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DRAFT CRITERIA FOR CONTROLLED TESTS FOR AIR TRANSPORT PACKAGES

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Prepared for:
U.S. Nuclear Regulatory Commission

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ENCLOSURE 1

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ABSTRACT

Section 5062 of Public Law 100-203 imposes requirements on plutonium air transport (PAT) packages to be used to ship plutonium from one foreign nation to another through U.S. airspace. The law requires the U.S. Nuclear Regulatory Commission (NRC) to certify to Congress the safety of a PAT package design. The law also requires, for certification of a PAT package design, the performance of an aircraft crash test or controlled tests that develop stresses in the containment vessel greater than would occur during the aircraft crash test. This document presents the draft criteria for the controlled tests.

These criteria are based on the accident conditions in an actual worst-case aircraft accident selected from documented severe aircraft accidents occurring world-wide during the last 38 years. The worst-case accident for impact is considered to be the PSA Flight 1771 crash in December 1987. The impact conditions in the PSA accident have been closely studied and are used as the basis for the controlled test criteria for impact load designed to test packages to the severe conditions required by law. Fire, puncture, and other accident parameters are also considered, and they are determined to be adequately addressed by the test criteria developed to satisfy Public Law 94-79.

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ACKNOWLEDGMENTS

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GLOSSARY

Accident—An event resulting in damage to an aircraft.

Airspeed—Velocity of an aircraft in the direction of flight at the instant of impact.

Applicant—The person making application to the Nuclear Regulatory Commission.

APU—Auxiliary power unit: an aircraft unit that generates primary electrical and hydraulic power.

BAe—British Aerospace Company, Ltd.

Cargo aircraft—An aircraft that is used to transport cargo and is not engaged in transporting passengers.

CFR—U.S. Code of Federal Regulations.

Controlled tests—PAT package qualification tests defined in this document and performed in lieu of the aircraft crash test specified in Subsection 5062(b)(2)(B) of U.S. Public Law 100-203.

Containment vessel—The vessel designed to meet the requirements of 10 CFR 71 and other applicable U.S. federal regulations for plutonium containment during transport.

DOT—U.S. Department of Transportation

Extreme accident—Accidents whose reported conditions exceed NUREG-0360 test conditions.

Fire containment time—The time from initiation of a fire accident until the fire is under control and only small spot fires remain.

Fire extinguish time—The time from initiation of a fire accident until all fire is fully extinguished.

Impact angle—The angle between the longitudinal axis of the fuselage of the aircraft and the representative impact plane. By definition, this angle is restricted to values less than 90°.

Impact velocity—The normal component of the airspeed if the impact angle is less than 30°; the airspeed if the impact angle is greater than 30° or the airspeed is greater than 129 m/s (422 ft/s).

Incidence angle—The angle between aircraft fuselage axis and trajectory.

NRC—U.S. Nuclear Regulatory Commission.

NUREG-0360—An NRC staff document entitled: "Qualification Criteria to Certify a Package for Air Transport of Plutonium."

Package—The protective packaging together with its radioactive contents as assembled for transport.

Packaging—The assembly of components necessary to ensure compliance with the packaging requirements of 10 CFR 71 and other applicable U.S. federal regulations. Packaging may consist of one or more containment vessels, absorbent materials, spacing structures, thermal insulation, radiation shielding, devices for dissipating heat from radioactive decay of the plutonium and increasing aerodynamic drag, and impact limiters. The tie-down system and auxiliary equipment may be designated part of the packaging.

PAT—Plutonium air transport.

PAT package—The package for air transport of plutonium, including the plutonium contents itself, the containment vessels, and all packaging components whose function relates to safety or protection.

PAT test package (or simply **test package**)—The PAT package (containing simulated plutonium) used to perform the tests specified in this document.

PSA—Pacific Southwest Airlines.

RQD—Rock quality designation, a measure (%) of the spacing of preexisting fractures in rock core samples. (See Appendix C.)

SAR—Safety analysis report for packaging. A document prepared by the applicant for submission to the NRC. A SAR provides the technical evaluation and review of the design, testing operational procedures, maintenance procedures, and quality assurance program followed in packaging plutonium for air transport. The purpose of the SAR is to demonstrate compliance with NRC safety standards and all other applicable requirements.

Severe accident—An accident that results in substantial damage or total loss of an aircraft.

S-number—Relative value of the softness (hardness) or penetrability of soil or rock determined by experimental measurement. The depth penetrated by a defined projectile fired at a measured velocity into soil or rock is used in an empirical correlation to determine the S-number. Values of less than 2 are generally found for rock structures; values of 2 to 4 for dry, cemented sand structures. (See Appendix C.)

10 CFR 71—Title 10, U.S. Code of Federal Regulations, Part 71: "Packaging and Transportation of Radioactive Material."

1. INTRODUCTION

The purpose of this document is to define the criteria for the "other tests" specified in Section 5062(b)(2)(B) of Public Law 100-203 (Transportation of Plutonium by Aircraft through United States Airspace, Ref. 1, reproduced in Appendix A of this document). The law pertains to the certification of package designs by the Nuclear Regulatory Commission (NRC) for the transportation of plutonium by aircraft through United States airspace from a foreign country to a foreign country. If approved by the NRC for a specific plutonium air transport (PAT) packaging design, the "other tests" can be performed in lieu of an aircraft crash test in the certification process (Ref. 2). The controlled test criteria in this document are the "other tests."

Standards for the integrity of packages used to ship plutonium and other radioactive materials are specified in 10 CFR 71 of NRC Regulations (Ref. 3) and 49 CFR 100-199 of DOT Regulations (Ref. 4). The standards are based on three main considerations: (1) protection of the public from external radiation; (2) assurance that any release of the contents of a package during either normal or accident conditions of transport will not exceed a specified limit; and (3) assurance that sub-criticality will be maintained.

In 1975 Congress enacted Public Law 94-79 (NRC Authorization Act for Fiscal Year 1976) amending the Energy Authorization Act of 1974 (Public Law 93-438). The text immediately following Section 201 but preceding Section 202 of Public Law 94-79 establishes general requirements and rules for both domestic and import/export shipments of plutonium by air. This portion of Public Law 94-79 provides, in major part, as follows:

> "The Nuclear Regulatory Commission shall not license any shipments by air transport of plutonium in any form, whether exports, imports or domestic shipments: . . . This restriction shall be in force until the Nuclear Regulatory Commission has certified to the Joint Committee on Atomic Energy of the Congress that a safe container has been developed and tested which will not rupture under crash and blast-testing equivalent to the crash and explosion of a high-flying aircraft."

In response to Public Law 94-79, the NRC established a certification program for packages used in air shipment of plutonium. The program consisted of three elements: (1) evaluation of the conditions that could be produced in severe aircraft accidents; (2) development of qualification criteria prescribing appropriate performance and acceptance standards for packages used to transport plutonium by air; and (3) establishment of a series of physical tests and engineering studies for plutonium packages to demonstrate their ability to meet the qualification criteria. The certification program and the qualification criteria to satisfy Public Law 94-79 are described in NUREG-0360 (Ref. 6).

Plutonium air transport (PAT) packages subject to the requirements of Public Law 100-203 must also comply with 10 CFR 71, 49 CFR 100-199, and Public Law 94-79 design requirements. The criteria contained in this document constitute additional confirmatory effort as required by Public Law 100-203.

1.1 Public Law 100-203

Public Law 100-203 enacted by Congress on December 22, 1987, contains Section 5062. Several provisions of Section 5062 are particularly relevant to implementation of the law. Subsection 5062(a) provides, in part, as follows:

> "In General - Notwithstanding any other provision of law, no form of plutonium may be transported by aircraft through the airspace 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). . ."

Subsection 5062(b) contains the following paragraph on testing:

> "(2) TESTING - In order to make a determination with respect to a container under paragraph (1) [Subsection (b)], 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 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."

Public Law 100-203 supplements Public Law 94-79 in that additional design requirements which specifically address worst-case aircraft crash accidents must be developed and met in terms of test criteria. The test criteria contained in this report pertain to the "other tests" stated in the above subsection and they are referred to as "controlled tests." An applicant for certification of a PAT package may select this testing method in lieu of an actual crash test (Ref. 2). If this option is accepted by the NRC, the drop test requirement specified in Subsection 5062 (b)(2)(A) must also be performed in accordance with criteria given in Ref. 2.

Subsection 5062(d) provides for test design as follows:

> "(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."

Subsection 5062(i) provides for inapplicability of the law as follows:

> "(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."

1.2 Development of Criteria

The primary objective of this document is to specify controlled test criteria in compliance with Section 5062 of Public Law 100-203. These tests are designed to cause stresses in the PAT test package that exceed those that the package would experience in a worst-case accident scenario of a cargo aircraft, as specified in Section 5062(b)(2)(B). A consequence of these tests is that they will also cause stresses that exceed those that the package would experience in any previously documented transport aircraft accidents.

In establishing the controlled test criteria, accident data for large commercial jet aircraft were collected and analyzed. All flight phases were considered: ground operations, taxi, takeoff, climbout, enroute, landing approach, and landing. Any of these flight phases can terminate in an accident which results in a *severe* environment for aircraft cargo. The data collection and analysis were limited to historically severe accidents which resulted in substantial damage to or the total loss of aircraft.

The historical accident data are analyzed to assess the probable loading conditions which could be imposed on a PAT package cargo. An initial screening process was performed to identify all historically severe accidents which could have resulted in loading conditions greater than those generated by the test criteria developed to satisfy Public Law 94-79. Severe accidents whose loading condition potentially exceeded those which result from the NUREG-0360 test criteria are considered to be *extreme* and are further analyzed. Results of the analysis indicate that *impact velocity* and the *duration* of an engulfing fire potentially result in the most damaging loading conditions to a PAT package cargo under extreme accident conditions (Sections 2.3 and 2.4). Based on the analysis, the crash of PSA Flight 1771 at high velocity is identified as the worst case aircraft accident which could potentially cause the most damage to a PAT package cargo (Section 2.3). The 3.5-hour engulfing fire which followed the crash of a Boeing 727 aircraft at Doha, Qatar is identified as the worst fire accident (Section 2.4). A probabilistic analysis of aircraft accidents involving impact velocities and/or fires was performed to assess if additional controlled test criteria are required for combined loading conditions (Section 2.5). Further analysis and engineering assessment concluded that only the

PSA Flight 1771 need be considered in establishing the controlled test criteria for compliance with Public Law 100-203.

2. AIRCRAFT ACCIDENT ANALYSIS

2.1 Introduction

Severe aircraft accidents are typically characterized and reported in terms of fatalities, injuries, property damage, and the events that lead to the accident. In developing criteria for controlled tests, the characterization of severe accidents is expressed in terms of the magnitude and frequency of physical loads that could be experienced by a PAT package cargo under accident conditions. Normally, the higher the loading the greater the potential for significant damage to a PAT package and a possible radioactive material release.

In an aircraft accident, both mechanical and thermal loads can impart damage to a PAT package. High mechanical loads caused by impact can cause large deformation of the package such that the containment leaks. High thermal loads caused by fires can cause the pressure in the PAT package to increase and the seals to deteriorate, which can result in the loss of containment. Severe accidents, which can result in the loss of the aircraft frame, usually have high mechanical and/or thermal loads associated with them.

Mechanical and thermal loads depend on the magnitude of the accident loading parameters. The same accident-caused load can occur for various combinations of loading parameters and loading magnitudes. For example, the same force can be generated by a low velocity impact on a hard surface or a high velocity impact on a soft surface. Also, the same thermal load can occur during a short-duration engulfing fire or a long-duration peripheral fire. Consequently, specific mechanical and thermal loading conditions could result from a variety of accident conditions.

Accident loading conditions must take into account many loading parameters, and the conditions must include a wide range of values for each loading parameter. The accident loading conditions can be derived from historical records of aircraft accidents. The aircraft accidents pertinent to this report are severe ones that result in substantial damage or loss of the airframe and that involve large commercial jet aircraft. Estimates of the severe accident occurrence rate and the magnitudes and frequencies of mechanical and thermal loads are presented in the following sections.

2.2 Aircraft Accident Rates

A survey of severe accidents of large commercial jet aircraft was conducted. The survey covered the years 1952 through early 1989. In that time period, there were 548 recorded severe accidents worldwide that resulted in substantial damage or loss of the airframe. These accidents do not include those due to military action, sabotage, terrorism, or those in the USSR. In Table 2-1, the number of severe accidents is listed by year with a break-down by flight phase. Over 91% of the accidents took place during taxi, take-off, climb, landing approach, and landing

Table 2-1. Severe accidents world-wide involving large commercial jet aircraft 1952 - 1989.*

Year	No. of events	Flight Phase: Ground activity	Taxi	Takeoff	Climb	Enroute	Landing approach	Landing	Unknown
1952	1	0	0	1	0	0	0	0	0
1953	3	0	0	1	1	0	0	1	0
1954	2	0	0	0	0	2	0	0	0
1955-1957**									
1958	0	0	0	0	0	0	0	0	0
1959	3	0	0	0	1	0	2	0	0
1960	6	0	0	0	1	0	4	1	0
1961	12	0	0	2	4	1	3	2	0
1962	7	0	0	2	1	0	4	0	0
1963	9	1	0	0	2	3	3	0	0
1964	6	0	0	1	1	1	1	2	0
1965	11	0	0	0	2	0	7	2	0
1966	15	0	0	2	1	2	10	0	0
1967	11	0	0	2	0	2	7	0	0
1968	18	1	0	4	3	1	7	2	0
1969	19	0	0	2	4	1	10	2	0
1970	27	0	0	6	6	0	9	6	0
1971	12	0	0	2	2	2	4	2	0
1972	30	0	1	4	4	3	12	6	0
1973	35	0	0	2	1	3	14	14	1
1974	19	0	1	1	6	1	8	2	0
1975	24	1	0	6	1	0	11	5	0
1976	20	0	0	3	3	2	7	5	0
1977	23	0	2	1	5	0	8	7	0
1978	21	0	0	4	3	0	7	7	0
1979	21	0	0		6	2	7	6	0
1980	27	0	0	3	3	1	11	9	0
1981	16	0	0	2	1	3	3	7	0
1982	21	0	0	2	3	0	5	10	1
1983	28	0	3	6	3	3	8	5	0
1984	10	1	0	2	0	1	2	4	0
1985	14	0	0	5	2	0	6	1	0
1986	14	1	1	3	0	1	4	4	0
1987	20	0	1	5	0	1	5	6	2
1988	24	0	0	4	6	1	10	6	0
1989	19	0	0	4	4	1	7	3	0
Total	548	5	9	82	78	37	206	127	4
Percent		0.9	1.6	15.0	14.2	6.8	37.6	23.2	0.9

---

*Excluding military action, sabotage, terrorism, and USSR flights.

**Commercial jet aircraft not in service.

phases of the flight. Only 6.8% of the accidents occurred enroute. Since there was no correlation between accident frequency and flight distance, it is reasonable to relate the accident rate to the number of departures rather than distance traveled.

In Table 2-2 the number of departures is listed for scheduled airline flights between 1975 and 1984 throughout the world, excluding those in the USSR. The number of departures during this time period was approximately 104 million. However, these flights are for all types of aircraft, including jets, turboprops, and propeller-driven craft. The percentage of large jet aircraft manufactured in western nations is estimated to be 65% (Ref. 7). Based on the data in Table 2-1, there were 211 severe accidents in the 1975 to 1984 time period.

Assuming the fraction of departures is essentially the same as the fraction of large jet aircraft, the severe accident rate per departure can be estimated as follows:

$$\frac{\text{Severe Accidents}}{\text{Flight}} = \frac{\text{Severe accidents involving large jets}}{\text{Number of departures involving all aircraft x Fraction of large jet aircraft}}$$

$$= \frac{211}{104 \times 10^{6} \times 0.65} = 3.1 \times 10^{-6}$$

or, one severe accident is expected to occur approximately every 323,000 departures.

The loading conditions during these reported accidents were analyzed in terms of their potential for damaging a PAT package. The results of the analysis are documented in the following sections.

2.3 Mechanical Loading in Accidents

Mechanical loads include forces caused by impact, puncture, or penetration by strong objects, and crushing by heavy objects. [illegible] of these potential forces must be considered in analyzing accident conditions and possible effects on a PAT package cargo. The primary factors affecting aircraft impact severity are: (1) airspeed, (2) impact angle, and (3) characteristics of the impact surface. Other factors which can affect crash severity include the angular orientation of the aircraft (roll, yaw, pitch), the magnitude of the force needed to collapse the airframe, and the energy-absorbing capacity of the airframe structure.

The expected impact velocity for a given type of aircraft is somewhat dependent upon its characteristics and capabilities, as well as the stage of flight in which the accident occurs. Although crashes can happen while the aircraft is cruising at high speed, most accidents occur during landing and takeoff when the airspeed of the aircraft is lower than at cruising altitude.

Table 2-2. **Summary of all commercial aircraft departures world-wide.***

Year	Aircraft Departures (Millions)
1975	9.649
1976	9.929
1977	10.108
1978	10.379
1979	10.674
1980	10.570
1981	10.087
1982	10.148
1983	10.715
1984	11.261

*Excluding USSR and military flights.

The impact velocity of an aircraft can be resolved into components of velocity normal and tangential to the impact surface (Fig. 2-1). Energy absorption in these two directions can differ significantly. Most aircraft crashes occurring on hard surfaces (such as runways) at impact angles up to 30° are accompanied by a rapid change in pitch angle to align the aircraft fuselage with the impact surface. Without substantial intervening obstacles, aircraft translation in the tangential direction is opposed primarily by frictional forces exerted on the aircraft surface by the impact surface. Although the deceleration pulses transmitted through the airframe under these circumstances are of irregular frequency, magnitude, and duration, the distance traveled by the aircraft before tangential motion is arrested can be quite large, resulting in an average deceleration of relatively low magnitude. If the compressive forces resulting from aircraft interaction with the surface become sufficiently high or if the skidding aircraft were to encounter a substantial obstacle, much of the kinetic energy would be dissipated through buckling and longitudinal collapse of the airframe. This energy-absorption process would occur at modest levels of force and deceleration until the energy absorption capability of the airframe was exceeded and collapse was essentially complete. However, in a high-speed accident, the aircraft undergoes high rates of longitudinal deceleration and collapse and consequent fragmentation. In such an event, the tangential velocity can be high and, therefore, the tangential velocity component must be included in the impact analysis of the package.

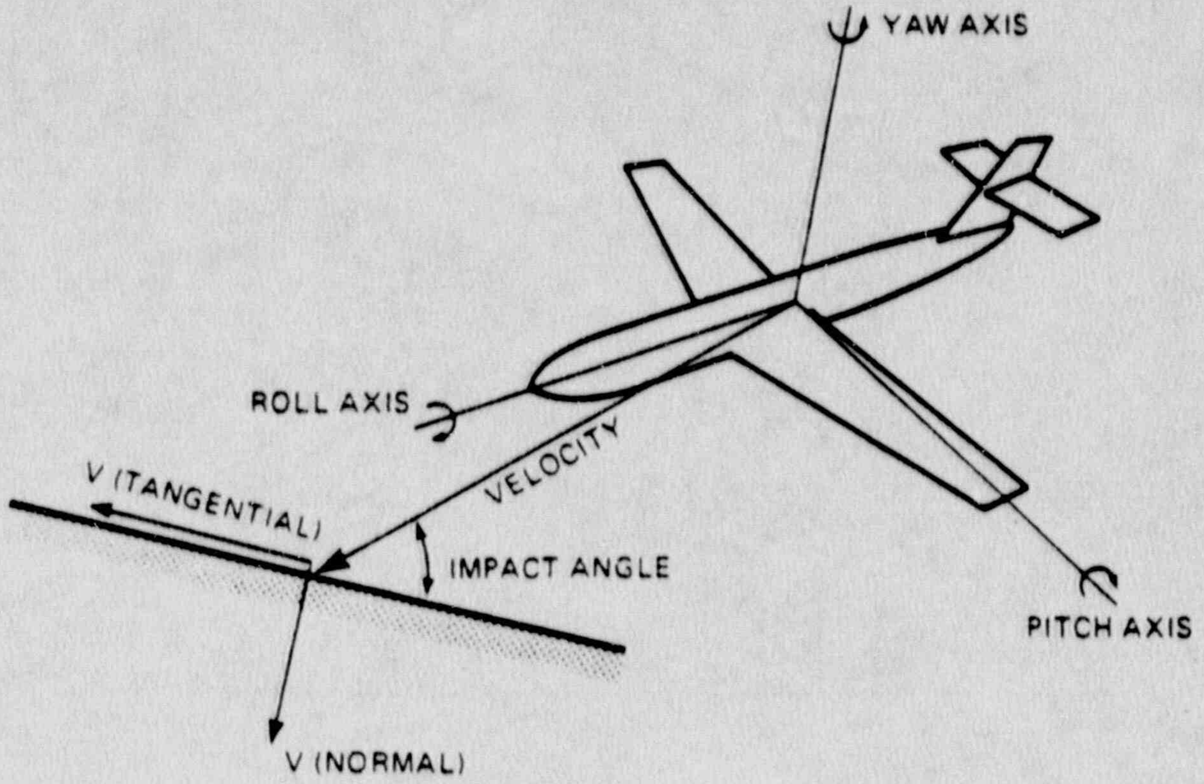

Figure 2-1. Velocity vectors at instant of impact.

In most cases, the normal velocity component is appreciably lower than the tangential component because most crashes occur during taxing, takeoff, or landing at small impact angles. However, in comparison to the tangential direction, velocity changes in the normal direction occur within only a short distance, producing large forces that rapidly decelerate the aircraft. The vertical dimensions of the lower hull and floor system afford little distance for kinetic energy to be dissipated by structural collapse. For this reason, the normal component of velocity is considered to be the parameter of primary significance with respect to impact severity.

Of the 548 accident records reviewed, only 188 contained information on impact velocities and surfaces impacted. These accidents were analyzed to determine if they could result in impact loading conditions worse than those specified in NUREG-0360. In Fig. 2-2 the 188 impact accidents are plotted as a function of the airspeed of the aircraft upon impact. For all practical purposes, the airspeed and direction of the aircraft just prior to impact are identical to their impact values.

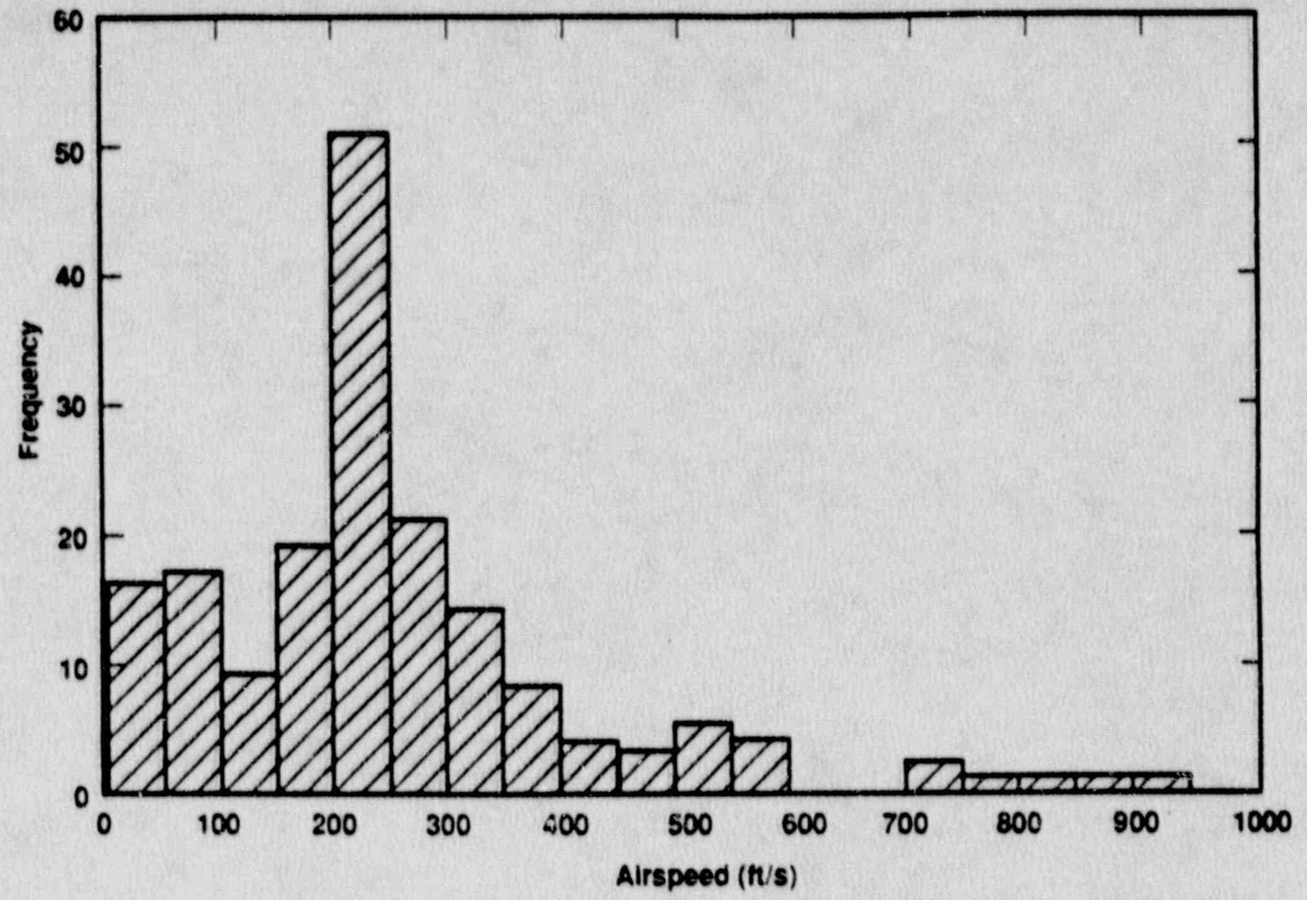

Figure 2-2. **Frequency of accidents and their estimated airspeeds. Only those accidents for which airspeeds can be estimated are included.**

The airspeed data show that 25 out of the 548 severe accidents exceed the 422 ft/s specified in NUREG-0360. These 25 accidents are considered to be extreme and are summarized in Table B.1, Appendix B. These extreme accidents were reviewed and analyzed in detail to determine the impact velocity and types of surfaces impacted. Higher impact loads are generated with higher impact velocities and harder surfaces. From this review and analysis, it was determined that the PSA Flight 1771 crash is the worst case with an impact velocity of 925 ft/s onto a rocky hillside.

A statistical analysis of the impact velocity was performed to predict the probability of exceeding the 422 ft/s specified in NUREG-0360. For airspeeds under 422 ft/s, and impact angles less than 30°, only the normal component of the velocity was used because most of the kinetic energy in the tangential direction would be absorbed by the airframe and would have little effect on a package. Using this analytical technique, the impact velocity for a package involved in an accident can be estimated. In Fig. 2-3 the number of impact accidents is plotted as a function of the estimated impact velocity. A statistical analysis of the estimated impact velocities in a severe accident (Ref. 7) indicates that the probability of exceeding 422 ft/s is 8.2%.

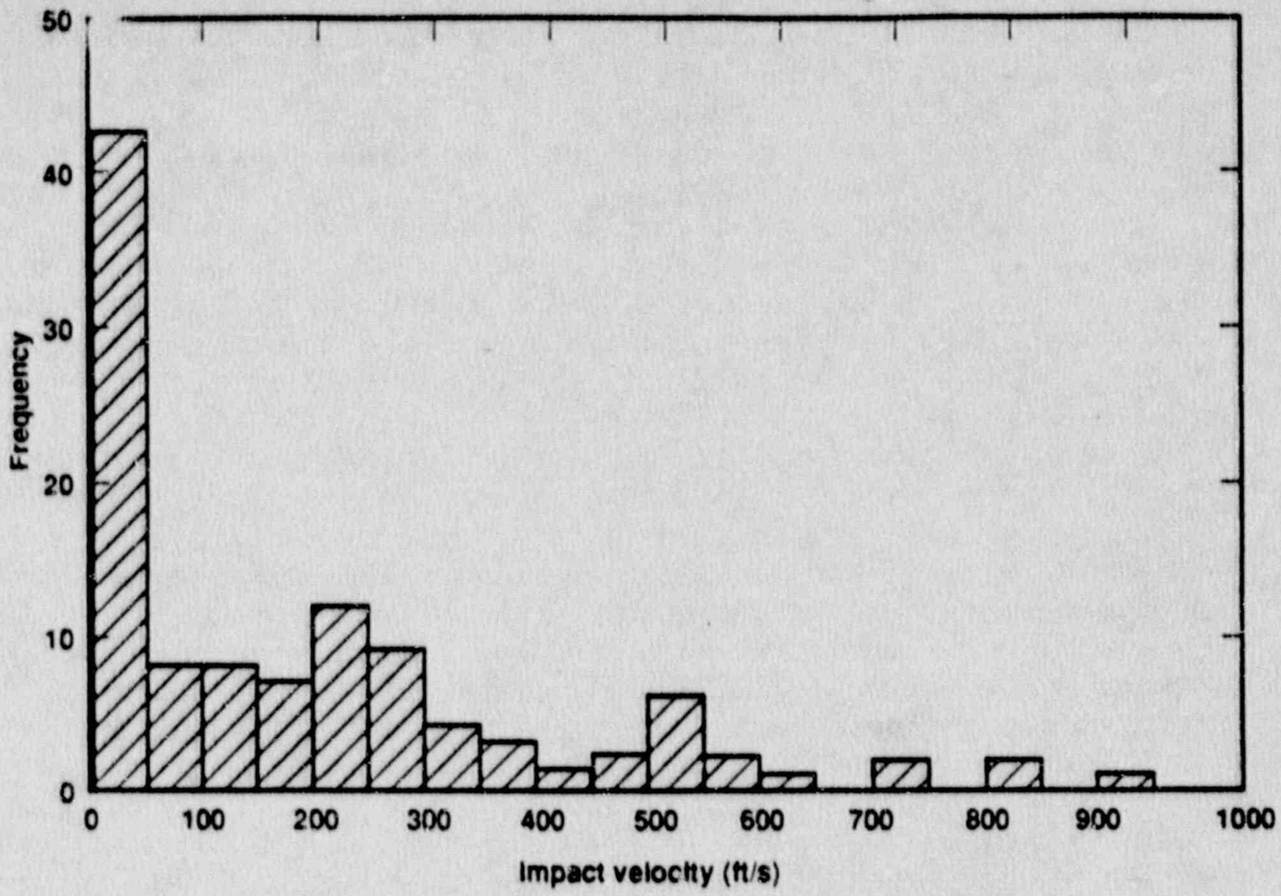

Figure 2-3. **Frequency of accidents and their estimated impact velocities. Only those accidents for which an impact velocity can be estimated are included.**

The impact surface specified in NUREG-0360 is an unyielding one. To estimate an equivalent velocity for impacting an unyielding surface instead of a real surface is a complex process because the equivalent velocity is surface, package, and velocity dependent. The probability of exceeding the loading conditions in NUREG-0360, namely 422 ft/s on an unyielding surface, was estimated to be 4.8% or an expected frequency of 1.3×10^{-7} per flight departure (Ref. 7). The loading conditions for the PSA Flight 1771 crash exceeded those specified in NUREG-0360.

2.4 Thermal Loading in Accidents

Thermal loads on a PAT package can result from heating by large fires, and decay heat from the plutonium inside the package. Large fires can potentially cause the worst damage to a PAT package.

Thermal loads from large fires depend on three primary factors: fire duration, flame temperature, and fire location with respect to the package. The fire duration affects the amount of heat that can be transferred to a PAT package. The longer a fire burns, the greater the amount of heat that can be absorbed by the package. Higher flame temperatures cause greater amounts of heat to be transferred to the package. The primary fuel for burning in an aircraft crash is its jet fuel, which can burn at temperatures of 2000°F. Only the burning of the jet fuel needs to be considered in aircraft crashes associated with large fires. The location of the fire with respect to the package affects the amount of heat that can be transferred. For the same duration, engulfing fire would transfer more heat than a peripheral fire.

Severe accidents involving reported fires were reviewed. Of the 548 aircraft accidents reviewed, only 262 had reported fire durations or sufficient other data to estimate bounds for the time of containment. Of these, 114 had specific containment or extinguish times. These are plotted in Fig. 2-4, where the number of fire accidents is plotted as a function of fire duration periods or ranges in terms of extinguishment and containment time for analysis. The time to contain a fire implies that the fire is no longer a large, hot, engulfing fire which can spread. The time to extinguish a fire includes cleanup operations and stand-by operations to put out flareups.

The fires in accidents were reviewed to determine which fires had reported durations that exceeded the 1 "engulfing" hour specified in NUREG-0360. Of the 548 aircraft accidents reviewed, only 12 of these accidents involved fires with reported durations of more than 1 hour. These 12 fire accidents are considered to be extreme; they are summarized in Table B-2, Appendix B. These extreme accidents were reviewed and analyzed in detail to estimate the size and extent of the fires. Only hot, large, engulfing fires, such as the test fire specified in NUREG-0360, can threaten a PAT package. Spot fires and smoldering fires are of little consequence. Also, fires within the aircraft cabin, but not involving jet fuel, are of little consequence because they cannot generate enough high-temperature heat to cause significant damage to PAT package. From review and analysis, it was determined that fires in accidents burning beyond the time required to contain them were no longer hot enough or large enough to damage a PAT package. The period of time between containment and extinguish usually included cleanup operations and standby for flare-ups.

From the review and analysis of fire data, it was determined that only fires with times equal to, or less than the reported containment time could cause significant damage to a PAT package. Therefore, the fire containment time was taken to be the equivalent time for a large engulfing fire. Also, only fires involving the burning of jet fuel were threatening. The worst-case fire accident was determined to be the Doha International Airport incident in Qatar on March 13, 1979, where the fire was brought under control 3.4 hours after impact.

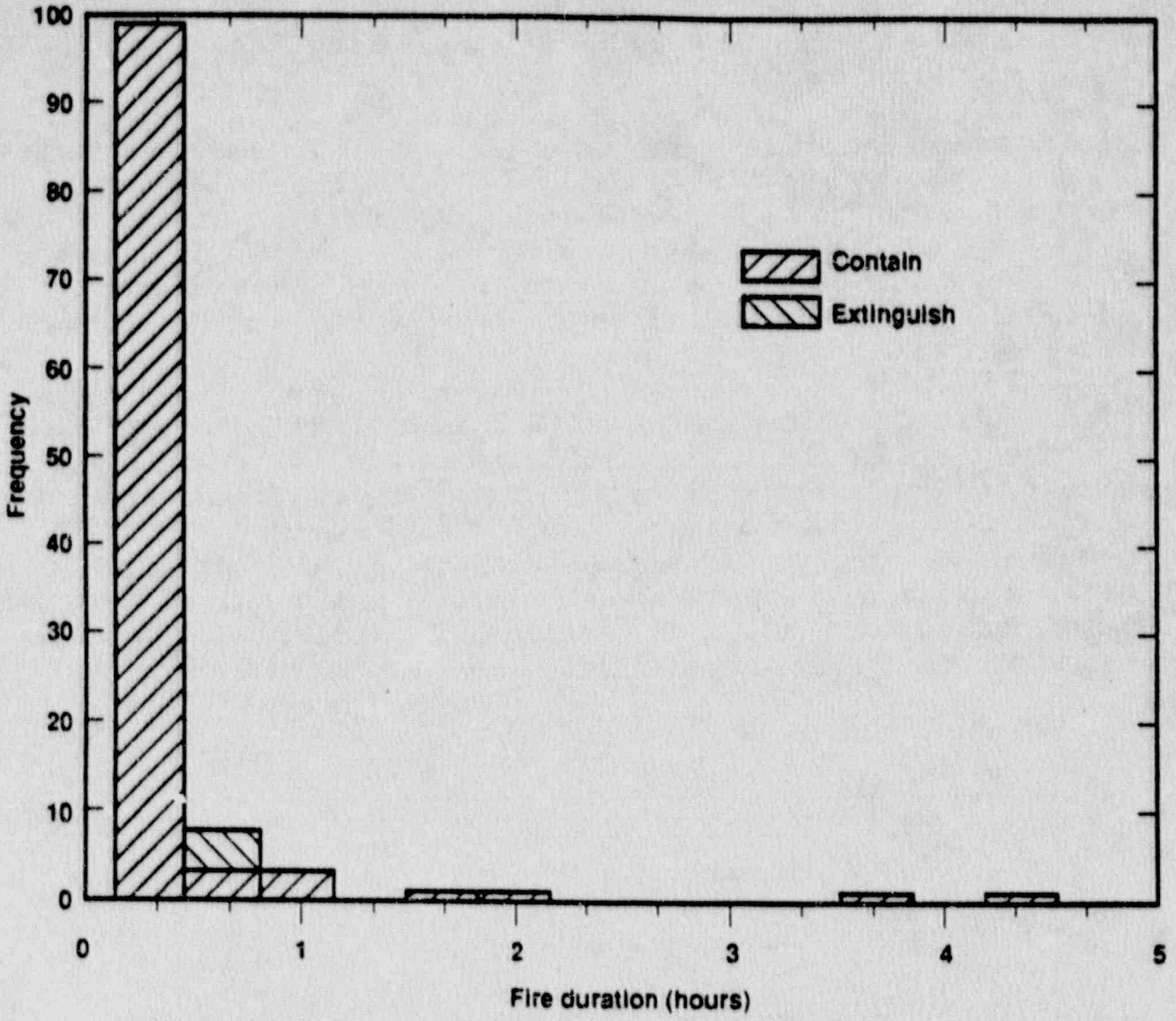

Figure 2-4. **Frequency of fires and their estimated duration. Only those accidents for which fire duration can be estimated are included.**

A statistical analysis of the fire data in Figure 2-4 was performed to predict the probability of exceeding the 1 hour specified in NUREG-0360. The containment time was used or estimated to normalize the fire duration to an engulfing fire. Also, only fires involving jet fuel were included as being potentially significant. The statistical analysis indicates that the probability of exceeding a 1-hour duration of an engulfing fire is 0.8% given a severe accident or an expected frequency of 2.3 x 10^{-8} per flight departure (Ref. 7).

2.5 Combined Loading Accidents

When accidents occur, especially severe ones, both mechanical and thermal loads on a PAT package can occur during the accident scenario. These can include impact, followed by puncture and laceration by aircraft parts, and subsequent fire. Possible combinations of different types of loading were assessed and evaluated with respect to NUREG-0360 test conditions.

At high impact velocities, especially those exceeding 422 ft/s, the aircraft airframe, components will break up or disperse and jet fuel will disperse. A dispersion analysis of the PSA Flight 1771 crash shows that high velocity impacts cause a wide dispersion of aircraft parts, and burial into the ground of the larger, more massive components such as landing gear and engines (Ref. 8). Also, the analysis shows that the jet fuel is widely dispersed, with very little fire occurring other than spot fires from jet fuel soaking into the ground.

In Fig. 2-5 the reported fire duration versus airspeed for 96 accidents is plotted. An analysis of the impact and fire data indicates that there are no significant fires following impacts at velocities higher than 422 ft/s. It was also concluded from the review and analysis that objects stored behind PAT package cargo need to be considered. Although combined loading can occur at low accident velocities, combined impact and fire accidents do not occur in extreme impact accidents because the fuel is dispersed. Test criteria specified in NUREG-0360 cover all other credible accident conditions based on historical accident data.

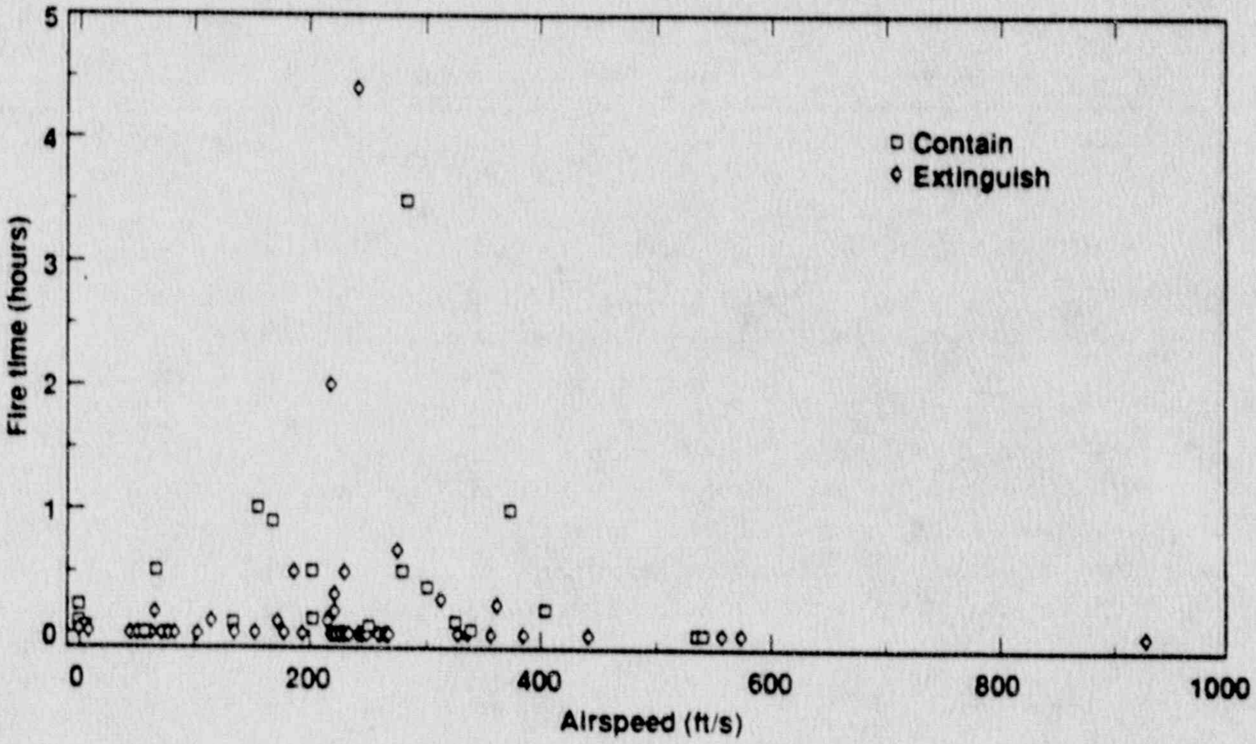

Figure 2-5. Fire duration versus airspeed. Only those accidents for which fire duration can be estimated are included.

3. DEVELOPMENT OF WORST-CASE CONDITIONS

3.1 Introduction

As required by Public Law 100-203, test criteria specified in Section 4 are based on worst-case aircraft accidents. Descriptions of the expected PAT package environment in the worst-case accident are given in the following sections. Controlled test criteria representing worst-case conditions are also described.

3.2 Worst-Case Impact Accident

The designated worst-case accident is the high-speed crash of a BAe-146 aircraft during PSA Flight 1771. However, PAT packages can be transported in many other types of cargo aircraft. The crash environment of a typical cargo aircraft with the same crash conditions as PSA Flight 1771 is described to establish a basis for the selected controlled test criteria.

3.2.1 PSA Flight 1771.

This designated worst-case aircraft accident occurred when an aircraft crashed into a hillside near Paso Robles, California, on December 7, 1987, while enroute to San Francisco from Los Angeles. The accident was the result of an onboard shooting incident during which the pilot and copilot were apparently injured critically. The aircraft made a slow spiral turn from 6.7 km (22,000 ft) altitude until impact on a hillside at 403 m (1322 ft) elevation. This accident was selected as the worst case on the basis of the impact velocity, angle, and site hardness. The resulting severity of the crash was dependent on these conditions.

The aircraft was a BAe 146-200—a high-wing, four-engine, jet-powered aircraft used in short-range inter-city flights. It has an overall length of 28.6 m, a wing span of 26.3 m, and a fuselage diameter of 3.6 m. Its estimated total weight at the time of the Flight 1771 crash was 29,300 kg (64,500 lb). The estimated fuel load on board at the time for the crash is 3,200 kg (1000 gallons).

The aircraft remained intact until impact. An extensive study of the accident (Ref. 9) establishes that the impact velocity was 282 m/s (925 ft/s), its Mach number was 0.83, and its trajectory angle was approximately 44°, nose down. The ground surface incline was 16°, resulting in a 60° angle between the aircraft axis and the ground surface.

The ground at the crash impact point is composed of a 0.3 m layer of topsoil on intensely weathered and fractured rock consisting of a sequence of interbedded clay-shales and fine-grained sandstones. In-situ measurements and laboratory tests on core samples taken from several drill holes have been studied to develop geotechnical property values and to characterize the crash site hardness (Ref. 10). The penetrability constant (S-number) is 2.5 ± 0.5, and the rock quality designation is 15.

The aircraft and its contents fragmented into many small pieces, mostly dispersed within a radius of about 100 m from the impact point. This breakup characteristic is conjectured to be caused by a combination of phenomena including high aerodynamic forces, high material strain rates, air compression in the fuselage, rapid phase change of liquids within the fuselage, interactions between fractured pieces, and dynamic coupling between the aircraft and ground.

The crash produced an irregularly shaped depression about 3.5 m deep by 6 m wide by 12 m long. The volume of soil displaced was about 74 m^3, weighing about 17,500 kg (195 tons).

There was no major fire after the crash, only minor ground fires. Also, there was no indication of any explosion occurring. A dense black smoke cloud was observed at the time of the crash, indicating that some of the on-board fuel apparently burned in the air above the impact point. A large portion of the fuel was dispersed on the ground, evidenced by a noted strong smell of jet fuel over a large area and at significant depths in the soil (Ref. 9).

3.2.2 Worst-Case Conditions

It is assumed that the aerodynamic and structural characteristics of cargo aircraft make it physically possible for them to achieve the impact conditions of the designated worst-case accident: i.e., impact velocity and angle. During these high velocity conditions the aircraft cannot attain large angles of yaw and incidence and the aircraft must be intact. Otherwise, the aerodynamic drag would be too great and would reduce the impact velocity. However, aerodynamic lift developed by the wings will cause a small incidence angle. The aircraft are expected to fragment much like the PSA Flight 1771 crash if impact conditions are equivalent.

Fire conditions are assumed to be the same as in the worst-case accident. That is, on impact the jet fuel extensively disperses and a short-duration, black fireball results. This phenomenon is the result of the impact causing some of the fuel to mix with expelled soil, which inhibits combustion, and some of the fuel to be finely dispersed, allowing rapid combustion. A few seconds after impact, only small spot fires dispersed around the crash site should exist from some of the expelled fuel. Thus, the packages would experience little heating by fire.

The packages are subjected to a variety of dynamic impacts during a worst-case accident. The impacts are hypothesized to be:

between packages,
between packages and objects that become missiles,
between packages and the aircraft,
between packages and the ground.

Computer analyses of these impacts were performed for worst-case crash conditions of a cargo aircraft (Ref. 11). A model of packages aligned in a typical cargo array and with selected cargo spacing between packages indicates that maximum stresses occur in the most forward package, which receives impacts from the ground and from packages stowed aft of it. However, the maximum stress in the most forward package is caused by impact with the ground. Impact with other packages produces lower stresses, independent of the initial spacing between packages. Also, lateral interactions between adjacent packages are relatively negligible. In addition, package stresses are effectively insensitive to the impact angle for angles between approximately 45 and 90 degrees. Packages impacting soil at high velocities behave somewhat like rigid objects for which soil geotechnical properties dominate over impact angle.

Since at high velocities the aircraft cannot impact at large angles of incidence or yaw, the only parts of the aircraft that can potentially interact with the packages are the fuselage and items within it. Wing, tail, and engine assemblies are outside the fuselage and are not able to develop sufficient lateral displacement during a high-speed crash to appreciably interact with the fuselage. Typically, members of the fuselage and cargo deck structures, cargo tie-down fixtures, an auxiliary power unit (APU), and landing gear assemblies are within the fuselage envelope. Except for landing gear assemblies and the APU, all items in the fuselage are composed of relatively lightweight aluminum and magnesium parts. The keel and wing spars are the largest structural assemblies and are generally beneath the cargo deck. Landing gear assemblies are also usually stowed beneath the cargo deck, and they would not interact with the packages. The APU is usually located in the tail area and near the fuselage axis and could collide with cargo packages. Figure 3-1 illustrates an example cargo configuration of PAT packages in a cargo aircraft and the relative location of major components.

Some jet transports have a tail engine within the fuselage envelope. In a worst-case crash condition for these aircraft, the tail engine could present an additional impact load on the cargo.

During a high-speed crash, principal contact between an aircraft fuselage and the ground behaves like a plane surface moving toward the aircraft tail. Fuselage internal-pressure increase causes outward buckling and failure of the fuselage outer wall structure. Also, relatively little velocity change occurs to any part of the fuselage until it meets the impact plane. These phenomena were observed in high-velocity impact tests with simulated fuselage models (Ref. 12). Consequently, the packages should have only a relatively small quantity of fuselage material to penetrate.

After penetrating the fuselage's zone of influence, the packages impact the soil. Before this impact, a crater develops from the fuselage impact in a manner that is affected by many factors, including soil expulsion and compaction. The soil disturbance is limited to a relatively shallow depth, and its influence on the

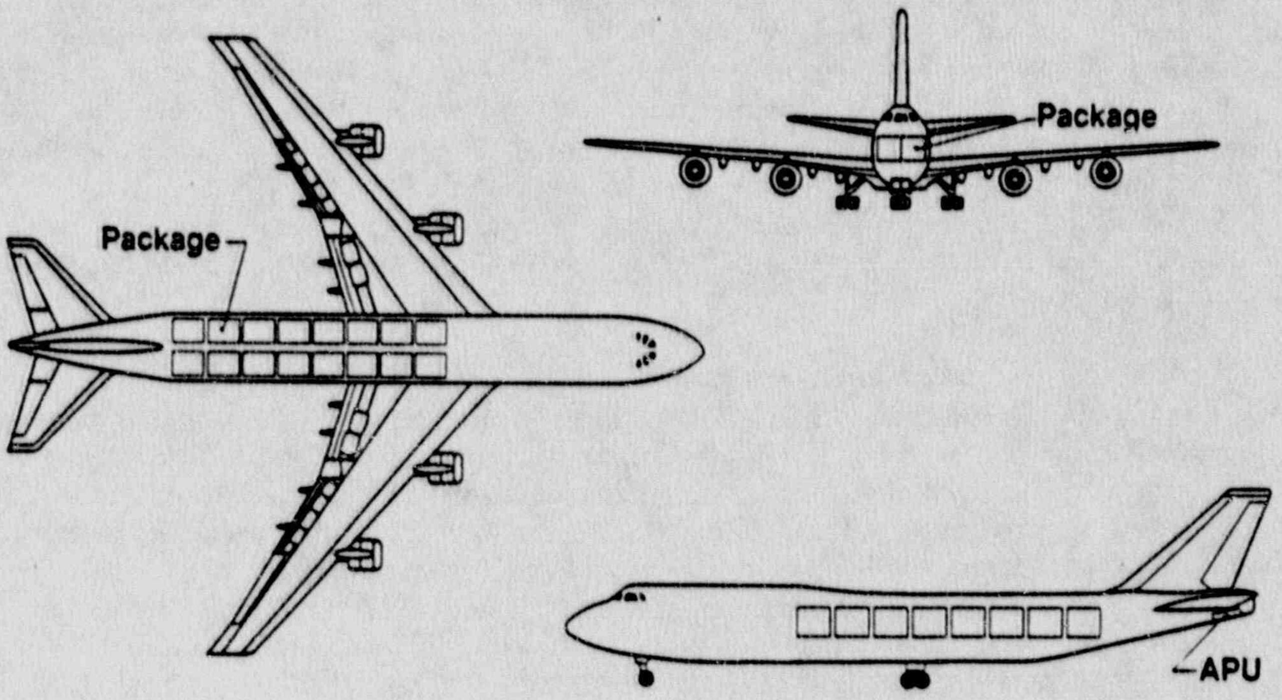

Figure 3-1. An example of a loading configuration for PAT packages.

packages should be small. Therefore, the packages experience about the same soil environment as undisturbed soil.

3.3 Worst-Case Thermal Accident

The aircraft accident that presents the apparent worst-case thermal conditions for a PAT package is the crash of a Boeing 727 (registered as Royal Jordanian 600) during landing at Doha International Airport, Qatar, on March 13, 1979. A long-duration major fire with accompanying explosions occurred. Other reported aircraft accidents involve fires of even longer duration but these fires would have been less severe to cargo. (A summary of extreme aircraft fires is given in Appendix B.)

3.3.1 Doha Accident

This accident was caused by an atmospheric downdraft on the aircraft while landing. The aircraft impacted the runway at approximately 87 m/s (287 ft/s) and 35 degrees impact angle. It bounced, and slid practically upside down into the fire station garage which housed flammable materials such as acetylene. The aircraft also reportedly had 146 kg of flammable liquid cargo and 9950 kg (21,890 lb) of fuel on board. The fire was thought to be under control within 21 minutes of impact at which time a severe explosion produced new fire outbreaks. The fire was brought under control 3.4 hours after impact. All but the tail section of the aircraft was destroyed by the impact and fire.

3.3.2 Worst-Case Conditions

Thermal conditions for a PAT package in a fire like one that occurred in the Doha accident would experience, at worst, a 3.4 hours fully-engulfing jet fuel fire. The package would experience little damage before the fire because of the relatively low impact velocity and impact angle of the crash.

NUREG-0360 qualification criteria specify sequential impact, crush, puncture, and thermal tests. The thermal test requires a package to be subjected to a fully-engulfing jet-fuel fire for at least 60 minutes. Typically, an undamaged package can be in this type of fire for several hours before attaining the same container temperature and potential damage that could be attained in the NUREG-0360 test (Ref. 7). The NUREG-0360 sequential tests can damage a package to the extent that heat is transferred more effectively to the container. Historical aircraft accidents involve severe fires not longer than a few hours, and impact velocities and angles low enough that a typical package would experience relatively little damage.

3.4 Test Criteria Development

3.4.1 Impact

The impact velocity and site hardness of the worst-case impact accident described in Section 3.2 are the principal criteria for the package impact test specified in Section 4.4. A test package must impact a target at not less than 282 m/s (925 ft/sec). The target hardness must not be less than the impact site of the worst-case accident. Although package stresses are negligibly affected by impact angle if it is greater than 45°, a test package should impact a target nearly perpendicular to its surface to minimize tangential displacement and to assure valid test results.

3.4.2 Crush

A worst-case accident would not subject a package to crushing forces more severe than a package would experience during a crush test specified in NUREG-0360. Packages tested in accordance with NUREG-0360 criteria are subjected to a 32,000 kg (70,000 lb) static compressive load. The package environment in a worst-case aircraft impact would be entirely dynamic and would not involve significant static crushing conditions. Thus, a crush test is not included in the controlled test criteria given in Section 4.

3.4.3 Puncture/Tear

The NUREG-0360 tests include dropping a test package onto a right circular cone from a height of 3 m (10 ft), unless the package weight is less than 227 kg (500 lb); then a 227 kg weight with an attached cone is dropped onto the package from a height of 3 m. Following this test, a 1.8-m (6-ft) long steel bar is dropped onto the package from a height of 46 m (150 ft) with the bar axis parallel to its trajectory path.

The probability of packages experiencing damaging puncture or tear during a low velocity aircraft crash is greater than during a high velocity crash, such as the worst-case accident. Piercing objects are more likely to be in the package collision path during a low velocity crash because the aircraft flight angles, (such as impact, incidence, roll, and yaw, shown in Fig. 2-1) can be such that these objects would intercept a package. During a high velocity crash, typical packages cannot impact any aircraft components that could significantly damage them. The only aircraft assembly that could be in a package collision path is the fuselage, which is a light-weight structure that presents little resistance to a typical package's kinetic energy. A nose landing-gear assembly is usually in the aircraft fuselage, but its characteristics are such that it would become buried in soil before a package could impact it.

Puncture tests specified in NUREG-0360 sufficiently address puncture and tear environments that packages would be subjected to in any recorded aircraft accident. Therefore, puncture tests are not included in the controlled tests specified in Section 4.

3.4.4 Thermal/Burial

The review of historical aircraft accidents presented in Section 2 does not disclose any fire conditions that are more severe to a PAT package than the thermal test specified in NUREG-0360. Fires of possibly longer duration may have occurred, but in those instances significantly less impact damage to a PAT package would also have been sustained (Section 3.3.2). Thus, to include a thermal test in the controlled tests specified in Section 4 is not justified.

Accidents could result in PAT packages buried in soil, debris, or other materials. This condition would cause heat dissipation from packages to be impeded by the insulating effect of the surrounding materials. The NUREG-0360 thermal test provides for greater heating of package containment vessels than burial conditions. Thus, a controlled test to simulate package burial is not needed.

3.4.5 Submersion

An aircraft accident could result in a package submerged in water. Qualification test criteria specified in NUREG-0360 include submersion in water for 8 hours with an external water pressure of 4.14 MPa (600 psi). Also, International Atomic Energy Agency regulations specify package capability to withstand water submersion to 200 m depth for at least one hour (Ref.13). These criteria adequately address any accidents that could occur in U.S. lakes or coastal waters. Thus, water submersion is not included in the controlled tests specified in Section 4.

3.4.6 Other Considerations

An aircraft assembly that can significantly impact packages during a high speed crash is the APU. It is usually located in the fuselage tail section (see Fig. 3.1) and has dimensions and mass that are similar to or less than those of a typical PAT package. As the potential hazard to a package by an APU may be dependent on the cargo aircraft, the cargo configuration and the PAT package design, the applicant must determine what measures, if any, are needed to adequately protect packages from impact by an APU.

Propulsion engines within the fuselage tail sections of aircraft pose a greater hazard to PAT packages. Jet engines are much larger and heavier than APUs and have a high amount of rotational energy. The most direct solution to this potential hazard is not to use this type of aircraft for transporting PAT packages.

4. CONTROLLED TEST CRITERIA

4.1 Introduction

Subsection 5062(b)(2)(B) of Public Law 100-203 specifies a crash test of a cargo aircraft fully loaded with PAT test packages. In lieu of this test, an applicant may conduct controlled tests on the PAT test packages. The purpose of this section is to identify the specific criteria that an applicant must satisfy when the controlled test option is selected.

The controlled test criteria include impact tests that are designed to develop stresses in a PAT package that would be at least as severe as those the package would experience during an actual worst-case aircraft accident. Consideration is given to the stages of development of the package environment during the crash of a cargo aircraft for PAT packages.

4.2 Responsibilities

4.2.1 Nuclear Regulatory Commission.

The NRC will be responsible for monitoring the controlled tests and reviewing and assessing the test results. The NRC will determine whether test packages were tested to the extent specified by the controlled criteria. The NRC will use these results, together with the results of other required tests and studies, to determine whether the PAT package design can be certified to Congress as safe for use in air transport of plutonium.

The NRC will convene an independent Scientific Review Panel and will determine, after consultation with the Panel, whether stresses in the container produced by the controlled tests used in developing the container exceed the stresses that would occur during a worst-case plutonium air-shipment accident.

4.2.2 Applicant.

The applicant for certification of a proposed PAT package design shall be responsible for providing all test hardware, packages, equipment, facilities, personnel, and all other necessary resources to be used in the controlled tests. The applicant shall also be responsible for the preparation of a test report, in accordance with Section 4.7, and its submission to the NRC.

4.3 Compliance with Other Regulatory Requirements

The package shall comply with all applicable requirements of 10 CFR Part 71 (Ref. 3) and 49 CFR 100-199 (Ref. 3).

The package shall satisfy all qualification criteria in accordance with Public Law 94-79 (Ref. 5).

A package drop test shall be performed as specified in Section 5062(b)(2)(A) of PL 100-203 (Ref. 1).

4.4 Test Criteria

A test package shall be subjected to the following physical conditions to determine their effect on the package's ability to contain plutonium within the limits specified in Section 4.6.1 of this report.

4.4.1 Impact Test.

The test package shall impact approximately perpendicular onto an effectively flat target at a velocity not less than 282 m/s (925 ft/s). Package impact orientation (e.g., end, side, corner) shall be the one that results in maximum damage to the container at the conclusion of the impact test. The target properties shall be those of natural soil as specified in Appendix C.

4.4.2 Optional Impact Test.

The applicant shall have the option of conducting the impact test defined in Section 4.4.1 above at a lower impact velocity onto an effectively unyielding target. Should this option be chosen, the applicant shall determine the lower velocity limit that results in container damage equivalent to the damage it would sustain during the impact test specified in Section 4.4.1. The applicant shall perform sufficient tests and analyses, specific to the test package characteristics, to support the selected impact velocity. The applicant shall also select an appropriate target design and perform supporting analyses verifying that it is effectively unyielding to the test package impact. Appendix D describes a method for determining an impact velocity that results in equivalent containment vessel damage.

4.5 Other Criteria

4.5.1 Contents.

A surrogate material shall be used in place of plutonium, one which simulates plutonium's nontoxic properties to the maximum extent practicable. The applicant shall specify the surrogate material and all its pertinent properties. The applicant shall also demonstrate or present supporting analytical assessments showing that the results of the physical tests would not be adversely affected to a significant extent by the presence, during the tests, of the actual contents that will be transported in the package.

4.5.2 Number of Tests.

At least one test that complies with these test criteria is required.

4.5.3 Other Considerations.

Packages transported in cargo aircraft having a propulsion engine or auxiliary equipment such as an APU in the tail section of the fuselage shall have adequate containment vessel protection from damage by the equipment during worst-case crash conditions described in Section 3.2.2 or it shall be demonstrated by analysis that the PAT packages will not be impacted. The applicant shall determine whether additional protection is required, and the method and design of any required additional protection, and shall demonstrate by sufficient analysis and/or test that the design is adequate.

4.6 Acceptance Criteria

4.6.1 Containment.

During and after the specified testing, the packaging shall not release more than an A_2 quantity of plutonium per week. Any amount of deformation is permissible, provided that the release limit is satisfied. (An A_2 quantity is defined in Ref. 3. An example procedure to determine an A_2 quantity is given in Ref. 6).

4.6.2 Exposure.

The radiation level at any point one meter from the package surface shall not exceed one Rem per hour. The package shall be in air, in its post-tested condition, and containing its maximum allowed quantity of radioactive material. Compliance with this criteria shall be demonstrated by submission of supporting analytical assessments.

4.6.3 Sub-Criticality.

A package or an array of packages shall be sub-critical in accordance with 10 CFR Part 71. The post-test condition of the package shall be considered. Appropriate analytical assessments shall be submitted to demonstrate compliance.

4.6.4 Post-Test Inspection and Evaluation.

Tests and inspections shall be designated and subsequently performed by the applicant to determine the effect of the test specified in Section 4.4 on the test package and if the test package met the specified acceptance criteria. Release and leakage tests may be used to determine that the content release limits have been satisfied. The release or leakage tests must be interpreted in terms of the corresponding release of actual plutonium that would result from such damage to the package. Reference 14 may be used as a guide for release or leakage tests to be performed and their acceptance criteria. Corresponding quantities of released plutonium shall be less than those specified in Section 4.6.1.

4.6.5 NRC Monitoring.

The NRC will have the option to witness, or appoint delegates to witness, the controlled tests and related test activities in order to verify conformance to the test criteria.

4.7 Required Submissions

The applicant shall submit to the NRC for approval a comprehensive report containing test methods, supporting analyses, results, and other pertinent information relating to the controlled tests. This report may be incorporated into the Safety Analysis Report specified in 10 CFR Part 71.

5. REFERENCES

1. United States Public Law 100-203, *Title V - Energy and Environment Programs, Subtitle A - Nuclear Waste Amendments, Part F - Miscellaneous, Section 5062* (December 22, 1987).

2. C. E. Walter, J. H. VanSant, and C. K. Chou, *Draft Criteria for Package Drop and Aircraft Crash Tests - An Interim Report*, UCID-21697, Lawrence Livermore National Laboratory, Livermore, CA (June 1989).

3. Nuclear Regulatory Commission, *Packaging and Transportation of Radioactive Material*, Title 10 Code of Federal Regulations, Part 71 (10 CFR 71), Washington, D.C.

4. United States Department of Transportation, *Hazardous Materials Regulations*, Title 49 Code of Federal Regulations, Parts 100-199 (49 CFR 100-199), Washington, D.C.

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13. International Atomic Energy Agency, "Regulations for the Safe Transport of Radioactive Materials," Safety Series 6, Paragraph 680, 1985 Edition. (Available from UNIPUB Inc., P.O. Box 433, New York, NY 10016.)

14. American National Standards Institute, Inc., *American National Standard for Radioactive Materials - Leakage Tests on Packages for Shipment,* ANSI N14.5-1987, New York, NY (1987).

APPENDIX A

REPRINT OF SECTION 5062 OF PUBLIC LAW 100-203.

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

(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 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.

(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 B

SELECTED SEVERE ACCIDENT DATA

Aircraft accidents which had an apparent impact velocity of more than 422 ft/s (NUREG-0360 impact test criteria) are listed in Table B.1. These accidents are from reported world-wide accidents (USSR and military excluded) involving large commercial aircraft and occurring during the period 1952 through 1989 (Ref. B-1). Impact velocities are determined from airspeeds and flight conditions given in accident reports.

The selected worst-case impact accident is the one that occurred at Paso Robles, California, on December 7, 1987 (PSA Flight 1771, Ref. B-2). No other accidents had a combination of impact velocity and site hardness resulting in as severe impact conditions as the Paso Robles accident.

Accidents involving a major fire that could possibly last longer than one hour (NUREG-0360 thermal test criteria) are listed in Table B.2. The apparent worst-case fire occurred March 13, 1979, at the Doha International Airport, Qatar. This fire accident lasted approximately 3.5 hours and produced a large fire that included explosions of flammable materials. Other fires of longer duration, such as the March 7, 1977, accident at Tenerife, Canary Islands, were less severe. During this incident, the fire was under control within 1.5 hours after it started, and approximately 10 hours were needed to fully extinguish the fire. The fire accident on Yap Island that occurred November 21, 1980, lasted approximately 8 hours because of limited fire-fighting resources. During landing, the aircraft dispersed jet fuel on a grass runway and in adjoining jungle growth, which apparently resulted in small scattered fires.

References

B-1. J. H. VanSant, et al., *Development of Criteria for Controlled Tests for Air Transport Packages*, UCRL-ID-104484, Lawrence Livermore National Laboratory, Livermore, CA (August 1990).

B-2. C. E. Walter, *Investigation of the Crash Environment and Impact Conditions of the PSA Flight 1771 Aircraft Crash on December 7, 1987*, UCRL-ID-103735, Lawrence Livermore National Laboratory, Livermore, CA (October 1989).

Table B.1 Summary of aircraft accidents with reported impact velocity exceeding 422 ft/s.

Date	Accident location	Aircraft type	Flight phase[a]	Impact speed (ft/s)	Comments
2/12/63	Everglades National Park, Miami, FL	B720-051B	ER	838	Swamp
2/25/64	Lake Ponchartrain, New Orleans, LA	DC8-21	C	759	Water
6/23/67	Blossburg, PA	BAC 1-11 204	ER	531	Wooded area
3/6/68	Guadaloupe, West Indies	B707-328C	LA	540	Heavily wooded, dense vegetation
4/20/68	Windhock, Nambia	B707-344C	C	457	Low impact angle into soil
1/18/69	Santa Monica Bay, Los Angeles, CA	B727-22C	C	550	Water
6/4/69	Monterey, Mexico	B727-64	LA	422	Mountain
2/21/70	Wuerenlingen, Switzerland	CV990-30A-6	C	712	Mountainous terrain
6/6/71	Duarte, CA	DC9-31	ER	675	Mountainous, 60° slope
3/3/74	Bosquet de Dammar, Paris, France	DC10-10	C	725	Level, flat, forest
12/1/74	Thiella, NY	B727-251	ER	800	10° slope, compact soil
9/10/76	Zagreb, Yugoslavia[b]	Trident 3B	ER	497	Level, flat, tree-cover, cultivated soil
9/10/76	Zagreb, Yugoslavia[b]	DC9-32	C	440	Hills, tree-cover, cultivated soil
9/19/76	Karatepe Mountain, Isparta, Turkey	B727-2F2	LA	442	Mountainous, tree-covered, compact soil
12/4/77	Gohore Strait, Malaysid	B737-2H6	LA	759	Level, flat, swamp, mud, wet soil
1/1/78	Bay of Bombay, India	B747-237B	C	556	Water
3/16/78	Gabare, 130 Km NE of Sofia, Bulgaria	Tu-134	C	582	Hilly, rocky, compact soil

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[b] Collision accident involving the two listed aircraft.

Table B.1 Summary of aircraft accidents with reported impact velocity exceeding 422 ft/s (Con't).

Date	Accident location	Aircraft type	Flight phase[a]	Impact speed (ft/s)	Comments
7/26/79	Serra dos Macacos, Petropolis, Brazil	B707-330C	C	499	Tropical forest, high slope, mountain side
11/28/79	Mt. Erebus, Ross Is., Antarctica	DC10-30	ER	438	Mountainous, ice, Mt. Erebus, 13° slope
4/25/80	Tenerife, Canary Is., Spain	B727-46	LA	438	Mountainous, 30° slope, tree-covered
12/21/80	Riohacha-Guajira, Columbia	SE210 Caravelle 6R	C	540	Level, flat, tree-covered, compact soil
10/6/81	Moerdijk, Netherlands	Fokker F28 Mk3000	ER	607	Level, flat sandy, low vegetation grass
6/8/82	Fortaleza, Pacatuba, Brazil	B727-212	LA	503	Mountainous, tree-covered, compact soil
5/30/84	Chalk Hill, PA	L-188A	ER	535	Wooded area, houses, lake
12/7/87	Paso Robles, CA	BAe146-200A	ER	924	Highest impact velocity, weathered rock, soil, worst-case accident

[a] ER = Enroute
LA = Landing approach
C = Climbout

Table B.2 Summary of aircraft accidents with reported fire durations exceeding one hour.

Date	Accident location	Aircraft type	Flight phase[a]	Fire contain (hr)	Fire extinguish (hr)	Impact speed (ft/s)	Comments
12/26/68	Elmendorf, AFB, AK	B707-321C	T/O	1.5		244	Large dispersion and ground absorption of fuel
3/31/71	Ontario Intn'l Airport, CA	B720-047B	C	1.0			Fire contained within 1 hour. Fire caused by impact.
4/5/76	Ketchikan, AK	B727-81	L		4.50	244	Fire fighting stopped at 1 hour, resumed 20-45 minutes later. Fully extinguished in 4.5 hours.
3/27/77	Los Rodeos Airport, Tenerife, Canary Is.	B747-206B	T/O	1.5	10.0	231	Large fire for approximately 1.5 hours.
9/25/78	San Diego, CA	B727-214	LA	1.0		371	Fire contained within 1 hour. Natural gas involved.
3/13/79	Doha Intn'l Airport, Qatar	B727-2D3	LA	3.5		286	Controlled in 21 minutes, then explosions and renewed outbreak of fire. Apparent worst-case fire.
10/7/79	Athens Hellinikon Airport, Greece	DC8-62	L	0.5	1.63	67	Fire contained in less than 1 hour.
8/19/80	Riyadh, Saudia Arabia	L1011-200 Tristar	C		~1.0	0	Cargo fire only; lasted over 1 hour, but did not involve jet fuel. Landed safely.
11/21/80	Yap Island, Carolina Islands	B727-92C	L		~8.0	193	Fuel absorption by soil reduced severity. No fatalities. Single fire fighter gave up after 8 hours.
6/2/83	Greater Cincinnati Intn'l Airport, KY	DC9-32	ER	0.5	1.28	0	Cabin fire only, did not involve jet fuel. Landed safely.
11/27/83	Mejorado Del Campo, Madrid, Spain	B747-283B Combi	LA		2.00	212	Fuel was dispersed in a wooded area.
12/23/83	Anchorage Intn'l Airport, AK	DC10-30CF	T/O	2.0	2.50	168	Collision with parked aircraft.

[a] ER = Enroute
LA = Landing approach
L = Landing
C = Climbout
T/O = Takeoff

APPENDIX C

TARGET REQUIREMENTS FOR CONTROLLED TESTS

C.1 Introduction

Target requirements for the package impact test specified in Section 4.4.1 are given in the following sections. These requirements are defined on the basis of geological similarity between the package target and the PSA Flight 1771 crash site.

C.2 Target Requirements

The applicant may use a natural geological target or an artificial target for the package impact test specified in Section 4.4.1. Requirements for the two target options are given in the following sections.

C.2.1 Natural Geological Target

C.2.1.1 *Surface*. The target site surface shall be approximately perpendicular (within 20 degrees) to the package trajectory path at impact.

C.2.1.2. *Properties*. The effective hardness of the target to impact by the test package shall not be less than the PSA Flight 1771 crash site (Section C.3). Properties of the target site shall be essentially constant within at least 15 package lengths of the impact point. Laboratory and/or in-situ tests to determine geotechnical properties of the site shall be performed by the applicant to verify compliance with these requirements.

C.2.2 Artificial Target

C.2.2.1 *Surface*. Surface requirements shall be the same as for a natural target (Section C.2.1.1).

C.2.2.2 *Properties*. Target property requirements for a natural target (Section C.2.1.2) shall apply to an artificial target.

C.2.2.3. *Target Maturity*. The target material shall be sufficiently aged that its properties are essentially stable and meet the specified requirements.

C.3 Geotechnical Properties of PSA Flight 1771 Crash Site

Detailed engineering geologic evaluation of the PSA Flight 1771 crash site is reported in Ref. C-1. Studies included aerial and land surveys, field exploratory drilling and soil/rock sampling, field geophysical measurements, in-situ dynamic penetrating tests, and laboratory tests on soil/rock samples. The site is covered with a layer of clayey silt colluvial soil having an average thickness of 0.4 m (1.3 ft) and containing sand and weathered rock fragments. The site is underlain by marine sedimentary rock consisting mainly of intensely weathered and fractured sandstone interbedded by shales or silt stones. The mechanical properties of the soils/rocks of the crash site are reported in Ref. C-2 for rocks and in Ref. C-3 for soils. Penetrability constants of the crash site, measured by gas-gun tests, are reported in Ref. C-4. Tables C.1 and C.2 show the average and the ranges (coefficient of variation) of rock and soil properties of the site, respectively. Definitions of penetrability constant (S-number) and rock quality designation are given in the following sections.

C.4 Penetrability Constant (S-number)

The penetrability constant (S-number) is an empirical constant that reflects the hardness of materials subjected to the dynamic loading of a penetrator (Ref. C-5). An S-number is obtained by firing a specially instrumented projectile into test soils. The resultant value represents an average over the penetration distance.

Equation (C1) is used to compute an S-number for rock or soil when the projectile velocity is greater than 61 m/s (200 ft/s).

$$S = \frac{8562\,Z}{(V - 30.5)\,N\,(W/A)^{1/2}} \qquad \text{(C1)}$$

where
A = projectile average cross-sectional area (m^2)
N = projectile nose performance coefficient
V = projectile impact velocity (m/s)
W = projectile mass (kg)
Z = penetration distance (m)

For penetration of soils and W less than 27 kg, the right-hand side of equation (C1) must be divided by a correction factor $K = 0.274\,W^{0.4}$. For penetration of rock and W less than 182 kg, the correction factor is: $K = 0.210\,W^{0.3}$.

The nose-performance coefficient (N) varies from 0.56 for a flat nose to 1.34 for a conical nose with length-to-diameter ratio of 3. A standard penetrator has a tangent ogive nose with a caliber-radius-head value of 6.0 and an N-value of 1.0.

Typical S-numbers for soil and rock are given in Table C.3. The S-number for soils ranges from 2 for dense cemented sand to 9 for moderately dense sand. The S-number for rock ranges from 0.5 for "hard" rock with some cracks and fissures to 5.0 for soil-like, severely weathered rock.

C.5 Rock Quality Designation (RQD)

Natural rock formations often contain joints and fractures, so the unconfined compressive strength of intact core specimens may fail to characterize the rock as a whole. The RQD has been used as an index for the degree of fracturing of the in-situ rock at a given site (Ref. C-6). The RQD value is determined by a modified core-logging procedure: the lengths of all solid pieces of core at least 10 cm long are added together, and this length is called the modified core recovery. The modified core recovery, when divided by the total length of the core run and multiplied by 100, is the value of RQD in percent.

C.6 References

C-1. Carpenter, D. W., J. C. Chen, and G. S. Holman, *An Engineering Geologic Evaluation of the PSA Flight 1771 Crash Site Near Paso Robles, CA*, UCRL-ID-104560, Lawrence Livermore National Laboratory, Livermore, CA (October 1989).

C-2. Blair, S. C., J. C. Chen, W. R. Ralph, and D. W. Ruddle, UCRL-ID-104556, *Mechanical Properties of Rocks from PSA Flight 1771 Crash Site*, Lawrence Livermore National Laboratory, Livermore, CA (December 1989).

C-3. Chang, C. Y., J. A. Egan, and J. C. Chen, *Constitutive Models and Dynamic Behavior of Soils under Impact Loading Conditions*, UCRL-ID-104556, Lawrence Livermore National Laboratory, Livermore, CA (December 1989).

C-4. Chen, J. C. and M. C. Witte, *Development of Soil/Rock Constitutive Models and Benchmark Analysis for Gas-gun Penetration Tests at the PSA Flight 1771 Crash Site*, UCRL-ID-104582, Lawrence Livermore National Laboratory, Livermore, CA (March 1990)

C-5. Young, C. W., *Equations for Predicting Earth Penetration by Projectiles; an Update*, SAND 88-0013, Sandia National Laboratory, Albuquerque, NM (1988).

C-6. Deere, D. V., "Technical Description of Rock Cores for Engineering Purposes, Rock Mechanics and Engineering Geology," *Journal of International Society of Rock Mechanics*, (Springer-Verlag, Vienna Austria), Vol. 1, p. 16 (1963).

Table C.1. Rock properties at the PSA Flight 1771 crash site.

Properties or parameters	Best estimate or average	Coefficient of variation
Bulk density (kg/m^3)	2370	0.1
Porosity (%)	8.0	
Unloading bulk modulus (MPa)		
First cycle (0 to 8 MPa)	2177	
Up to four cycles (8 to 250 MPa)	5100	
Unconfined compressive strength (MPa)		
Weathered rock	22	0.25
Unweathered rock	102	0.45
Weathered and unweathered rock	53	0.92
Shear modulus (MPa)		
Unconfined	1307	
Confined (25 to 250 MPa)	3394	
Poisson's ratio	0.26	
Seismic wave properties		
Shear wave velocity (m/s)	610	0.3
Compression wave velocity (m/s)	1220	0.3
Penetrability constant (S-number)	2.5 ± 0.5	
Rock quality designation	15	0.9

Table C.2. Soil properties at the PSA Flight 1771 crash site.

Properties or parameters	Best estimate or average	Coefficient of variation
Bulk density (kg/m^3)	2090	0.1
Moisture content (%)	16.2	0.3
Porosity (%)	32.0	0.2
Unloading bulk modulus (MPa) (varies with mean effective stress)	130.0	
Ultimate strength (MPa) (at 1.5 m depth from surface)	0.73	
Shear modulus (MPa) (defined at 50% stress level)	11.6	
Poisson's ratio	0.45	
Liquid Atterberg limit, LL (%)	34 ± 2	
Plasticity index, PI (%)	11 ± 4	
Penetrability constant (S-number)	3.4 ± 0.3	

Table C.3. Ranges of S-numbers for various soil/rock materials.[a]

0.5 - 1.4	Hard rock with crack spacing of 0.2 to 1.2 m (the S-number varies inversely with crack spacing). This is the effect of cracks and fissures, independent of the weathering effects.
1 - 2.5	Weathered rock, but still "rock". To some extent, weathering will result in lowering the unconfined strength and increasing the bulk porosity. Weathering may also drastically increase the size of the cracks or fissures, resulting in hard blocks of rock, with several centimeters of a soil-like material between blocks. Weathering may be very superficial, but typically may extend over 10 m below the rock surface. Bedrock at depth may or may not be weathered, depending on when the soil cover was laid down relative to when the weathering occurred.
2.5 - 5	Technically weathered rock, but having the appearance and feel of soil. It can usually be dug with a shovel and has a porosity similar to that of soil.
2 - 4	Dense, dry, cemented sand (such as the hard layers in the dry lake playas at the Tonopah Test Range). Dry caliche. Massive gypsite and selenite deposits (White Sands Missile Range).
4 - 6	Sandy gravel, no cementation.
6 - 9	Moderately dense to loose sand (>80% sand), no cementation, water content not important.

[a] From Ref. C-4, modified.

APPENDIX D

UNYIELDING SURFACE EQUIVALENCE METHODOLOGY FOR CONTROLLED TESTS

D.1 Introduction

The objective of this appendix is to present a methodology by which the impact velocity concept is used to relate the package impact velocity onto target surfaces having various degrees of hardness to an "equivalent" impact velocity of the same package onto an unyielding surface that would result in an equal or greater damage to the package.

D.2 Discussion

One method used to relate the hardness of various surfaces is to determine the relative response of a rigid sphere impacting each of the surfaces (Ref. D-1). This method is based on the elastic response of an infinitely rigid ball impacting on an elastic half space. This simplified approach provides a measure of relative hardness; however, it does not account for any penetration into the surface or any energy absorption by the sphere. This method does not realistically model the impacting of a PAT transport package onto various real surfaces.

Another method to relate the hardness of surfaces is to determine the relative responses of penetrators impacting the surfaces (Ref. D-2). This method accounts for the energy absorption caused by the penetration into the earth, but essentially no energy is absorbed by the penetrator itself. The penetrator essentially acts as a rigid body in its direction of penetration. This method does not realistically model a PAT transport package that will undergo significant deformation and will absorb significant kinetic energy upon impact.

A finite element analysis (FEA) is the best method to relate the PAT transport package responses to impacts on various surfaces (Ref. D-2). Many FEA codes are available to perform the analysis, but they must include the capability to correctly analyze large deformations (Refs. D-3 and D-4). These codes can allow both large deformations to the package and penetration into the earth with energy absorption. This method has the capabilities required to correctly relate the package impact velocity onto a surface to an equivalent impact velocity of the same package onto an unyielding surface that would result in an equal or greater response or amount of damage to the package.

D.3 Procedure

An FEA computer code can be used to estimate an equivalent velocity for a package impacting an unyielding surface in lieu of the PSA crash site surface (Ref. D-2). This method requires the following:

(1) The FEA code must be benchmarked against test data to demonstrate its capability to analyze a package impacting unyielding and real surfaces with resulting high deformation and penetration.

(2) The PSA crash surface must be modeled using the information in Appendix C for the analysis.

(3) The package is impacted using the FEA code at various orientations at a velocity of 925 ft/s onto the PSA crash surface to determine the worst response or maximum damage to the package. The responses being measured to indicate the severity of damage are: stress, strain, and deceleration of the package.

(4) The package is then impacted using the FEA code at the worst orientation onto an unyielding surface to determine its response at various impact velocities. The impact velocity that results in stress levels, strain levels, and deceleration levels equal to or greater than that calculated for impact onto the PSA crash surface becomes the equivalent velocity for conducting actual testing on an unyielding surface.

D.4 References

D-1. Unites States Nuclear Regulatory Commission, *Final Environmental Statement on the Transportation of Radioactive Materials by Air and Other Modes*, NUREG-0170, Washington, D.C. (December 1977).

D-2. J. H. VanSant, et al., *Development of Criteria for Controlled Tests for Air Transport Packages*, UCRL-ID-104484, Lawrence Livermore National Laboratory, Livermore, CA (August 1990).

D-3. J. O. Hallquist, *DYNA 3D User's Manual*, UCID-19592, Rev. 5, Lawrence Livermore National Laboratory, Livermore, CA (May 1989).

D-4. L. M. Taylor and D. P. Flanagan, *PRONTO-2D: A Two-Dimensional Transient Solid Dynamics Program*, SAND 86-0594, Sandia National Laboratories, Albuquerque, NM (March 1987).

List of Technical Reports

Phase One Summary Reports:

Plutonium Air Transport Certification (PATC) Program, Phase One Final Report, Project 2: Development of Draft Criteria for Package Drop and Aircraft Crash Tests Feasibility Review (Report No. UCRL-103497)

Plutonium Air Transport Certification (PATC) Program, Phase One Final Report, Project 1: Development of Draft Criteria for Controlled Package Tests, Compilation of Revelant Accident Data Base, and Feasibility Review (To be provided October 12, 1990)

Background Reports:

Investigation of the Crash Environment and Impact Conditions of the PSA Flight 1771 Aircraft Crash on December 7, 1987 (Report No. 90-01)

Fuselage Model Crash Test (Report No. 89-03)

An Engineering Geologic Evaluation of the PSA Flight 1771 Crash Site Near Paso Robles, California (Report No. 89-04)

Mechanical Properties of Rocks from PSA Flight 1771 Crash Site (Report No. 89-05)

Constitutive Models and Dynamic Behavior of Soils Under Impact Loading Conditions (Report No. 89-06)

Technical Feasibility of a PAT Aircraft Crash Test (Report No. 89-07)

Technical Fesibility of a Pat Package Drop Test (Report No. 89-08)

Ballistic Analysis of Free-Falling PAT Packages (Report No. 89-09)

PAT Package Drop Test - Target Accuracy Analysis (Report No. 89-10)

Structural Impact Analyses (Report No. 89-11)

Development of Soil/Rock Constitutive Models and Benchmark Analysis for Gas-Gun Penetration Tests at the PSA Flight 1771 Crash Site (Report No. 89-12)

Plutonium Air Transport Certification (PATC) Program, Interim Report Abstracts (Report No. 90-02)

The Mechanical Response to Impact of A Representative Package (To be provided October 12, 1990)

ENCLOSURE 2

Proposed Agenda

October 18, 1990

- NRC Introduction
- Review of Regulatory Requirements
- Description of Worst-Case Conditions
  - Worst-Case Accident
  - Worst-Case Thermal Load
  - Mechanical Loads
  - Submersion

- Discussion of Draft Controlled Test Criteria
  - Impact Test
  - Optional Impact Test

October 19, 1990

- Discussion of Draft Controlled Test Criteria (continued from Oct. 18)
  - Container Content
  - Number of Tests
  - Acceptance Criteria

- PNC Presentation
  - Status of Package Development
  - Schedule
  - Overview of Related Projects

- Phase I Extension of Feasiblity Studies, NRC/PNC Discussion
  - Scope of Feasiblity Studies
  - Priorities of Issues
  - Schedule

ENCLOSURE 3

Participants in the Tokyo Meeting

October 18-19, 1990

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ENCLOSURE 4