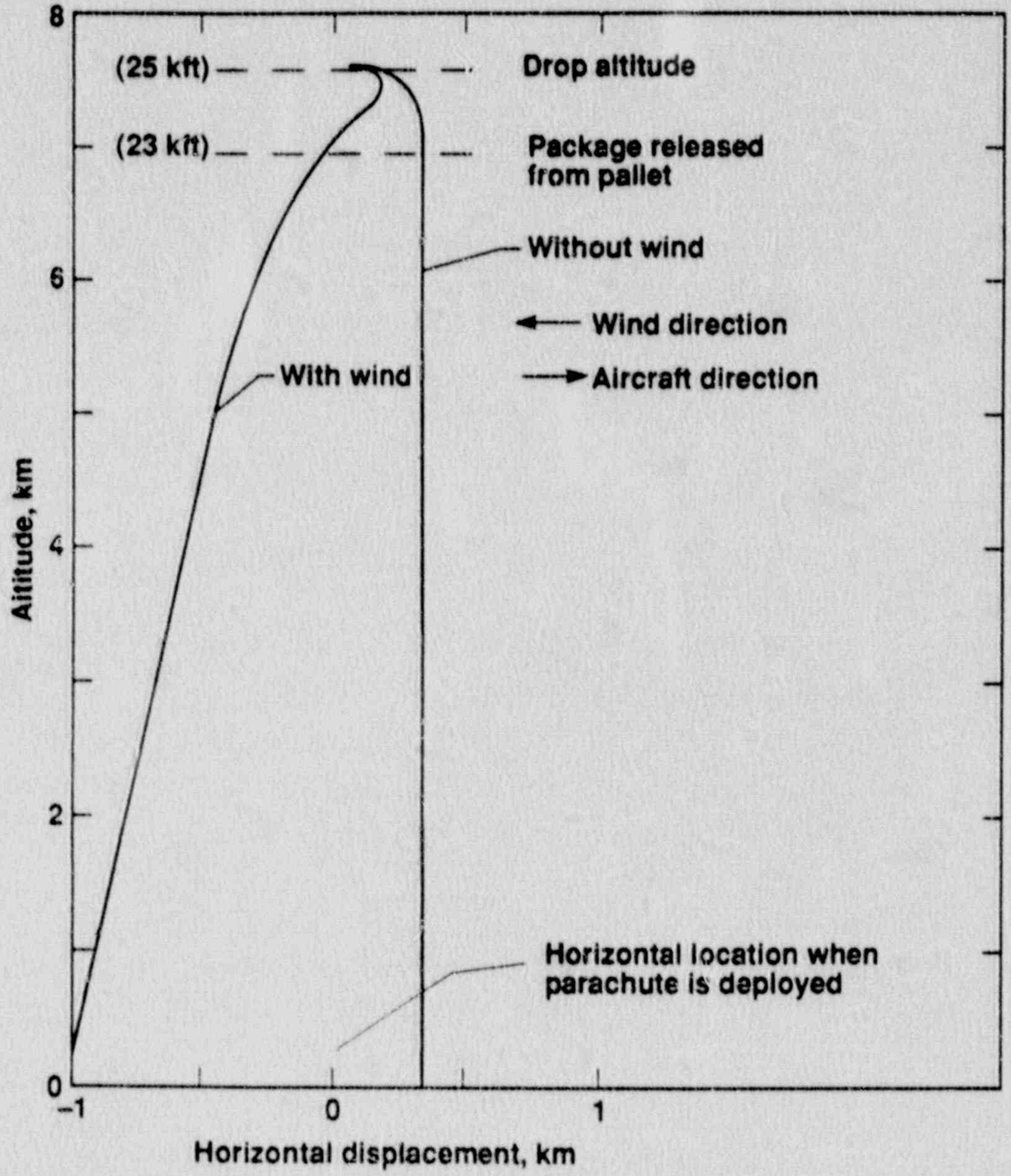

Fig. 4.2-4. Horizontal displacement of the basis PAT package dropped from a PPP assembly released from an aircraft flying into the model wind. Aircraft ground speed is 77.3 m/s; package-drop altitude is 7 km.

Figure 4.2-4 includes a curve for the same aircraft conditions but without wind. In this case, the aircraft ground velocity is 100 m/s. The horizontal displacement is in the same direction as the aircraft direction and considerably less than with the model wind acting.

4.3 Impact Area Requirements

The Law (see Appendix 1) does not specify the impact surface for the package-drop test. This omission leaves two important characteristics to be defined: (1) impact surface elevation; and (2) geo-technical properties of the impact surface. A third important characteristic—a safety issue—is the size of the impact area required. The latter is a second tier requirement that must be generated from analysis of the test phenomena. We examined impact area size because of its implications on feasibility.

4.3.1 Impact Surface Elevation

We have assumed that the impact surface elevation can be any convenient value that allows the desired impact velocity. Figure 4.3-1 shows the envelope of acceptable impact area elevation for a maximum cruising altitude of 13.75 km (Boeing 747-400) as a function of package-drop altitude for the basis PAT package (Section 3.2). For example, from Fig. 4.3-1, it is necessary to choose an elevation between 0.5 and 2.8 km to allow the impact speed to exceed sea level impact speed from maximum cruising altitude of a Boeing 747-400 (13.75 km, Ref. 14) for a package-drop altitude of 7 km. There are many test ranges in the U.S. that could provide the required impact elevation. (It should be noted that the lower branch of the curve in Fig. 4.3-1 is identical to the curve in Fig. 4.1-4.)

4.3.2 Geotechnical Properties

It appears reasonable to require that the geotechnical properties of the impact area for the drop test be equivalent to those at the PSA Flight 1771 crash site. This will provide consistency in geotechnical properties between the package-drop and aircraft-crash tests.

4.3.3 Impact Area Size

In order to assess the size of the area required to assure that the package impacts within it, we performed an impact-point accuracy analysis based on the drop method described in Section 4.2. The complete analysis is reported in Ref. 15. The results are summarized below.

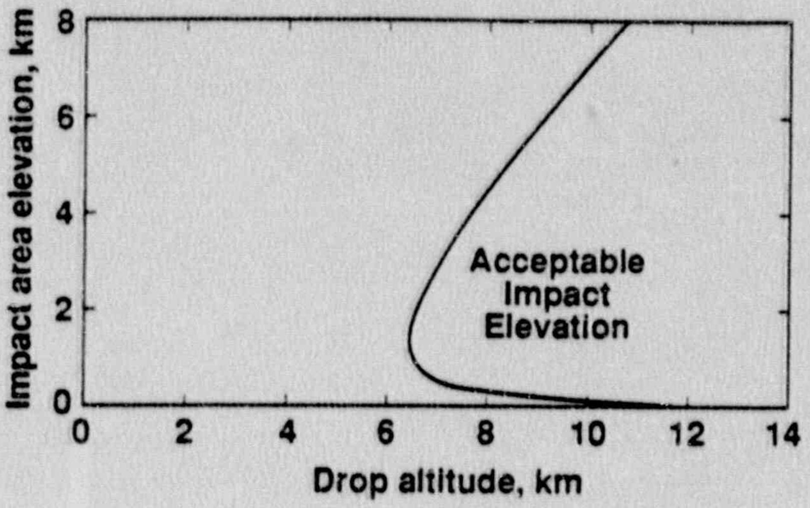

Fig. 4.3-1. Acceptable impact elevations to achieve impact velocities which exceed the sea level velocity for free fall from 13.75 km.

4.3.3.1 Drop Scenario

The C-130 drop aircraft is flown with partially extended landing flaps to achieve a reduced airspeed: e.g., 100 m/s [194 kt TAS, 130 kt indicated airspeed (IAS)] at 7.6 km altitude. Under these conditions, the aircraft pitch angle is slightly positive (+3°, nose-up) to facilitate the release of the PPP assembly out the rear cargo door. The PPP assembly is supported by an inclined roller platform, and it is ejected with an air cylinder to increase its exit velocity. Minimizing exit time reduces the relative ground velocity of the PPP assembly and improves the probability that the PAT test package will impact at the desired location.

Prior to the drop, air density and altitude profiles of wind velocity and direction are measured. These data are used in the computer code that predicts the PAT test package trajectory and impact velocity. Computations are performed to determine the required aircraft direction and release altitude. On the way to the predetermined drop point for the PAT test package, the C-130 aircraft is flown at the predetermined altitude, speed, and direction (into the wind so that the ground speed will be reduced). A ground radar tracking system in communication with the aircraft is used to direct the aircraft to the drop point. The rear cargo door is opened and the primary cargo tie-down latches are released. These events would be initiated, most likely, from a control panel aboard the C-130 aircraft.

When the aircraft reaches a prescribed location in airspace, secondary holding straps are released and the air cylinder is actuated remotely. The PPP assembly is ejected from the aircraft, the parachutes are deployed, and the timing device is activated. The parachutes slow the PPP assembly to a low velocity. After a predetermined time delay, explosive cutters on the pallet are actuated and the PAT test package falls free of the pallet and parachutes.

4.3.3.2 Impact Point Accuracy Analysis

Nominal parameter values and conditions were assigned to the drop scenario for the impact-point accuracy analysis listed in Table 4.3-1. We used engineering judgement to assign error values for each of the nominal parameter values. These are listed in Table 4.3-2. On the basis of these values, lists of constants and random error variables were prepared and used with equations developed to describe the package coordinates as a function of time.

Table 4.3-1. Parameter values and conditions for impact-point accuracy analysis.[a]

	Parameter/condition	Value
1.	Aircraft true airspeed	99.8 m/s (195 kt)
2.	Aircraft heading is into the wind	
3.	Aircraft ground speed	77.3 m/s (150 kt)
4.	Aircraft altitude	7.62 km (25,000 ft)
5.	Wind velocity at altitude of 7.62 km (25,000 ft)	22.2 m/s (43.7 kt)
6.	Wind velocity at altitude of 10.67 km (35,000 ft)	45.7 m/s (89 kt)
7.	PPP assembly exit velocity relative to the aircraft	1 m/s
8.	Reaction time of engineer to release PPP	0.5 s
9.	Time from PPP assembly release to parachute deployment	3 s
10.	Time from parachute deployment to package release	18 s
11.	Package velocity at drop from pallet	46.7 m/s
12.	Package direction of travel on drop from pallet (from horizontal with respect to aircraft heading)	117°
13.	Package altitude on drop from pallet	7.01 km (23,000 ft)
14.	Horizontal distance from PPP assembly release to parachute deployment	232 m
15.	Horizontal distance from parachute deployment to package drop	-85 m[b]
16.	Horizontal distance from package drop to impact	-894 m
17.	Total horizontal distance from PPP assembly release to impact	-979 m
18.	Pallet weight	100 kg
19.	Package weight	2,600 kg
20.	Package diameter	1.2 m
21.	Package length	2.5 m
22.	Drag parachute diameter (deployed)	5 m
23.	Number of drag parachutes	2
24.	Maximum deceleration on package during drop	2.4 g
25.	Ground impact elevation	1,220 m
26.	Package impact velocity	208 m/s

[a] Items 7–9 and 17–21 have assumed values; other values are based on results of analyses or demonstrated performance.

[b] A negative distance means a direction opposite to the aircraft flight direction.

Table 4.3-2. Half-band error values for impact-point accuracy analysis.

	Parameter/condition	Value
1.	Aircraft heading	1/2°
2.	Aircraft altitude	30 m
3.	Aircraft true airspeed	5 m/s (10 kt)
4.	Aircraft location (3-D space) (at time engineer receives signal to release PPP assembly)	60 m
5.	Reaction time of engineer to press release button	0.5 s
6.	Time for PPP assembly to exit the aircraft and parachutes to be deployed	1 s
7.	Activation of timer for explosive cutters	0.2 s
8.	Run time of timer to fire explosive cutters	0.2 s
9.	Velocity of test package when released from pallet	10 m/s
10.	Direction of test package when released	10°
11.	Altitude of test package when released relative to aircraft (velocity, direction, and altitude errors account only for uncertainties in the parachute trajectory calculations)	30 m
12.	Wind velocity	7 m/s
13.	Wind direction	30°
14.	Calculation of impact point (accounts for uncertainties in the method and data used in the package trajectory calculations)	100 m

The location of the actual impact point relative to the desired impact point was characterized schematically (Ref. 15). Both triangular and uniform error distributions were calculated, and 50,000 drop sequences were simulated. The resulting "miss" distance distributions are listed in Table 4.3-3 and plotted for the triangular error distribution, in Fig. 4.3-2.

Table 4.3-3. Impact-point accuracy distribution for nominal triangular and uniform components.

		Impact-point accuracy (m)	
Distance percentile, %		Triangular	Uniform
1		49	62
5		110	137
10		157	196
20		229	284
30		290	354
40		347	415
50		402	471
60		459	525
70		522	576
80		591	628
90		681	699
95		750	764
99		881	885
Deviations:	Average	413	461
	Standard	198	191
	Maximum (in 50,000 drops)	1260	1140

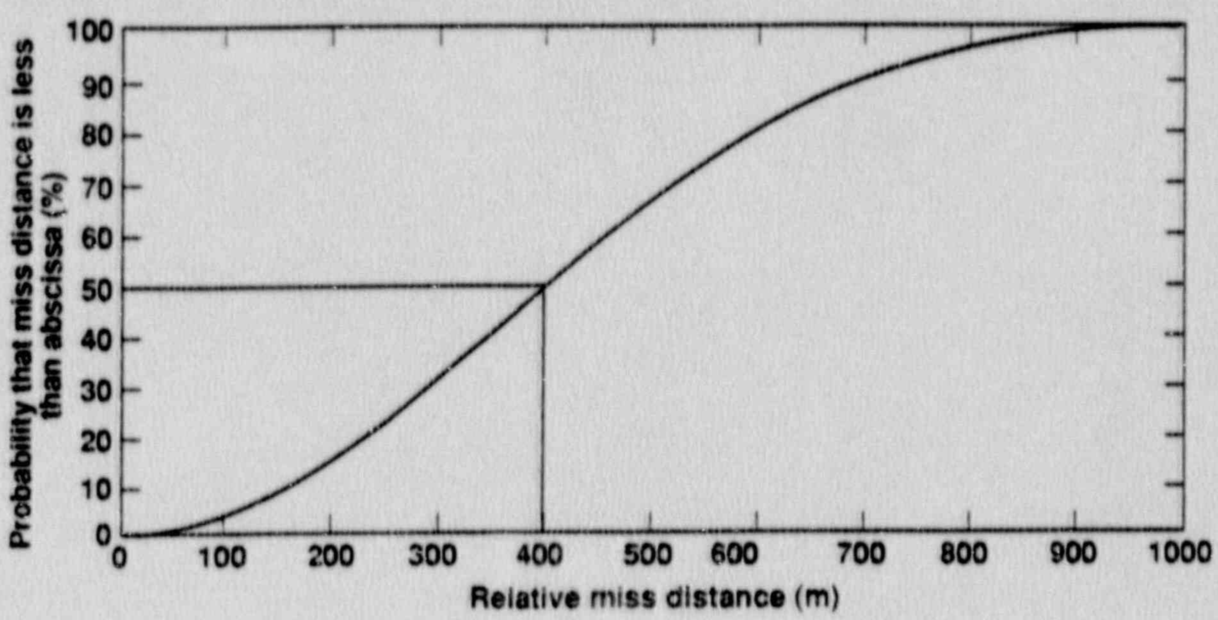

Fig. 4.3-2. Calculated probability as a function of "miss" distance for triangular error distribution.

For this selected drop test scenario, the probability that the package will impact within about 900 m of a designated target is 99%. This distance is reduced to about 700 m for a 90% probability.

A sensitivity study indicates that the test parameter errors having the greatest effect on the impact-point accuracy are errors in wind velocity and direction and errors in test package initial velocity and direction. Therefore, reducing these errors would have the most influence on improving impact-point accuracy.

Performing practice drops could improve overall accuracy of the drop test and confidence in achieving good accuracy. If test conditions and results of the practice drops could be measured and used in conjunction with the aerodynamic analysis code (Ref. 13), a correction of the PPP assembly drop point could be determined and used to modify the drop scenario.

The calculation method and equations in our impact-point accuracy analysis are generally valid, and they could be used to analyze alternate package-drop methods.

4.4 Evaluation of Test Results

After the PAT test package impacts the surface, two situations must be assessed and evaluated to determine whether package-drop test results are successful: (1) validity of the test; and (2) integrity of the package.

4.4.1 Test Validity

As specified by Ref. 7, the test plan that is to be provided to NRC for the drop test will include analyses and discussion of how the important test parameters will be obtained and how they will be measured. Where specific values are to be obtained in the package-drop test, we generally specified the limiting value in Ref. 7—a value with an implied unilateral tolerance. We believe that meeting those values will satisfy the requirement of the Law. Although we did not specify accuracy requirements for analytical results or for measurements pertaining to the test, Ref. 7 specifies that resolution and accuracy of the measurements are to be defined prior to the test.

As part of the approval of the test plan, which is required before the package-drop test is conducted, it will be necessary to evaluate the accuracy of the drop trajectory analyses. This evaluation will include a review of the planned instrumentation and expected resolution and accuracy of measurements to be made. With this information, a procedure for determining the test validity can be readily prepared. The package-drop test should be considered to be a valid test if the reduced test data, evaluated according to the test validity procedure, satisfies the test criteria as stated in Ref. 7 (or a subsequent revision).

4.4.2 Package Integrity

Given a valid package-drop test, it is then necessary to evaluate whether the integrity of the package meets the acceptance criterion stated in Ref. 7. The procedure for evaluating package integrity will be described in detail in the test plan and subsequently approved by NRC. From the results obtained by following this procedure, a determination can be made by NRC whether the container released its contents during testing.

4.5 Package Drop Test Criteria

Draft criteria for the package-drop test are included in the interim report, Ref. 7. They are also listed, in part, below. NRC plans to issue these criteria for public comment at the beginning of Phase II of the PATC program (see Section 1).

Programmatic

- NRC reviews and approves documentation.
- NRC determines safety of package design.
- Applicant provides certain prerequisites.
- Applicant prepares and documents test plan and certain studies.
- NRC has option to witness test.
- Test conductor is not specified.

Technical

- Test package is a replica of proposed PAT package.
- Surrogate plutonium contents are nontoxic.
- Proposed cargo aircraft and maximum cruising altitude are identified.
- Impact velocity is greater than at sea level for drop from maximum cruising altitude.
- Drop orientation is uncontrolled.
- Package altitude, velocity, orientation, and time at start and end of free-fall are measured.
- Impact area elevation is above sea level.
- Impact area size is specified.
- Geotechnical properties at impact location are equivalent to PSA Flight 1771 crash site.
- Only one drop test is conducted.
- Acceptance is based on less than A_2 quantity release in one week.

4.6 Drop Test Feasibility Assessment

We assessed the technical feasibility of satisfying the package-drop test criteria by describing an example drop test. The assessment (Ref. 16) is based on supporting analyses, available equipment, technology, and test ranges that would be suitable for conducting the test.

The principal tasks of the package-drop test are identified in Ref. 16, and methods for accomplishing the tasks are also suggested there. At least one of several candidate test ranges is considered to be an acceptable test site, a C-130 aircraft is a suitable drop-test aircraft, and conventionally used tracking radar and cinetheodolite cameras are suitable equipment for tracking the test package during free fall and measuring its trajectory parameters. From our assessment, we conclude that conducting the package-drop test according to the criteria specified in Ref. 7 is technically feasible. Table 4.6-1 summarizes the items that were addressed and corresponding assessments that lead to this conclusion.

Table 4.6-1. Summary of technical feasibility review of PAT package-drop test.

Topic	Remarks
1. Geotechnical properties	Required properties expected to exist at several candidate test ranges. Measurements of selected target area are needed.
2. Safety	All requirements achievable at several candidate test ranges.
3. Accessibility	Acceptable at several candidate test ranges.
4. Weather	Suitable at several candidate test ranges.
5. Environmental impact	Will not be an issue at several candidate test ranges.
6. Services	Required services available at several candidate test ranges.
7. Test package modifications	Not needed.
8. Surrogate plutonium	Acceptable materials available; selection must be made.
9. Test package ballistics	Computer code available. Ballistic properties of package are needed.
10. Drop altitude	Can be lower than maximum cruising altitude of cargo aircraft.
11. Test aircraft	C-130, B-52, or helicopter aircraft would be acceptable, depending on drop altitude.
12. Aircraft modifications	Not needed. Instrumentation, data recorders, and package release device will probably be needed.
13. Package drop	Can be done with C-130, B-52, or helicopter aircraft using drag parachute and timed release device. Impact accuracy is acceptable.
14. Drop measurements	Cinetheodolite cameras with tracking radar can be used.
15. Package recovery	Test instrumentation can be used to locate; conventional equipment can be used to recover the package.
16. Package testing	Leakage testing applied to PAT-1 package can be used.
17. Rehabilitation of impact area	Conventional equipment can be used.
18. Reliability	Expected to be high; analysis needed to assure success.

5. AIRCRAFT CRASH TEST

Section 5062 of Public Law 100-203 (see Appendix 1) requires in paragraph (b)(2)(B) that certification testing of a proposed PAT package must include a crash test of an aircraft fully loaded with PAT packages, unless other prescribed procedures apply (i.e., the provisions that are the focus of Project 1 as briefly described in Section 1). The crash test must replicate or exceed the conditions surrounding the crash of PSA Flight 1771, defined by NRC (Ref. 8) to be the worst-case accident.

We believe that the aircraft-crash test criteria (Ref. 7) that we developed satisfy the requirement as stated in the Law. Material in this section is organized to correspond with Project 2 subtasks that are related to the aircraft-crash test. Additional information on overall aircraft-crash test feasibility is presented at the end of this section.

5.1 Aircraft Crash Test Parameters

We established aircraft-crash test parameters to replicate the crash of PSA Flight 1771. As discussed in Section 2, a considerable effort (see also Ref. 9) was needed to quantify the conditions of the basis accident. Ten key parameters that resulted and the values or conditions that we assigned to them are listed in Table 5.1-1. We discuss some of these parameters in more detail below.

The choice of test aircraft and loading arrangement is discussed in detail in Section 5.2. The attitude of the aircraft at impact that replicates the basis accident can be a relatively shallow dive into a steeply sloping hillside or a relatively steep dive into level ground. In either of these situations, the test aircraft is to be in its normal "top side up" attitude. The limit value of the roll angle is set to approximately match the basis accident condition. This limit value could be exceeded with negligible effect on test validity provided that the nose of the test aircraft strikes the ground sufficiently before its lower wing tip.

Table 5.1-1. Aircraft crash test parameters.

Parameter	Value
Impact attitude	Nose down
Roll angle	Less than 10°
Fuselage incidence angle	Less than 10°
Trajectory angle (with surface)	60 to 90°
Impact inertial velocity	282 m/s
Impact elevation	Sea level or above
Surface material	Intensely weathered and fractured shale and sandstone
Aircraft type	As planned for plutonium shipments
Cargo arrangement	As planned for plutonium shipments
Fuel loading	Minimum sufficient for test operation

The value of the trajectory impact angle and the fuselage incidence angle could not be precisely defined as a result of our studies. BAe concludes that the fuselage incidence angle was about 3° at impact, and any greater value must be accounted for by errors in the recorded data. Our analysis of the FDR data, however, yields a considerably greater difference between the pitch angle and the trajectory angle as computed from FDR data. The computation requires the use of aircraft velocity as well. We resolved this discrepancy by specifying the average of the recorded pitch angle at impact and the calculated average trajectory angle over the last four seconds of flight (see Section 2 or Ref. 9).

Reference 7 specifies the geotechnical properties of the impact area in a qualitative manner (see Table 2.3-2). To experienced geologists, this method of definition is relatively explicit. Based on our description, they will be able to judge, the geotechnical similarity of a proposed impact area to the basis accident crash site. Confirmatory quantitative values of the properties that we obtained at the crash site are given in Ref. 7 to assist in detailed assessment of the proposed test area.

Only the amount of fuel required for safe and reliable test operations should be loaded on the test aircraft. This provision replicates the condition of the basis accident in that eyewitness accounts and the residual debris indicate that most of the fuel that burned was airborne (Ref. 9). Although a more intense fire would not be expected in the aircraft-crash test even if the test aircraft were fully fueled, photographic coverage of the impact event could be adversely affected. We believe that good impact photography will be extremely desirable. Examination of aircraft accident data (e.g., in the accident data base developed for Project 1) leads us to the conclusion that, for low impact speeds, large fires are possible, while for high impact speeds, only small fires result. Therefore, we chose to limit the size of a fire, if any, as much as practicable.

5.2 Test Aircraft Selection

5.2.1 Test Aircraft Cost

It does not seem reasonable to require that the aircraft used for the crash test have considerable remaining service life. We made inquiries about surplus jet transports and found that there are a number of out-of-service aircraft available. Their costs range according to their service condition and the demand for the type of aircraft. Costs for some types of flyable aircraft are listed in Table 5.2-1. It should be noted that the used aircraft market is volatile, which makes aircraft prices variable. For example: the recent decision by the Air Force (Ref. 17) to buy used Boeing 707s for additional surveillance aircraft is almost certain to increase their market price.

Table 5.2-1. Approximate cost of flyable surplus aircraft (mid-1989 data).

Aircraft type	Cost ($M)
Boeing 707	1.5 - 2.0
Boeing 720	0.5 - 1.0
Boeing 737	4.5 - 6.0
Lockheed 1011	25
McDonnell-Douglas 10	25
Boeing 747	14 - 35

Test aircraft selection cannot be made solely on the basis of minimum acquisition cost. Several technical factors will also enter into the decision of which aircraft to buy. The two most important factors are that the test aircraft provide: (1) equivalence of crash environment for the planned cargo aircraft; and (2) structural integrity prior to impact. We discuss these factors below. Other factors that will increase the overall cost of the test aircraft are refurbishment, maintenance, spare parts availability, needed modifications for remote control or structural integrity, and ease of recertification if necessary.

5.2.2 Equivalence of Crash Environment

We studied briefly the environments that a PAT package would be exposed to in a crash of a Boeing 747 and a Boeing 707 to determine if there are significant differences. We find that there is general equivalence of the crash environments as sensed by a PAT package. There are three aspects to be considered: (1) loading arrangement of the packages; (2) unique aircraft components that could cause puncture or localized high deformation of the package; and (3) hardening of the impact surface resulting from aircraft impact.

Analyses results of the physical arrangement of the packages are reported in Ref. 18. For the nearly nose-on (60°) impact specified for the aircraft-crash test, we discount the significance of lateral loading on the packages. In other words, we believe that there is little lateral package interaction. As a result, we conclude that a single linear series of packages on the aircraft is subjected to essentially the same loading as multiple linear arrays. We analyzed the loading on a linear arrangement consisting of five packages. We performed analyses for two types of impact material having differing hardness. We concluded that the front package is subjected to the highest load at impact, regardless of the number of packages in line behind it. Loading for the front package is 46% higher than for the second package in the case of hard rock impact and 25% higher for weathered rock impact.

From the aspect of loading arrangement on the aircraft, we conclude that crash environment equivalence will exist between any likely cargo aircraft and any test aircraft that can accommodate at least one package.

We also examined the inventory of massive components that are present in the Boeing 747 and Boeing 707 to ascertain differences. We found (Ref. 19) that there are substantially more massive components in the former. For example, a large auxiliary power unit is located in the tail of the Boeing 747, the landing gear is more massive, and so are the flap tracks. When the cargo aircraft is specified, it should be possible to assess its massive components of concern and install those in a physically equivalent (but not operational) manner on another type of aircraft selected for the aircraft-crash test. Equivalence of crash environment should be achievable. A firm conclusion can be made after the cargo aircraft is specified and compared with a candidate test aircraft.

Finally, we examined the issue of impact surface hardening caused by the fuselage on impact (Ref. 18). Simplified models of Boeing 747 and Boeing 707 aircraft were used; the models considered the fully loaded fuselage mass distributed uniformly in a solid cylinder of equivalent fuselage diameter and length. The impact surface material was represented by the two-layer material representative of the PSA Flight 1771 crash site. The results from this simplified treatment indicate that there is not a substantial difference in hardening caused by impact of either aircraft. The Boeing 707 impact shows slightly more soil compaction, slightly higher soil pressure, greater penetration, and roughly equivalent deceleration. Thus, the results indicate that a Boeing 707 test aircraft would provide a slightly more severe crash environment than would a Boeing 747, however we would not expect the package response to be measurably different.

Our overall conclusion is that it should be practical to achieve equivalence of crash environment in a test aircraft that is not the same type as the specified cargo aircraft.

5.2.3 Integrity of Test Aircraft Prior to Impact

As noted in Ref. 9, the allowable flight envelope was exceeded substantially by PSA Flight 1771, and yet the BAe-146 aircraft remained intact until impact. At issue in considering the aircraft-crash test is whether the cargo aircraft would remain intact until impact if it could accidentally suffer an upset equivalent to flying the trajectory required to meet the criteria of Ref. 7. If a Boeing 747 is the cargo aircraft, the outcome is uncertain, especially since probable routes are likely to be mostly over sea level terrain. This is illustrated in Fig. 5.2-1, which shows the flight altitude/ speed envelopes for the Boeing 747-400 adapted from Ref. 14. The (linear) curve V_i represents aircraft EAS to achieve the inertial impact speed that we determined for the PSA Flight 1771 crash. Consideration of the relationships in Fig. 5.2-1 indicates that it may be desirable to test at a lower impact speed than that of PSA Flight 1771. Package loading could be maintained by requiring an appropriately harder impact material.

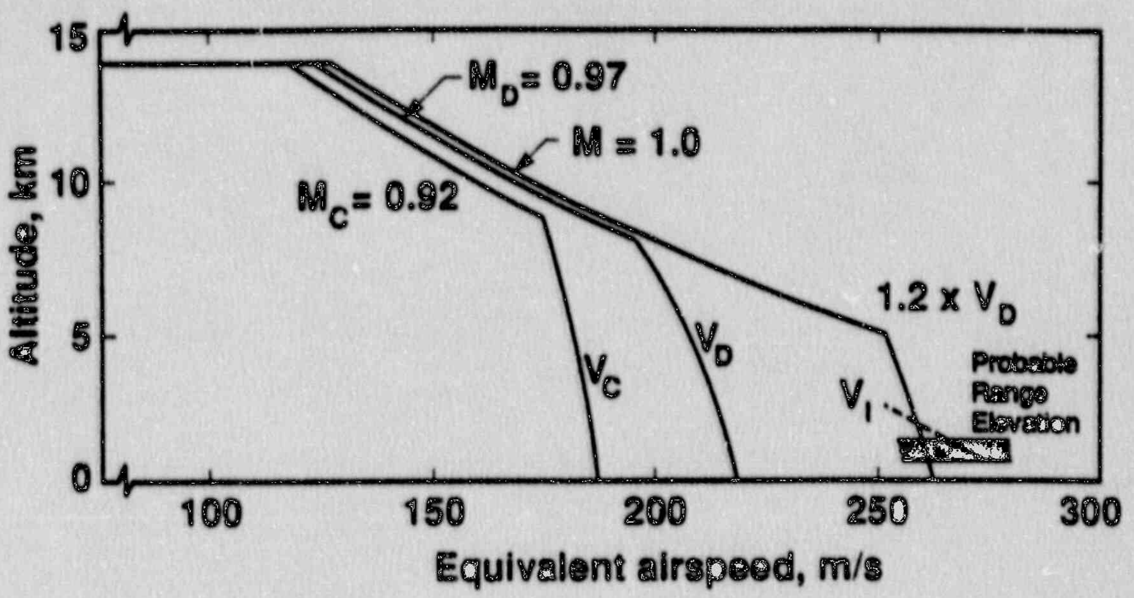

Fig. 5.2-1. Flight altitude/speed envelope for Boeing 747-400 (adapted from Ref. 16) showing relationship to impact environment for aircraft-crash test.

While it is possible to rationalize the uncertainty of the cargo aircraft remaining intact until impact, it is necessary to have a high degree of assurance that the test aircraft has a high probability of successfully impacting at the intended speed. To obtain this assurance, it is necessary to study the design capability of the selected test aircraft in relation to the test conditions. If those characteristics are the same as for the Boeing 747-400, for example, the necessary assurance would require that the test range elevation be at least 1800 m (5900 ft) if the impact speed remains at 282 m/s (548 kt). Candidate test ranges that we visited had lower elevations, as noted in Fig. 5.2-1.

We have found two pertinent examples (we didn't look for more) where aircraft upsets occurred that were severe enough to cause severe damage to the aircraft and yet the aircraft were landed safely. One example is the China Airlines incident near San Francisco, California, in February 1985 (Ref. 20) in which a Boeing 747 dived from an initial cruising altitude of 41,000 ft to 9,000 ft. Because of severe vibration, the FDR provided only intermittent or erroneous data during the descent, and it is unclear what maximum airspeed was reached.

A similar example is reported (Ref. 21) for a Boeing 707 operated by Pan American World Airways in February 1959 on Flight 115 between Paris and New York (with intermediate stops in London and Gander, Newfoundland). The aircraft made an uncontrolled descent from 29,000 ft before recovering at 6000 ft. Although extensive structural damage to the aircraft resulted, it continued its flight and landed safely in Gander. The aircraft was subsequently flown without incident to Seattle, Washington (without passengers) for repair. Airspeed information* is limited because the foil/stylus type analog FDR on this aircraft had run out of metal foil on an earlier flight. Nevertheless, attempts to read the data "indicated that the airspeed reached by the aircraft was equivalent to a Mach number of 0.95" (Ref. 21).

While these examples most likely exceeded normal flight speeds, it is not clear that the flutter-free speeds were exceeded or what the mechanisms were for structural damage. High maneuver loads were certainly present. Buffeting and vibration may be the result of transonic phenomena. Incipient flutter, if present, did not become catastrophic. A thorough study to determine the boundaries of the flutter-free regime for the test aircraft selected will be necessary to assure that the test aircraft remains intact until impact.

5.3 Remote Operation Feasibility

In this section we summarize consideration of the feasibility of converting the crash test aircraft for remote operation to achieve the specified impact conditions. Specifically, these conditions are to: (1) achieve an impact velocity of at least 282 m/s which may be outside the design flutter-free envelope as discussed above; (2) impact so that the angle between the trajectory and the impact surface is a minimum of 60°; (3) impact so that the roll angle is within 10°; and (4) impact so that the horizontal velocity component normal to the vertical plane containing the aircraft trajectory is less than 5% of the impact velocity.

At issue are: (1) the dynamic response of the aircraft and the ability to control the aircraft in flight to achieve the stressing conditions that are required; (2) whether the control architecture provides for autonomous operation or remotely piloted (man-in-the-loop) operation; and (3) whether there is related experience or will new technology be required. We discuss these issues below.

5.3.1 Related Experience

The first large, multiengined aircraft flown without a pilot on board were converted B-17s, called QB-17s. In 1948, these aircraft were taken-off with a pilot who would parachute from the aircraft after reaching the desired flight conditions. These aircraft were flown in a race-track pattern over nuclear weapon tests performed in the atmosphere. Their function was to sample radiation produced by the nuclear weapon test. After sampling, the aircraft were landed remotely and reused on subsequent tests.

The flight control systems for those aircraft were developed by Sperry Flight Systems, which was eventually bought by Honeywell, Inc. Honeywell has converted numerous aircraft into remotely piloted vehicles (RPVs). A partial list includes QF-

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* The weekly paper, the *Gander Beacon*, February 5, 1959, provided passenger film-star Gene Kelly's view: "I'll bet we were doing close to 800 miles an hour straight down."

80, QT-33, QB-47, QF-104, QF-86, QT-38, PQM-102, QF-86F, QF-100, QF-106, QS-55, and QF-104J. The aircraft have included supersonic jet aircraft and fully maneuverable helicopters. The primary application for the most recent drones is for use as a target for air-to-air and surface-to-air missiles. The control architectures for these aircraft have always been of the remotely-piloted vehicle type.

Another major U.S. company that has converted single jet engine aircraft to remotely-piloted vehicles is Tracor Flight Systems. Tracor has converted a number of QF-86, QF-100, and QF-106 aircraft.

A 4-engine jet aircraft (Boeing 720) was modified to an RPV by NASA Ames Research Center, Dryden Flight Research Facility (Ref. 22). The modified aircraft was used for the controlled impact demonstration (CID) test performed jointly by NASA and the FAA (see Appendix 2 for a summary of the CID test).

Thus, we conclude that considerable experience has been gained with RPVs over the last 40 years in pilotless flight of large aircraft. Table 5.3-1 summarizes this experience in an "order-of-magnitude" fashion.

Table 5.3-1. Order-of-magnitude summary of pilotless aircraft control systems (RPVs).

No. of aircraft	No. of engines	Type of aircraft	No. of missions	Time of use
100	4	Propeller bomber	1000	1950
10	4	Jet bomber	100	1960
1	4	Jet passenger	10	1980
100s	1	Jet fighter	1000s	1960-90

Note in Table 5.3-1 that in general, each aircraft converted for pilotless flight performs about 10 missions. This is a measure of the capability of the flight control system to function repeatedly. The end objective in many applications, however, was to destroy the aircraft, so that 10 missions does not necessarily represent a control system limitation.

5.3.2 Autonomous or Remotely Piloted

There are several ways to control aircraft during the crash test. The NASA/FAA aircraft used in the CID was remotely piloted from a ground cockpit. The cockpit instruments included two forward-looking video receivers, attitude direction indicator, radar altimeter, airspeed, altitude rate, engine speed, fuel flow, exhaust gas temperature, and engine pressure-ratio indicators. The data were transmitted from the aircraft to the ground station at a rate of 200 Hz per parameter. The goal was for the aircraft to impact in a defined area at a true airspeed of 78.5 ± 1.3 m/s, with a pitch angle of 1 ± 1°, and a roll angle of 0 ± 2°. The defined impact area was rectangular with these halfside dimensions: ±4.6 m lateral and ±22.9 m longitudinal.

Not all the impact requirements were achieved. The impact speed was 77.9 m/s, the pitch angle was -0.25° and the lateral displacement was +6.1 m. However, the aircraft impacted at a roll angle of -12° and a longitudinal displacement of -86 m (short) of the desired impact point. Even though the pilot had performed 13 remote practice landings, the final RPV flight proved to be a much more demanding task than any of the practice landings. Because all the critical impact parameters were not achieved, the principal test objective—to demonstrate the fire suppressing characteristic of animisting fuel—was not achieved.

The PATC impact criteria (Ref. 7) are more exacting than for the CID test, and we recommend that the final impact be entirely under automatic control on-board the aircraft. A microwave beacon placed at the desired impact point for a terminal homing guidance system in the aircraft appears to be a reasonable approach. (This is similar to a terminal guidance system used for a guided missile.) A miss distance of—at most—a few meters (assuming no severe wind gust) can be expected with this guidance system based on the accuracies attainable with modern surface-to-air missiles.

5.3.3 Dynamic Aircraft Response

No new technology is required to fly a large aircraft with a terminal homing guidance system. The ability to remotely fly a large aircraft has been demonstrated on numerous occasions, and this is not an issue. However all remotely flown aircraft to date have flown within the aircraft's design altitude/speed envelope. As can be seen in Fig. 5.2-1 (which is applicable to a Boeing 747-400), the required EAS at probable test range elevations is well outside the aircraft's never-to-exceed limit, and even beyond the 1.2 x V_D flutter-free airspeed limit.

It may be necessary to augment the existing control systems—rudder, stabilizer, elevator, and aileron actuators—in the test aircraft in order to obtain sufficient control authority. Until the test aircraft is selected, there is insufficient information available to determine the feasibility of converting an existing aircraft for autonomous operation that will achieve the specified impact conditions.

In order to answer the question, it will be necessary to perform a simulation of the selected test aircraft (Ref. 23). Figure 5.3-1 shows a block diagram of the relevant components of the dynamic model to be simulated. To construct the model, it is necessary to have the aerodynamic data and accurate models of the actuators at the flight conditions of interest. It is also necessary to have accurate models of the actuators on the conditions of interest. The actuator models must include the limits of their control authority. The simulation will provide the control authority required by the actuators—rudder, stabilizer, elevator, and aileron actuators. If there is insufficient control authority, augmentation of the existing system will be necessary. For example, it may be necessary to install more powerful actuators.

It will be essential to perform flight simulations to develop the aircraft trajectory that leads to the desired impact conditions. Because of the inherent stability of the aircraft, the trajectory and control surface trim settings must be chosen in such a way that control forces are manageable. An optimum trajectory that provides the desired impact conditions while minimizing control forces can be developed in a flight simulator that represents the test aircraft. We did this in an approximate manner with the aid of an experienced pilot and a Boeing 727 simulator.*

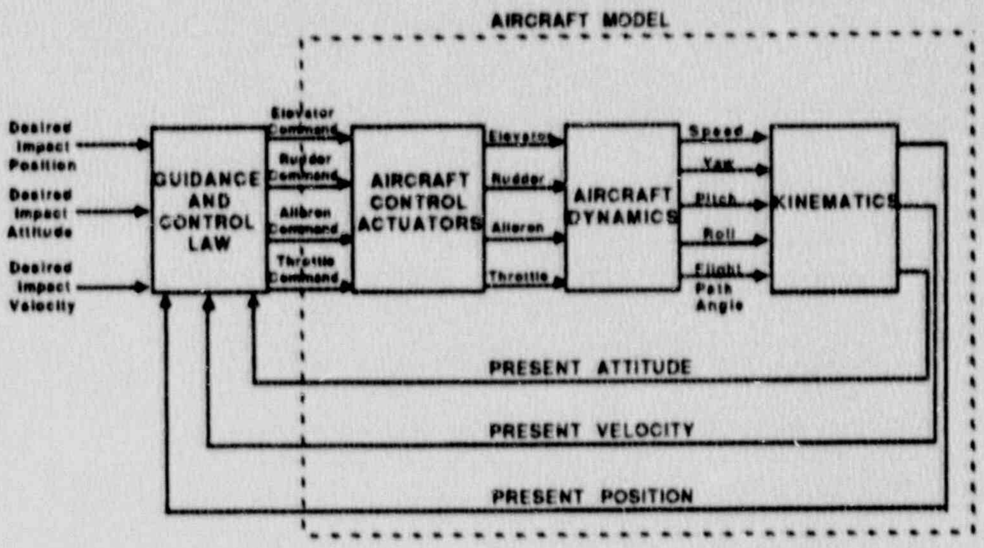

Fig. 5.3-1. Guidance and control law in dynamic performance analysis.

Although there is only one opportunity to perform the crash test, developmental and practice flight tests that will achieve all the specified impact conditions can be performed without crashing the aircraft. We consider this to be necessary. To do this, however, the elevation of the test range (where the crash would eventually take place) must be high enough to accommodate a dive pull-out maneuver with a sufficient safety margin at another location where the surface is at a lower elevation. For example, practice flight tests achieving a dive angle of 60° and an EAS consistent with an impact velocity of 282 m/s at the test range elevation can be performed at a sea-level location other than the chosen test range. Figure 5.3-2(a) shows a typical trajectory for a practice dive. At an elevation, h, above the minimum safety margin above the surface, a pull-up maneuver must be initiated to avoid crashing. Figure 5.3-2(b) also shows the maneuver load as a function of the elevation above the safety

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* We are especially indebted to Barry Scott, FAA, and Bob Shiner, NASA, for their assistance and the use of the Boeing 727 flight simulator at NASA, Ames Research Center.

margin elevation where pull-out of the dive must begin to avoid crashing. The maneuver load is derived assuming a constant velocity turn at 282 m/s. If the test aircraft can withstand 4 g for a short time, a dive at 282 m/s at 60° is feasible at an altitude of 1 km over the minimum safety elevation. A dive of less than 60° may be adequate if the slope of the surface of the test range provides a fraction of the required 60°.

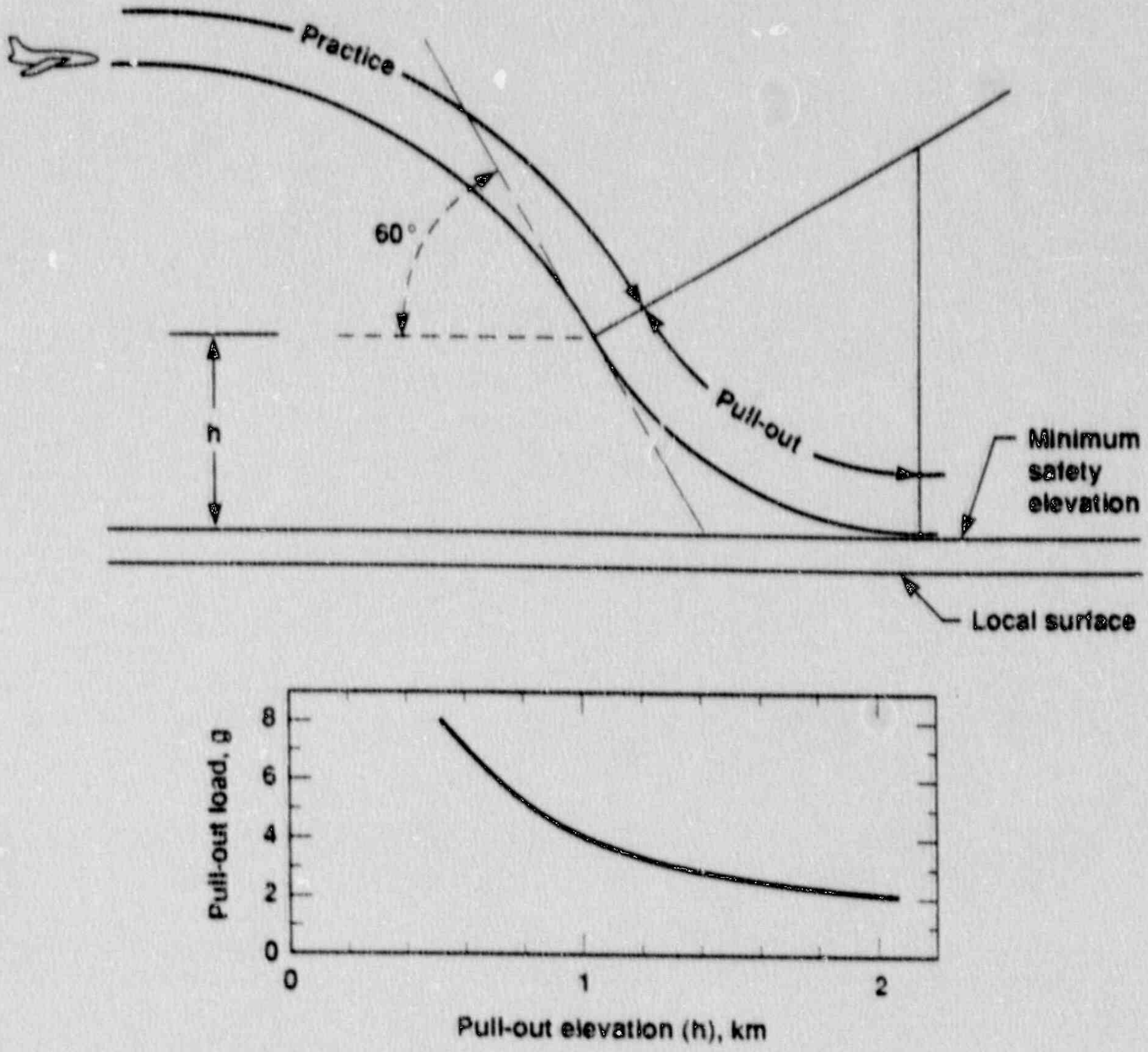

Fig. 5.3-2. (a) Practice dive trajectories; and (b) maneuver loads versus pull-out elevation.

Early development flights with a pilot on board would be required to exercise the control system in a regime that does not highly stress the aircraft. Practice flights of the crash maneuver are also desirable for gaining experience with the behavior of the flight control system before conducting the crash test. These practice flights would be flown without a pilot on board. Unless these practice flights are found to be unnecessary, they place an additional constraint on the elevation of the aircraft-crash test impact location. For example, if the impact location is to be on level ground and a load of 4 g is allowed on the test aircraft, the value of h from Fig. 5.3-2(b) is 1 km. A safety margin of 300 m may be acceptable. In this case, the minimum elevation of the impact location for the crash test must be 1.3 km MSL (~4300 ft).

5.4 Candidate Test Ranges

We visited four test ranges in the western states. Three of these appear to be suitable for conducting the package-drop and aircraft-crash tests. However, our examination of these test ranges was cursory, so even the fourth test range should not be dismissed from future consideration. Our intent was only to establish the existence of at least one usable test range. A systematic selection process should be followed for selecting the optimum test range. We have briefly considered how that process should work.

5.4.1 Test Range Selection

The test range should not be chosen until after the test aircraft is selected, its flutter characteristics are determined, and an aircraft-crash test plan is approved. The process for range selection begins with a global list of test ranges. For convenience, we assume that only U.S. ranges would be used. It would be desirable to conduct the package-drop test at the same range as the subsequent aircraft-crash test, so this should be kept in mind during the selection process. The initial list of test ranges would be reduced on the basis of a five-step procedure:

- Reject on the basis of test range descriptions provided in response to a general letter of inquiry.
- Reject on the basis of response to a specific set of questions.
- Reject on the basis of additional information obtained during site visits.
- Reject on the basis of geotechnical property measurements.
- Accept the best test range that survives the down-selection procedure listed above.

Evaluation criteria would need to be developed to conduct the down-selection in a consistent manner. The objective of the process would be to obtain the best test range in order to ensure a successful (one-time only) aircraft-crash test, while minimizing the cost of the selection process. The cost of test range selection will be minimized by reducing the number of site visits and the number of geotechnical investigations that need to be conducted. Success of the aircraft-crash test will be enhanced if the the package-drop test is conducted at the same test range. In this way, the test group will become acquainted with the range personnel and range procedures during the less critical test. This experience could also be important in establishing procedures for the aircraft-crash test.

5.4.2 Test Range Visits

We visited Edwards Air Force Base (AFB) near Lancaster, California; Naval Weapons Center (NWC) near China Lake, California; White Sands Missile Range (WSMR) near Las Cruces, New Mexico (NWC); and Utah Test and Training Range (UTTR) near Salt Lake City, Utah. On the basis of these visits, we formed the opinion that the package-drop and aircraft-crash tests could be conducted at WSMR and UTTR, possibly at Edwards AFB, and probably not at the NWC.

The higher general ground elevation at WSMR and UTTR make these ranges particularly attractive. WSMR is an extremely busy test range; this gives their personnel broad experience in conducting many different types of tests. UTTR, on the other hand, is more a training than a test range. The management of the range for both UTTR and Edwards AFB is at the latter location. There could be reservations on the part of range management to use the lake beds at Edwards AFB as an aircraft impact location, and the properties of the lakebed are influenced by rainfall. The available area at the NWC is relatively small, the ground is relatively soft, and there may be environmental limitations.

5.4.3 Test Range Geotechnical Characteristics

We performed a brief literature review of geotechnical information for WSMR, UTTR, and Edwards AFB.

The purpose of this review was to consider in greater detail—without the benefit of geotechnical investigations—test range ground conditions that meet the requirements of package-drop/aircraft-crash tests. On the basis of preliminary information, we identified several locations at WSMR and UTTR for further studies. Our information includes rough estimates of *S*-numbers and the geotechnical characteristics for selected locations within the test ranges.

We determined that four locations at WSMR are suitable, and five locations near UTTR seem to be acceptable and may indicate that suitable conditions will be found there. The data from Rogers Dry Lakebed at Edwards AFB indicate that the lakebed is probably not suitable for the aircraft-crash test. None of our findings with respect to test range geotechnical characteristics should be considered to be conclusive.

5.4.3.1 White Sands Missile Range (WSMR)

Pertinent information reviewed for WSMR is given in Refs. 24-27. WSMR is a generally flat, sandy desert with an elevation of about 1.2 km MSL (4000 ft). Mountain ranges that parallel the east and west WSMR boundaries provide more complex outcrop and rock land. The nature of the terrain and the sparseness of ground cover should facilitate prompt recovery and clean-up of flight test instrumentation, crashed aircraft parts, and PAT packages for post-test analysis. To meet the geotechnical requirements of the aircraft-crash test, the following four locations show promising characteristics that warrant further investigation.

- The area close to the North Oscura Range Center. This area is located at the northern part of the range at the intersection of the WSMR Routes #331 and #9. The area consists of shale rock land. This land is about 35% barren shale outcrop, 35% stony land, and 15% each very shallow and shallow soils. The shale outcrop is bedded sandstone and soft shale that in place is capped with limestone. Rock outcrop and stony land dominate the landscape, except in narrow valleys and some irregularly shaped areas. The soil cover in most areas is less than 30 cm. The rock type is similar to that of the PSA Flight 1771 crash site. The *S*-number should be less (harder) than 2.5. The main concern is probably the steep slope of the hill, but this might also be used to advantage.

- The area between the Chupadera Mesa and WSMR Route #333. This large area consists of two types of soil series and mapping units. The south part of the area belongs to the shale rock land (described above); the north part of the area is described as rock land, cool series. The rock land cool series consists mainly of about 35% barren rock outcrop, 30% stony land, and 20% shallow and very shallow soils. The soil cover is less than 15 cm. The *S*-number is estimated to be between 1 and 2.5. High hill slopes are present.

- The foothill area around Rack and Hanford. The area is located southeast of the San Andres Mountains. The area belongs to the so-called rock land, warm series. The land consists of steep, rough foothills and low mountain slopes. The rock outcrop is limestone, acid igneous rock, sandstone, basalt, shale, and gypsum. Limestone generally caps the tops of hills and low mountain slopes. The shallow soils are interspersed between the rock outcrop. Stony land is mostly below but adjacent to the rock outcrop. The *S*-number should be less than 2.5. Accessibility to this location may be a concern.

- The Northrup Strip area. The soil series in this area is termed level gypsum land. This mapping unit consists of level to nearly level gypsum deposits in an old lakebed. The thickness of gypsum over the overlying lacustrine sediments ranges from 0.3 m along the outer margins of the old lakebed to more than 1.5 m near the center. The area may show some gypsum rock land. Low-velocity penetration tests on the geological material (mainly gypsite) showed that the confined compressive strength is about 24 MPa, while the compressive strength increases to 83 MPa with the confining pressure of 0.2 MPa. Poisson's ratio is about 0.18. The in-situ density is about 1920 kg/m^3 with water content of 41%. The penetrability of gypsum land is comparable with the PSA Flight 1771 crash site (S = 2.5 ± 0.5). The material is weaker than intact sandstone/shale at the PSA Flight 1771 crash site. However, because this gypsum land is less fractured, this site may be a suitable location.

5.4.3.2 Utah Test and Training Range (UTTR)

Our review of geotechnical characteristics of UTTR is based on work performed in support of the State of Utah's superconducting super collider proposal, as reported in Refs. 28-30. The proposed sites are the of Cedar Mountain and Ripple Valley regions located on the eastern boundary of UTTR near U.S. Interstate 80. Comprehensive geotechnical studies were performed for both sites. The study involved the evaluation of existing geologic information, soil and rock boring and tests, field mapping, and a seismic exposure study. The resulting data provided a characterization of the site and engineering properties of soils and rocks. The comprehensive soil/rock borings were made along the proposed collider tube (the tunnel is about 85 km in circumference with a 3 m internal diameter), so the exploration program provided a large area of subsurface profile in those regions. The cross-sections on four major directions of the tubes (east, west, north, and south segments) were made, and detailed geotechnical properties of the sites were given.

In general, the soil deposit of the Ripple Valley site is too deep and soft to meet aircraft-crash test criteria. The soils are predominantly fine-grained lake deposits consisting of silts and clays with low strength, and the lake deposit areas apparently do not meet our criteria. However, in the cross-section of the south ring segment, there are two sections of outcrop areas within Wendover Air Force Range where the outcropping area looks promising and warrants further investigations. In the cross-section of the north ring segment, an outcrop area (about 2.25 km in the east-west direction) within Hill Air Force Base Range may also be considered for further investigation. Two mild hill slopes on the Cedar Mountain site area are also selected for consideration In general, several rock outcrop areas within UTTR, as characterized by Refs. 28-30, appear to be harder than the PSA Flight 1771 crash site.

- <u>The outcrop area across the southwest part of the proposed Ripple Valley collider tube near the Boring #21</u>. This outcrop is approximately 3 km in the east-west direction within Wendover Air Force Range. The site consists of a layer of lake deposits and the underlying limestone bedrock. The thickness of the lake deposits is unknown at this time. However, the intact rock strength ranges between 90 and 200 MPa. The block size is about 30 to 90 cm. Fracture spacing ranges from medium to very wide. The deformation modulus is about 69 GPa. Density is about 2600 kg/m^3. The S-number is estimated to be 1.2 to 1.8. The outcrop area is about 16.9 km south of U.S. Interstate 80 (in the direction of the UTTR).

- The outcrop area in the south end of the proposed Ripple Valley collider tube between Boring #10 and #22. The outcrop runs in the north-south direction, crossing the proposed tube. The width of the outcrop is approximately 1.8 km. The site consists essentially of limestone with medium spacing fractures. The block size is small (30 to 90 cm). The density is about 2680 kg/m^3, and the intact rock deformation modulus is about 83 GPa. The S-number is estimated between 1.0 to 2.0. The location is about 13 km south of U.S. Interstate 80 (in the direction of UTTR).

- The outcrop area across the northern part of the proposed Ripple Valley collider tube near Boring #27. The outcrop runs in a southwest-northeast direction across the proposed tube. The width of the outcrop is about 1.6 km. The site consists essentially, of limestone and calcareous sandstone with medium to wide fracture-spacing. Medium-size block limestone has medium to very high strength. The intact compressive strength is about 69 to 200 MPa. The deformation modulus is 48 GPa, and the density is about 2680 kg/m^3. The S-number is estimated in the range of 1.2 to 2.0. The site is about 21 km north of U.S. Interstate 80.

- The area around Boring #P-11 of the proposed Cedar Mountain collider tube. The area is located on the western hill of Cedar Mountain. It appears that the open area has a mild slope, and the area is wide enough for conducting the aircraft-crash test. The site geology consists essentially of sandy limestone and quartzite. The observed characteristics show that rock mass fracture-space ranges from close to wide. The block size of the rock ranges from 15 to 30 cm. The intact rock compressive strength is about 117 to 200 MPa. The density is about 2600 kg/m^3, and the deformation modulus is 48 GPa. We estimate the S-number to be less than 2.5.

- The area around Boring #P-6 on top of Grassy Mountain of the proposed Cedar Mountain collider tube. This southern section of Grassy Mountain appears to have mild slopes on both hillsides. The area is approximately 4.8 km wide. The site consists of limestones and calcareous sandstones. The compressive strength of intact rock ranges from 103 to 290 MPa. The intact rock deformation modulus is about 48 GPa. The density is about 2600 kg/m^3. A large scale of rock fractures ranges from very close to wide with small rock-block size. The S-number is estimated in the range of 0.8 to 1.5. The location is about 10 km north of U.S. Interstate 80 (away from UTTR).

5.4.3.3 *Edwards Air Force Base (Edwards AFB)*

Our information on Edwards AFB, California consists of Automated Cone Penetration test data obtained on several runways in Rogers Dry Lakebed during June 1989 (Ref. 31). The test results from the cone penetrometer were plotted over the section of the tested runways in terms of cone index strength in psi. The test results at each location were then compared to the minimum acceptable value of the California Bearing Ratio (CBR) of 20, which is needed to support shuttle landings. CBR is a semiempirical index of the strength and deflection characteristics of soil that has been correlated with pavement performance to establish design curves for pavement thickness. A CBR value of 20 is equivalent to a bearing strength of 8.3 MPa. The CBR test is performed on a 6-in. diameter by 5-in. thick disk of either compacted or undisturbed soil that is confined in a steel cylinder. The CBR is the ratio (expressed as a percent) of the actual load required to produce a 0.1-in. deflection to that required to produce the same deflection in a standard crushed stone.

Among a total of nine lakebed runways (or shoulders) tested by cone penetrometer, Runway 27 showed that the cone index strength exceeded 27.6 MPa at most test locations. This implies that part of the runway is virtually as hard as concrete and could not be penetrated with a 0.5 in^2-cone. It is a very hard runway. The S-number may range between 2 to 4. In this category of soil, the soil is described as a dense, dry, cemented sand (such as the hard layers in the dry lake playas at some testing and training ranges). It is noted that the tests were conducted in June, the driest and hottest season of the year, when the lakebed may have the highest strength. As seasonal moisture-changes occur, the strength may change and become weaker in the wet season. Even in June, the test results indicate that there are several weak sections on this runway. Thus, the dry lakebed does not seem to be a suitable location for the aircraft-crash test.

5.5 Crash Test Plan Guidelines

We assume that only one aircraft-crash test will be performed. It is extremely important, then, that the planning and execution of the test be extremely well done. In particular, the planning should be subjected to a detailed review at early stages of the project. Only in this manner and with continuing oversight by NRC can the test be conducted successfully (independent of package survival).

With this in mind, we devised guidelines for the preparation of an acceptable aircraft-crash test plan. A list of topics that the test plan must include is specified in Ref. 7 and reproduced below.

1. *Test range description.* Define the selected test range: for example—location, owners, management organization, size, elevation, etc.

2. *Compliance with policies and procedures.* Define applicable policies and procedures that will be required by the test range management and describe how they will be satisfied.

3. *Support equipment, services, and facilities.* Define equipment, services, and facilities that will be required: e.g., electrical power, water, communications, buildings, roads, transportation, moving equipment, operating and service personnel. Define the sources of required support items and how they will be acquired.

4. *Pretest preparations.* Define all site activities that must be completed before the crash test can be performed and describe how these activities will be accomplished: e.g., impact surface preparations; impact area security; aircraft loading; start-up and checkout; aircraft guidance system activation and checkout; practice flights; instrument installation; activation; checkout.

5. *Test procedures.* Describe in detail the step-by-step events and procedures that test personnel will follow when the crash test is performed. The procedures shall address at least the period beginning with assembly and installation of the test packages in the test aircraft and ending with completion of the acceptance test and refurbishment of the impact area.

6. *Instrumentation and data acquisition and reduction.* Describe all measurements that will be made during the crash test and the sensing instruments that will be used to make the measurements. Describe the data acquisition equipment and the data reduction methods that will be used. Also, define resolution and accuracy of the measurements and uncertainty values of the reduced data.

7. *Test aircraft.* Define the aircraft that will be used in the crash test. Describe services, modifications, and added equipment that will be required for the aircraft and how they will be installed and implemented. Present the analyses and results that indicate the aerodynamic and structural capability of the test aircraft to achieve the required impact conditions.

8. *Aircraft flight plan.* Define in detail the aircraft flight plan beginning with initial roll-out to the crash. Define up to what point in the flight plan the test flight can be aborted and the aircraft returned safely. Include alternate plans that can be implemented if necessary.

9. *Impact conditions.* Specify the test aircraft's impact velocity and orientation. Describe how these impact conditions will be achieved: e.g., what type of guidance system will be used in this terminal flight phase, how it will be monitored and controlled, how the aircraft velocity and orientation will be controlled.

10. *Aircraft guidance system.* Describe the type of aircraft guidance system (e.g., remote, automatic, manual) that will be used to control the test aircraft during all phases of practice and test flights. Describe the systems to be installed in the aircraft and on the ground and where the ground system will be located. Describe the method and procedures for operating the systems.

11. *Flight training.* Describe in detail the types and number of flight training sessions, ground and air, that will be implemented to develop a high level of confidence that the aircraft can be controlled as required. Describe in detail each training phase and how it will be conducted. Define the flight personnel qualification standards established by the test range management.

12. *Aircraft recertification.* Define all steps necessary to recertify the test aircraft that may be required by the FAA or any other regulatory agency.

13. *Test packages.* Describe the cargo configuration of test packages that will be used in the test aircraft. Describe the method of loading them into the aircraft and the method of tie-down.

14. *Reliability.* Discuss the reliability analysis performed for the aircraft-crash test and the steps taken to ensure high reliability.

15. *Test package recovery.* Describe how the test packages will be located after the crash and how they will be retrieved. The recovery plan shall take into account the possibility that the test packages may not come to rest at the final impact site and also that they may be out of sight below the ground surface. This implies that a locater device may be needed for each test package.

16. *Acceptance testing.* Describe in detail the process for testing the test packages after the crash test in accordance with Section 2.4.2 to determine whether the inner and outer containers have ruptured. Define the measurements that will be made, the instruments used to make them, and the expected accuracies and sensitivities.

17. *Weather data.* Describe any limitations that weather conditions may impose on test program activities. Define seasonal periods during which these weather conditions can be expected and how they are accounted for in the test plan. Describe weather data that will be needed for the aircraft-crash test.

18. *After-test refurbishments.* Define any after-test refurbishments required for the test site. Describe how they will be accomplished and the acceptance criteria they must meet.

19. *Environmental impact mitigation.* Define possible environmental concerns that could develop from the aircraft-crash test activities and how they will be mitigated.

20. *Schedule.* Provide a time schedule of crash test events from commencement of operations at the test range to final departure from the range. Include all major milestones, such as the following:

- Range occupied.
- Aircraft received.
- Aircraft guidance system installed.
- Aircraft recertification completed.
- Flight training completed.
- Crash site preparation completed.
- Test range safety evaluation completed.
- Test packages delivered and loaded.
- Crash test completed.
- Acceptance testing completed.
- Refurbishment completed.
- Range departure.
- Delivery dates of reports due to NRC.

21. *Test personnel.* Provide an organization chart of personnel who will have key responsibilities during the aircraft test program. List test personnel, their technical disciplines, and assigned responsibilities. Show who is the responsible test director and give the relationships and responsibilities of the test director to the test range management and any other participating agencies.

22. *Safety and security.* Incorporate the results of the safety evaluation required in Section 3.5.1.8. Describe how the operating plans and procedures will be implemented to assure safety during all phases of the crash test.

23. *Emergency plan.* Develop a plan that can be implemented in the event of an accident or emergency condition. Describe how the plan would be implemented should an emergency occur.

5.6 Aircraft-Crash Test Feasibility Assessment

We assessed the technical feasibility of satisfying the aircraft-crash test criteria by describing an example methodology by which the aircraft-crash test can be accomplished. The assessments are based on supporting analyses and available equipment, technology, and test ranges that would be suitable for conducting the test. Our assessment is described in detail in Ref. 32, and summarized below.

For the assessment, we identified methods for accomplishing the principal tasks that must be done to complete the aircraft-crash test. At least one of several candidate test ranges is an acceptable test site, and a Boeing 707 aircraft equipped with a remote control system and having appropriate structural modifications is a suitable test aircraft. Conventionally used tracking radar and cinetheodolite cameras are suitable equipment for tracking the test aircraft prior to impact and measuring its trajectory parameters. Preparation for the test will require the development of a guidance system and the completion of all structural modifications that are needed to successfully fly the aircraft during the conditions preceding the crash. Access to manufacturer's data on the structural and flight characteristics of the test aircraft will be necessary to complete these tasks.

The conclusion of our assessment is that the criteria specified in Ref. 7 are technically feasible. Table 5.6-1 summarizes items that we addressed and corresponding assessments that lead to this conclusion.

Table 5.6-1. Summary of technical feasibility review of aircraft-crash test.

Item	Remarks
Test site	
Geotechnical properties	Required properties expected to exist at the example test range. Geotechnical measurements of impact area needed.
Safety	All requirements achievable at the example test range.
Accessibility	Acceptable at several candidate test ranges.
Weather	Acceptable at several candidate test ranges.
Environmental impact	Will not be an issue at several candidate test ranges.
Services	All required services available at several candidate test ranges.
Test aircraft selection	
Cargo aircraft performance	Analytical tools exist; expert support available; aircraft performance characteristics and structural design details needed.
Test aircraft performance	Analytical tools exist; expert support available; aircraft performance characteristics and structural design details needed. Flight system or structural modifications may be needed if performance during the test is different from the cargo aircraft.
Aircraft equivalence	Need to develop computer models for comparison studies; cargo and test aircraft design details needed. Analytical tools and support available.
PAT test packages	
Modifications	Not needed.
Surrogate plutonium	Acceptable materials available; selection must be made.
Remote aircraft guidance	
Methodology	Simulation and prototype systems must be developed and demonstrated; this is the major task of the test program.
Availability	Several organizations have expertise to develop a system; may be able to modify an existing autopilot system.
Emergency flight termination	
Methodology	Must chose a method agreeable to test range management.
Availability	Several methods have previously been demonstrated.
Postcrash activities	
Recovery of test packages	Conventional equipment can be used.
Package tests	Leakage testing applied to PAT-1 package can be used.
Cleanup and rehabilitation	Services available. Conventional equipment can be used.
Reliability analysis	Needed for assured success.

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Appendix 1
Reprint of Section 5062 of Public Law 100-203

SEC. 5062. TRANSPORTATION OF PLUTONIUM BY AIRCRAFT THROUGH UNITED STATES AIR SPACE.

42 USC 5841 note.

(a) In General.—Notwithstanding any other provision of law, no form of plutonium may be transported by aircraft through the air space of the United States from a foreign nation to a foreign nation unless the Nuclear Regulatory Commission has certified to Congress that the container in which such plutonium is transported is safe, as determined in accordance with subsection (b), the second undesignated paragraph under section 201 of Public Law 94-79 (89 Stat. 413; 42 U.S.C. 5841 note), and all other applicable laws.

(b) Responsibilities of the Nuclear Regulatory Commission.—

(1) Determination of safety.—The Nuclear Regulatory Commission shall determine whether the container referred to in subsection (a) is safe for use in the transportation of plutonium by aircraft and transmit to Congress a certification for the purposes of such subsection in the case of each container determined to be safe.

(2) Testing.—In order to make a determination with respect to a container under paragraph (1), the Nuclear Regulatory Commission shall—

(A) require an actual drop test from maximum cruising altitude of a full-scale sample of such container loaded with test materials; and

(B) require an actual crash test of a cargo aircraft fully [77] loaded with full-scale samples of such container loaded with test material unless the Commission determines, after consultation with an independent scientific review panel, that the stresses on the container produced by other tests used in developing the container exceed the stresses which would occur during a worst case plutonium air shipment accident.

(3) Limitation.—The Nuclear Regulatory Commission may not certify under this section that a container is safe for use in the transportation of plutonium by aircraft if the container ruptured or released its contents during testing conducted in accordance with paragraph (2).

(4) Evaluation.—The Nuclear Regulatory Commission shall evaluate the container certification required by title II of the Energy Reorganization Act of 1974 (42 U.S.C. 5841 et seq.) and subsection (a) in accordance with the National Environmental Policy Act of 1969 (83 Stat. 852; 42 U.S.C. 4321 et seq.) and all other applicable law.

(c) Content of Certification.—A certification referred to in subsection (a) with respect to a container shall include—

(1) the determination of the Nuclear Regulatory Commission as to the safety of such container;

(2) a statement that the requirements of subsection (b)(2) were satisfied in the testing of such container; and

(3) a statement that the container did not rupture or release its contents into the environment during testing.

(d) Design of Testing Procedures.—The tests required by subsection (b) shall be designed by the Nuclear Regulatory Commission to replicate actual worst case transportation conditions to the maximum extent practicable. In designing such tests, the Commission shall provide for public notice of the proposed test procedures, provide a reasonable opportunity for public comment on such procedures, and consider such comments, if any.

(e) Testing Results: Reports and Public Disclosure.—The Nuclear Regulatory Commission shall transmit to Congress a report on the results of each test conducted under this section and shall make such results available to the public.

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[77] Copy reads "full".

President of U.S.

(f) Alternative Routes and Means of Transportation.—With respect to any shipments of plutonium from a foreign nation to a foreign nation which are subject to United States consent rights contained in an Agreement for Peaceful Nuclear Cooperation, the President is authorized to make every effort to pursue and conclude arrangements for alternative routes and means of transportation, including sea shipment. All such arrangements shall be subject to stringent physical security conditions, and other conditions designed to protect the public health and safety, and provisions of this section, and all other applicable laws.

(g) Inapplicability to Medical Devices.—Subsections (a) through (e) shall not apply with respect to plutonium in any form contained in a medical device designed for individual human application.

(h) Inapplicability to Military Uses.—Subsections (a) through (e) shall not apply to plutonium in the form of nuclear weapons nor to other shipments of plutonium determined by the Department of Energy to be directly connected with the United States national security or defense programs.

(i) Inapplicability to Previously Certified Containers.—This section shall not apply to any containers for the shipment of plutonium previously certified as safe by the Nuclear Regulatory Commission under Public Law 94-79 (89 Stat. 413; 42 U.S.C. 5841 note).

(j) Payment of Costs.—All costs incurred by the Nuclear Regulatory Commission associated with the testing program required by this section, and administrative costs related thereto, shall be reimbursed to the Nuclear Regulatory Commission by any foreign country receiving plutonium shipped through United States airspace in containers specified by the Commission.

Appendix 2
Summary of the FAA/NASA Controlled Impact Demonstration Test
by Charles J. Herget and Carl E. Walter

Introduction

In 1984, the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) conducted a controlled impact demonstration (CID) test using a remotely-piloted jet transport aircraft. This Appendix contains a brief summary of the test program as described in Refs. A2-1 and A2-2.

The CID test was conducted at Edwards Air Force Base, California (Air Force Flight Test Center), for the acquisition, demonstration, and validation of technology for the improvement of transport aircraft occupant crash survivability. The objectives of the CID program were: (1) to demonstrate a reduction of postcrash fire through the use of antimisting fuel; (2) to acquire transport crash structural data; and (3) to demonstrate the effectiveness of existing improved seat-restraint and cabin structural systems.

The aircraft used in the CID test was a 4-engine Boeing 720 jet transport manufactured in the early 1960s. The crash scenario was to be representative of a survivable accident, such as could occur following a missed landing approach or an aborted takeoff. The single initial objective of the test was to demonstrate that, under these conditions, an antimisting compound added to the jet fuel would inhibit fire at impact. Additional test objectives subsequently were introduced, and these eventually compromised achievement of the initial objective.

Flight Requirements

The airspeed, sink rate, and pitch angle were selected to maintain fuselage integrity during acquisition of longitudinal and vertical acceleration data at impact. Combining all the CID test objectives into one flight resulted in a desired set of impact conditions, as shown in Table A2-1.

It was further specified that the impact would be with the landing gear in the retracted position, flaps at 30°, and a maximum amount of fuel aboard. With the landing gear retracted, it became necessary to construct "wing-cutter" stanchions in the impact area to provide a mechanism for fuel spill. Thus the aircraft had to impact precisely with respect to these stanchions so as to cut the wings.

Table A2-1. Impact flight specifications and measurements for the controlled impact demonstration (CID) test.

	Specification	Measurement
True airspeed (m/s)	78.5 ± 1.3	77.9
Rate of sink (m/s)	5.2 ± 0.3	5.3
Pitch angle (deg)	1 ± 1	-0.25
Bank angle (deg)	0 ± 2	-12
Heading (deg)	0 ± 2	1.5
Lateral displacement (m)	0 ± 4.6	+6.1 (right)
Longitudinal displacement (m)	0 ± 22.9	-86 (short)

Test Aircraft

The Boeing 720 aircraft is a swept-wing, swept-tail, four-engine, medium-range jet transport. Its empty weight is 44,500 kg, and the structural design gross weight is 92,300 kg. The gross weight at takeoff for the impact flight was 91,000 kg.

Extensive modifications were required to convert the test aircraft from a piloted vehicle (crew of three) to a remotely-piloted vehicle (RPV) while retaining the piloted capability of the crew for RPV checkout. Instrumentation was added to support each experiment on the flight and the RPV systems.

Primary flight controls were ailerons, elevator, and rudder. The ailerons and elevator were controlled by aerodynamic tabs and assisted by aerodynamic balance panels. The rudder was hydraulically powered and assisted by aerodynamic balance panels; however, a manually operated aerodynamic tab backup was provided. The outboard ailerons were designed to stay in the faired position with the flaps retracted and then to operate with increasing authority as a function of increasing flap deflection. Spoilers on the upper wing surface augmented roll control with the inboard ailerons and also operated as speed brakes. Double slotted flaps and leading edge flaps provided lift and drag control for slow-speed flight.

Pitch trim was through a variable incidence stabilizer. Roll and yaw trim were operated through aileron and rudder, respectively. The existing PB-20D autopilot was modified and used to operate as the primary RPV flight control. To eliminate potential failure points, unused portions of the autopilot were deactivated as a part of the modification for remotely piloted operation.

Flight Test Procedure

The primary approach in checking out the Boeing 720 RPV systems was by piloted flight tests. Both the on-board pilot and copilot could disengage all RPV system functions with a disengage switch on their cockpit control wheels.

Prior to the final unmanned flight, 14 piloted test flights were made with the crew aboard. These flights included 10 remote takeoffs, 13 remote landings, and 69 remote approaches (planned test flight aborts). All remote takeoffs were flown from the Edwards AFB main runway, and remote landings were made on an emergency-recovery lakebed runway. During the remotely controlled portions of these test flights, the crew aboard the airplane kept hands off but were ready to take over should the remote control fail.

Remotely Piloted Vehicle System

The existing autopilot was capable of receiving instrument landing system (ILS) radio signal command inputs to the elevator and aileron channels. Replacing the ILS radio signal command paths with uplinked elevator and aileron command signals provided the basic RPV capability. Rudder pedal commands were added to the basic parallel-yaw damper. The autopilot retained its orientation-hold feedback paths so that only uplink commands from the ground were required; that is, no feedback paths from the aircraft were required to be closed on the ground. Both proportional and discrete commands had to be implemented from the ground station. Primary pitch, roll, and yaw commands, as well as the throttle and brakes, were proportional, while flaps, engine fuel shutoff, landing gear up-down, nosewheel steering left-right, and emergency brakes were discrete commands. The ground system was primarily dual-channel for increased reliability; however, some less critical elements were single-channel. The airborne system was simplex or single-channel.

Emergency Flight-Termination System

An independent emergency flight-termination system was installed aboard the Boeing 720 aircraft to ensure that it would not pose a threat to populated areas in the event of any RPV guidance system failure. This system was designed to be isolated, as much as possible, from the on-board Boeing 720 flight control systems. Activation of the emergency flight-termination system resulted in the following actions on board the aircraft:

- Engines 1, 3, and 4 fuel valves were commanded to the "off" position immediately. To retain aircraft electric and hydraulic power, the number 2 engine was programmed to shut down 25 s later.
- Emergency pneumatic brakes were activated.
- Landing gear was lowered.

- Throttles were moved to the idle position.
- Stabilizer was commanded to the maximum leading-edge up (nose down) position.
- Rudder was commanded to full nose right.

The flight-termination command was irreversible, once issued. It was demonstrated during ground tests, but it was not active during piloted flights.

Test Results

The final CID test flight was made on December 1, 1984. Complete results of the test are given in Ref. A2-1.

The aircraft came down with the left wing low, 86 m short of the desired impact point. The number 1 engine struck the ground and forced the aircraft into a 35-40° left yaw angle. Only the right wing at the inboard engine engaged a wing cutter, and the aircraft fuel immediately erupted in flames.

The final RPV flight proved to be a more demanding task for the remote pilot than the earlier practice RPV landings. Not all the impact parameters were achieved. The actual impact conditions compared to the design goals are summarized in Table A2-1.

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