NUREG-0360

QUALIFICATION CRITERIA TO CERTIFY A PACKAGE FOR AIR TRANSPORT OF PLUTONIUM

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Manuscript Completed: December 1977
Date Published: January 1978

Transportation Branch
Division of Fuel Cycle and Material Safety
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Abstract

The document describes qualification criteria developed by the U.S. Nuclear Regulatory Commission to certify a package for air transport of plutonium. Included in the document is a discusson of aircraft accident conditions and a summary of the technical basis for the qualification criteria. The criteria require prototype packages to be subjected to various individual and sequential tests that simulate the conditions produced in severe aircraft accidents. Specific post-test acceptance standards are prescribed for each of the three safety functions of a package. The qualification criteria also prescribe certain operational controls to be exercised during transport.

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Preface

These qualification criteria to certify a package for air transport of plutonium were developed by the staff of the U.S. Nuclear Regulatory Commission (NRC). Prior to publication of this document, the criteria received an independent technical review and endorsement by both the NRC Advisory Committee on Reactor Safeguards and the Aeronautics and Space Engineering Board of the National Academy of Sciences.

I. INTRODUCTION

Public Law 94-79, enacted on August 9, 1975, places the following restriction on the Nuclear Regulatory Commission (NRC):

> The Nuclear Regulatory Commission shall not license any shipments by air transport of plutonium in any form, whether exports, imports, or domestic shipments; provided, however, that any plutonium in any form contained in a medical device designed for individual human application is not subject to this restriction. 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.

Standards for the integrity of packages used to ship plutonium and other radioactive materials are set forth in 10 CFR Part 71 (Ref. 1) of NRC Regulations and 49 CFR Parts 170-178 (Ref. 5) of Department of Transportation (DOT) Regulations. These standards have undergone continual evaluation and improvement by cognizant United States and international agencies since first established in 1948 and are consistent with those followed by over 70 foreign countries and the International Atomic Energy Agency. The standards are based on two main considerations: (1) protection of the public from external radiation; and (2) assurance that the contents are unlikely to be released during either normal or accident conditions of transport or, if the package is not designed to withstand accidents, that its contents are so limited in quantity as to preclude a significant radiation safety problem if released.

The safety of air transportation of plutonium and other radioactive materials was under active study by the NRC when Public Law 94-79 was enacted. As part of its review of the regulations and procedures originally promulgated by the Atomic Energy Commission, the NRC initiated a reevaluation of rules concerning the transportation of all radioactive materials by air. This was announced in the Federal Register on June 2, 1975. The announcement included notice that a rulemaking proceeding was being initiated and that a generic environmental impact statement would be prepared to reevaluate its regulations governing air transportation of radioactive materials from the standpoint of health, safety, and protection against diversion and sabotage. A final environmental impact statement was subsequently issued in December 1977 (NUREG-0170, Vols. 1 and 2).

On February 9, 1976, the NRC published its decision in the Federal Register that air transportation of special nuclear material, other than plutonium, under currently effective regulations, need not and should not be suspended or otherwise limited during the period the rulemaking proceeding was being conducted. For plutonium, other than in medical devices, Public Law 94-79 foreclosed continued air shipment until such time that a package had been certified by the NRC.

As a result of Public Law 94-79, the Nuclear Regulatory Commission established a certification program consisting of: (1) evaluation of the conditions which could be produced in severe aircraft accidents; (2) development of qualification criteria prescribing appropriate performance requirements and acceptance standards for packages used to transport plutonium by air; and (3) a series of physical tests and engineering studies of plutonium packages to demonstrate their ability to meet the qualification criteria.

The purpose of this Report is to describe the specific tests, assessments, acceptance standards, and operational controls that are included in the qualification criteria to certify a package for air transport of plutonium, and to discuss their adequacy with regard to severe aircraft crashes. Other elements of the certification program, such as package design features, test results, and requirements for package fabrication, inspection, and operation, will be addressed in separate documents or reports.

Basic Considerations

A complete assessment of the overall risk to the public and the environment as a result of transporting plutonium by air would relate possible adverse consequences to the probability of their occurrence. One important factor in this type of assessment is the expected accident frequency. For air shipment of plutonium, the probability of accident involvement is very low. This is based upon the excellent safety record of commercial aviation (Ref. 19) and the small number of plutonium shipments expected to be made by air. If a package were to be involved in an accident, safety would not necessarily be jeopardized since many aircraft accidents are relatively minor and would not seriously threaten high-integrity cargo. Accidents which could pose a serious threat occur less frequently.

The overall risk of transporting plutonium by air is somewhat dependent upon the relationship between package crashworthiness and the distribution of aircraft accident severities. However, the degree of package crashworthiness is not a factor which dominates overall risk since the probability of involvement in a severe aircraft accident is very low. Any resulting adverse consequences would depend upon several circumstances, such as the nature and location of the accident, the particle size and quantity of material released (if any), the existing meteorological conditions, and the effectiveness of remedial actions. In terms of probabilities and consequences, the overall risk of transporting plutonium by air is very small.

Public Law 94-79 focuses upon package crashworthiness, although it is only one facet of transport safety. The Law's explicit requirement for certification is that packages will not rupture as a result of testing equivalent to the crash and explosion of a high-flying aircraft. This requirement precludes the development of criteria based exclusively upon an assessment of overall risk in terms of probabilities and consequences. However, the criteria cannot be based upon a philosophy of zero risk since it is not possible to unconditionally guarantee that a package could never be ruptured under any set of conceivable aircraft accident circumstances. The approach taken in this Report to satisfy Public Law 94-79 is to provide a high degree of assurance that plutonium packages can withstand virtually all aircraft accidents. Packages are to possess sufficient integrity to insure adequate safety even in the unlikely event of aircraft crash involvement. The possibility that a package could rupture if involved in an accident, while not zero, is to be exceedingly remote.

The qualification criteria in this Report assure that package survival will approach certainty in aircraft accidents occurring during take-off, landing, or ground operations. These types represent the majority of all aircraft accidents and are most likely to occur in an urban area. The intention was to clearly and conservatively encompass a reasonable upper limit of severity for accidents of this type with minimal reliance being placed upon factors which could mitigate damage done to cargo. Considering the conservatism inherent in the qualification criteria for protecting against take-off and landing accidents, and the numerous factors present in an accident situation which could mitigate package damage, the criteria also assure a high degree of protection against accidents which occur in other phases of flight. This includes accidents of extreme severity such as mid-air collisions and high speed crashes.

Development of Criteria

The physical tests that are included in the qualification criteria are intended to simulate the accident environments that could be produced in severe aircraft accidents. Initial consideration was given to the environments that could occur at various stages of an accident (Figure 1). Each environment was examined separately and a qualification test or operational control was devised to provide suitable protection against that environment. The objective was for the resulting test or control to be as simple as possible and to provide clear and definite assurance that a high degree of protection was being provided. Sequential qualification test criteria were then obtained by combining the individual tests in a logical order corresponding to the order in which the environments could be expected to occur.

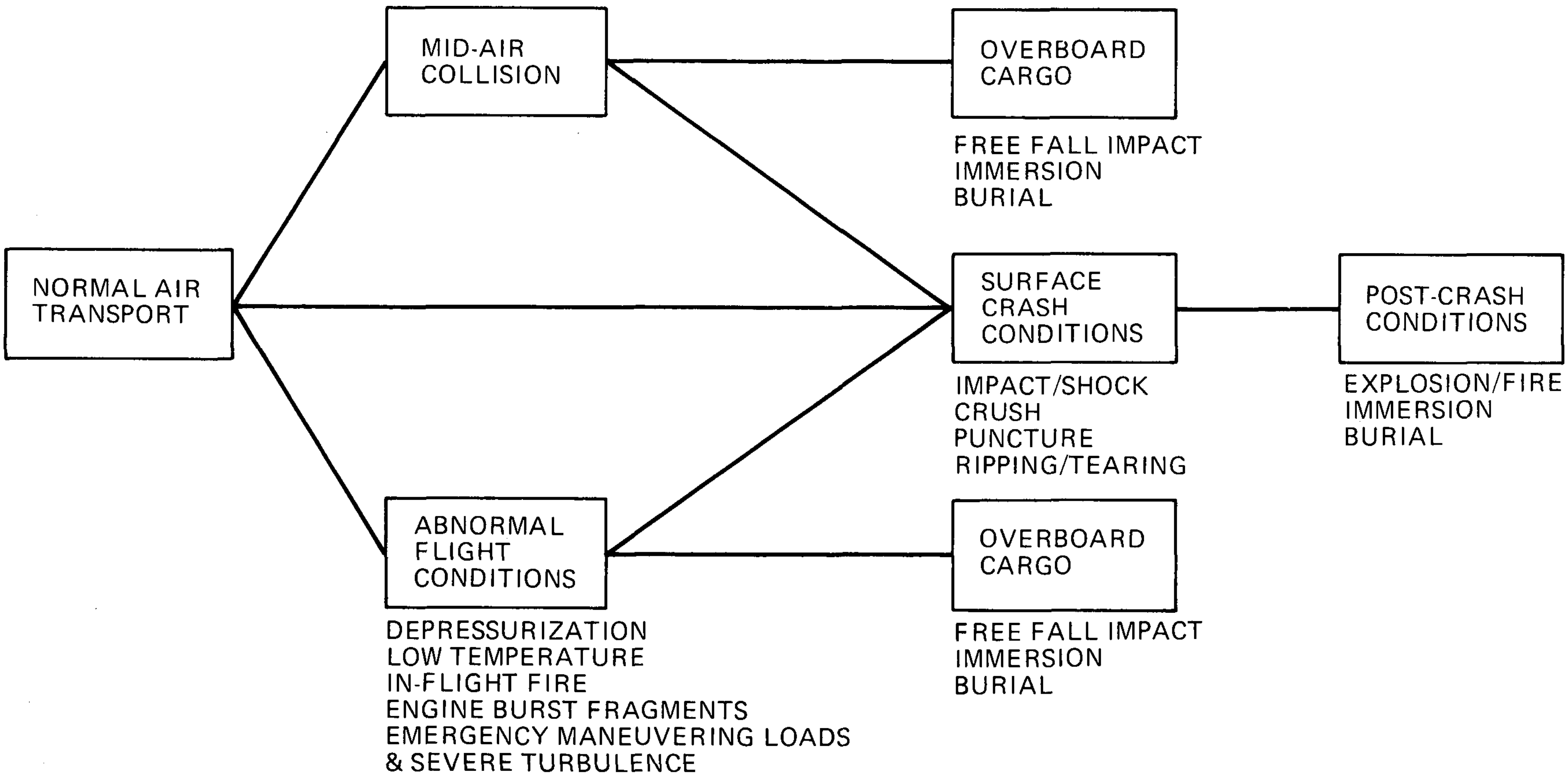

FIGURE 1. AIRCRAFT CARGO ENVIRONMENTS

Because of the large number of variables, the limited availability of data concerning accidents of the severity being considered, and the need for the qualification criteria to afford a high degree of safety, a reasonable degree of conservatism was used in simulating the accident environments. Although not precisely quantifiable, the qualification tests are conservative for two additional reasons:

1. A fundamental characteristic of a sequential test series is that the total damage produced is an accumulation of the effects produced by each individual test. This means that the article being tested must be somewhat overdesigned for any single test in order to meet the tests prescribed in the sequence. In general, a plutonium package that can meet the prescribed test sequence could be expected to withstand testing to a more severe magnitude if the environment simulated by that test were to be considered alone and not as part of a sequence. To be comprehensive, without requiring an inordinate number of different test sequences, the qualification criteria must necessarily prescribe a severe magnitude of test for all environments. However, few, if any, actual accidents would produce all environments at commensurate severity levels.

2. The qualification criteria represent a minimum level of required package performance. However, plutonium packages will have some degree of reserve margin since it is not practicable (or economical) to specify materials, dimensions, thicknesses, and weights that will result in a design capable of withstanding the minimum requirements and no more.

The qualification criteria also prescribe standards for determining the acceptability of plutonium packages following the physical tests. These acceptance standards are related to the three safety functions of packaging used to transport fissile material: (1) containment of the contents, (2) acceptable external radiation levels, and (3) maintenance of a sub-critical condition. The prescribed acceptance standards are conservative with respect to each of these three safety functions and are consistent with those specified by the International Atomic Energy Agency (IAEA) Transport Regulations (Refs. 6, 7).

II. QUALIFICATION CRITERIA TO CERTIFY A PACKAGE FOR AIR TRANSPORT OF PLUTONIUM

A. Compliance With 10 CFR Part 71

The package shall meet all applicable requirements of 10 CFR Part 71, "Packaging of Radioactive Material For Transport and Transportation of Radioactive Materials Under Certain Conditions."

B. Aircraft Accident Conditions

	Sequential Tests
Method of Demonstration:	A package shall be physically tested to the following conditions and in the order indicated to determine their cumulative effect.

Conditions:

1. Impact at a velocity of not less than 422 ft/sec at a right angle onto a flat, essentially unyielding surface, in the orientation (e.g., side, end, corner) expected to result in maximum damage at the conclusion of the test sequence.

2. A static compressive load of 70,000 pounds applied in the orientation expected to result in maximum damage at the conclusion of the test sequence. The force on the package to be developed between a flat steel surface and a two-inch wide, straight, solid, steel bar. The length of the bar to be at least as long as the diameter of the package and the longitudinal axis of the bar to be parallel to the plane of the flat surface. The load to be applied to the bar in a manner that prevents any members or devices used to support the bar from contacting the package.

3. Packages weighing less than 500 pounds to be placed upon a flat, essentially unyielding, horizontal surface and subjected to a weight of 500 pounds falling from a height of ten feet and striking in the position expected to

result in maximum damage at the conclusion of the test sequence. The end of the weight contacting the package to be a solid probe made of mild steel. The probe to be the shape of the frustum of a right circular cone, 12 inches long, eight inches in diameter at the base, and one inch in diameter at the end. The longitudinal axis of the probe shall be perpendicular to the horizontal surface. For packages weighing 500 pounds or more, the base of the probe to be placed on a flat, essentially unyielding surface and the package dropped from a height of ten feet onto the probe, striking in the position expected to result in maximum damage at the conclusion of the test sequence.

4. The package to be firmly restrained and supported such that its longitudinal axis is inclined approximately 45° to the horizontal. The area of the package which made first contact with the impact surface in test (1), above, to be in the lowermost position. The package to be struck at approximately the center of its vertical projection by the end of a structural steel angle section falling from a height of at least 150 feet. The angle section to be at least six feet in length with equal legs at least five inches long and 1/2-inch thick. The angle section to be guided in such a way to fall end-on, without tumbling. The package to be rotated approximately 90° about its longitudinal axis and struck by the steel angle section falling as before.

5. The package to be exposed to luminous flames from a pool fire of JP-4 or JP-5 aviation fuel for a period of at least 60 minutes. The luminous flames to extend an average of at least three feet and no more than ten feet beyond the package in all horizontal directions. The position and orientation of the package in relation to the fuel to be that which is expected to result in maximum damage at the conclusion of the test sequence. An alternate method of thermal testing may be substituted for the above fire test provided that the alternate test is not of shorter duration and would not result in a lower heating rate to the package. At the conclusion of the thermal test, the package shall be allowed to cool naturally or shall be cooled by water sprinkling, whichever is expected to result in maximum damage at the conclusion of the test sequence.

6. Immersion under at least three feet of water for at least eight hours.

Acceptance Standards:

1. Containment - The containment vessel must not be ruptured in its post-tested condition and the package must provide a sufficient degree of containment to restrict accumulated loss of plutonium contents to not more than an A_2 quantity* in a period of one week.

2. Shielding - Demonstration that the external radiation level would not exceed one Rem per hour at a distance of three feet from the surface of the package in its post-tested condition in air.

3. Sub-Criticality - A single package and an array of packages shall be demonstrated to be sub-critical in accordance with 10 CFR Part 71, except that the damaged condition of the package shall be considered to be that which results from the above qualification tests rather than the conditions specified in Appendix B of 10 CFR Part 71.

Individual Test I
(Free-Fall Impact)

Method of Demonstration: Physical test of an undamaged package to the following conditions. This test is not required if the calculated terminal free-fall velocity of the package is less than 422 ft/sec or if a velocity not less than either 422 ft/sec or the calculated terminal free-fall velocity of the package is used in Test 1 of the sequential tests, above.

Conditions: Impact at a velocity not less than the calculated terminal free-fall velocity at mean sea level at a

*An A_2 quantity of plutonium is defined in Table VII of the International Atomic Energy Agency Regulations for the Safe Transport of Radioactive Materials, IAEA Safety Series No. 6. (See Appendix A of this document.)

right angle onto a flat essentially unyielding surface, in the orientation (e.g., side, end, corner) expected to result in maximum damage.

Acceptance Standards: Same as for the sequential tests, above.

Individual Test II
(Deep Submersion)

Method of Demonstration: Physical test of a package to the following conditions.

Conditions: The package to be submerged and subjected to an external water pressure of at least 600 psi for not less than eight hours.

Acceptance Standards: No detectable leakage of water into the containment vessel of the package.

C. Other Requirements

1. Demonstration or analytical assessment showing that the results of the physical testing for package qualification would not be adversely affected to a significant extent by:

   a. The presence, during the tests, of the actual contents that will be transported in the package, and

   b. Ambient water temperatures ranging from +33°F to +100°F for those qualification tests involving water, and ambient atmospheric temperatures ranging from -40°F to +130°F for the other qualification tests.

2. Demonstration or analytical assessment showing that the ability of the package to meet the acceptance standards prescribed for the accident condition sequential tests would not be adversely affected if one or more tests in the sequence were deleted.

D. Operational Controls

Through special arrangement with the carrier, the shipper shall ensure observance of the following operation controls for each shipment of plutonium by air:

1. Plutonium packages must be stowed aboard aircraft on the main deck in the aft-most location possible for cargo of their size and weight. No other type of cargo may be stowed aft of plutonium packages.

2. Plutonium packages must be securely cradled and tied down to the main deck of the aircraft. The tie-down system must be capable of providing package restraint against the following inertia forces acting separately relative to the deck of the aircraft: Upward, 2g; Forward, 9g; Sideward, 1.5g; Downward, 4.5g.

3. Cargo which bears one of the following hazardous material labels may not be transported aboard an aircraft carrying a plutonium package:

    Explosive A
    Explosive B
    Explosive C
    Spontaneously Combustible
    Dangerous When Wet
    Organic Peroxide
    Non-Flammable Gas
    Flammable Liquid
    Flammable Solid
    Flammable Gas
    Oxidizer
    Corrosive

    The above restriction does not apply to hazardous material cargo labeled solely as:

    Radioactive I
    Radioactive II
    Radioactive III
    Magnetized Materials
    Poison
    Poison Gas
    Irritant
    Etiologic Agent

III. DISCUSSION OF QUALIFICATION CRITERIA TO CERTIFY A PACKAGE FOR AIR TRANSPORT OF PLUTONIUM

Normal Conditions of Air Transport

Packages used for air shipment of plutonium must be adequate for the normal rigors of handling and air transport as well as having the capability to withstand aircraft accidents. The tests and standards that apply to packages for normal conditions of transport are prescribed in 10 CFR Part 71 of NRC Regulations (Ref. 1). The NRC Regulations also specify requirements for loading, unloading, and operation of packages as well as requirements for inspection, maintenance, records, and reports.

In addition, NRC Regulations require radioactive material packages to be transported in accordance with DOT Regulations (Ref. 5). The DOT Regulations contain provisions for the marking, labeling, loading and storage of packages. DOT Regulations also have requirements for placarding, monitoring, and reporting. Except for small quantities intended for medical or research purposes, DOT Regulations require that air transport of radioactive materials be by cargo-only aircraft.

As evidenced by the safety record established from hundreds of thousands of shipments of radioactive materials over a period of years, the NRC and DOT requirements have provided a high degree of safety under normal conditions of transport by all modes, including air transport. The qualification criteria do not include any additional test requirements for normal conditions of air transport beyond the package conforming to the provisions of 10 CFR Part 71.

Abnormal Flight Environments

Various abnormal or accident conditions could occur in flight that may potentially damage cargo or affect its ability to withstand a succeeding surface crash. However, as discussed below, the Normal Conditions of Transport prescribed in 10 CFR Part 71 are adequate to assure package integrity under abnormal flight environments.

A. Depressurization - It is possible that a package could be subjected to a reduced atmospheric pressure during transport as a result of compartment depressurization. This would increase the pressure differential between the internal cavity and the atmosphere and could have a minor effect upon the heat transfer characteristics of the package. As a Normal Condition of Transport, 10 CFR Part 71 prescribes an ambient pressure test of one-half standard atmosphere. Assuming that a package could be exposed to an ambient pressure as low as one-tenth standard atmosphere, corresponding to an altitude of approximately 52,800 feet above mean sea level on a standard day (Ref. 10), the increase in pressure differential beyond that required by the 10 CFR Part 71 test is only about six psi. Because pressure differences of this magnitude are negligible in comparison to the internal pressures that can build up in a post-crash thermal environment, and are also insignificant with respect to the capabilities of the types of pressure vessels used in plutonium packages, the qualification criteria do not include additional depressurization requirements beyond the one-half atmosphere test specified in 10 CFR Part 71.

B. Low Temperatures - A reduction of ambient temperature could accompany the loss-of-compartment pressurization. Cold temperatures could have an adverse effect upon the mechanical properties of some materials and cause stresses due to differential thermal expansion. Although the atmospheric temperature corresponding to an altitude of 52,800 feet on a standard day is -69.7°F, temperature inside a cargo compartment is not likely to approach this degree of coldness. Cargo compartments on jet aircraft are equipped with a temperature control system that would continue to supply heat. Also, corrective measures taken by pilots in the event of compartment depressurization (i.e., lowering altitude as much as possible) would not allow sufficient time for a significant reduction of compartment temperature to occur. In addition, a significant period of time would be required for the temperature of a package to respond to a lower ambient temperature. The qualification criteria do not include any additional temperature requirements for air transport beyond the -40°F requirement specified in 10 CFR Part 71 as a Normal Condition of Transport. An atmospheric temperature of -40°F corresponds to an altitude of approximately 28,000 feet on a standard day (Ref. 10).

C. Engine Burst Fragments - Operating experience indicates that burst-type failures can occur to the blades and rotors used on commercial jet aircraft engines. When this occurs, fragments are generally contained within the nacelle or the engine case. In some instances, the fragments are not contained and, because of their kinetic energy, could potentially become missiles which may damage a package on board the aircraft.

An assessment of the degree of this possible threat (Ref. 41) was made by a consultant to the NRC staff. A plutonium package on board an aircraft would not be damaged by an uncontained rotor failure unless it was in the path of a missile. Depending upon its size and distance from the engine, the package would occupy only a small portion of the 360° arc through which the engine components rotate.

The longitudinal location of the package with respect to the engines is also a factor. An FAA document (Ref. 42) reports the probable impact area of fragments to be within 15° fore and aft of the plane of rotation of the major rotor assemblies in the engine. Other FAA data indicate that uncontained rotor failures occur approximately once per 909,000 jet engine operating hours.

For several types of jet aircraft, these considerations were used to calculate the probability that a typical plutonium package containment vessel would be in the path of a major fragment in the event of a rotor burst failure. The package was assumed to be located within the probable impact area (i.e., within 15° fore and aft of the plane of rotation of the assemblies). The average flight duration was conservatively assumed to be five hours. The results varied, depending upon the type of plane. When located in the probable impact area, the calculated probability that the containment vessel would be in a position to be struck ranged from approximately 3.2% to 0.5%. Combining this information with the observed rate of uncontained rotor failures indicates that the probability of a plutonium package being in the path of a rotor fragment is extremely low. The estimated probability ranges from one per 5.3 million flights to one per 37.2 million flights.

The above assessment did not consider other factors which reduce this small threat still further:

1. An operational control discussed later in this report will require plutonium packages to be located in the aft portion of the aircraft. This control will exclude plutonium packages from locations within the probable impact area of fragments from wing-mounted engines.

2. A containment vessel located in the path of a rotor burst fragment would not necessarily be struck; and if struck, would not necessarily be penetrated or ruptured. The translational and rotational kinetic energy of a fragment would, in part, be dissipated by the effort required to penetrate various portions of the aircraft structure and enter the fuselage. After entering the cargo area, the kinetic energy of the fragment would be further reduced (perhaps dissipated completely) if the fragment were to strike intervening cargo before striking the package. Should the package be struck, the angle and direction of impingement may be such that the fragment would be deflected; should the package be struck directly, the various shells and energy-absorbing materials may be adequate to resist penetration.

Based upon these qualitative considerations, as well as the low probability of a package being struck, the threat from this source is considered to be negligible. The qualification criteria do not include any test conditions to simulate an engine rotor burst fragment.

D. Emergency Maneuvering and Severe Turbulence - Emergency aircraft maneuvering or severe turbulence conditions can be expected to produce cargo acceleration loads of only a few g's magnitude. Adequate protection against this occurrence is afforded by present regulations which require, as a Normal Condition of Transport, that packages withstand a free-drop from heights up to four feet onto an essentially unyielding surface without experiencing any damage that significantly reduces the effectiveness of the package. The requirement assures that a shock environment of this type would not produce any damage which would degrade the ability of a package to survive a subsequent accident. Additional assurance in this regard is provided by the inherently rugged nature and high degree of integrity required for packages to withstand the tests that simulate crash conditions. The qualification criteria do not include any additional requirements for this purpose beyond the free-drop requirement specified as a Normal Condition of Transport by 10 CFR Part 71.

E. In-Flight Fire - It is possible for fire to occur aboard aircraft in flight. If the location and duration of an inflight fire cannot be controlled, it is likely that either an expeditious landing or a crash would ensue. Assuming a package to be in the vicinity of an in-flight fire, it is reasonable to expect that the intensity and duration of the fire would not produce sufficient heat to the package to significantly detract from its ability to withstand possible succeeding accident conditions, and that the overall damage potential of in-flight fires is considerably less than for fires on the ground. The qualification criteria do not include any test conditions to simulate an in-flight fire environment.

Surface-Crash Conditions

The damaging conditions produced in an airplane crash can be extremely severe. With the exception of minor accidents, where the measurement capabilities of flight recorder accelerometers were not exceeded (+6g, -3g), there is essentially no information obtained by instrumented measurement at the time of occurrence. However, a limited amount of data is available concerning various aircraft flight parameters at the time of crash (e.g., speed, pitch, impact angle, etc.). These data, together with other information, such as the design characteristics of the aircraft and its ancillary equipment, have been extensively studied for accident severities where human tolerance is marginal (Refs. 20, 22, 23, 24, 45).

The severe accidents pertinent to this report have been studied to various degrees in connection with the nuclear airplane program, the pacemaker and artificial heart programs, and the program to develop an accident-resistant container (ARC) for nuclear weapons. Information developed from the ARC study was used as the basis for a probabilistic study by DOT/ERDA of the severity of cargo aircraft accidents. In addition, aircraft flight recorders are designed to specific criteria (Ref. 3) to assure accident survivability. There is a large data base of information concerning the performance and accident survival rate experienced by these devices in hundreds of accidents (Ref. 21).

Both the ERDA/DOT study of cargo aircraft accident severity and the flight recorder qualification criteria, characterize aircraft crash conditions by three separate types of environments--impact, crush, and puncture. Aircraft crash conditions are similarly designated in this report. An additional test is included to simulate ripping/tearing environments. The specific tests and controls that protect against these crash environments are outlined below. Other conditions, such as fire and immersion, which could occur shortly following a surface crash, are discussed later under Post-Crash Conditions. In-flight accidents, such as mid-air collision and overboard cargo, are also discussed later as a separate subject.

A. Impact/Shock - The primary factors affecting aircraft impact severity are velocity, impact angle, and 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 force needed to collapse the airframe, and the energy-absorbing capacity of the airframe structure.

The expected crash speed 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 take-off where aircraft speeds are much lower than at cruising altitude. Maximum flight speeds of aircraft in the United States are governed by the following Federal Regulations (Ref. 4):

1. The maximum airspeed permitted at altitudes lower than 10,000 ft (MSL) is 250 knots (422 ft/sec) (14 CFR §91.70(a)).

2. Within an airport traffic control area, the maximum airspeed permitted for reciprocating engine aircraft is 156 knots (264 ft/sec). The maximum airspeed permitted for turbine powered aircraft is 200 knots (338 ft/sec) (14 CFR §91.70(b)). An airport traffic control area is defined as extending within a radius of five miles from the airport and extending up to 3,000 feet above the airport elevation.

3. Within a terminal control area, the maximum airspeed permitted is 200 knots (338 ft/sec) (14 CFR §91.70(c)). A terminal control area is designated for 22 major airports in the U. S. which have a high density of aircraft traffic (Ref. 15). Although the precise boundary varies for individual airports, the terminal control areas are defined in terms of altitude and radial distance from the runway, ranging out to distances of 20 to 30 miles and altitudes up to 12,500 ft.

To protect against the impact environment produced by aircraft crashes, the qualification criteria specify that plutonium packages be impact tested at a velocity of at least 422 ft/sec (250 knots), at a right angle onto a flat, essentially unyielding surface, in the orientation (e.g., side, end, corner) expected to result in maximum damage at the conclusion of the test sequence.

The velocity of the test is based upon the FAA speed limitation of 422 ft/sec (250 knots) at altitudes less than 10,000 ft. This test velocity, together with the right-angle impact requirement, provides a reasonable upper limit for aircraft speed, impact angle, and orientation for crashes which occur during approach, landing, take-off, climb-out, and operations on the ground.

The essentially unyielding surface is specified because accidents can occur onto airport runways, concrete highways, and against rock surfaces which have relatively little potential for mitigating impact severity. An example of an essentially unyielding surface is given by the IAEA (Ref. 7) as being a block of concrete set on firm soil and covered on top by a 1/2-inch-thick steel plate that has been wet floated into place. The mass of the concrete should be at least ten times greater than the mass of the package. The plane dimensions of the block should be at least 20 inches larger on all sides than the package and the shape of the block should be as close to cubical as practicable. This type of test target requires the package itself to dissipate essentially all its own kinetic energy.

Without relying upon other mechanisms which could dissipate kinetic energy and mitigate damage to cargo, the test virtually precludes the possibility that the type of aircraft crashes which occur in the vicinity of airports and surrounding urban areas (Table 1) could produce an impact environment which exceeds the minimum capabilities of a package. The test also provides a high degree of protection against crashes which occur in a phase of operation other than approach, landing, take-off, and climb-out. Crashes at speeds less than 422 ft/sec are bounded by the test regardless of phase of operation. As discussed later, only a small number of cargo-type aircraft crashes have occurred at speeds above 422 ft/sec. The adequacy of the test to protect against crash speeds greater than 422 ft/sec is considerably enhanced by the following factors, which can substantially lessen the crash severity:

1. As discussed below, the component of crash velocity normal to the impact surface is the parameter of primary significance with respect to impact severity. In the majority of aircraft crashes, the normal component of velocity will be considerably less than the crash velocity of the aircraft.

2. The component of crash velocity tangential to the impact surface may be arrested at low force levels over large distance as the aircraft comes to rest.

3. Portions of the kinetic energy may be dissipated through deformation or disintegration of the aircraft structure. Other cargo located forward may deform to dissipate energy and cushion the impact environment for an aft located package.

4. Displacement and deformation of a relatively soft impact surface, such as soil, may cushion the impact and reduce decelerations in the normal direction.

5. The package orientation with respect to the surfaces that are contacted may change as the crash progresses, allowing more than one impact event in which to dissipate its total kinetic energy and permitting deformation of its impact-absorbing materials to occur over a larger surface area and in a more efficient manner than in the qualification test.

The general progression of damage in aircraft accidents is discussed in a U. S. Army Mobility Research and Development Laboratory document (Ref. 31). As described in this report, "The structure which first contacts the impact surface usually is the first to begin to deform. This localized deformation continues either until the kinetic energy of the aircraft is absorbed at low speeds over relatively large distances or until there is enough structure involved in the deformation to produce a significantly high decelerative force on the aircraft mass. If the quantity of kinetic energy to be absorbed

Table 1

U.S. AIR CARRIER ACCIDENTS*, 1963-1974, BY PHASE OF OPERATION**

Flight Phase	All Aircraft (543 Accidents)	Cargo Aircraft (89 Accidents)
Static	7%	1%
Taxi	9%	10%
Take-Off	15%	20%
Landing	46%	54%
In-Flight	23%	15%

*Excludes non-crash turbulence accidents and fire in engine or wheel nacelle.
**Source: Reference 36.

is small, structural damage may be minor, and the aircraft may simply come to rest without endangering occupants" (or cargo). "When the initial kinetic energy is high, there is more likelihood that forces will build up until total aircraft decelerative forces become large. Once these high decelerative forces are reached, then buckling throughout the aircraft may occur."

The velocity of an aircraft at the instant of crash can be resolved into components of velocity normal and tangential to the impact surface (Fig. 2). Energy absorption in these two directions can

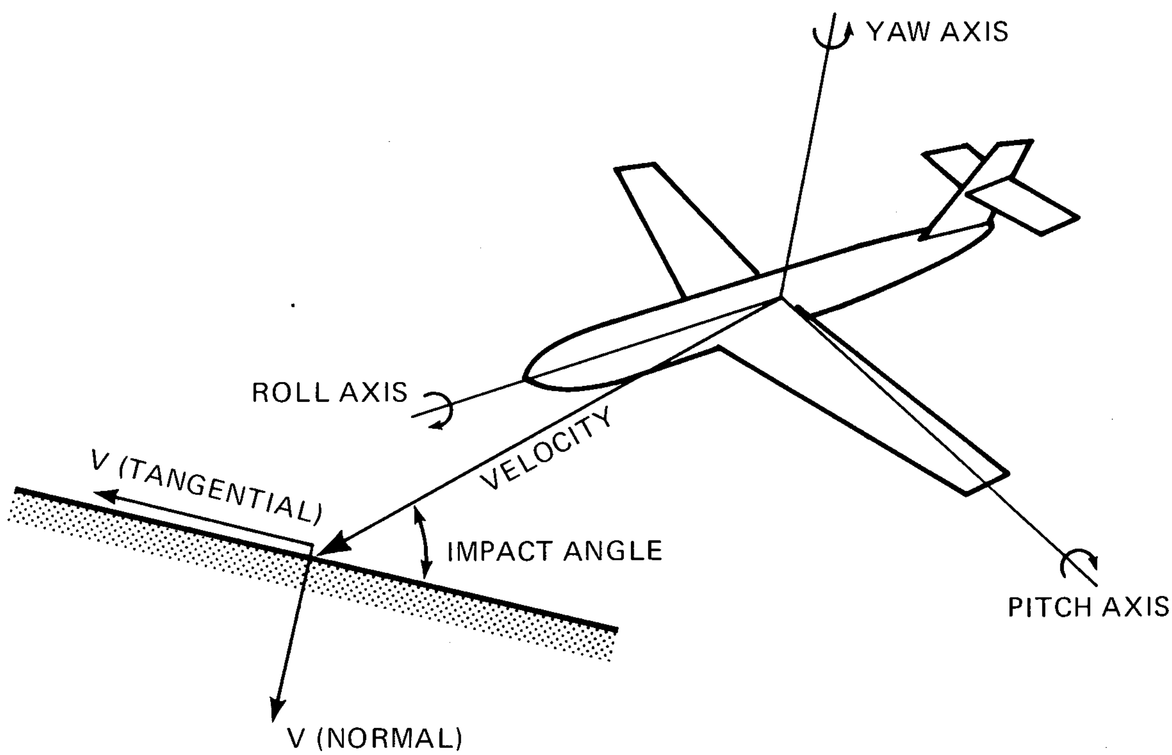

FIGURE 2. VELOCITY VECTORS AT INSTANT OF IMPACT

differ significantly. Most aircraft crashes occurring 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 and by airframe "plowing"-type interaction with terrain irregularities. Although the acceleration 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, corresponding to 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, 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 acceleration until the energy absorption capability of the airframe was exceeded and collapse had essentially "bottomed-out."

In most cases, the normal velocity component is appreciably lower than the tangential component because most crashes occur at small impact angles. However, in comparison to the tangential direction, velocity changes in the normal direction occur within only a short distance. Bearing pressures acting over the surface contact area produce large forces which rapidly decelerate the aircraft in the normal direction. 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. Although there is essentially no possibility that motion in the normal direction can be arrested over protracted lengths of time or distance, the impact surface for cargo can be considerably less damaging than the essentially unyielding surface prescribed in the qualification test. Deformation of the impact surface, collapse of the underside structure of the aircraft, and compression or crushing of debris between package and the impact surface may provide several inches of stopping distance which are not available in the qualification test. This would lower the average deceleration forces experienced by a container and mitigate the severity of impact.

A report published by the FAA (Ref. 32) contains a general evaluation of the crash and destruction of a twin-engine piston propelled aircraft and a four-engine jet propelled transport aircraft. The assumed crash speeds were 150 ft/sec for the 45,000-lb piston aircraft and 220 ft/ sec for the 150,000-lb jet aircraft. The results of this report, summarized in Table 2, indicate that the g-loads which accompany deformation and collapse of the aircraft are not sufficiently large to be a major threat to plutonium packages. However, structural collapse of the airframe will not dissipate a large percentage of the kinetic energy possessed by aircraft at flight speeds. The kinetic energy of a crash must essentially be dissipated by aircraft interaction with the surface (displacement, deformation, and friction). If the normal component of velocity at impact is small, the energy absorbing capacity of the lower fuselage will not be exceeded and decelerations produced in this direction will be modest. Crashes involving higher rates of descent may produce fuselage damage leading to aircraft disintegration by subsequent longitudinal decelerations. If forces in the tangential direction, due to friction and "plowing"-type interaction with the surface, do not become excessive (i.e., 5 to 10 g's for the jet aircraft), longitudinal collapse of the airframe will not occur and the aircraft will come to rest over a relatively large distance. But if the skidding aircraft strikes a substantial obstacle, longitudinal collapse can occur at low force levels without dissipation of substantial kinetic energy.

This type of airframe energy absorption performance was observed in a series of tests done for the U.S. Air Force by the Flight Safety Foundation (Ref. 33). In these tests, three C-119C cargo aircraft were loaded with a 13,000-lb container and crashed at a speed of 207 ft/sec. Two of the aircraft were crashed at 90° into a 30-inch thick concrete wall backed by an earthen embankment; the third was crashed at an angle of 20° into an earthen mound. For the two tests into the wall, the container experienced low acceleration as structure forward of the container progressively collapsed longitudinally. After collapse had proceeded sufficiently, the container struck the crushed portion of the forward fuselage intervening between the container and the wall at a velocity of 190 ft/sec (only 17 ft/sec less than the impact velocity of the aircraft). The wall was displaced six inches and energy-absorbing materials provided on the container were crushed 14 inches. The report estimates that the 17 inches of debris between the container and the wall was crushed 50%, providing a total stopping distance for the inner container of 28.5 inches, resulting in an average deceleration of 236 g's, with a peak

Table 2

ENERGY ABSORPTION CAPABILITY OF TYPICAL AIRFRAMES*

	Twin-Engine Piston Transport Aircraft (1)		Four-Engine Jet Transport Aircraft (2)	
	Fraction of Kinetic Energy Dissipated**	Maximum Deceleration	Fraction of Kinetic Energy Dissipated**	Maximum Deceleration
Longitudinal Crushing of Fuselage Forward of Wings	20%	7g	8%	4g
Loss of Both Wings by Chordwise Shear or Bending	4%	19g	8%	11g
Vertical Crushing of Lower Fuselage	1.3%	11g	1.3%	14g

(1) 45,000 pounds
(2) 150,000 pounds

* See Reference 32.
** Fraction based on impact speed of 150 ft/sec for the piston aircraft and 220 ft/sec for the jet aircraft.

of approximately 708 g's. In the third test, at 20° into an earthen mound, the container remained attached to the fuselage floor as the forward section collapsed. When the forward edge of its shipping pallet struck the crushed aircraft structure, the container was released and thrown free from the disintegrating aircraft. The aircraft wreckage continued to move for several hundred feet while the container struck the front face of the slope, tumbled over the crest, and came to rest at the base of the mound. In each of these three tests, the velocity component normal to the impact surface was sufficient to cause collapse or disintegration of the fuselage with minimal protection being afforded to cargo by the aircraft. In the first two instances, cargo impact was mitigated by a small reduction in container velocity before impact, by cratering and displacement of the wall, and by compression of aircraft debris between the wall and the container. In the third case, the total kinetic energy of the container was not dissipated in a single impact event. The container orientation changed with respect to the surfaces that were contacted, permitting more effective utilization of the surrounding impact-absorbing materials. Container impact was also mitigated by cratering and depression of the soil surface.

In other crash circumstances, the aircraft structure can provide considerable additional protection to cargo. This is illustrated in two reports published by the FAA concerning full-scale crash testing of a DC-7 and a Lockheed Constellation aircraft (Refs 34, 35). Although both of these tests were conducted at speeds similar to those used for the Air Force tests (235 and 189 ft/sec), the degree of aircraft damage was much less. The crashes occurred at small impact angles and had lower velocity components normal to the impact surface. The main portion of both fuselages remained essentially intact and the impact environment experienced by cargo in these crashes was not sufficient to cause failure of the restraining systems.

Considerable variation exists in the velocities at which aircraft crashes have occurred. For commercial aviation accidents, little quantified data concerning velocity and other flight parameters at the time of crash could be located by the NRC staff or its consultants. However, extensive records of this sort are maintained for military aviation accidents at Norton Air Force Base, California. At least three statistical studies have been made of this data. In May of 1971, NASA published preliminary impact speed and angle criteria for the nuclear airplane (Ref. 27). This report was based upon analysis of 96 major military accidents occurring between 1960 and 1965 involving multi-engine jet cargo and bombardment aircraft. In November of 1971, the Advanced Concepts Department of Lockheed Georgia Company published a report concerning large military aircraft accident statistics (Refs. 25, 26). The data used in this study combined the 96 jet aircraft accidents used in the NASA study with the records of 218 accidents between 1964 and 1970 involving large, multi-engine transport, bombardment, and special-mission aircraft operated by the Air Force. The resultant sample comprised 311 accident digests. All accidents except those involving ground contact following a controlled flight-airborne phase were eliminated. Also, all accidents involving aircraft with a sonic, or higher, speed capability were rejected as were those accidents which failed to provide numerical estimates of impact speed. The final data set consisted of 128 accidents involving eleven different types of aircraft. The results of the study are probabilistic in nature and are normalized in terms of velocity at impact to maximum low altitude (30,000 feet) speed capability as well as in terms of normal velocity at impact to maximum low altitude speed capability.

The results of both the NASA study and the Lockheed Georgia study are based upon the combined accident data for heavy bombardment aircraft (B-47, B-52) and military cargo aircraft. Because bombardment aircraft data were included in the study sample, the results may not be applicable to commercial aviation. Unlike commercial cargo aircraft, the mission of bomber aircraft sometimes involves high- speed flight at low altitudes above terrain.

Some results of the Lockheed study are shown below; speed characteristics of typical cargo aircraft are listed in Table 3.

1. The ratio of average crash speed to maximum aircraft speed capability at low altitudes for the sample was approximately 0.34. For an aircraft with a maximum speed capability of 920 ft/sec, this would correspond to an average crash speed of 312 ft/sec. For crashes which occurred during landing and takeoff, the ratio of average crash speed to maximum aircraft speed capability was approximately 0.29.

2. In 90% of the cases, the ratio of crash speed to maximum low altitude speed capability was 0.67 or less. In 95% of the cases, the ratio was 0.77 or less.

3. Ninety percent of the crashes were reported to involve impact angles less than 60°. Impact angles less than 15° were involved in 76% of the crashes. In 90% of the cases, the ratio of the velocity component normal to the impact surface to the maximum low altitude speed capability of the aircraft was 0.325 or less.

Table 3

APPROXIMATE SPEED DATA FOR TYPICAL CARGO AIRCRAFT*

Aircraft Designation	Take-Off (1) (ft/sec)	Aircraft Stall in Take-Off Configuration (2) (ft/sec)	Landing (3) (ft/sec)	Aircraft Stall in Landing Configuration (ft/sec)	Cruise (ft/sec)	Maximum (ft/sec)
Turbo-Jet Aircraft						
B-707-320C	290	250	230	175	800	920
B-727-100QC	255	225	205	160	800	910
B-737-200QC	245	215	195	150	845	860
B-747F	320	280	255	195	850	940
DC-8F	300	265	240	185	800	880
DC-9-30F	275	240	220	170	815	880
DC-10-10CF	285	245	235	180	820	895
Turbo-Prop Engine Aircraft						
FH-227D	-	-	175	135	425	440
L-100-20	-	-	215	165	515	565
Reciprocating Engine Aircraft						
DC-7F	-	-	200	155	365	525
1049H	-	-	-	-	415	-
1649A	-	-	195	150	345	440

(1) Assumed relationship: Take-off velocity ÷ landing velocity = 1.25

(2) Estimated using relationship, take-off speed = 1.15 times stall speed (14 CFR 25.107)

(3) Estimated using relationship, landing speed = 1.3 times stall speed (14 CFR 25.75 and 25.125)

* References 12 and 13.

In August of 1975, Sandia Laboratories published a report concerning the accident environments expected for C-5, C-141, and C-130 aircraft accidents (Ref. 29). This report was, in part, derived from information collected for a study of the severities of transportation accident environments (TAC Study) performed for ERDA and DOT (Ref. 30). The aircraft portion of the TAC Study is based upon analysis of 305 accident records documented at Norton Air Force Base. These accidents represent all Air Force aircraft flight accidents resulting in aircraft damage for a selected group of cargo aircraft from 1962 through 1972. As defined by the Air Force, aircraft flight accidents resulting in aircraft damage require more than 150 man-hours for repair and occur within the period from which the engines are started for the purpose of authorized flight until the engines are stopped and the brakes are set. Of the 305 accidents, 149 were classified in the report as impact accidents. In cases where a necessary flight parameter was not included in the accident record, the missing data was either assigned a value appropriate to the accident category or estimated through a statistical distribution treatment. The results are in the form of a probabilistic relationship for the normal velocity component at impact. Through use of U.S. Air Carrier accident rates, the study also includes a probabilistic estimate relating the normal component of velocity in accidents to miles of travel for expected occurrence in commercial aviation.

The data sample (Ref. 29) used in the TAC Study indicates that only a small number of military cargo aircraft crashes have occurred at speeds greater than 422 ft/sec. Of the 149 military cargo aircraft accidents that involved impact, only eight were estimated to have occurred at a speed in excess of 422 ft/sec (Table 4). Of these eight, only one is known to have had a normal velocity component greater than 422 ft/sec. However, normal velocity estimates are not available for four of the eight cases.

The National Transportation Safety Board (NTSB) maintains accident data records for U.S. air carriers. In the 13-year period from 1962 through 1974, there were 243 U.S. air carrier accidents involving collision of aircraft over 12,500 pounds with ground, water, or other objects. (These figures do not include collision between aircraft in flight.) Estimates of speed at impact are available for only 12 of these 243 collision accidents (Ref. 28). For these 12 accidents (Table 5), the highest estimated crash speed is 397 ft/sec.

The adequacy of the proposed impact test is supported by: (1) the rules and regulations which apply to flight, (2) the operating characteristics of aircraft, (3) the conservatisms included in the proposed test, and (4) the available data from previous crashes. Based upon these considerations, the test is judged to be sufficient to protect against impact environments that may be produced in severe aircraft crashes.

Table 4

MILITARY CARGO AIRCRAFT ACCIDENTS*, 1962-1972, ESTIMATED TO INVOLVE IMPACT SPEEDS OF 400 FT/SEC OR MORE**

Aircraft Type	Impact Speed (fps)	Impact Angle With Surface	Velocity Component Normal to Surface (fps)
KC-135	High	35°	-
KC-135	High	-	-
-	507	-	-
KC-135	500	-	-
-	500	55°	410
-	490	70°	460
C-135	461	18°	142
KC-135	440	3°	23
-	422	3°	22
-	422	75°	408
-	410	40°	264
-	405	70°	381
KC-135	401	50°	307

.136 Other Impact Accidents At Speeds Less Than 400 ft/sec.

* Total of 305 accident cases, of which 149 are categorized as impact accidents.

** Source: Reference 29.

Table 5

U.S. AIR CARRIER ACCIDENTS*, 1962-1974, FOR WHICH NTSB HAS NUMERICAL ESTIMATES OF SPEED**

Aircraft Type	Impact Speed (fps)	Impact Angle With Surface	Velocity Component Normal to Surface (fps)	Flight Phase
727	397	-	-	Approach
707	316	-	-	Take-off
508	287	-	-	Approach
DC-6	262	60°	227	Climb to Cruise
707	253	-	-	Approach
DC-9	245	4°	17	Approach
440	226	-	-	Approach
707	220	45°	156	Approach
FH 277	202	8°	28	Descent From Cruise
580	179	90°	179	Approach
DC-3	160	-	-	Approach
DC-9	135	-	-	Take-off Abort

* Accidents/Incidents involving collision of aircraft weighing over 12,500 pounds with ground/water or other objects (not including collisions with other aircraft in flight). Total of 243 cases in this category.

** See Reference 28.

B. Crush - As used in this report, crush refers to static or dynamic compression of a package by the weight or inertia force of an impinging object. Essentially no data could be located concerning either the mechanisms that have produced crush in aircraft crashes or its severity. Therefore, the qualification criteria proposed to protect against that environment are based upon an engineering estimate.

The two most probable causes of crush in an aircraft are cargo-to-cargo interaction and cargo interaction with the aircraft. In the longitudinal direction, deceleration forces may exceed the capabilities of the cargo-restraint system, allowing cargo to move forward relative to the aircraft. Under these circumstances, a package could be compressed between bulkheads or cargo located forward and other cargo located aft. An assessment of this environment made by a consultant to the NRC staff shows that the resulting crush load on the package could be considerable, depending upon the weight and relative velocity of the impinging objects and the deceleration rate of the aircraft (Ref. 43). Because of the variety of circumstances affecting the potential severity of this load, no satisfactory means was found to simulate or bound this environment by a specific test. Instead, the qualification criteria in this report specify an operational control requiring that plutonium packages be located in the aftmost area of the aircraft possible for cargo of their weight and dimensions. This assures that there will be no large mass of cargo located aft of the package to produce a high crushing force. In addition to providing protection against longitudinal crush, this location affords maximum advantage of the airframe to mitigate impact severity. The FAA requires that flight recorders be located as far aft as practicable for this specific purpose (Ref. 21).

In the vertical direction, the primary potential for producing a crush environment is through collapse of the lower fuselage. A package located in a cargo compartment below the main deck could be compressed between the hull and the floor structure (Figure 3).

However, the qualification criteria includes an operational control which requires plutonium packages to be stowed on the main deck of the aircraft. Although the operational control precludes the possibility of a package being compressed in a lower cargo compartment, the qualification criteria specifies the following physical test to assure that plutonium packages will have a very high degree of resistance to crush damage:

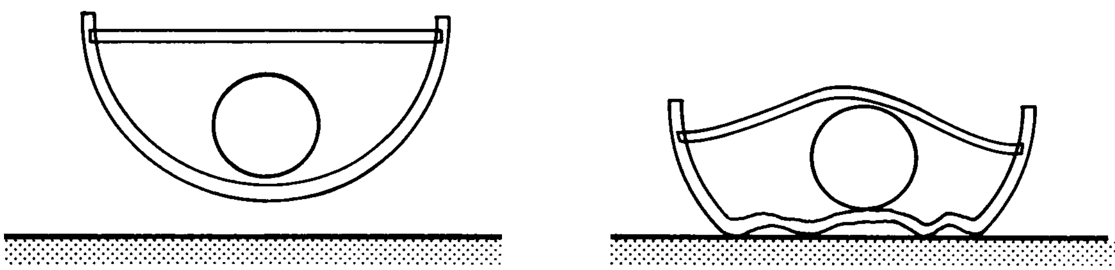

FIGURE 3. COLLAPSE OF LOWER CARGO COMPARTMENT

> A static compressive load of 70,000 pounds applied in the orientation expected to result in maximum damage at the conclusion of the test sequence. The force on the package to be developed between a flat steel surface and a two-inch wide, straight, solid, steel bar. The length of the bar to be at least as long as the diameter of the package and the longitudinal axis of the bar to be parallel to the plane of the flat surface. The load to be applied to the bar in a manner that prevents any members or devices used to support the bar from contacting the package.

The 70,000-pound load corresponds to the force required to cause upward bending, buckling, or shear failure of the floor system above lower cargo compartments (Ref. 43) and represents a limiting condition for this type of crush load. The two-inch dimension is a typical value for width of floor beams in cargo aircraft.

A third possible mechanism for producing a crush environment is through package interaction with major pieces of the aircraft. For this type of crush, one or more breaks in the cargo compartment must have occurred during the accident. The probability that a portion of a disintegrated aircraft would overlap the area occupied by a package is estimated in the Sandia study of accident severities (Ref. 30). Based upon the extent to which major debris has been scattered in several crashes, the report estimates the probability of a crash producing this type of crush to be in the range of 0.01 to 0.06.

If such a crush environment is produced, there is no suitable method to estimate its severity. However, a package which can withstand the other physical tests included in the qualification criteria has an inherently high resistance to damage from this cause. In addition, the 70,000-pound crush requirement is based upon the deformation capability of the load bearing floor structure of the aircraft. If a large piece of the aircraft fuselage should land upon a package, it is possible that the fuselage would deform around the package or that the package would be pressed into the surface without damage. Based upon these considerations, the qualification criteria do not include any additional tests to protect against this type of crush environment.

C. <u>Puncture</u> - As used in this report, puncture refers to a package striking or being struck by a small or pointed object which may cause a localized penetration. In an aircraft accident, a package could be struck by small pieces of free-flying debris, such as bolts, cable clamps, bits of splintered wreckage, etc., which may penetrate. A puncture may also be produced by a package striking a pointed object such as a protruding airframe member, tree limb, or jutting rock.

Because no data is available concerning puncture environments in aircraft accidents (causes or severity), any qualification test to protect against this threat must be somewhat arbitrary.

The puncture test included in the qualification criteria is an adaptation of the puncture test prescribed for radioactive material packages (10 CFR §71.36) and the puncture test prescribed for flight recorders (14 CFR §37.150). The severity of the adapted test exceeds the severity of either of the two tests from which it was derived. The two tests are conducted in a similar manner with the exception of the method used to apply the force. In the case of radioactive material packages, the container is dropped 40 inches onto a probe. In the case of flight recorders, a 500-pound weight is dropped ten feet onto the device. One factor affecting the relative severity of these two tests is whether the weight of the object being tested exceeds 500 pounds. This is also relevant to an accident since either a heavy package could strike a stationary pointed object or a light package at rest could be struck by a heavier pointed object.

To assure that plutonium packages have a high resistance to penetration from contact with pointed objects, the qualification criteria specifies the following test:

> Packages weighing less than 500 pounds to be placed upon a flat, essentially unyielding, horizontal surface and subjected to a weight of 500 pounds falling from a height of ten feet, striking in the position expected to result in maximum damage at the conclusion of the test sequence. The end of the weight contacting the package to be a solid probe made of mild steel. The probe to be the shape of the frustum of a right circular cone; 12 inches long, eight inches in diameter at the base, and one inch in diameter at the end. The longitudinal axis of the probe shall be perpendicular to the horizontal surface. For packages weighing 500 pounds or more, the base of the probe to be placed on a flat, essentially unyielding surface and the package dropped from a height of ten feet onto the probe, striking in the position expected to result in maximum damage at the conclusion of the test sequence.

This test assures that plutonium packages will have a high degree of resistance to penetration or puncture. The test is substantially more severe than the test prescribed for flight recorders where the device rests on a sand surface which is relatively easy to deform and where the probe attached to the falling weight is a length of 1/4-inch diameter bolt which is free to buckle, bend, or shear when it comes in contact with a hard surface. The test is also more severe than the puncture test specified in 10 CFR Part 71; three times more kinetic energy is associated with a ten-foot fall than with a 40-inch fall, and the shape of the probe is more conducive to penetration.

Although weights and velocities (25 ft/sec) greater than those in the test may be envisioned in an aircraft crash, several requirements would be necessary to penetrate the containment vessel of a plutonium package.

1. The penetrating object must be of sufficient length to extend through the energy-absorbing and thermal-insulating materials surrounding the inner containment vessel.

2. The penetrating object must be of sufficient rigidity to provide a penetrating force without itself being crushed or collapsed.

3. The penetrating object must be sufficiently aligned with the center of gravity of the container in the direction of travel to preclude non-penetrating deflection.

4. Sufficient kinetic energy must be present in the system to produce containment vessel penetration.

Based upon these considerations, the specified test is judged to be sufficient to assure that plutonium package containment vessels would not be mechanically punctured in a severe aircraft crash.

D. Ripping/Tearing - During an aircraft crash a package could come into contact with objects or surfaces that could rip or tear the outer shells and thermal insulation surrounding the containment vessel. Although ripping/tearing environments would not directly threaten the integrity of the inner containment vessel, they could conceivably affect the performance of a package during an ensuing fire. Depending upon the particular package design, rips, tears or surface exposures could possibly contribute to burning, smoldering or decomposition of insulating materials. The following physical test is specified in the qualification criteria to assure that the mechanical and thermal characteristics of insulation components are adequate to protect the containment vessel against the combined effects of ripping/ tearing environments and a subsequent fire:

> The package to be firmly restrained and supported such that its longitudinal axis is inclined approximately 45° to the horizontal. The area of the package which made first contact with the impact surface in test (1), above, to be in the lowermost position. The package to be struck at approximately the center of its vertical projection by the end of a structural steel angle section falling from a height of at least 150 feet. The angle section to be at least six feet in length with equal legs at least five inches long and 1/2-inch thick. The angle section to be guided in such a way to fall end-on, without tumbling. The package to be rotated approximately 90° about its longitudinal axis and struck by the steel angle section falling as before.

Since there is no quantified data available to estimate the magnitude or frequency that packages would be subjected to ripping/tearing environments, a test to simulate these conditions must necessarily be based upon engineering judgement. For a package to be threatened by this mechanism, it must be subjected to two separate accident environments: (1) a ripping/tearing environment of sufficient violence to damage its fire-resistance characteristics, and (2) a subsequent thermal environment of sufficient duration and intensity to elevate the temperature of the containment vessel above the temperature it experiences as a result of the one-hour test specified in the test sequence. The Sandia study of transport accidents (Ref. 30) estimates that a fire occurs in only 34% of the incidents which meet the FAA definition of an accident; only 22% of the incidents involve both impact and fire.

The qualification criteria specifies three tests to be conducted in sequence prior to the test for ripping/tearing. These three tests - impact, crush, puncture - are conducted with the package oriented in the position that will produce maximum damage. The final damage done to package insulating materials is the accumulated damage done by each test in the sequence.

The impact test produces large deformations of package insulating materials, distorting their geometry differently in each test orientation. Crushing, shredding and displacement of the insulating materials during the impact test could cause the containment vessel to be moved to a potentially more vulnerable location closer to the outer surface. If the package does not have high integrity, the outer shell could spall, tear, or rupture, causing the insulating materials to be exposed or lost. The crush test is capable of further compounding the damage done to insulating materials. Application of the 70,000-pound force over a two-inch wide strip could, depending on package design, reduce the thickness of the insulating materials and locally rupture the outer shell. The conical probe drop test is also capable of puncturing the outer shell and penetrating well into the insulating materials of virtually any package that is likely to be designed for air transport of plutonium. These three tests, which preceed the ripping/tearing test, represent a severe combined challenge to thermal insulating materials; packages must possess a high degree of integrity to maintain their thermal resistance when subjected to these tests.

Further assurance of the integrity of plutonium package insulating materials is provided by the ripping/tearing test which sequentially follows the impact, crush and puncture tests. The ripping/tearing test is conducted with the package firmly supported in an inclined position. This provides an opportunity for the falling object to cause gashing, cutting and removal of insulating materials. The package is directly struck, two times, by the end of a structural steel angle section weighing approximately 97 pounds and traveling at approximately 98 ft/sec. The cross-sectional shape of the falling steel member is conducive to penetrating the outer shell of a package and ripping or tearing the insulating materials. The two impacts of the steel member are at points on the package that are circumferentially spaced to provide an opportunity for a ventilation pathway to form during the subsequent fire test.

If the insulating materials of a package were to be more extensively damaged in an actual accident and the package exposed to a subsequent fire, the temperature of the containment vessel would not necessarily exceed the temperature that it achieved during the qualification tests. The mass and thermal characteristics of a package capable of meeting the qualification criteria can reasonably be expected to be such that a relatively long exposure time would be required for the containment vessel to approach thermal equilibrium with the fire temperature. The thermal inertia (time constant) of a plutonium package containment vessel is significant with respect to the duration of typical aircraft accident fires, even if the insulating materials are badly damaged or completely removed.

Based upon the foregoing considerations, the ripping/tearing test, in conjunction with the other sequential tests, is judged to be sufficient to assure adequate thermal and mechanical performance of package insulating materials in severe aircraft crashes.

Post-Crash Conditions

Following an aircraft crash, cargo could be subjected to various potentially damaging environments, including thermal explosion, immersion, and burial. A potentially damaging thermal environment may also occur during the course of ground operations and not be preceded by aircraft crash conditions. Post-crash burial of a package could occur if the package is thrown free of an aircraft in flight (or during a crash) onto a soft surface. Heat transfer characteristics could be different for this situation, possibly resulting in higher internal temperatures and pressures. Package immersion is associated with accidents that occur over, or into, a body of water. Under these conditions, a package could be subjected to increased external pressure. The specific tests included in the qualification criteria to protect against these environments are outlined below.

A. Thermal Explosion/Fire - A thermal explosion could occur following an aircraft crash or during the course of various aircraft operations on the ground. The severity of this environment depends upon the nature of the explosion, its intensity, and its duration. The qualification criteria prescribe the following physical test to assure that plutonium packages can withstand the thermal environments that can be produced in severe aircraft accidents:

> The package to be exposed to luminous flames from a pool fire of JP-4 or JP-5 aviation fuel for a period of at least 60 minutes. The luminous flames to extend an average of at least three feet and no more than ten feet beyond the package in all horizontal directions. The position and orientation of the package in relation to the fuel to be that which is expected to result in maximum damage at the conclusion of the test sequence. An alternate method of thermal testing may be substituted for the above fire test provided that the alternative test is not of shorter duration and would not result in a lower heating rate to the package. At the conclusion of the thermal test, the package shall be allowed to cool naturally or shall be cooled by water sprinkling, whichever is expected to result in maximum damage at the conclusion of the test sequence.

In considering the type of explosions and thermal environments that may be produced in an aircraft accident, a distinction must be made between an explosion characterized by a combustion wave and an explosion characterized by a detonation wave. A combustion wave propagates by the processes of heat transfer and diffusion, while a detonation wave is a shock wave which is sustained by the energy of the chemical reaction initiated by the temperature and pressure of the wave. Combustion waves are subsonic while detonation waves travel above the sonic velocity of the medium. An explosive medium may support either type of wave, depending on the various conditions of the explosive mixture, such as confinement and mixture composition (Ref. 39).

A thermal energy load will be imposed upon objects which are exposed to the effects of an explosion. This is true whether the explosion is characterized by a combustion wave or by a detonation wave. If the explosion is of the detonation type, there may also be a substantial pressure load (i.e., shock wave). If the explosion is of the combustion type, no significant pressure load will be produced since combustion waves travel at subsonic speeds and exhibit a constant pressure equal to the ambient pressure on either side of the wave. As discussed below, aviation fuels are not susceptible to detonation in an aircraft accident and do not pose a shock-load threat to plutonium packages. From the standpoint of jet engine design, aviation fuels are ideally developed to burn very rapidly or deflagrate, with a subsonic combustion-type wave. A very fast combustion wave is desirable to ensure complete combustion of the fuel. A detonation wave, however, is not desirable since it would tend to damage the engine. Typical jet fuels, therefore, have very high burn rates but do not detonate under the conditions found in a jet engine combustion chamber. To extend this to the case of fire accidents, J. H. Meidl (Ref. 40), in discussing fire-fighting techniques for gasoline and jet-fuel fires, considers the fuels to present a deflagration rather than a detonation hazard to firemen and others in close proximity to such an accident.

Two possibilities are considered for the post-crash thermal explosion. In the first case, the fuel tanks are ruptured, and the fuel spilled, followed by ignition. Since ignition occurs without confinement of the explosive mixture, only deflagration ensues. In the second case, ignition somehow occurs in a partially empty fuel tank that is intact following a crash. The vapor/air mixture over the liquid fuel in the tank will burn rapidly but without detonation. This could result in a rapid increase in temperature and internal pressure in the tank, causing the tank to rupture and disperse the fuel as fine atomized droplets. Rupture of the tank and sudden release of hot gases, possibly as a pressure wave, represent the greatest hazard for detonation of the dispersed fuel in air. However, once the rupture occurs, there is no longer confinement of the explosive mixture, and the pressure wave emanating from the ruptured tank rapidly decreases in strength as the flow diverges. The droplets of fuel that are dispersed in the air will burn at a very rapid rate and may ignite fuel that has spilled onto the ground, but no detonation-type process will be produced. Burning of a fuel mist can result in a large rapidly enveloping fire which often leads observers to believe that detonation has occurred (Ref. 36). However, fires of this type persist for only a few seconds and do not produce a detonation-type shock wave. Based on these considerations, protection against thermal explosion in an aircraft accident can properly be limited to the deflagation process.

Factors which can affect the intensity or average temperature of an aircraft fire include: the type of fuel, the ventilation conditions, the location of the fire, and the contribution of cargo and aircraft structural materials. The Sandia study of aircraft accident severities (Ref. 30) concludes that the flame temperature of the fuel is the most significant parameter which affects intensity. The results of tests performed by B. E. Bader (Ref. 37) and L. H. Russel and J. A. Canfield (Ref. 38) for JP-4 and JP-5 aviation fuel indicate temperature variations from 1400°F to 2400°F for JP-4 fuel and from 1400°F to 1975°F for JP-5 fuel. The height over the fuel pool was found to have a strong influence on fire intensity in both investigations.

The intensity and effectiveness of a fire are also related to its size and ventilation. In the case of a small fire, good ventilation is provided by the surrounding air. However, because the fire is small, the air entering into the combustion process is not pre-heated and tends to cool the flames. Also, the flames of a small fire are not very thick and correspond to a somewhat translucent condition with low effective emissivity. This tends to reduce the ability of a small fire to impart its energy to an object immersed in its flames. A large fire would have very thick, nearly opaque flames. The flame emissivity would be high and conditions would be effective for imparting energy to an immersed object. In addition, the ventilating air would be heated by the ongoing fire before entering into the combustion process. This would reduce the cooling effect of the air. However, in very large fires the surrounding air is not adequate to fully ventilate central locations within the fire. This tends to reduce their intensity and effectiveness.

The above discussion indicates the need to prescribe a range of flame thickness for JP-4 and JP-5 fuel fires to assure reasonable uniformity from test to test. For this purpose, the IAEA specifies an open petroleum fuel fire (Ref. 7) in which the flame thickness ranges from 0.7 m (2.3 feet) to 3 m (9.8 feet). The thermal test in the qualification criteria specifies a similar condition. While only the geometric thickness of the flame is specified, the optical thickness of the flame is the parameter of interest. The Sandia study of accident severities (Ref. 30) reports that for JP-4, a flame thickness of three to four feet is sufficient to be considered optically thick. The data indicates a three-foot thick JP-4 flame has an effective total emissivity of greater than 0.95. Specification of a test with a flame thickness between three feet and ten feet corresponds to the most severe type of conditions that can be expected to occur in a JP-4 or JP-5 aviation fuel fire.

The location of a package within a fire influences the effectiveness of the fire. The precise location and orientation that would be the most damaging are variables that depend upon the package configuration and the size of the fire. In general, the highest temperatures and heat rates are measured two feet to four feet above the fuel surface in a central location within the fire.

In addition to intensity, a duration is needed to specify the total energy incident to a package from a fire environment. The primary factors that affect fire duration are the extent of fuel dispersion, the quantity of fuel on board the aircraft, and the thermochemical properties of the fuel. The extent of dispersion and the quantity of fuel are factors which may vary considerably, depending upon the nature of the accident, the phase of flight at which the accident occurs (e.g., landing or take-off) and the characteristics of the aircraft. The thermochemical properties of interest to this study for various aviation fuels are, however, fairly uniform.

The fuel dispersion problem was considered in some detail in the Sandia study of cargo aircraft accident severities (Ref. 30). In that report, a correlation could not be found between fuel-dispersion and impact-accident parameters. To explain this unexpected result, the investigators concluded that for low-angle crashes, the fuel tanks remain nearly intact and are carried along with the aircraft. For high-angle crashes, the fuel tanks are destroyed, but the resulting fuel spill remains close to the aircraft. The assumption that the fuel remains in the proximity of the aircraft is conservative for both crash and non-crash induced fire accidents.

The Sandia study suggests that fire duration is proportional to fuel quantity and inversely proportional to dispersion area and burn rate. This relationship was used to develop a model for fire duration prediction, given by:

$$t = \frac{W}{pAR} \qquad (1)$$

where:

- t = fire duration (minutes)
- W = weight of fuel (lb)
- p = fuel density (48.7 lb/ft^3, for JP-4 fuel)
- A = dispersion area (ft^2)
- R = surface recession rate (1.33×10^{-2} ft/min, for JP-4 fuel)

This equation was used to estimate maximum fire durations for several typical jet cargo aircraft, conservatively assuming the fuel tanks to be full at the time of the accident. The dispersion area was considered to be a horizontal projection of the wings and fuselage. This will be defined as the crash imprint area. In a crash, the aircraft was assumed to form a shallow crater which could confine the fuel into a pool. If such a pool is not formed, as in a non-crash fire, the fuel would be dispersed by flowing over a much larger area. This would result in a fire over a larger area, but of shorter duration. The fire duration expression given in equation (1) is shown in Figure 4 as a function of the ratio of fuel weight to crash imprint area. The fuel capacities (Table 6) and crash imprint areas have been calculated for various commercial cargo aircraft (Ref. 12). These values are presented in Figure 4, which shows a maximum expected fire duration of 54 minutes for the DC-8.

This analysis indicates that exposure to a jet-fuel fire for 60 minutes exceeds the most severe fire environment that a package would be likely to encounter in an aircraft accident environment.

Aircraft accidents may occur in remote or inaccessible locations where fire-fighting equipment is not readily available to extinguish flames or to douse smoldering cargo. In such a situation, it is possible that various materials used in the outer construction of a plutonium package would continue to burn or smolder after the aviation fuel was consumed. To assure that the design of plutonium packages is adequate for this possibility as well as the possibility that the package could be cooled as a result of fire-fighting efforts or rainfall, the qualification criteria specify that the package be allowed to cool naturally or be cooled by water sprinkling, whichever will result in maximum damage at the conclusion of the sequential tests.

Recognizing that an actual fire test may not always be the most practical or expedient means of conducting a thermal test, the qualification criteria permit alternate test methods to be used provided that the alternate test is not of shorter duration and would not result in a lower heating rate to the package.

In conducting an alternate test, the intensity of the source should be such that the rate of heat input to the package during the test is no less than the rate of heat input that would be expected in the fire test. Previous investigations (Ref. 37) indicate that a black body radiation source of 1850°F provides a good simulation of a JP-4 aviation fuel fire. Therefore, a source equivalent to a black-body radiation source of 1850°F would be adequate in an alternate thermal test. In some instances, it may be necessary to make a correction

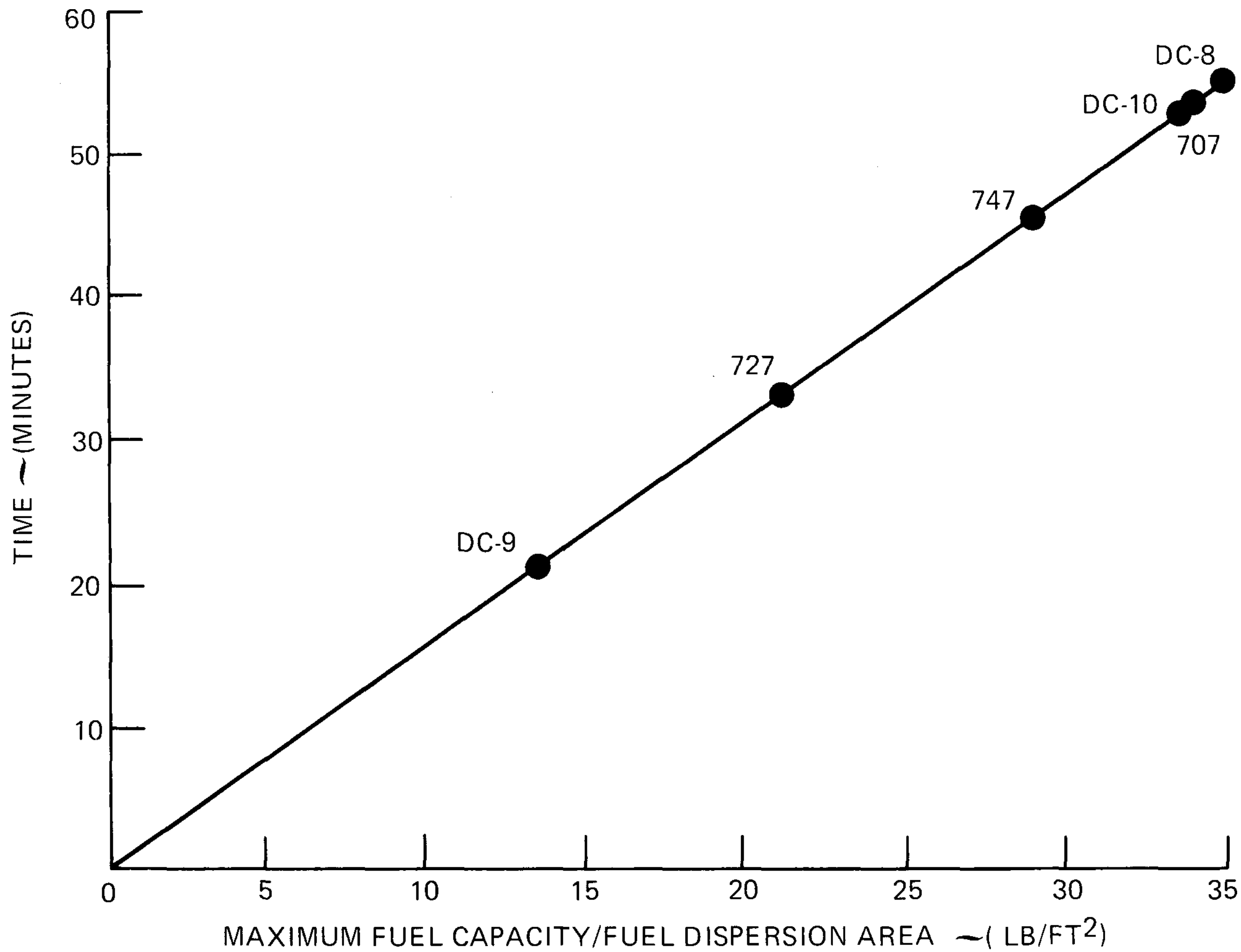

FIGURE 4. FIRE DURATION IN AIR TRANSPORT ACCIDENTS

Table 6

APPROXIMATE WEIGHT DATA FOR TYPICAL CARGO AIRCRAFT*

Aircraft Designation	Take-Off	Landing	Maximum Cargo	Typical Fuel
	Weight in Thousands of Pounds			
		Turbo Jet Engine Aircraft		
B-707-320C	333.6	247	94.4	150
B-727-100QC	-	142.5	46.0	60
B-737-200QC	115.5	103	35.5	25
B-747F	800	630	254.9	300
DC-8F	-	258	95.1	150
DC-9-30F	98	102	37.9	25
DC-10-10CF	440	363.5	125.3	210
		Turbo-Prop Engine Aircraft		
FH-227D	-	45	14.5	-
L100-20	155	130	48.1	-
		Reciprocating Engine Aircraft		
DC-7F	-	108.9	33	-
1049H	-	104	30	-
1649A	-	128.8	33	-

*Source: References 12, 13, 14, and 30.

to the source strength. The correction would account for differences between the expected surface radiation properties of a package in an aviation fuel fire and the surface radiation properties that are expected during the alternate thermal test. For example, a package exposed to an aviation fuel fire would develop a thin layer of soot on metal surfaces or char on organic surfaces, thereby increasing its ability to absorb the incident thermal energy. The same package exposed to a radiation source in a furnace test may not undergo a significant change in its ability to absorb incident thermal energy. Such a situation would require a determination of the difference in surface radiation properties under the two conditions. Accordingly, the source strength would need to be adjusted to assure that the heating rate to the package is not lower in the alternate test than in the fire test.

The thermal test condition specified in the qualification criteria is conservative with respect to aircraft fire accidents. There are a number of possible factors which could mitigate the severity of the thermal environment and enhance the protection afforded by the specified fire test:

1. The duration of the aircraft fire may be shorter than the specified test because: (1) the fuel may be dispersed over a larger area; (b) the type of aircraft involved in the accident may have less total fuel capacity; or (c) the accident may occur with less than a full fuel load aboard the aircraft.

2. The package may not be exposed to the effects of the fire for the full time that it burns. In accidents where debris and cargo are scattered over a large area, the postcrash location of the package may not coincide with the principal location of the fire. There may be only a small amount of fuel available in the vicinity of the package.

3. The specified test requires that the package be located within the flames so that it will receive the maximum effect of the fire. In an actual aircraft fire, the package may not be so optimally located and could also be partially shielded by other cargo or debris. These factors could have a significant effect on the incident thermal energy to which the package would be exposed.

If an actual fire were to be of higher intensity, the probable cause would be burning of other cargo or the aircraft structure itself. Fire from either of these sources would be brief and localized. For a fire in which thermal radiation is the dominant mode of heat transfer, the energy contribution from these brief, localized sources is insignificant when compared to the energy from combustion of the fuels. If an actual fire were to be longer, the probable cause would be smoldering materials present in the accident. Smoldering sources would not contribute significantly to a fire because of their characteristically low intensity and possible separation from a package. Also, it is unlikely that a package would be completely surrounded by smoldering sources. Another possible cause of a longer fire would be extended burning of the fuel. For this to occur, dispersion of fuel would have to be restricted to a very small area, or the fuel would have to be released at a slow rate from the tank. In either event, the size of the thermal source area and the extent of the fire would be small. Under these circumstances, the effectiveness of the fire would be reduced because of the lower visibility of the package to the fire and the increased visibility of the package to the colder ambient environment.

B. Deep Submersion - A package could be submerged as a result of an aircraft accident that occurs over a body of water. Depending upon the depth, large hydrostatic pressures could be applied to the package. Of primary concern is possible rupture of the containment vessel in inland waters or near the coastline.

The Sandia study of accident severities (Ref. 30) estimates the probable depth of immersion following an aircraft crash into inland or coastal waters. The report estimates that 98% of all immersion-type accidents would not result in submersion to a depth greater than 400 feet. Virtually no accidents would occur in water more than 1000 feet deep. Although some small lakes are of exceptional depths (e.g., Crater and Chelan Lakes), Lake Superior, which reaches 1333 feet at its deepest point, is the only large inland body of water in the United States that has a maximum depth greater than 1000 feet (Ref. 11).

To protect against the external pressure of deep immersion, the qualification criteria specify that packages be subjected to an external water pressure of at least 600 psi. This pressure corresponds to a depth of water in excess of 1350 feet.

C. Burial - A third potential post-crash environment is package burial. Packages involved in a high-velocity crash may be covered by debris, or buried in soil. Heat dissipation under these circumstances may be impeded, resulting in increased package temperatures and internal pressures.

The potential effects of package burial have been assessed by the NRC staff (Ref. 44). In this assessment, the heat transfer characteristics of a package were represented by means of a mathematical model. The package was considered to be buried to an infinite depth in soil having poor conductivity (e.g., dry sand), with an ambient temperature of 70°F. Burial was assumed to be of sufficient duration for the package to reach its maximum temperature (thermal equilibrium). Significant parameters were varied to represent a wide range of package sizes, design features, and internal decay heat loads.

The results of this assessment led to the general conclusion that deep burial does not pose a potential safety problem for the types of packages that are expected to be used to transport plutonium by air. Under the most unfavorable combination of significant parameters, the resulting temperatures and internal pressures were only nominally more severe in terms of containment of the package contents than those that could result from the Normal Conditions of Transport in 10 CFR Part 71, and were substantially below those that would result from a fire test of the package. The temperatures and pressures were within the range for which the types of seals and closure devices used on plutonium packages can operate for extended service.

Based upon these considerations, the qualification criteria do not include any test requirements to protect against burial.

Mid-Air Collision/Overboard Cargo

Failure of the aircraft frame or hull can lead to cargo being ejected overboard while in flight. Objects as large as a casket have been lost overboard as a result of rapid depressurization of cargo compartments. Another mechanism for cargo ejection is through in-flight disintegration of the aircraft. This could be produced by mid-air collision or by major in-flight structural failure of the aircraft.

If a package is ejected overboard because of cargo compartment depressurization, the concern is free-fall impact of the package onto the surface of the earth. In a situation involving free-fall from high altitude, it is reasonable to expect that the package would not be subsequently exposed to a crush, puncture, or fire environment. If either burial or water immersion to a significant depth should occur, the effects of impact would be substantially mitigated because of the nature of the impact surface. (The possibility of burial or water immersion has been addressed previously in this report.) To protect against a free-fall environment, the qualification criteria specify the following physical test:

> Impact at a velocity not less than the calculated terminal free-fall velocity at mean sea level at a right angle onto a flat essentially unyielding surface, in the orientation (e.g., side, end, corner) expected to result in maximum damage.

Impact at the calculated terminal velocity is specified because actual free-fall testing of a package may not be practicable, considering required alignment precision for release, wind effects, drop height required to reach terminal velocity, and area of available targets. A more practical test method is to propel the package into the prescribed surface (e.g., by rocket sled). Plutonium packages are not designed to be aerodynamically stable in free-fall and could be in various orientations at impact. Consequently, the qualification criteria specify that the package be impact-tested in its most damaging orientation. The terminal velocity of many packages is less than 422 ft/sec. Therefore, the test is not required if the calculated terminal velocity of the package is less than the 422-ft/sec velocity included in the surface-crash test sequence or if its terminal velocity (exceeding 422 ft/sec) is used in the surface-crash test sequence.

If a mid-air collision or in-flight structural failure does not result in aircraft disintegration, the aircraft may land safely or experience a surface-crash accident, as previously discussed. In the event of in-flight disintegration, it appears reasonable to expect that the cargo restraint systems would not be adequate to prevent separation of the package from the aircraft wreckage. If the package should not be separated from a major section of the disintegrated aircraft, the terminal free-fall velocity of the combination is impossible to predict. However, the fuselage of aircraft are of relatively lightweight construction and have a large surface area. It is reasonable to expect the density of a major aircraft fuselage section to be relatively low, especially in comparison to a relatively massive and compact shipping package. Because of the larger surface area and the lower overall density expected for the fuselage-and-package combination than for the package alone, the effects of drag can be anticipated to be much more pronounced, resulting in a smaller terminal velocity for the combination than for the package alone.

For mid-air collision, it is possible for the relative closing velocity between aircraft to be greater than the velocity of either aircraft alone. However, mid-air collision does not necessarily involve fuselage-to-fuselage contact between aircraft. Collision which damages a wing or control surface could cause the aircraft to become unstable in flight, increasing drag and producing aerodynamic forces which result in aircraft tumbling and disintegration (a situation discussed above). In the event of fuselage-to-fuselage collision, the effects upon a package are expected to be similar to those of aircraft disintegration, assuming that the package is not located in an area struck directly by the other aircraft. If the package is in a position to be struck directly, the severity of the resulting impact is difficult to predict. Although the impact speed could exceed 422 ft/sec or the terminal velocity of the package, the impact surface would not be essentially unyielding as prescribed in the qualification criteria. As noted in the previous discussion, aircraft fuselages are readily susceptible to deformation. This could mitigate the severity of impact considerably. Deformation of cargo located between the package and the other aircraft could provide additional mitigation of impact. Also, the package will be capable of resisting a crush load sufficient to deform the load-bearing cargo deck structure of an aircraft. Considering this capability, together with the general structural weakening and failure that would be expected in the localized vicinity of contact, it is possible that the package could penetrate the aircraft shell and be ejected overboard.

Another consideration is the relative size of the aircraft involved. While a mid-air collision between a large aircraft and a small aircraft may result in the disintegration of both, the impact severity for cargo aboard the larger airplane may be relatively moderate at the time of contact. Because of the relative mass of the aircraft, collision with a small light plane may not produce a large or sudden change in the momentum of a large airplane. Under these circumstances, it is also reasonable to expect that the small plane would be more frangible and would disintegrate more readily than the large plane, thus enabling cargo aboard the larger airplane to benefit from its structure and larger size. Although mid-air collision between two large aircraft can occur, a more typical incident involves collision between a large commercial airplane and a small plane of the type used in general aviation. The NTSB data for U.S. air carrier accidents in the years 1962 through 1974 (Ref. 28) indicates 14 mid-air collisions. Of these 14, 12 involved collision of the commercial airplane with a general aviation type aircraft and one with a military aircraft.

Based upon these considerations, the qualification criteria do not include any additional tests to simulate the environments that could be experienced by a package in a mid-air collision other than the sequential tests and the terminal velocity free-fall test previously discussed.

IV. STANDARDS FOR ACCEPTANCE

To assure that a package will adequately perform its intended safety function, the qualification criteria prescribe specific acceptance standards for containment, radiation shielding, and nuclear sub-criticality.

Compliance with 10 CFR Part 71

The qualification criteria specify that plutonium packages shall meet all applicable requirements of 10 CFR Part 71, "Packaging of Radioactive Material For Transport and Transportation of Radioactive Materials Under Certain Conditions."

Aircraft Accident Conditions

For the individual and sequential physical tests which assure protection against aircraft accident conditions, the qualification criteria specify the following standards for acceptance.

A. Sequential Tests and Individual Test I:

1. Containment - The containment vessel must not be ruptured in its post-tested condition and the package must provide a sufficient degree of containment to restrict accumulated loss of plutonium contents to not more than an A_2 quantity in a period of one week. An A_2 quantity of plutonium is defined in Table VII of the International Atomic Energy Agency Regulations for the Safe Transport of Radioactive Materials (IAEA Safety Series No. 6).

2. Shielding - Demonstration that the external radiation level would not exceed one Rem per hour at a distance of three feet from the surface of the package in its post-tested condition in air.

3. Sub-Criticality - A single package and an array of packages shall be demonstrated to be sub-critical in accordance with 10 CFR Part 71, except that the damaged condition of the package shall be considered to be that which results from the above qualification tests rather than the conditions specified in Appendix B of 10 CFR Part 71.

The above acceptance standards for the shielding and sub-criticality functions of a package are conservative and are consistent with those prescribed in 10 CFR Part 71. With regard to the containment function of a package, P. L. 94-79 specifies that a container "will not rupture under crash and blast testing equivalent to the crash and explosion of a high-flying aircraft." In defining the suitability of a package for certification, one important consideration is to specify what constitutes an acceptable condition of the package after it has been subjected to tests that are equivalent to an aircraft crash. The degree of package integrity required by a set of qualification criteria is strongly influenced by the stringency of the post-test acceptance standards. The IAEA acceptance standards for multi-lateral approved packages (Refs. 6, 7) are regarded to be an appropriate translation of the no-rupture wording of the law into engineering-type specifications. Under post-accident conditions, the IAEA rules permit the release of an A_2 quantity within a period of one week. The exact amount of plutonium which constitutes an A_2 quantity depends upon the particular isotopic mixture of plutonium being transported. For a typical plutonium oxide mixture, an A_2 quantity would be about 46 millicuries (2.55 milligrams). The IAEA procedure for determining an A_2 quantity of plutonium is discussed in Appendix A of this report.

Regulatory Guide 7.4, "Leakage Tests on Packages for Shipment of Radioactive Materials," dated June 1975 (Ref. 8), describes an acceptable method for determining the degree of leaktightness required for a package to meet the IAEA containment requirements. The Guide also describes an acceptable method for measuring leaktightness. Regulatory Guide 7.4 is based upon ANSI Standard N14.5, dated November 1974, of the same title (Ref. 9). The ANSI Standard describes methods and procedures for determining the release rate of materials in liquid or gaseous form. The Standard recognizes that these methods are overly conservative when applied to material in other forms, such as a slurry or a powder. Consequently, the Standard permits the use of more accurate methods provided that their adequacy can be substantiated. The appropriateness of the method used to show compliance with the IAEA containment requirement depends upon the form of the contents and the individual package design. Therefore, the validity and applicability of the methods used to assess containment will be addressed on an individual basis in other reports or documents that pertain to the adequacy of particular package designs.

B. Individual Test II:

> No detectable leakage of water into the containment vessel of the package.

The purpose of the deep submersion test is to assure that hydrostatic pressure would not cause the containment vessel of a package to fail or to rupture. If a containment vessel exposed to a 600-psi external hydrostatic pressure for eight hours does not exhibit inleakage of water, it is reasonable to expect that there is viable containment and that there would be no significant release of material.

V. OTHER REQUIREMENTS

It is generally understood that when physical tests are conducted to demonstrate the accident survivability of a package, the prototype being tested will not contain the radioactive material that is to be transported (plutonium). Instead, prototypes may contain materials to simulate various characteristics of the intended package contents (e.g., weight, moisture context, etc.). In some instances, it may not be practicable (or possible) to simulate all of the physical, chemical, and thermal properties of the actual contents that could have an effect on package performance. Also, the crashworthiness of some package designs could possibly be affected by high or low ambient temperatures that may be envisioned at the time or site of an accident. To assure that the influence of conditions or characteristics that cannot be simulated in the qualification tests would not have an adverse effect on an actual package, the following requirements are included in the criteria.

> Demonstration or analytical assessment showing that the results of the physical testing for package qualification would not be adversely affected to a significant extent by:
>
> a. The presence, during the tests, of the actual contents that will be transported in the package, and
>
> b. Ambient water temperatures ranging from +33°F to +100°F for those qualification tests involving water, and ambient atmospheric temperatures ranging from -40°F to +130°F for the other qualification tests.

The qualification criteria also require a demonstration or analytical assessment showing that the ability of the package to meet the acceptance standards prescribed for the accident condition sequence tests would not be adversely affected if one or more tests in the sequence were deleted. The purpose of this requirement is to assure that the ability of a package to withstand any individual environment in the sequence does not depend upon the necessary occurrence of a prior or subsequent accident environment.

VI. OPERATIONAL CONTROLS

In addition to specifying tests, assessments, and acceptance standards related to package integrity, the qualification criteria also prescribe that various operational controls be observed during transport. The purpose of these operational controls is to prevent or mitigate certain accident conditions and to enhance safety. As a condition for authorizing a licensee to deliver plutonium to an air carrier for transport in a certified package, the NRC will require the licensee to ensure (through special arrangements with the carrier) that the following operational controls are observed during shipment.

Stowage Location

An operational control on stowage location is needed to assure that plutonium packages would not be subjected to large crush forces that could be developed in a crash by other types of cargo located aft of the packages. The aft-most location also affords maximum advantage of the airframe to mitigate impact severity. The requirement for a main deck location reduces the possibility of package interaction with abrupt terrain irregularities in the type of accidents that involve the aircraft skidding on its lower fuselage.

> Plutonium packages must be stowed aboard aircraft on the main deck in the aft-most location that is possible for cargo of their physical size and weight. No other type cargo may be stowed aft of plutonium packages.

Tie-Down System

The purpose of the operational control on plutonium package tie-down systems is to provide positive assurance that packages will remain secured to the deck of the aircraft and not shift position during normal or abnormal flight conditions preceeding an accident. In some types of accidents, the tie-down system can contribute to package crashworthiness by attenuating peak shock levels and dissipating kinetic energy. The acceleration values specified below as consistent with the acceleration values specified in FAA Regulations for emergency landing conditions (Ref. 2).

> Plutonium packages must be securely cradled and tied-down to the main deck of the aircraft. The tie-down system must be capable of providing package restraint against the following inertia forces acting separately relative to the deck of the aircraft: Upward, 2g; Forward, 9g; Sideward, 1.5g; Downward, 4.5g.

Other Cargo

The purpose of the operational control on other cargo is to assure that no materials which could significantly enhance the accident environments experienced by a package will be transported aboard an aircraft in company with plutonium packages. DOT Regulations designate categories of hazardous materials and specify labeling requirements for these materials. In the operational control below, certain categories of labeled materials that could potentially affect package crashworthiness are required to be excluded from the aircraft. Those categories of materials that would not affect package performance are not required to be excluded.

Cargo which bears one of the following hazardous material labels may not be transported aboard an aircraft carrying a plutonium package:

Explosive A
Explosive B
Explosive C
Spontaneously Combustible
Dangerous When Wet
Organic Peroxide
Non-Flammable Gas
Flammable Gas
Flammable Liquid
Flammable Solid
Oxidizer
Corrosive

The above restriction does not apply to hazardous material cargo labeled solely as:

Radioactive I
Radioactive II
Radioactive III
Magnetized Materials
Poison
Poison Gas
Irritant
Etiologic Agent

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where:

M_L = mass of plutonium associated with an A_2 quantity of the mixture (mg),

f_i = fraction of mixture by weight that is composed of plutonium isotope i,

α_i = specific activity of plutonium isotope i (Ci/gm),

$(A_2)_i$ = A_2 activity limit of plutonium isotope i (mCi).

<u>Example Calculation</u>: (Typical Recycle Plutonium Oxide Mixture)

Isotope (i)	Composition by Weight (f_i)	Specific Activity (α_i)*	IAEA Activity Limit $(A_2)_i$*
		(Ci/gm)	(mC_i)
Pu-238	0.03	$1.7\ (10)^{1}$	3
Pu-239	0.45	$6.2\ (10)^{-2}$	2
Pu-240	0.28	$2.3\ (10)^{-1}$	2
Pu-241	0.16	$1.1\ (10)^{2}$	100
Pu-242	0.08	$3.9\ (10)^{-3}$	3

From (1) the mass limit (M_L) associated with an A_2 quantity of the mixture is:

$$M_L = 2.55 \text{ mg of plutonium.}$$

The average specific activity of the mixture ($\bar{\alpha}$) is given by:

$$\bar{\alpha} = \sum_i f_i \alpha_i = 18.2 \text{ Ci/gm.}$$

An A_2 quantity of the mixture is given by:

$$A_2 = M_L \ \bar{\alpha} = 46.4 \text{ mCi.}$$

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*From IAEA Tables.

APPENDIX A

PROCEDURE FOR DETERMINING AN A_2 QUANTITY OF PLUTONIUM

The Rules of the International Atomic Energy Agency (IAEA) specify acceptable standards for containment of radioactive material after accident-condition testing of a package. For a multilateral approved package, these rules require that no more than an A_2 quantity of material be released within a week. The activity limits corresponding to an A_2 quantity of various isotopes of plutonium are given as follows:

Isotope	A_2 Activity Limit (mCi)	Specific Activity (Ci/gm)	Mass Corresponding to A_2 Activity Limit (mg)
Pu-238	3	$1.7\ (10)^{1}$	0.18
Pu-239	2	$6.2\ (10)^{-2}$	32.26
Pu-240	2	$2.3\ (10)^{-1}$	8.70
Pu-241	100	$1.1\ (10)^{2}$	0.91
Pu-242	3	$3.9\ (10)^{-3}$	769.23

In the case of a mixture of different isotopes of plutonium, the permissible activity of each plutonium isotope R_1, R_2, ---- R_n shall be such that $F_1 + F_2 +$ ---- F_n is not greater than unity, where:

$$F_1 = \frac{\text{Total activity of } R_1}{A_2 \text{ activity limit of } R_1}$$

$$F_2 = \frac{\text{Total Activity of } R_2}{A_2 \text{ activity limit of } R_2}$$

$$F_n = \frac{\text{Total activity of } R_n}{A_2 \text{ activity limit of } R_n}$$

For a particular isotopic mixture of plutonium, the mass of plutonium associated with an A_2 quantity can be calculated as follows:

$$M_L = \frac{1}{\sum_i \frac{f_i \ \alpha_i}{(A_2)_i}} \qquad (1)$$