2

SANDIA REPORT SAND76–0708 • Unlimited Release
Reprinted May 1983

An Analysis of the Qualification Criteria for Small Radioactive Material Shipping Packages

James D. McClure

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

Issued by Sandia National Laboratories, operated for the United States *Department of Energy by Sandia Corporation.*

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A06
Microfiche copy: A01

SAND76-0708
Unlimited Release
Printed October 1977

SAND--76-0708

DE88 002405

AN ANALYSIS OF THE QUALIFICATION CRITERIA FOR SMALL RADIOACTIVE MATERIAL SHIPPING PACKAGES

James D. McClure
Applied Mechanics Division II, 1282
Sandia Laboratories
Albuquerque, New Mexico 87115

ABSTRACT

The protection levels provided by existing qualification criteria for the certification of small radioactive material shipping packages have been examined. Based upon the findings, modifications to these criteria are recommended.

ACKNOWLEDGMENTS

The author wishes to thank his coworkers, J. T. Foley, W. F. Hartman, D. W. Larson, and the late R. K. Clarke, for their work in developing the principal reference of this study, Severities of Transportation Accidents, SLA-74-0001, and for their assistance during this study. In addition, thanks is due to T. G. Priddy and W. A. Von Riesemann for their assistance and helpful comments and to W. W. Smith of the Technical Information Department of Sandia Laboratories for editorial assistance.

CONTENTS

Explanation of Terms

Inasmuch as many of the terms necessary for discussion of this analysis possess a rather vague connotation, more specific working definitions are required. Each of these definitions is discussed in detail in the report or appendices.

Aircraft Accident — Any mishap which occurs when intent for flight exists and in which substantial damage to the aircraft results. This definition is consistent with a standard civil air carrier definition.

Crush (generic term dealing with mechanical loading that cannot be characterized as impact, puncture, or immersion) — Compression caused by relatively long time (>> 10-ms) loading on a package as a result of inertial loading from other cargo in truck or train accidents or from heavy sections of the vehicle resting on top of the package.

Crush accidents are described by the total force applied to the package.

Fire — A high-temperature environment produced by combustion. Two quantities, the effective radiating temperature and its duration, are addressed. Generally, in transportation accidents, one is concerned with hydrocarbon fuel fires, which possess a mean radiating temperature of about 1000°C (1832°F). Between temperature limits of about 800° and 1200°C, container response can be approximated as a product of this temperature, T, and the time duration, t, of the fire.

Immersion — Submersion of a package in a liquid medium, most frequently water. The environmental criterion used to define the immersion threat is the depth of water in which the package is located.

Impact — Collision between a package and some other body where the force of the collision is applied over a wide area of the package. Impact is characterized in this study by the quantity E_D/W, where E_D is the energy available to damage the package and W is the package weight. For nominal impact velocities, this quantity is equivalent to drop height as employed in the standard impact test. The forces involved in the process typically occur over time scales of tens of milliseconds or less.

Puncture — Striking or being struck by an object which penetrates the protective structures of the package. This environment can be described, to the first order, by the ratio of the relative impact velocity, v, between the package and the potential penetrator to the radius of the penetrator, R.

Small Package — A small package is defined as one of relatively limited size; its mass may be several hundred kilograms but not more than about 500 kg at a maximum. In the transport mode several such small packages, perhaps 10 to 20, may be transported in an enclosed van or other conveyance.

Train Accident — Any mishap arising in connection with the operation or movement of trains, locomotives, or cars that results in railroad equipment, track, or roadbed damage in excess of $750. The definition is that set forth by the United States Code of Federal Regulations.

Truck Accident — Any truck mishap which results in fatalities, injuries, or property damage of $250 or more. The definition is consistent with that for Class I and Class II Interstate Motor Carriers of Property established by the Bureau of Motor Carrier Safety, Federal Highway Administration of the United States Department of Transportation. The BMCS accident definition was changed January 1, 1973, but the old definition has been retained here to be consistent with the accident data from the pre-1973 period.

Regulatory Test Standards — The terms qualification test criteria, qualification standards, qualification test standards, qualification criteria, regulatory test standards, etc. are used interchangeably and are meant to be synonymous terms which represent the simulated accident test conditions (see Fig. 1) which a candidate package design must sustain during its testing program.

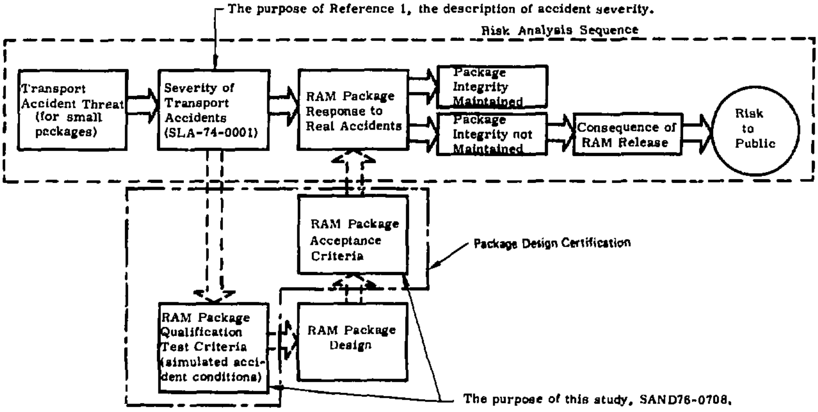
Acceptance Criteria — The term acceptance criteria has a distinct meaning (see Fig. 1). Acceptance criteria is not meant to be synonymous to qualification criteria (see Regulatory Test Standards). An acceptance criterion refers to those standards which must be met (or satisfied) by a candidate package design following it's subjection to the simulated accident conditions (qualification criteria).

SUMMARY

This study has used Severities of Transportation Accidents[1] as a data base to examine the regulatory test criteria[2,3] which are required to be met by small packages containing Type B quantities of radioactive material (RAM). The basic findings indicate that the present regulatory test standards provide significantly higher levels of protection for the surface transportation modes (truck, rail) than for RAM packages shipped by aircraft. ("Small package" is defined in the preceding section, Explanation of Terms.) It should also be noted that various risk assessment studies[11,12,13,14] have shown that the risk to the public due to severe transport accidents by surface and air transport modes is very low.

Figures 1 and 2 and Table V from the main body of the report have been repeated in this summary to help describe the scope and the results of the study. Figure 1 describes the risk analysis sequence and shows how the Qualification Test and Acceptance Criteria for a RAM package relate to the entire risk analysis sequence. A key element in this study was the quantification of the severity of the transportation accident environment and the severity of the present qualification test standards (called qualification test standards in this document) so that a direct comparison could be made between them to assess the effectiveness of the existing qualification test standards. The manner in which this was accomplished was by defining the following comparative measure:

> Accident Severity Comparison Criterion (ASCC) represents the percentage of all accidents of a given transport mode (truck, rail, aircraft) which provide an environment equal to or less severe than a specified measure of accident severity.


The purpose of Reference 1, the description of accident severity.

The purpose of this study, SAND76-0708.

Figure 1. Schematic Diagram - The Risk Analysis Sequence

Transportation accidents were described in Reference 1 in terms of the following categories of accident environment: impact, fire, crush, puncture, and immersion. The use of the ASCC can best be described by example and Figure 2 will be used to demonstrate the use of the ASCC for the aircraft impact environment. Figure 2 shows the aircraft impact ASCC plotted versus impact velocity, which is the most important parameter in the definition of the impact accident. The units on the ordinate in Figure 2 are percentage of aircraft accidents.

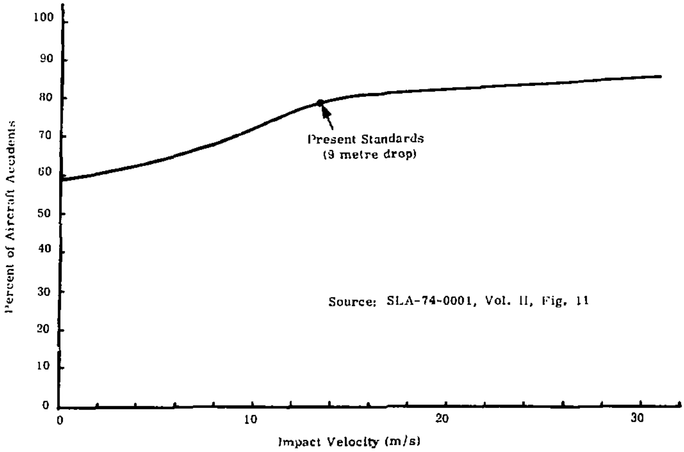
Using the definition of ASCC given above, if one enters Figure 2 on the accident-severity (impact-velocity) scale at 20 m/s (65.6 ft/s), the curve shows an ASCC value of 82%. That is, 82% of all aircraft accidents, as described in Reference 1, have an impact equal to or less severe than a 20 m/s impact velocity onto an unyielding target. The ASCC curves, only one of which is shown here, represent the locus of ASCC values over a wide range of the respective severity parameters. It is also possible to locate the severity of the present qualification test standards on the ASCC curves. Referring to Figure 2 again, we see that the 9 m (30 ft) drop test, which has an impact velocity of 13.4 m/s (44 ft/s), has an ASCC value of 79%. Thus, 79% of all aircraft accidents, according to Reference 1, are equal to or less severe than the existing impact qualification criterion. In a similar manner, the existing qualification criteria can be evaluated for all of the accident environments for which criteria presently exist and to all of the transport modes--truck, rail, and air.

Joint probability analyses were performed in Reference 1 which, in effect, determined the relative influence of the aircraft accident categories. For example, in the aircraft accident, impact and fire are of primary influence and crush, puncture, and immersion are of secondary influence. A compact presentation of the results of the joint probability analyses and the comparison of the severity of the present qualification criteria with transportation accidents is shown in Table V.

Examining Table V, one can make several observations.

- For the surface transport mode (truck and rail), the ASCC values for the existing qualification criteria are in the 99 to 100% range. The level of severity in the existing qualification test standards appears to be essentially fully reflective of the damage that small packages are likely to incur in the surface transport accident environment (except for the crush environment).

- The existing standards do not specify crush tests and, since the crush environment is of primary influence in the surface transport mode, the addition of a crush test will make the qualification test standards more relevent to the actual accident stresses which were determined in the base study.[1]



Source: SLA-74-0001, Vol. II, Fig. 11

Figure 2. Accident Severity Comparison Criterion (Air) vs Impact Velocity

TABLE V

Percentage of Accidents in a Given Mode Which Provide an Environment Equal to or Less Severe Than Existing Qualification Test Criteria

Accident Environment Categories

		Impact	Fire	Crush	Puncture	Immersion
Transportation Mode	Air Influence	79% Primary	90% Primary	Not Defined (1) Secondary	92-98% Secondary	97% Secondary
	Truck Influence	100% Secondary	99% Primary	Not Defined (2) Primary	100% Primary	100% Secondary
	Rail Influence	100% Secondary	99% Primary	Not Defined (3) Primary	100% Secondary	100% Secondary

Note (crush tests not specified in existing standards):

(1) 70,000 lb single-axis crush test will protect against essentially 100% of aircraft accidents.

(2) 8,000 to 10,000 lb single-axis crush test will protect against essentially 100% of truck accidents.

(3) 70,000 lb single-axis crush test will protect against essentially 100% of rail accidents.

- The ASCC values representing the existing qualification criteria in the air transport mode are lower than for surface transport. The protection in the air transport mode can be increased and made more comparable to that provided in surface transport if the severity of the qualification tests for air transport are increased.

The Package Design Certification Process

The RAM package design certification process is shown in Figure 1 and has two important elements, testing and acceptance. These terms sound very similar but they have specific meanings (see Explanation of Terms). Qualification testing in the context of this study is the imposition of simulated accident test conditions upon the candidate package design. (Normal transportation environments may also be included.) Following qualification testing the acceptance criteria provide the performance levels which, if demonstrated, indicate the ability of the RAM package to sustain the severity of the qualification testing sequence and yet maintain specified levels of package integrity.

Revised Qualification Standards

The observations presented above on the information in Table V were used in the formulation of a revised set of qualification tests. The guidelines and rationale for these qualification test proposals are as follows:

- A separate set of qualification tests are proposed for the surface and air transport modes.

- The level of severity in the existing qualification criteria appears to be adequate with respect to the surface transport accident environment.

- To provide a comparable level of protection in both surface and air transport modes, the air transport qualification criteria are, in some categories, increased in severity from their present levels.

- A crush test should be defined for both surface and air transport modes.

- The existing qualification criteria require the sequential testing of the RAM package to the impact, fire, puncture, and immersion environments. The test proposals described herein specify the sequential testing, in a logical order, of only the environments of primary influence. In addition, the test proposals will specify the individual testing of the RAM package to the environments of secondary influence.

- The organization of the qualification test proposals for surface and air transport are similar in format but differ in severity. Because of this similarity it is possible to establish such a hierarchy in the qualification testing that RAM packages qualified for air transport may also be qualified for the surface transport mode. RAM packages qualified for surface transport only should not be authorized for shipment in the air transport mode.

- The protection levels provided by the existing qualification test standards are at or near the 100% level in the surface transport mode which indicates that the existing standards may be "overly severe" and could, perhaps, be relaxed from their present levels without any significant decrease in safety to the public.

The Qualification Test proposals for surface and air transport are described in detail in Tables VI and VIII and Appendix G of the main report and are summarized as follows.

RAM Package Qualification Test Proposal - Surface Transport

Sequential Tests (puncture followed by crush followed by fire)

a. Puncture - One metre (40 in.) free drop of package onto puncture probe.

b. Crush - 310 000 N (~ 70,000 lb) static loading.

c. Fire - 1000°C (1832°F) fire, duration 30 min.

Individual Tests

a. Impact - Nine metre free-fall drop onto unyielding target

b. Immersion - Immersion in water, 15 m depth, duration 8 hr.

RAM Package Qualification Test Proposal - Air Transport

Sequential Tests (Impact followed by fire)

a. Impact - 90 m/s (295 ft/s) onto unyielding target.

b. Fire - 1000°C (1832°F) fire, duration 40 min.

(Puncture followed by fire)

a. Puncture - 12 m/s (40 ft/s) onto aluminum I beam probe.

b. Fire - 1000°C (1832°F) fire, duration 40 min.

Individual Tests

a. Impact - 110 m/s (360 ft/s) onto unyielding target.

b. Fire - 1000°C (1632°F) fire, duration 60 min.

c. Puncture - 30 m/s (100 ft/s) onto aluminum I beam probe

d. Immersion - 2 MPa (300 psi) hydrostatic pressure, duration 8 hours.

e. Crush - 310 000 N (~ 70 000 lb) static loading.

Acceptance Criteria - Surface and Air Transport

The acceptance criteria which would be imposed on the RAM package following the individual and sequential tests for both surface and air transport are the existing criteria specified in Reference 2. The compliance with these criteria is detailed in U. S. Nuclear Regulatory Commission Regulatory Guide 7.4.

Conclusions

The qualification test proposals presented above for small RAM packages were developed, in part, by comparing the existing qualification standards[2] with the severity of known transport accidents.[1] The existing qualification standards, except for the crush environment, are equal to or more severe than 99 to 100% of the surface transport (truck, rail) accidents. Hence, it is concluded that, except for crush, the existing qualification standards adequately protect against the surface transport accident environment. A crush test has been defined to address these environments.

In a similar manner it has been shown that it is necessary to define a crush test and increase the severity of the qualification tests if RAM packages subjected to an aircraft accident are to have levels of protection comparable to those subject to surface transport accidents.

Sequential testing is recommended for those accident environments which have been shown to have primary or first-order influence as determined by a joint probability analysis. It is recommended that environments of secondary influence be individually tested. Thus, both of the qualification test proposals described herein (surface and air) have severity levels based on a comparison with known transport accidents and offer a high degree of protection. In addition, the test proposals provide a format with respect to test severity and test sequence which maps the influence of the accident environment categories of impact, fire, crush, puncture, and immersion that has been observed in truck, rail, and aircraft accidents.

With the formulation of these RAM package qualification test proposals, an attempt has been made to "simulate" in a general sense the transport accident environment. The term "simulate" needs to be qualified since it is not possible to make a direct or complete simulation of the accident environment. The qualification tests create a standardized laboratory environment which is greatly simplified from that of real transport accidents. The qualification tests are intended, however, to provide to the package the key threats of the transport accident environment in severity and with respect to the relative influence of the accident environment categories.

It is the conclusion of this study that

a. If a RAM package design is subjected to a series of individual and sequential accident environment tests, each of which is very severe with respect to the historical severity of transport accidents and,

b. If these tests are coupled with an acceptance criterion which limits or controls the loss of radioactive contents,

then the package designers, government regulatory agencies, and--most important--the general public can have confidence that every practical effort has been made to ensure public safety.

The judgements in this study with respect to the severity level of the qualification tests were made entirely within the reference framework provided by known transportation accidents.[1] Several risk assessment studies[11,12,13,14] have shown that the overall risk to the public due to severe transport accidents is very low and hence it may be concluded that the existing qualification test standards offer a high degree of protection, especially in the surface transport mode (truck and rail). However, the changes in the qualification test standards proposed in this document will produce qualification test criteria which will be more consistent from mode to mode, and will be more representative of the accident conditions likely to be encountered. Further, there will be an increase in the level of safety in the air shipment of radioactive materials (RAM) from the present level of risk[11,12,13,14] which is already judged to be very low.

It must be recalled that the certification process for a package design (see Fig. 1) consists of two distinct phases, testing and acceptance. The existing acceptance criteria, which this study recommends be continued in use, can impose an essentially leakproof standard for RAM packages, resulting in no loss of radioactive contents. If no contents are lost, then the complete risk analysis sequence shown in Figure 1 would conclude that there is no risk to the public with respect to radioactive hazards. Relaxing the acceptance criteria so that the loss of some finite quantity of radioactive contents is permitted does not necessarily imply that public safety has been compromised but would require that the complete risk analysis sequence be performed in order to assess the public risk.

AN ANALYSIS OF THE QUALIFICATION CRITERIA FOR SMALL RADIOACTIVE MATERIAL SHIPPING PACKAGES

Introduction

The purpose of this study is to examine the maximum or near-maximum environmental stresses produced in truck, rail, and aircraft transport accidents, and to compare these environmental severities with the severity of existing qualification test standards to which radioactive material (RAM) containers are subjected under the Federal Regulations. The objective of this study is to recommend new qualification tests or test options for consideration by regulatory agencies, if it is judged that existing test standards do not offer an adequate or appropriate level of protection to the public. The data base for this study is the detailed derivation of the severities of transport accidents provided in Reference 1, and a basic theme of this study is to quantify the severity of the accident environment categories of impact, fire, crush, puncture, and immersion so that those involved with the regulatory process can visualize the degree of protection a given set of qualification test standards will provide in the interest of public safety.

This introduction will pose some basic questions and provide some background information. A summary of the severities of transport accidents from Reference 1 and a comparison with current criteria will be provided in the next section. Then the environmental summary and criteria comparison will be expanded upon with a presentation of proposed new qualification criteria, first for the surface transport modes (truck and rail), and then for air transport. The conclusions of this study are to be found at the end of the report proper, followed by several appendices which give the technical details to support the study.

Background

In March 1972 the Transportation Branch of the Division of Waste Management and Transportation of the U.S. Atomic Energy Commission requested that Sandia Laboratories study accident data and develop accident test criteria. The Sandia staff determined that adequate accident data and analysis techniques were not then available to provide the necessary description of transport accidents which would allow the development of relevant accident qualification criteria to simulate the environmental elements of real accidents. Sandia Laboratories offered an alternative proposal that a study of aircraft accidents, then underway, be expanded to include the severity of truck and rail accidents as well by collecting available accident data and developing analytical techniques. Sandia published the final report, "Severities of Transportation Accidents," in July 1976.[1]

The present study was undertaken as a follow-on to the work in Reference 1 to focus on an interpretation of the accident severity information in light of existing and any newly proposed qualification test standards for use in the licensing of RAM shipping packages.

The Basic Question

The basic question to be answered is "How well do the existing Federal regulatory qualification test standards for RAM packages compare with the stresses that actually occur in real transportation accidents?" As a corollary to this question, if it is determined that there is some area where existing criteria appear not to assure adequate integrity, then this report will present alternative criteria for consideration by regulatory bodies and other interested agencies.

Existing Criteria and Their Regulatory Basis

The regulations for packages which are used to ship radioactive materials are Title 10, Chapter 1, Code of Federal Regulations—Energy, Part 71, commonly referred to as 10CFR71,[2] and Title 49, Code of Federal Regulations, Parts 170-178, Department of Transportation Hazardous Materials Regulations.[3] These standards have undergone continual evaluation and improvement since they were first established in 1948 and are consistent in most respects with regulations developed by the International Atomic Energy Agency which are in use by 70 foreign countries.

Appendices A and B of 10CFR71 refer, respectively, to the Normal Conditions of Transport and the Hypothetical Accident Conditions which are to be applied to a package designed to contain a specific quantity and type of radionuclide. The emphasis in this study will be on the qualification criteria as stated in Appendix B of 10CFR71, (or 49CFR 173.398) namely, the Hypothetical Accident Conditions relating to free drop (impact), puncture, thermal (fire), and water immersion.

Verifying RAM Package Integrity

Any engineered component or system should have sufficient integrity and a long enough service life that it can perform its intended use in a safe and economical manner. In structures such as public buildings, bridges, dams, aircraft, ships, pressure vessels, reactor vessels, etc. the safety requirements of a design are readily apparent. These conveyances, structures, and equipment items must function in some proximity to people and the effects of their failure could constitute a disaster.

The design process, precise though it may appear to be, is in many ways approximate and iterative. Because of approximations in the design process the integrity of a design may be certified or proved by some combination of the following methods:

- Analysis
- Testing
    Models
    Full-scale

Analytical techniques are constantly being improved. The finite-element method is available through a wide variety of computer codes for the analysis of the static and dynamic response of structures.[4] Scale-model testing[5] has been conducted, especially in areas where the full-scale item is not available or is prohibitively expensive to construct and test. The comparison of scale-model testing with results of analytical methods confirms the scaling laws which exist between model and prototype structures. The performance of a series of full-scale tests would appear to constitute a complete proof of RAM package integrity; however, this is not so. Only a limited number of tests can usually be performed, usually in a mode or orientation which is considered to be most damaging to the structure. This does not diminish the importance of testing, however, since every opportunity should be taken to validate the integrity of a package design by both tests and analytical methods.

The ability of a package to perform well during a qualification test is very important in procuring a package design certification. Package qualification testing should represent an accurate enough simulation of the maximum or near-maximum environmental severity which can occur in a transport accident so that there is confidence by the technical community, regulatory agencies, and the general public that, if a RAM package is involved in a transport accident, its integrity will be maintained.

Measuring Accident Severity

The basic categories which were considered to be components in the description of an accident environment were impact, fire, crush, puncture, and immersion. (Note that crush is not now included in the hypothetical accident environments in Appendix B of 10CFR71.) To accomplish the objectives and purpose of this study, the severity of these environments must be quantified so that the severity of existing qualification criteria can be compared with the severity spectra provided by Reference 1 for the truck, rail, and air modes of transport. The individual measure of severity for each of the various accident environment categories is given in Table I.

TABLE I

Measures of Accident Environment Severity

Category	Severity Measure
Impact	Velocity, target description
Fire	Temperature, duration
Crush	Force, target description
Puncture	Probe velocity, geometry
Immersion	Depth (in water), time

The fundamental parameter used in this study to compare the severity of various categories of accident environments with each other and with the severity of existing qualification criteria is defined below.

Accident Severity Comparison Criterion -- The accident severity comparison criterion (ASCC) represents the percentage of all accidents of a given transport mode (truck, rail, aircraft) which provide an environment equal to or less severe than a specified measure of accident severity.

Later in this report the ASCC will be used as the reference framework to which the severity of existing criteria will be compared.

Risk Analysis

Figure 1 is a simplified diagram of the risk-analysis process which delineates the sequence of the process and describes which portions of it are addressed by the present study. One reason for presenting the risk—analysis sequence is to emphasize that the final or ultimate measure of public safety, upon which social judgments are based, is expressed in terms of risk.[6] The units of risk are often couched in terms of expected fatalities or latent fatalities over some time interval. Alternative forms for the expression of risk have included an economic measure of risk such as the loss of capital investment, land use denial, etc.

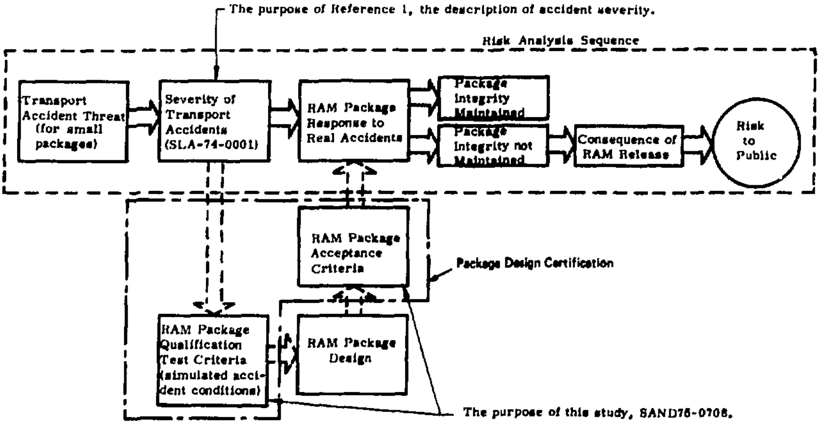


Figure 1. Schematic Diagram - The Risk Analysis Sequence

The transport accident environment can be described in terms of several parameters such as accident probabilities, accident rates, impact velocities, fire temperatures and durations, etc. All of these descriptions contain a degree of technical jargon which may or may not be easily understood. The public needs to know that it is being protected, and to what degree, from potential accidents involving the transport of radioactive materials. It is this author's opinion that risk, in terms of fatalities, is the best measure of the overall effect upon the public of any kind of accident or natural disaster. Furthermore, this measure of risk is a very personal and easily understood concept, especially if it is viewed in terms of the risks associated with other natural or man-caused events which have occurred and thus are already known to society.

This study, as shown in Figure 1, is an adjunct to the risk-analysis sequence and not, strictly speaking, a part of it. The package design acceptance criteria are normally considered a part of the overall package qualification criteria and act as a regulator on risk since the acceptance criteria places a limit on radioactive material contents loss. The qualification criteria simulates an extreme transport accident and the acceptance criteria requires that any loss of radioactive material contents from the package will, if the consequences are analyzed, constitute an acceptably low risk. The two-fold sequence of (1) accident simulation through some combination of analysis and test and (2) controlling the risk level through the acceptance criteria is very important. The minimization of the consequences of a transport accident involving radioactive materials implies the acceptance of risks (fatalities) below some specified level which is a social-value judgment.

Severity of Transport Accidents

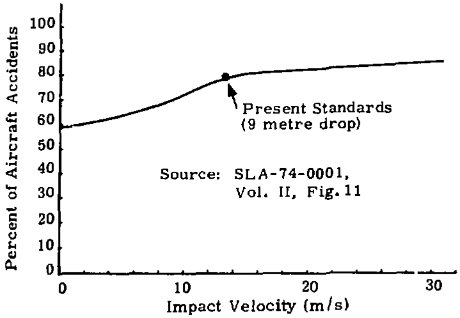
This section will present a digest of the information presented in Reference 1, which describes the severity of air, truck, and rail transport accidents, and compare these severities with those of the current hypothetical accident criteria in Appendix B of Reference 2.

The accident severity comparison criterion (ASCC) will be used in making these comparisons. ASCC was defined on page 9.

Aircraft Accidents

Aircraft Impact -- The severity of the impact environment for aircraft accidents is shown in Figures 2 and 3. The ASCC is plotted as the ordinate and impact velocity on the abscissa. The severity of the existing impact qualification test standard is shown in Figure 2 and should be interpreted in the following manner: 79% of all aircraft accidents produce an impact severity (impact velocity) equal to or less than the presently specified 13.4 m/s (44 ft/s), 9 m drop test. Figure 3 shows the impact severity plot for larger impact velocities.

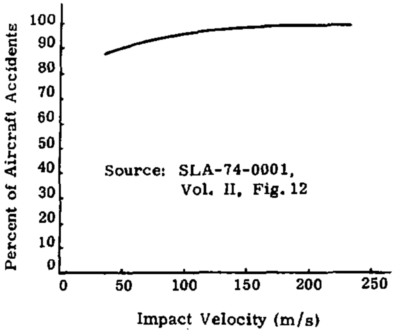
Aircraft Fire -- The severity of the fire environment for aircraft accidents is shown in Figure 4. Existing fire severity standards from Appendix B, Reference 2, have an ASCC value of 90%; i.e., 90% of all aircraft accidents have fire environments with a severity (temperature-time product) equal to or less severe than the severity of existing qualification standards: 800°C for 30 min. (1475°F for 30 min.).



Present Standards
(9 metre drop)

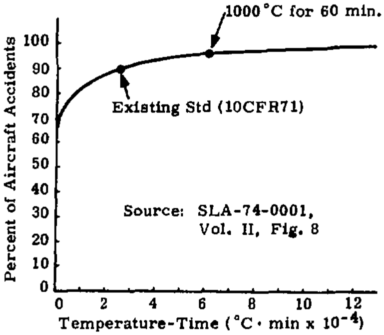
Source: SLA-74-0001,
Vol. II, Fig. 11

Figure 2. Accident Severity Comparison Criterion (Air) vs Impact Velocity



Source: SLA-74-0001,
Vol. II, Fig. 12

Figure 3. Accident Severity Comparison Criterion (Air) vs Impact Velocity



1000°C for 60 min.

Existing Std (10CFR71)

Source: SLA-74-0001,
Vol. II, Fig. 8

Figure 4. Accident Severity Comparison Criterion (Air) vs Temperature-Time Product

Aircraft Crush -- Reference 1 concludes that an estimate of the aircraft crush occurrence probability is in the range of 0.01 to 0.06, given an impact accident. Appendix A of this report details the results of a study of the severity of the crush force in an aircraft accident. It should be emphasized that the 310 000 N (~ 70,000 lb) maximum crush force stated in Appendix A is for vertical crush only. Longitudinal crush can occur and such loads may be of the order of millions of newtons. Longitudinal crush will be dealt with by other means and, for the present, we shall consider only vertical crush. Recalling that 41% of all aircraft accidents involve impact, the two crush probabilities stated above can be converted into the percentage of aircraft accidents providing a crush environment as follows.

Percentage range of aircraft accidents with a crush environment:

	ASCC Value (%)
Low = (0.01)(0.41)(100) = 0.41%	99.59
High = (0.06)(0.41)(100) = 2.46%	97.54

From these calculations we can see that a large percentage of all aircraft accidents do not produce a crush environment. Appendix A analyzes the crush environment for a worst-case situation and the ASCC is shown in Figure 5 with an assumed linear variation between zero crush load and a 100% protection level at a crush force of 310 000 N (~ 70,000 lb).

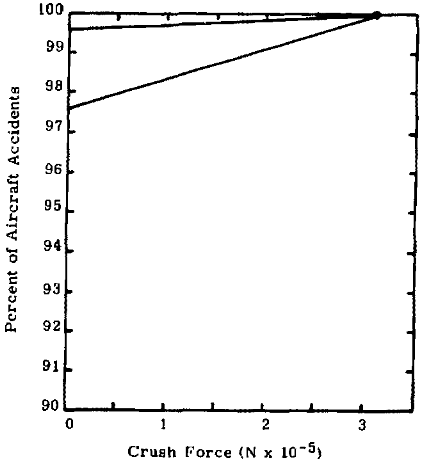


Figure 5. Accident Severity Comparison Criterion (Air) vs Crush Force

Aircraft Puncture -- The ASCC for aircraft puncture is shown in Figure 6. Reference 1 (Vol. II, Table XII) used two sets of assumptions in calculating the puncture probability in an aircraft accident. Figure 6 displays the functional relationship for these assumed conditions—one relationship involves a nominal level of risk and the other relationship employs high-risk assumptions and, as a consequence, produces a decreased level of protection. The approach velocity of the probe, as prescribed in existing puncture test criteria (Reference 2, Appendix B) is shown in Figure 6. Using the "nominal" puncture relationship and assuming the existing puncture probe design, the existing puncture test criteria provide a severity level equal to that encountered in 97 to 98% of all aircraft accidents.

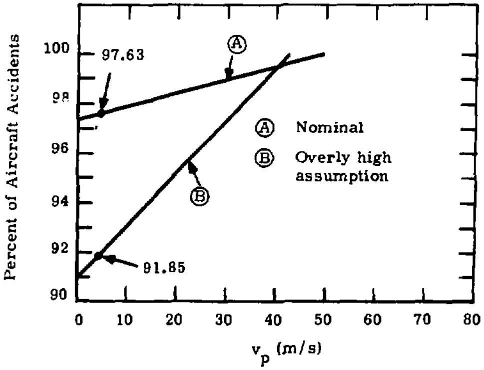


Figure 6. Accident Severity Comparison Criterion (Air) vs Puncture Probe Velocity

Aircraft Immersion -- Reference 1 estimates the probability of immersion in U.S. inland, peripheral, and coastal waterways. The probability of immersion given an impact is 0.07. Since the probability of an impact, given an aircraft accident, is estimated as being 0.41, the probability of immersion is estimated as

$$(0.41)(0.07) = 0.029 \text{ or } 2.9\% .$$

Consequently, an estimated 97.1% of all aircraft accidents do not experience an immersion environment. The ASCC for immersion is shown in Figure 7 along with existing standards from Appendix B of Reference 2 and existing IAEA Standards.[7] The severity level imposed by currently specified immersion tests encompasses the severity of 97 to 98% of all expected aircraft accidents.

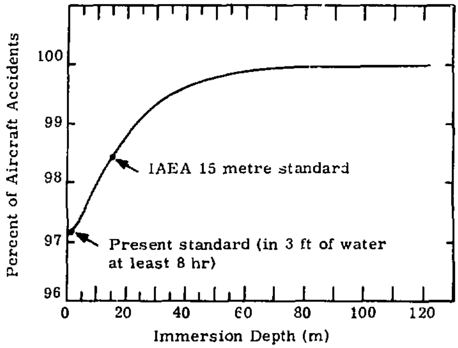


Figure 7. Accident Severity Comparison Criterion (Air) vs Water Immersion Depth

Aircraft Accident Joint Probability -- Table II summarizes the relative influence of the aircraft accident environment categories as determined by the joint probability analysis conducted in Reference 1. The joint probability expression in that source (Vol. II, p. 92) was differentiated with respect to the individual environment probabilities and it is these partial derivatives which are shown in the table.

TABLE II

Relative Influence of Environmental Categories
(Aircraft Accidents)

Impact	$\frac{\partial P}{\partial P_I} = 0.36$	Primary Environments
Fire	$\frac{\partial P}{\partial P_F} = 0.22$	
Puncture	$\frac{\partial P}{\partial P_P} = 0.04$	Secondary Environments
Crush	$\frac{\partial P}{\partial P_C} = 0.01$	
Immersion	$\frac{\partial P}{\partial P_{im}} = 0.01$	

The relative influence of the accident environment categories as measured by the joint probability analysis allows the designation of two strata of environmental importance, namely, primary and secondary environments. In an aircraft accident the primary environments, impact and fire, have a significant effect upon the probability of exceeding a selected environmental severity level. Puncture, crush, and immersion are designated as secondary environments since they have relatively little effect upon the probability of exceeding such a level in aircraft accidents.

Truck Accidents

Truck Impact -- The ASCC for the truck impact environment is shown in Figure 8. The existing qualification criterion for impact appear to protect against essentially 100% of the expected truck impact accidents.

Truck Fire -- The ASCC for the truck fire environment is shown in Figure 9. The existing qualification criterion of Reference 2, Appendix B, provides a fire test severity which is greater than 99.86% of all truck accidents.

Truck Crush -- The ASCC for the truck crush environment is shown in Figure 10. Existing standards in Appendix B of Reference 2 do not include the designation of a crush environment. The crush force magnitudes shown in Figure 10 are due to both static and inertial crush loads. Note that essentially all occurrences of crush loading in a truck accident can be protected against with an 35600 to 44500 N (8,000 to 10,000 lb) static crush load.

Truck Puncture -- Figure 11 shows the result of the low probability of occurrence of the puncture environment in a truck accident. The probability of puncture is so low that for practically any value of the puncture severity parameter essentially all accidents are protected. The existing qualification puncture test standards[2,3,7] are shown to protect packages against the puncture environment in essentially all truck accidents.

Truck Immersion -- The immersion environment is similar to puncture for the truck accident in that immersion is an infrequently occurring environment. These infrequent occurrences of immersion manifest themselves (see Figure 12) in a manner similar to puncture in that even small water immersion depths provide a severity level such that protection is provided against essentially all occurrences of immersion in truck accidents.

Truck Accident Joint Probability -- The relative influence of the accident environment categories in truck accidents is displayed in Table III. This information is taken from Reference 1, Volume III, Table XIV.

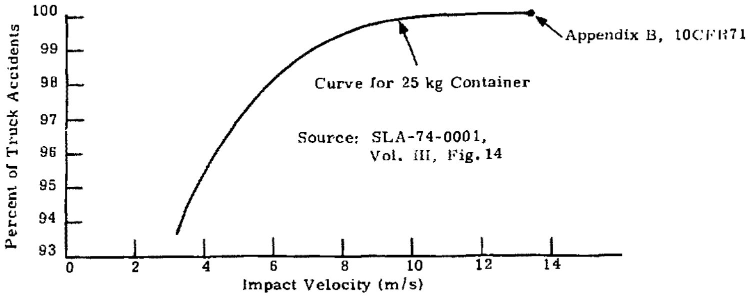


Figure 8. Accident Severity Comparison Criterion (Truck) vs Impact Velocity

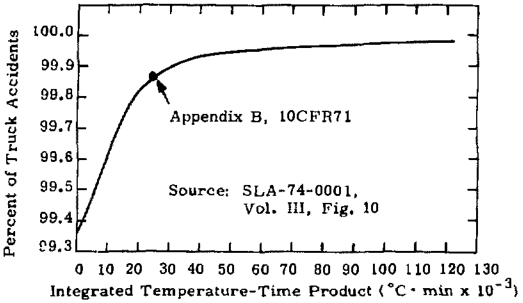


Figure 9. Accident Severity Comparison Criterion vs Temperature-Time Product

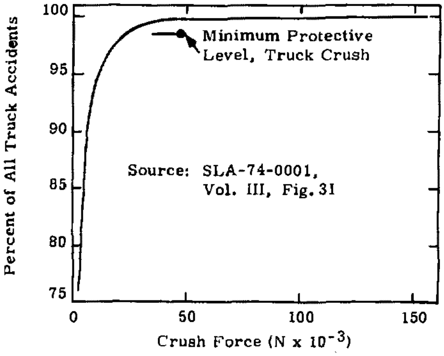


Figure 10. Accident Severity Comparison Criterion (Truck) vs Crush Force

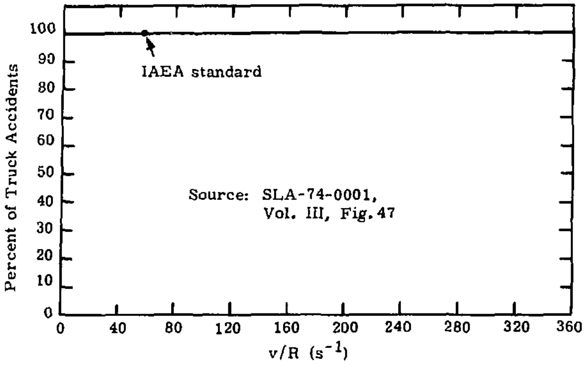


Figure 11. Accident Severity Comparison Criterion (Truck) vs Puncture Parameter (v/R)

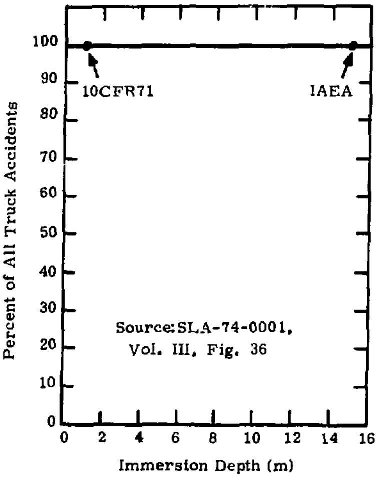


Figure 12. Accident Severity Comparison Criterion (Truck) vs Immersion Depth

TABLE III

Relative Influence of Environmental Categories (Truck Accidents)

Environmental Category	Estimated Probability of Exceeding IAEA Severity Levels	
Crush	0.00270	Primary Environments
Fire	0.00130	
Puncture	0.00045	
Impact	0.00005	Secondary Environments
Immersion	Negligible	

Crush, fire, and puncture are observed to be the three most significant environments in the truck accident. These three environments are designated as primary environments. Impact and immersion are designated as secondary environments because they make a negligible contribution to the overall probability that a test array of several envornments at IAEA severity levels will be exceeded.

Rail Accidents

Rail Impact -- The ASCC for rail impact is shown in Figure 13. The abscissa in this figure has a maximum value of 6 m/s. Since the qualification criterion in Reference 2 and in the IAEA standards currently specify a 30 ft (9 metre) drop, the existing impact test velocity of 13.4 m/s (44 ft/s) protects against essentially all expected occurrences of rail impact.

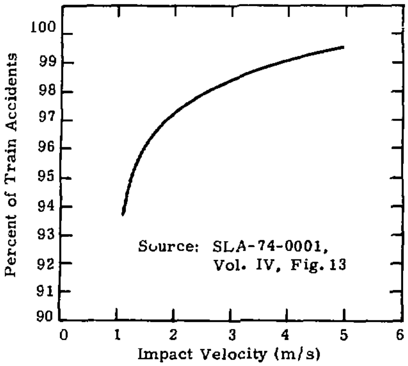
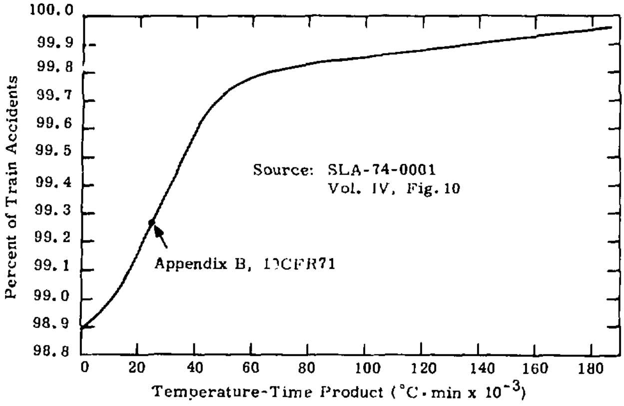


Figure 13. Accident Severity Comparison Criterion (Train) vs Impact Velocity

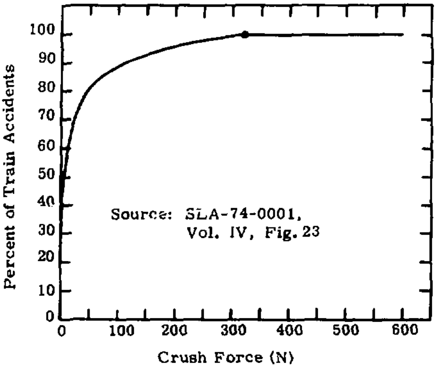
Rail Fire -- Figure 14 displays the severity comparison criteria for the rail fire accident environment. The ordinate in this figure is the percentage of rail car accidents and it can be seen that the protection level provided by existing qualification test standards is so high that about 99.3% of all rail fire accidents have a fire environment equal to or less severe than existing qualification test standards.

Rail Crush -- Existing qualifcation criteria do not specify crush tests for radioactive materials packages. The ASCC for rail cars is shown in Figure 15. In the absence of specifications for crush, the force which would provide protection against essentially all occurrences of crush is about 310 000 N (~70,000 lb). This is the test force that would be applied to a package placed between the platens of the testing machine in a single-axis, static crush test.



Source: SLA-74-0001
Vol. IV, Fig. 10

Figure 14. Accident Severity Comparison Criterion (Rail) vs Temperature-Time Product



Source: SLA-74-0001,
Vol. IV, Fig. 23

Figure 15. Accident Severity Comparison Criterion (Rail) vs Crush Force

Rail Puncture and Rail Immersion -- The severity comparison criteria for the rail puncture and immersion environments are shown in Figures 16 and 17. The reason for combining the discussion of these environments is that they occur so infrequently in rail cars that qualification testing of low severity (or perhaps even no testing of these environments) would provide protection for a large percentage of rail accidents.

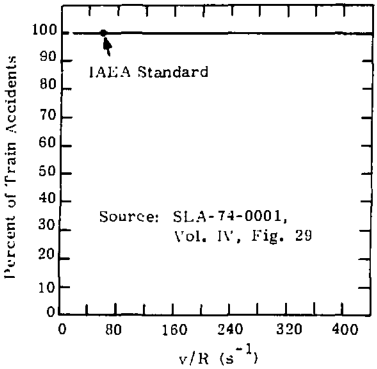


Figure 16. Accident Severity Comparison Criterion (Rail) vs Puncture Parameter (v/R)

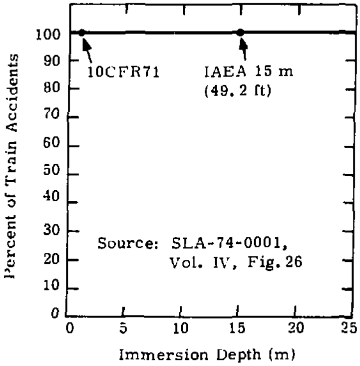


Figure 17. Accident Severity Comparison Criterion (Rail) vs Immersion Depth

Rail Accidents Joint Probability -- Table IV shows the relative influence of the basic accident environment categories in rail accidents. Again, the designation of primary and secondary environments is somewhat arbitrary, but it is still indicative of the relative influence that these environmental categories have on rail accidents.

TABLE IV

Relative Influence of Environmental Categories
(Rail Accidents)

Environmental Category	Probability per Mile of Exceeding Specified Severity Levels	
Crush	1.4×10^{-7}	Primary Environments
Fire	1.2×10^{-8}	
Impact	$<10 \times 10^{-10}$	Secondary Environments
Puncture	6×10^{-10}	
Immersion	$\sim 5 \times 10^{-11}$	

Summary of Transport Accident Severity

A summary of the severity of the basic accident categories of impact, fire, crush, puncture, and immersion in relation to the severity level of existing qualification criteria for radioactive material packages is shown in Table V. In addition, for each transportation mode, the relative influence of each environment is classified as primary or secondary.

TABLE V

Percentage of Accidents in a Given Mode Which Provide an Environment
Equal to or Less Severe Than Existing Qualification
Test Criteria

		Accident Environment Categories				
		Impact	Fire	Crush	Puncture	Immersion
Transportation Mode	Air Influence	79% Primary	90% Primary	Not Defined (1) Secondary	92-98% Secondary	97% Secondary
	Truck Influence	100% Secondary	99% Primary	Not Defined (2) Primary	100% Primary	100% Secondary
	Rail Influence	100% Secondary	99% Primary	Not Defined (3) Primary	100% Secondary	100% Secondary

Note (crush tests not specified in existing standards):

(1) 70,000 lb single-axis crush test will protect against essentially 100% of aircraft accidents.

(2) 8,000 to 10,000 lb single-axis crush test will protect against essentially 100% of truck accidents.

(3) 70,000 lb single-axis crush test will protect against essentially 100% of rail accidents.

The tabulated percentages are the ASCC's associated with the severity of existing qualification criteria. For example, 79% of all aircraft accidents provide an impact severity equal to or less than the impact severity (44 ft/s)of existing impact qualification criteria. A similar interpretation may be made of the other environment categories and transportation modes.

Since crush is not defined in existing qualification criteria, the footnotes in Table V state the magnitude of crush force required to prove this qualification for essentially all occurrences of the crush environment. This will be discussed in detail in the next section. It must be emphasized that the environmental influence designation of primary and secondary recognizes that the basic accident categories are the constituents or forcing functions which physically describe the overall severity of each accident; however, these constituent environments do not contribute to the same degree in each transportation mode.

Assuming a defacto judgement as to what constitutes a reasonable level of protection, say 97% or greater, then the following observations may be made from the information in Table V:

- The surface transportation modes of truck and rail seem to be adequately protected by existing qualification standards except for the crush environment which is not currently specified as a qualification test.

- The air transportation mode needs to have its protection levels increased for the impact and fire environments. In aircraft accidents puncture and immersion environments are of secondary influence, but existing standards provide a high degree of protection for them. Aircraft crush is defined in Appendix A and, using this information as a basis, a crush test needs to be formulated since existing standards do not test the crush environment.

- Crush is a primary influence in truck and rail accidents and a crush test needs to be formulated for these transportation modes.

Qualification Test Proposal - Surface Transport

The preceding section compared existing qualification test criteria for radioactive material packages with the severity of real transportation accidents, and this information was summarized in Table V. In this section we will formulate a test proposal to qualify small packages designed to protect radioactive material against surface transport accident environments. In the next section we will formulate a similar proposal for the hypothetical accident environments of aircraft.

The surface transport modes (truck and rail) are grouped together since they are normally by truck only or by a mixture of truck and rail. If we examine again the results in Table V, the existing qualification criteria provide protection against essentially all occurrences of impact, fire, puncture, and immersion in real accidents. Crush testing is not currently specified and, since crush is an environment of primary influence in the surface transport modes, a crush test will be defined. Due to the mixed-mode nature of truck and rail transport, the crush test will specify a crush force of 310 000 N (~70,000 lb)--although only 35600 to 44500 N (8,000 to 10,000 lb) would encompass most occurrences in truck accidents.

The existing qualification criteria for Type B packages and accident conditions[2,3,7] require the sequential application of the following environments: free drop (impact), puncture, thermal (fire), and water immersion--in the order stated. The test sequence suggested in this report requires sequential testing of only the environments designated to be of primary influence. It is proposed that the package design be tested individually (not sequentially) to the severity of the environment which are designated to be of secondary influence. The rationale for this kind of testing sequence is that only the primary environments exhibit a significant effect on the joint probability results and the inclusion of the secondary environments in a serial testing sequence may possibly lead to stringent qualification tests which represent a very improbable environmental sequence. In light of the results in Reference 1, this study provides proposals whose criteria reflect not only the severity of real accident environments but, additionally, the testing sequence will attempt to reflect the dominance of the environmental categories that has been observed in real transport accidents.

The surface transport proposal which follows includes environmental test parameters for impact, puncture, fire, and immersion which are not substantially increased above currently specified standards. The 1 m (~ 3 ft) water immersion test is increased to 15 m (49.2 ft) in order to be consistent with international standards. The existing fire criterion specifies flame temperatures of 1475°F and a fire duration of 30 min. The revised criterion for the fire test in surface transport and air transport will specify differing durations in an 1000°C (1832°F) fire. In Reference 1 it was found that burning JP-4 jet fuel often produces flame temperatures in the range of 760° to 1320°C (1400° - 2400°F).

In addition, it should be noted that the protection levels at or near the 100% level in the surface transport mode indicate that those values may be "overly severe" and could, perhaps, be relaxed from their present levels without any significant decrease in safety to the public.

The qualification criteria and test proposal for the surface transport modes (truck and rail) are summarized in Table VI.

TABLE VI

Test Proposal - Surface Transport

1. Sequential Tests (primary environments, one package required)

The following environmental tests are to be applied to a single package sequentially and in the order indicated to determine their cumulative effect. Following the sequential testing, the package must satisfy the leak rate specified in the Acceptance Criteria.

Environmental Category	Environmental Severity*
a. Puncture	1 m (40 in.) free drop of package onto puncture probe
b. Crush	310 000 N (70,000 lb) static loading
c. Fire	1000°C (1832°F) fire, duration 30 min

2. Individual Tests (secondary environments, two packages required)

The following environmental tests are to be applied individually (and to separate packages) to determine the individual effect of the environment on the package. Following each individual test, the package must satisfy the leak rate specified in the Acceptance Criteria.

Environmental Category	Environmental Severity*
a. Impact	9 m (30 ft) free-fall drop onto unyielding target
b. Immersion	Immersion in water at a 15 m (49.2 ft) depth for 8 hr

3. Complete Sequence Testing

If it is desired, a single package may be tested in a single and complete sequence of impact, puncture, crush, fire, and immersion--in the order listed. The severity of these environments is as stated above. This sequence is to be viewed as an option, not a requirement, of this test proposal. Following the complete sequence testing, the package must satisfy the leak rate in the Acceptance Criteria.

4. Acceptance Criteria

Existing acceptance standards (Reference 8).

---

*See Appendix G for description of test details.

Qualification Test Proposal - Air Transport

Introduction

This section will present a test proposal for the qualification testing of radioactive material package designs against aircraft transportation accidents. As has been mentioned in preceding sections, the severity of transportation accidents, based on the study in Reference 1, is summarized in Table V of this report. For aircraft accidents the environmental categories of impact and fire are designated in that table as the environments of primary influence, crush, puncture, and immersion being of secondary influence.

Primary Environments

Impact -- Table V shows that 79% of aircraft accidents are expected to involve impacts equal to or less severe than the conditions imposed by the existing impact test criteria, i.e., 13.4 m/s (44 ft/s) onto an unyielding surface. Therefore, it is judged that existing qualification criteria do not provide as much impact protection for aircraft accidents as they do for rail and truck accidents.

Obviously aircraft accidents can involve impact velocities much greater than 44 ft/s. Using impact as an example, Table V presents a quantifiable argument as to the adequacy of existing qualification criteria. Referring to Figure 3, it is possible to determine the increased level of protection for higher impact velocities. For example, if the velocity is increased to 130 m/s (425 ft/s) 97.5% of all aircraft accidents will have an impact equal to or less severe than that.

At this point, we must emphasize the role played by the hardness of the impact test target. Figures 2 and 3 do not incorporate any effects of target hardness; a more detailed discussion of its effects is presented in Appendix H. If the impact velocity is less than, or in the range of, 20 to 30 m/s and if the package design is similar to the 6M or LLD-1, then all targets appear to be hard to the package. As the magnitude of the impact velocity is increased, the effects of target hardness become more pronounced (see Appendix C). Essentially unyielding targets, such as outcroppings of rock, are encountered rarely; the exact probability, although finite is unknown. Indeed, the severity probabilities tabulated in Appendix C were formulated with respect to unyielding targets for two reasons: (1) impact onto unyielding targets is a real possibility, and (2) the construction of unyielding impact targets of reproducible hardness and quality is more readily accomplished than that of soft targets such as soil.

In addition, the analysis reported in Appendix C was performed to provide a better description of the high-velocity tail of the aircraft impact severity distribution curve. The data presented in Reference 1 was derived to define the probabilities in the neighborhood of the present 13.4 m/s (44 ft/s) impact test and is not applicable at velocities in the range of 45 to 60 m/s or above. In reality the package must be designed to sustain a variety of target hardness and not just the unyielding target used in qualification testing.

Fire -- Referring once again to Table V, we see that 90% of all aircraft accidents provide a fire environment equal to or less severe than the temperature-time product provided by existing fire qualification test standards. On the assumption that a severity level should be higher than 90%, the test proposal described in this section calls for more severe fire qualification test standards than now exist.[2,3,7]

The aircraft thermal environments defined in Reference 1 did not attempt to define the location of the RAM package with respect to the aircraft fire or the related probability that the resulting thermal environment experienced by the package in the aircraft fire will be similar to the environment that the package will sustain in a qualification test. To use the data in Reference 1 requires the tacit assumption that all packages are directly exposed to the fire in the most threatening orientation. In an attempt to improve upon this description, the aircraft fire accidents were reanalyzed as described in Appendix D. This reanalysis led to a more realistic estimate of the probability of the exposure to a given package and the duration of this exposure.

Secondary Environments

Crush -- Actual data on the crush environment is not available at this time. Crush is of secondary influence in the aircraft accident but nevertheless a destructive environment that can possibly occur; therefore, the study reported in Appendix A was conducted. Based upon the results described in that appendix, a crush test specification is included in the proposed test criteria described in this section.

A potentially large longitudinal crush force exists in aircraft accidents which is not addressed in the qualification criteria which will be proposed for the air transport mode. An attempt was made to analyze the longitudinal crush mode and the methodology is described in Appendix A. The analysis in Appendix A states that the longitudinal crush force could easily reach hundreds of thousands or even millions of Newtons if the RAM package were in the forward part of a heavily loaded cargo compartment. The longitudinal crush forces can obviously exceed the 310 000 N (70 000 lb) vertical crush criterion which will be proposed.

Puncture -- Table V indicates that the numerical puncture relationship shown in Figure 6 provides such a severity level that 98% of all aircraft accidents are protected by the existing puncture qualification criteria. The 98% level of environmental assessment, plus the fact that puncture is designated a secondary environment, is judged to be a satisfactory level of protection, based on a comparison with other values in Table V. It should be noted that the puncture test is essentially an arbitrary test in that a probe of defined dimensions is imposed upon a package by the impact of the package. The arbitrary (but defined) probe size is to represent the class of all possible puncture probes. Even if the puncture test is arbitrary in its definition, the test does offer a satisfactory level of protection based on the results of Reference 1.

Immersion -- The immersion environment severity for aircraft accidents is assessed at a 97% level by existing IAEA standards. The U. S. standards provide a slightly lower level of protection. The level of protection indicated in Table V for immersion in aircraft accidents, with the additional consideration that immersion is designated as a secondary environment, resulted in the judgment that immersion is at a satisfactory level of protection in aircraft accidents.

Even though the existing puncture and immersion qualification tests provide a high level of protection, the test proposal for the air transport of RAM packages which will now be presented will provide for increased severity above the existing standards for the puncture and immersion environments. The rationale for these increased severity levels is as follows.

- The high velocities associated with aircraft accidents provide the possibility of severe puncture of RAM packages even though joint probability analysis indicate that puncture is of secondary influence in aircraft accidents.
- The location of some airports adjacent or near open ocean and the possibility of international shipments of RAM packages by air require a more severe immersion requirement than for transport over inland and coastal waterways. The attainment of an increased capability to resist the effects of immersion are often provided indirectly by meeting the design requirements for other severe accident environments such as impact.

Test Proposal

The same test rationale will be used in the assessment of the adequacy of a radioactive material package design against the severity of an aircraft accident environment that was used in the test proposal for surface transportation modes. Once again, the accident environment categories that are of primary influence will be sequentially tested in the test proposal. The environments of secondary influence will be proposed as individual tests. The primary environments for the aircraft accident are impact and fire. From a physical viewpoint the proposed sequential tests for impact and fire embrace the expected chronology of the accident, namely, impact followed by fire. In addition, since actual aircraft accidents involve cases of impact alone and fire alone, individual occurrence of these environments will also be included in the proposed test plan. The individual tests for the secondary environments of crush, puncture, and immersion will assess these environments in accordance with the degree of influence that they exert in actual aircraft accidents.

A detailed joint probability analysis of the impact-fire environment for the aircraft accident is presented in Appendix E. The analysis considered the protection level provided by several impact-fire test sequences. Consulting Table VII (a duplicate of the information in Appendix E, Table E-III) one can see that Case 6 provides the highest protection level because it represents the most severe impact-fire test sequence considered in the analysis (although all the cases tabulated in Table VII represent very severe environments). The test proposal presented in this section represents a set of qualification criteria which simulates the crash of a high-flying aircraft. The impact-fire sequence of the test proposal is specified by Case 4 of Table VII.

Some preliminary predictions of this study[9] were forwarded to ERDA in September of 1977 in response to a request regarding suggested criteria for packages to permit the air transport of plutonium. In addition to the arguments presented here, Reference 9 also used public risk estimates to assess the adequacy provided by the suggested plutonium package capabilities and the benefits which could be provided by increasing this protection. In summary, the risk was found to be several orders of magnitude less than that found in the nuclear reactor safety study,[10] and that this risk level decreased very slightly as the qualification levels were made more severe than those proposed here.

There is, however, one difference between the air transport criteria proposed in Reference 9 and the air transport criteria proposed in this report. This difference has to do with the acceptance criteria imposed following the qualification testing of the RAM package. This report specifies the use of existing acceptance standards, Reference 8, which impose a more severe standard than suggested in Reference 9. The reason for this difference is Reference 9 set its acceptance levels on the basis of the hazards to the public which were estimated by the performance of a complete risk analysis. Since this study did not perform a risk analysis the more strict standards of Reference 8 were recommended.

Table VIII represents a simulation of the aircraft accident environment which can be used to qualify a small RAM package design against such accidents. The impact-fire parameters represent the values used in Case 4 of Table VII. It should be noted that Case 4 does not represent the most severe combination of the impact-fire parameters, but Case 4 does have a protection level of approximately 99%. The rationale for selecting Case 4 for the impact-fire test severity is detailed in the following paragraph.

TABLE VII

Tabulation of Test Proposal Probability Calculations

	Individual Tests		Sequential Tests		Protection Level[*] (%)	
Case	Impact Velocity (ft/s)	Fire Duration (min)	Impact Velocity (ft/s)	Fire Duration (min)	P_T	P_E
1	425	60	425	60	99.56	.44
2	425	60	425 350 250 200	15 25 40 60	99.41	.59
3	350	60	250	30	98.35	1.65
4	350	60	300	40	98.74	1.26
5	425	60	300	30	99.25	.75
6	500	90	300	40	99.63	.37

[*] P_T = The percentage of all aircraft accidents equal to or less severe than the designated impact-fire test sequence.

P_E = The percentage of all aircraft accidents more severe than the designated impact-fire test sequence

$$P_T + P_E = 100\% \ .$$

The impact and fire criteria were increased in severity from existing standards in order to provide increased protection levels as determined by joint probability analysis. It can be observed from Table VII that a number of impact-fire test sequences provide levels of protection quite close in their numerical values. Considering the accuracy of the input data, one would not expect the calculations to be as accurate as shown in Table VII. Therefore, for example, Cases 4 and 5 could be rounded off to 99% protection levels. Similarly, Cases 1 and 6 could be rounded off to essentially 100% protection. These protection levels are close and include some variation in the magnitudes of impact velocity and fire duration. Case 4 was chosen for the test proposal because it increases the protection to a high level and yet does not make the impact and fire parameters unnecessarily severe. This choice was a judgment between test parameter severity and protection levels. The main point of Table VII is that, while other test sequence cases could have been considered and perhaps other judgments could have been made for the final test proposal. The judgment was made based upon a numerical value of the protection provided rather than basing such a decision on a subjective analysis.

Somewhat contrary to this preceding statement, the air transport test proposal also includes a puncture-fire sequential test. This test is proposed because of the concern that puncture or something similar to puncture easily could destroy the fire barrier of the container during the accident and greatly decrease the fire protection. There is no statistical evidence to substantiate this concern but the violent nature of the aircraft accident makes such events a distinct possibility and, therefore, ones for which protection should be provided.

TABLE VIII

Test Proposal (Air-Transport)

1. Testing Primary Environments*

   a. Individual Tests

   The following environmental categories are to be applied individually to a previously untested package and, following the individual tests, the package must satisfy the leak rate specified in the Acceptance Criteria.

   I.T. 1 Impact, v = 110 m/s (360 ft/s) onto unyielding target
   I.T. 2 Fire, 1000 °C (1832 °F) 60 min duration

   b. Sequential Tests

   The following environmental categories are to be applied sequentially to a previously untested package and in the order indicated in order to determine their cumulative effect. Following the sequential testing the package must satisfy the leak rate specified in the Acceptance Criteria.

   S.T. 1 Impact, v = 90 m/s (295 ft/s) onto unyielding target
   followed by
   Fire, 1000 °C, 40 min duration

   S.T. 2 Puncture, 12 m/s (40 ft/s) onto aluminum I beam
   probe, followed by
   Fire, 1000 °C (1832 °F) 40 min duration

2. Testing Secondary Environments*

   The following environmental categories are to be applied individually to a previously untested package and following the individual test, the package must satisfy the leak rate specified in the Acceptance Criteria.

   I.T. 3 Crush, static loading 310 000 N (~70,000 lb) applied with
   a uniformly distributed loading
   I.T. 4 Puncture, 30 m/s (100 ft/s) onto aluminum I beam probe
   I.T. 5 Immersion, 2 MPa (300 psi) hydrostatic pressure,
   duration 8 hours

3. Acceptance Criteria

   Existing acceptance standards (Reference 8)

*See Appendix C for a description of test details.

A radioactive material shipping package can be subjected to normal and accidental transport environments. This study has examined the hypothetical accident qualification criteria for the licensing of radioactive material packages, and the relation of these criteria to the severity of real transport accidents; the normal transport environment has not been examined.

Small Packages

Since the information presented in this report uses the information in Reference 1 as a primary reference source, it must be emphasized that the results of this study are subject to the assumptions used in that source. It was assumed in that study of the severity of transport accidents that the radioactive material would be in small packages. What, then, constitutes a small radioactive material (RAM) package? For the purposes of Reference 1 and this study, it is defined as a package of relatively limited size; its mass may be several hundred kilograms but not more than about 500 kg at a maximum. In the transport mode several such small packages, perhaps 10 to 20, may be transported in an enclosed van or other conveyance.

An additional consideration with respect to small packages, as defined above, is that with them one has the luxury of being able to analyze and test the prototype. This fact must be emphasized, otherwise it might be concluded that this study makes a series of conclusions and recommendations that are applicable to all RAM package designs regardless of their size. A separate investigation is being conducted for large casks (where weights are measured in tons). The results of this study and the test proposals described herein are not necessarily applicable to large casks.

Need for Radioactive Material Shipments

This study has not considered the necessity for shipping radioactive materials. It was assumed that there are many bona fide reasons and operational requirements which make the shipment of radioactive materials necessary. This study has evaluated the protection levels provided by the existing qualification criteria, given that RAM shipments occur in each transport mode. The justification and analysis of the requirements for shipments in the truck, rail, and air transport modes are not within the province of this study.

How Safe is Safe Enough?

In general, a system or device is judged to be safe if its risks are acceptably low.[6] The viewpoint expressed in this report is that, to make a judgment as to when the risk associated with a given RAM design is "acceptably low," one must express the ultimate hazard of package failure in terms of risk. There are two component parts of this type of analysis. First, the RAM package must be designed and tested to produce no significant (in terms of real public danger) loss of contents under some array of accident environment severities. If no RAM contents are lost, then there should be no risk to the public with respect to radioactivity. A known amount of contents loss must be translated into the terms of risk, i.e., fatalities, land use denial, dollar loss, etc. The first portion of the problem is technical in nature and can be analyzed in some detail. The second portion of the problem involves judging the results of a risk analysis relative to other known and accepted risks such as natural disasters, etc. This portion of the problem requires a judgment of social values as to whether the risk is acceptable or not. The basis under which such a judgment is made may vary from time to time or with individuals. This report has described the degree of coverage that existing qualification criteria provide with respect to the severity of real-world transport accidents. This study is not a risk analysis. This study uses only the first component of the risk product; i.e., the probabilities of occurrence, to achieve several recommendations regarding potential alterations to the existing regulatory standards.

Protection Levels Provided by Qualification Criteria

The accident severity comparison criterion (ASCC) has been used in this study to provide a measure of the protection provided by a specified qualification test. The ASCC was plotted against the accident environment severity level (see Figures 2 through 17). Entering these figures with the severity levels of the existing qualification criteria for RAM packages allows the determination of the protection provided by these criteria. These protection levels were summarized in Table V. Further, it was assumed (arbitrarily, for the purposes of this study) that the protection level (ASCC) should be at least 98%. Based on that assumption one can make the following conclusions.

Conclusions - Surface Transport

1. The protection levels provided by existing qualification criteria for surface transport, i.e., truck and rail, is almost complete. That is, the severity of existing qualification criteria is such that nearly 100% of all truck and rail accidents are equal to or less severe than the severity of existing qualifications criteria. It must be recalled that crush is an environment that is not specified in existing qualification criteria. In view of this fact and the primary influence of crush in truck and rail accidents, crush qualification criteria need to be defined for the surface transport mode.

2. Crush, puncture, and fire have primary influence in truck transport. Crush and fire have primary influence in rail transport. Truck and rail transport do not always occur as individual modes but are in, many cases, mixed-mode in nature. For example, one might use a truck to reach a railhead, etc. Therefore, the surface transport test proposal described earlier reflects a composite approach where crush, puncture, and fire are designated as primary environments and impact and immersion are designated as secondary environments. Obviously, if rail transport could be assuredly excluded, then

only the truck environments would need to be considered. From a practical viewpoint, however, the design differences between truck-only and rail-only packages would be too small to justify the added complexity of separate qualification test standards for truck and rail.

3. The nearly complete protection that the existing qualification criteria provide for the surface transport mode was evident in Table V and discussed in Conclusion 1. The test proposal for surface transport consists of a reorganization of the existing qualification criteria and a newly defined crush test and minimal changes in the severities of the individual tests. The reason for not drastically changing these severity parameters is that they represent over 25 years of successful experience in qualifying RAM packages. Consider, however, the following argument, using impact as an example: If one refers to Figures 8 and 13, the asymptotic nature of those plots indicates that the severity of the surface transport impact tests could be relaxed from present standards and not significantly degrade the protection levels provided. This observation might be made for other accident environmental categories as well.

Conclusions - Air Transport

1. An examination of Table V indicates that all the aircraft accident environments do not have the same influence. Impact and fire have strong primary influence; crush, puncture, and immersion have secondary influence.

2. As with surface transport, existing qualification criteria do not include crush testing. It was therefore necessary to define crush qualification criteria for air transport.

3. Existing qualification criteria for puncture and immersion offer a high degree of protection. Even with this degree of protection it was concluded that due to the uncertainties of the aircraft accident environment and the higher-velocities of such accidents that the puncture and immersion qualification standards should be increased. Coupling these revisions with the definition of a crush qualification criterion means that a high level of protection can be provided for all of the secondary environments in aircraft accidents.

4. The existing qualification criteria when used with respect to the air transport mode should be increased to achieve a level of safety consistent with that provided for the surface transport modes (see Qualification Test Proposal - Air Transport).

5. An examination of the test forces required to provide protection against the crush environment are given in the footnotes in Table V, where it can be seen that the aircraft and rail transport modes are controlling and have the same crush force magnitude (i.e., 310 000 N force).

Recommendations

It is recommended that the qualification criteria used to certify a RAM package design embrace the following concepts:

- The severity level of the individual accident environment should be chosen with respect to the protection indicated by the ASCC. In order to make such a judgment, Reference 1 or a similar basis must be used.

- The mix of sequential and individual testing of the accident environment categories should reflect the relative influence that the environmental categories have exhibited in real transport accidents. The test proposals for surface and air transports have attempted to use these concepts. Specific recommendations of the study are:

1. It is recommended that the truck and rail modes of transport be considered as a mixed-mode option, "surface transport," and that the qualification criteria for RAM packages in that mode be as stated in Table VI.

2. It is recommended that the qualification criteria for air transport be as stated in Table VIII.

3. It is recommended that a single crush test be defined (see Tables VI and VIII and Appendices A and G) for surface and air transport. Because of the absence of any real crush severity data, a study to quantify the crush forces in the aircraft accident is reported in Appendix A. This analysis and consideration of the secondary importance of crush in aircraft accidents led to the recommendation that these be a single-axis static crush test of 310 000 N (~70,000 lb) distributed over the dimensions of the package most vulnerable to the crush environment, and that this test be used for both surface and air transport qualification criteria.

4. Since the longitudinal crush mode can produce forces which exceed the crush criterion which was established on the basis of the vertical crush mode it is recommended that the imposition of administrative controls be considered to ensure that RAM packages are transported in the aft end of aircraft cargo areas in order to reduce the possibility of longitudinal crush.

5. An additional precaution can be taken with respect to the 310 000 N (70 000 lb) vertical crush mode in the aircraft crash. Vertical crush is the result of a RAM package being captured in the lower cargo bay beneath the cargo deck. It is recommended that, on aircraft with lower cargo areas, the RAM package be shipped on the aft end of the main cargo deck to greatly diminish the possibility of the occurrence of both vertical and longitudinal crush. (The accessibility of RAM cargo for aircraft crews (FAR. 103.31) may already require that RAM cargo be located on the main cargo deck.)

6. The fragmentation problem, from turbine blade failure, is addressed in Appendix B of this report. The possibility of fragments from failed blades in aircraft engines striking RAM packages is considered to be very remote. Since the fragmentation problem is remote, it is not specifically recommended that cargo exclusion zones be established to combat this problem. However, in locating the RAM cargo in the aft end of the cargo compartment (Recommendations 4 and 5) an awareness of the fragmentation problem should be kept in mind, especially in aircraft with aft engines.

7. The acceptance criteria recommended by this study, after the completion of the qualification tests for surface or air transport, are the existing acceptance criteria of 10CFR71.[2] The compliance with these criteria is as provided by Regulatory Guide 7.4, U.S. Nuclear Regulatory Commission.[8]

8. This study recommends two sets of qualification criteria, one for surface transport and one for aircraft. Because of the relative severity of the environments in both of these modes, it is recommended that there be a hierarchy of the proposed qualification criteria; this hierarchy is described in Figure 18, and is as follows: It is recommended that RAM package designs that can pass the air transport qualification criteria be automatically licensed for air and surface transport. It is recommended that RAM package designs that pass the surface transport qualification criteria be licensed for surface transport only.

Package Qualification Criteria	Air Transport Qualification Criteria	Surface Transport Qualification Criteria
Transport Mode Permitted	Air Transport Surface Transport	Surface Transport

Figure 18. Hierarchy of Qualification Testing

9. The existing U.S. standards for immersion in 10CFR 71, Appendix B, specify a 3-foot water immersion depth. The existing IAEA criteria specify a 15-metre immersion depth. Immersion was classified as a secondary environment in both surface and air transport and it is recommended that the IAEA standard be adopted for the surface transport mode and a 2 MPa (300 psi) standard be adopted for the air transport mode.

10. When the study of the severities of transport accidents was begun in 1972, it was difficult to obtain data on the severity of the accident environments experienced by cargo packages. Part of the reason for this situation was the understandable emphasis on safety as it related to saving human lives and on those statistics. The cargo response and the accident environment were secondary considerations. Since the regulatory guidelines for transporting RAM packages are reviewed periodically, it is recommended that a system be adopted to gather environmental data with respect to accidents and cargo,[15] to avoid such data acquisition problems in the future.

Closing Remarks

This study has stated the level of protection provided by existing qualification test standards for small radioactive material packages in simple and quantifiable terms. The need to quantify the argument was necessary so that numerical comparisons could be made between the protection levels provided by existing or proposed qualification criteria and the severity of real transport accidents. The term "protection level" as used in this study refers to the ratio of a particular environmental test severity to the severity of a real accident. Hence some measure of "protection" is determined by the ability of a package design to survive a specified test or test sequence. However, the term "protection level" does not imply an absolute quantity known to great accuracy. It is judged, however, that when considerations are made for margins of safety, material variability, the approximate nature of the design process, etc., that the protection levels will be even higher than stated in this report.

The reason for the quantification of protection with respect to the transport of radioactive materials is that we have what might be called a technical/regulatory interface. The technical community can conceive, design, fabricate, and test a radioactive material shipping package. The regulatory process will involve members of the technical community and the appropriate branches of government, so interpreting technical information that judgments can be made which hopefully will assure public safety. The correct interpretation of a technical design or process is the key ingredient in rendering a protective regulatory judgment, and it is for this reason that we have emphasized the use of measures of safety in quantifiable terms such as the accident severity comparison criterion (ASCC).

The quantification of the severity levels of existing criteria and the comparison of these values with the severity of real surface transport accidents showed that the existing qualification criteria are equal to or more severe than essentially all known truck and rail accidents. A RAM package tested to the criteria in Table VI, and surviving, means that it has withstood the environment of a simulated accident which, to a high degree of probability, exceeds the environmental severity of most surface transport accidents. The term simulated accident must be qualified. First, the test proposals in this report are not a direct simulation of an accident; they represent a standardized laboratory environment which is a simplification of a real accident, but they do simulate key elements of the environment of transportation accidents. Qualification testing cannot accomodate all possible accident scenarios but such a testing and acceptance process builds confidence, in the absence of any absolute guarantees, that RAM package designs can survive severe accident environments without loss of contents and thus involve minimal risk for the public.

Quantification of the severity levels of existing qualification criteria allowed the judgment to be made that it was necessary to increase the severity level of the qualification criteria for airshipped RAM packages. Subjecting a RAM package design to the test proposal in Table VIII provides a representation of an accident more severe than essentially all known aircraft accidents. Not all aircraft accident scenarios can be simulated but it can be stated with a high level of confidence that close to 100% of all aircraft accidents will be less severe than the test array in Table VIII.

The basic question undertaken by this study will be repeated here: "How well do the existing Federal regulatory qualification standards for RAM packages compare with the stresses that actually occur in real transport accidents?" The answer to this question is summarized in Table V. The corollary to the basic question was that, if it was determined that there was an area where existing criteria appeared to provide inconsistent levels of public safety, then this study would recommend alternative qualification criteria for consideration by regulatory bodies and other interested agencies.

The existing criteria of 10CFR 71, Appendix B, offer essentially complete protection for surface transport. A slight reorganization of these criteria and the additional requirement of a crush test appear in the surface transport test proposal in Table VI. However, the significant fact is that the existing criteria do offer a high degree of public protection and, while this may have been suspected, it had not previously been stated in quantifiable terms.

The other significant result of this study is that it is apparent that the present qualification criteria do not offer the same degree of protection in the air transport mode that they do for surface transport. Hence it is concluded that, to provide a high and consistent level of protection for all transport modes, it is necessary to provide a separate, and more severe, set of qualification criteria for air transport as shown in Table VIII.

References

1. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, "Severities of Transportation Accidents," SLA-74-0001, Sandia Laboratories, July 1976.

2. United States Nuclear Regulatory Commission, Rules and Regulations, Title 10, Chapter 1, Code of Federal Regulations - Energy, Part 71.

3. United States Department of Transportation Regulations, Title 49, Code of Federal Regulations, Parts 170 to 178.

4. *Structural Mechanics Computer Programs, Surveys, Assessments, and Availability*, edited by W. Pilkey, K. Saczalski, and H. Schaeffer, University Press of Virginia, 1974.

5. W. B. Baker, P. S. Westin, and F. T. Dodge, *Similarity Methods in Engineering Dynamics: Theory and Practice of Scale Modeling*, Hayden Book Co., Rochelle Park, NJ, 1973.

6. W. W. Lowrance, *Of Acceptable Risk, Science and the Determination of Safety*, William Kaufmann, Inc., Los Altos, CA, 1976.

7. IAEA Regulations, Safety Series No. 6, 1967.

8. Regulatory Guide 7.4, Office of Standards Development, U.S. Nuclear Regulatory Commission, June 1975.

9. Risk-Based Criteria for Certification of Packages for Air Shipment of Plutonium, SAND77-1313, Sandia Laboratories, September 1977.

10. "Reactor Safety Study," WASH-1400, October 1975.

11. T. I. McSweeney and J. F. Johnson, "An Assessment of the Risk of Transporting Plutonium Dioxide by Cargo Aircraft," BNWL-2030, Battelle Northwest Laboratories, Richland, WA, June 1977.

12. "Draft Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes," NUREG 0034, March 1976.

13. "An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck," BNWL-1846, August 1975.

14. R. J. Hall, Program Coordinator, D. K. Davis, S. W. Heaberlin, J. F. Johnson, and P. L. Peterson, "An Assessment of the Risk of Transporting Plutonium Dioxide and Liquid Plutonium Nitrate by Train, BNWL-1996, February 1977.

15. J. T. Foley, "ERDA Transportation Accident Data Needs," letter to Distribution, Sandia Laboratories, March 2, 1976.

APPENDIX A*

Crush Environment for Small Containers Carried by U.S. Commercial Jet Aircraft

CONTENTS

PLEASE NOTE*

The units used in these appendices are expressed in the English gravitational system because (1) this report uses SLA-74-0001 (which uses English units) as a principal reference, (2) much of the accident data is in English units and (3) the data in this document is compared with Federal Regulatory Standards, (e.g. 10CFR71), which uses English units. Because of international considerations with respect to RAM regulatory standards the main body of this document has been written in dual notation, SI and English.

APPENDIX A

Crush Environment for Small Containers Carried by U.S. Commercial Jet Aircraft

J. D. McClure
Applied Mechanics Division II, 1282

and

W. A. Von Riesemann
Design Technology Division, 5431

Introduction

The purpose of this report is to examine and report the magnitude of crushing loads which can be imposed on small shipping containers during the crash of a commercial airplane. These loads are, for the main part, estimations of the maximum the container could experience, and there has been no attempt to predict how frequently loads of this magnitude will occur. The crushing modes of the vertical and horizontal crush environment are examined.

The type of container considered was a typical small container, about 15 inches in diameter, 18 inches in length, with a weight of approximately 50 to 100 pounds. The aircraft types that were examined in this study included the Boeing 707, 727, 737, 747, and the McDonnell-Douglas DC-8, DC-9, and DC-10.

Crush Environment - Aircraft Crash

When an airplane crashes, a shipping container aboard the aircraft may be subjected to a number of accident environments such as impact, fire, crush, puncture, and immersion (Reference A-1). This report will detail the results of the study of the crush environment attendant to an aircraft crash. The shipping container used in this study was of the 6M Type (Reference A-2) which was considered to be typical of a class of small, lightweight containers. A series of specific aircraft cargo types were examined, namely, the Boeing 707, 727, 737, 747, and the McDonnell-Douglas DC-8, DC-9, and DC-10. A large fraction of aircraft cargo shipments occur within these aircraft types. The results of this study are judged to be applicable to similar types of aircraft not specifically included in this study.

Crush loads in the context of this study are considered to be large magnitudes of force applied over an area defined by the major dimensions of the container as opposed to the localized application of force which can cause puncture of the container. The rise time and duration of the crush force with respect to the natural period of the container are such that the crush forces are considered to be static rather than dynamic. This report is divided into two main sections, one investigating vertical crush and the other examining the longitudinal crush environment. The specific meaning of these two crush modes are defined below.

The term crush means to produce compression between two or more hard bodies, to produce violent compression or to destroy the natural configuration, integrity or shape of a body. One can visualize a heavy object or weight lying at rest on top of an adjacent package or container and depending upon the load magnitude and the container structural strength, crushing may or may not occur. Generally speaking, crush loads are considered to be static loadings; that is, the response of the structure to the crush loading is a relatively long-time effect with respect to the natural period of the structure being crushed.

In general, in an aircraft crash situation the crush forces are generated dynamically; but due to the relatively long time of load application with respect to the container's period, the simulation of crush forces can be accomplished in a static test.

Since impact is an environment very much a part of the aircraft accident, a distinction should be made between the impact and crush environments. One of the principal reasons that crush can be considered as a static loading situation in an aircraft crash is due to the fact that cargo can be entrapped within the fuselage structure as the aircraft structural frame undergoes large deformations during the crash. In the crushing process, the container can be compressed, i.e., "pinched" between other cargo or between structural members of the airframe.

Impact is associated with high loadings, short rise times, and is a dynamic rather than a static situation. Impact loadings occur as the aircraft crashes. Cargo is torn loose from its tie-downs and is propelled with some velocity into other cargo or into the airframe structure. In addition, breakup of the airframe structure during the crash can impose impact loadings on containers, allowing release of the cargo from the airframe structure with some subsequent opportunity for crush loadings depending on the final configuration of the aircraft and the cargo following the crash.

This report is concerned with two modes of crush, namely, vertical crush and longitudinal crush. The vertical crush mode occurs due to the large deformation of the airframe structure with the resultant crushing of the entrapped cargo along an axis essentially normal to the aircraft longitudinal axis (see Figure A-1). The longitudinal crush mode occurs due to the large deformation of the airframe structure and the resultant crushing of the cargo along the aircraft longitudinal axis. This mode may occur during a crash landing or during the impact of the aircraft into a building or the abrupt face of a terrain feature (Figure A-1).

Analysis of the Crush Environment

In considering the aircraft crush and the possibility that crush loadings could be applied to a shipping container, it is logical to think of the problem in terms of the vertical and longitudinal crush modes which have just been defined. Crushing in one or the other, or both, of these modes may or may not occur in an aircraft crash, and this analysis attempts to define reasonable upper limits on these forces without attempting to predict how frequently these forces will be experienced.

In general, the crush forces are a function of the container location, the cargo mass, rigidity and location, the airframe structural strength, and the vertical or longitudinal velocity of the aircraft.

Vertical Crush

Vertical crush deals mainly with the lateral deformation and breakup of the airframe as the aircraft crashes. This mode is depicted in Figure A-2. If the aircraft has a lower cargo hold as shown in Figure A-2 and the shipping container is in this location during transport, it is possible during an aircraft crash (such as wheels-up crash) that the container will be captured between the main cargo deck and the lower cargo deck as the fuselage deforms. If the shipping container is carried on the main cargo deck, there will be less opportunity for vertical crush forces to be applied to the container during crash. This section will examine the situation where the shipping container is captured between the lower fuselage and the main cargo deck.

An estimate of this vertical crush force on the container can be made by considering the ultimate load capacity of the main cargo floor beams. A schematic of the floor structure for a Boeing 707-320C (cargo version) is shown in Figure A-4. The cargo floor beams interact with the cargo and the captured shipping container as shown in the free body diagram for vertical crush as shown in Figure A-3. The shipping container reacts against the floor beams in the manner shown as the lower fuselage is deformed. The maximum load which can be applied to the container is limited by the ultimate load carrying capacity of the floor beams.

In order to evaluate the crush load for a shipping container for vertical crush, an ultimate load analysis of the deck beams was performed. The analysis included both the ultimate flexural and shear capacity response and plastic analysis of the beam.

The ultimate load analysis required detailed information from the airframe manufacturers about the sizes of the structural members and their constituent materials. This information was received from the Boeing Company and McDonnell-Douglas Corp. (References A-3 and 4). In summary, the ultimate load analysis and the information received from the Boeing Company and McDonnell-Douglas Corp. showed that in the vertical crush mode a maximum crush load of 70,000 lb force may be produced. This is the maximum load expected in any of the aircraft investigated, namely the Boeing 707, 727, 737, and 747 and the McDonnell-Douglas DC-8, DC-9, and DC-10. The value ranged from 18,000 to 70,000 lb, depending on the type of aircraft. This loading is based upon the ultimate load capacity of a single cargo deck beam.

The floor beams are spaced longitudinally 20 inches center to center, and the width of the lower flange of the floor beam (an I beam section) is 2 to 2.5 inches (nominal). Typically, the depth of the floor beams varies from 7 to 10 inches. As seen in Figure A-4, the top and bottom flanges of the floor beam are constrained by longitudinal stabilizers and seat tracks and by a centerline seat track beam.

The values, quoted above, for the ultimate load capacity of the floor beam did not directly consider either lateral buckling of the beam or web crippling. These points were discussed with representatives from the two airplane companies and it was determined that due to the "grillage" method of construction of the floor, lateral buckling is unlikely to occur, and web crippling could or could not occur depending on the point of application of the load. It is recommended that the proposed test for vertical crush not be based on web crippling since its occurrence cannot be assured.

Longitudinal Crush

The other possibility for a crush environment for a shipping container in an aircraft crash is that of longitudinal crush. This event can occur as the aircraft crashes into the vertical face of objects such as mountains and other terrain features or as the aircraft careens into a structure as it is skidding to a halt in the crash sequence. In any event, however it happens, large decelerations can be applied to the aircraft which will in turn apply large crush loads to containers carried in the forward portion of the cargo volume.

Two methods were used to calculate the magnitude of the longitudinal crush force. The first was a simple approximation using rigid body mechanics, and the second was a lumped-mass model of the longitudinal crush problem.

Longitudinal Crush - Simplified Model -- The simplified model of the longitudinal crush problem was formulated as shown in Figure A-5. This model consists of a series of masses which are representative of the cargo mass. It was assumed that all of the cargo remained in the aircraft. The container mass is shown in the forward part of the aircraft, and as an estimate, it was assumed that the deceleration was 20 g. This value is based on an estimate to the lowest deceleration that the cargo might be subjected to yet high enough to break the cargo tie-downs. Design criteria in the Federal Aviation Regulations (Reference A-6) specify 9 g as the design load for cargo tie-downs.

Preliminary information from an airframe manufacturer indicated that aircraft cargo decks are loaded, on the average, to 100 psf. Using an estimated length of 135 feet for the cargo deck of a Boeing 747 results in a load of 13,500 lb per foot width of cargo deck. (The total capacity of a 747 is 254,640 lb.) Therefore, considering the cargo as a rigid body and using 20 g deceleration, a crushing force of 270,000 lb per foot width would result. Assuming these conditions, this load is a lower bound for the severe accident considered here.

This simplified approach indicates that if the shipping container is placed in the forward part of the cargo area, it can be subjected to very large crush loads. If the decelerations are caused by an impact into an abrupt face, massive crush loads can occur, and accelerations far in excess of 20 g could be expected. However, even if impact into an abrupt face does not occur, skidding, etc., in the crash process may generate considerable deceleration and hence significant crush loading of the forward cargo. This may be a transient situation since the forward bulkheads in the aircraft would probably fail and the cargo would be dispersed from the aircraft structure.

Longitudinal Crush - Lumped Mass Model -- The preceding calculation was admittedly a very simple approach to a complex problem, but it served the purpose of obtaining an approximation to the magnitude of the longitudinal crush forces. From this estimate it seemed evident that the longitudinal crush force could exceed the maximum vertical crush force of 70,000 lb.

A more refined model was developed which described the cargo as a series of lumped masses interconnected by springs representing the cargo stiffness. With this model, a more detailed investigation could be made of the crush environment. The model is shown in Figure A-6, the equations of motion for which are solved by the computer program SHOCK (Reference A-7).

A Boeing 747 Freighter can carry up to 29 cargo containers measuring 10 ft long, 8 ft high, and 8 ft wide on the main cargo deck, and 30 lower-lobe containers each of 173 ft^3 capacity and an additional 800 ft^3 of bulk cargo. Using the total capacity of the 747 and dividing the cargo equally into the available volume results in a load of 6780 lb/cargo container for the main cargo deck. Since these cargo containers are placed side by side, a lumped mass model consisting of 14 masses of 6780 lb each was used as a representation of the cargo (total load of 94,920 lb).

The container carrying the hazardous material was assigned a weight of 100 lb, and the stiffness of the container was assigned a value of 5.3×10^6 lb/in. (Reference A-8). An initial velocity of 422 ft/s (288 mph impact)* of masses 2 through 16 was used in the analysis.

The stiffness of the cargo is not known with any degree of confidence, and the calculations were performed by varying the cargo stiffness as a parameter, using values of 1×10^3, 1×10^5, and 1×10^6 lb/in. Also, since the nonlinear stiffness (crush) characteristics of the cargo are not known, linear springs were used in the analysis. This somewhat restricts the validity of the range of the results, but nevertheless indicates the magnitude of the expected crushing forces.

Figures A-7 and A-8 are plots of the calculated crushing load on the container vs time with the container in the forward-most position (Figure A-6a). In Figure A-7 a cargo stiffness of 1×10^6 lb/in. resulted in a maximum crushing force of 22 million pounds, while in Figure A-8 a stiffness of 1×10^5 lb/in. resulted in a force of 7.4 million pounds. As can be seen, both are essentially static loads. A further reduction of the cargo stiffness to 1000 lb/in. resulted in a crushing force of 0.3 million pound.

The container was also placed toward the rear of the aircraft in two different positions. In one case, it was assumed that there was one cargo container behind the shipping container (Figure A-6b) while in the other case, the cargo was in the rear (Figure A-6c). For these calculations only, a cargo spring stiffness of 1×10^6 lb/in. was used. Figure A-9 is the result for the former case (i.e., Figure A-6b), while Figure A-10 is the result for the latter case (i.e., Figure A-6c). In both cases the force has decreased from the situation where the shipping container is forward. In addition, the character of the response has changed and is now dynamic in nature.

In reality, the variation of crushing force with position in the cargo compartment is even more pronounced than the data in Figures A-7 through A-10 indicate. Since it is not possible to estimate accurately the effective spring constants for the transport (cargo) containers in general, an attempt was made to explore the situation parametrically by changing the linear spring constants. A further complication is that the linearity assumption implies no crushing of the containers; i.e., no "snow plow" effect, and this would alter the calculated loads. The few calculations which have been made of this type, in which the exact shape of the nonlinear deformation curve has been determined experimentally, tend to verify the conclusion that the loads decrease in a somewhat linear fashion with container distance from the front of the aircraft. In either case, the conclusions are the same: Under this type of extreme accident and large aircraft cargo compartment, the crush loads can become extremely large, but will decrease as the container is positioned further to the aft end of the aircraft.

---

*This value was used at the suggestion of the U.S. Nuclear Regulatory Commission.

Observations and Concluding Remarks

Vertical Crush

For the vertical crush mode a load of 70,000 lb was determined to be the maximum load. One appropriate test for this situation could be the application of a 70,000 lb load onto the package, which is resting on a 2-inch-wide by 7-inch-deep solid beam (either steel or aluminum), or a similar test. The choice of the 7-inch depth is based on the fact that the higher loads occur for the smaller aircraft which have the smaller depth beams. Obviously, this test and the magnitude of the load only approximate what the real situation could be. However, there is justification for the choices made, and the test is a reasonable one which can be performed relatively easily.

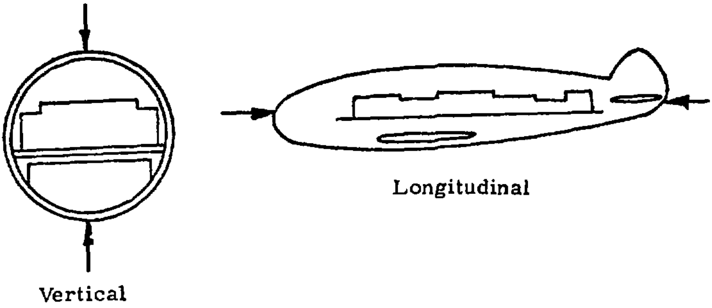
While the initial force applied to a container during vertical crush may be a localized loading, as indicated above, an alternative would be for the crushing process to spread the loading on the package due to the integrated construction of the floor beams, longitudinal track beams, floorbeam stabilizers, and floor panels as shown in Figure A-4. Figure A-11 represents a severe crush environment which is indicative of the possible localized loading which occurs initially. An alternative crush test would be to uniformly load the package with 70,000 lb between the testing machine platens which is indicative of the concept of crush load spreading.

It should also be noted that if the package is located on the main cargo deck rather than the lower cargo deck, if one is present, that the package could not be subjected to this vertical crushing force.

Longitudinal Crush

From the results of the analysis, it can be seen that very large container crush loads could result if the container were in the forward section of the aircraft. It is, therefore, recommended that the container be placed as far aft as is practicable.

When the container is in the rear of the aircraft, it is still subjected to high loadings due to a crash of the plane; however, these loads are now dynamic in nature (see Figures A-9 and A-10). In fact, for the case given in Figure A-10 it is an impact problem. It should be noted that the response in Figure A-9 (container slightly forward) is quite similar to the impact situation (Figure A-10). For these cases, the impact test specified for the container will simulate these conditions; that is, no crush test will have to be performed. While probability estimates cannot be made, it is obvious that static loads of this magnitude are probably close to the maximum that could ever be expected. This calculation has considered only the aircraft with the largest cargo capacity.



Vertical

Longitudinal

Figure A-1. Aircraft Crush Environment

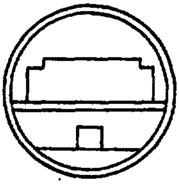


Figure A-2. Vertical Crush

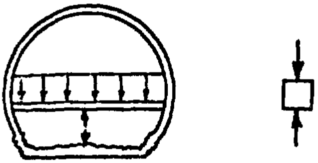


Figure A-3. Failure Mode

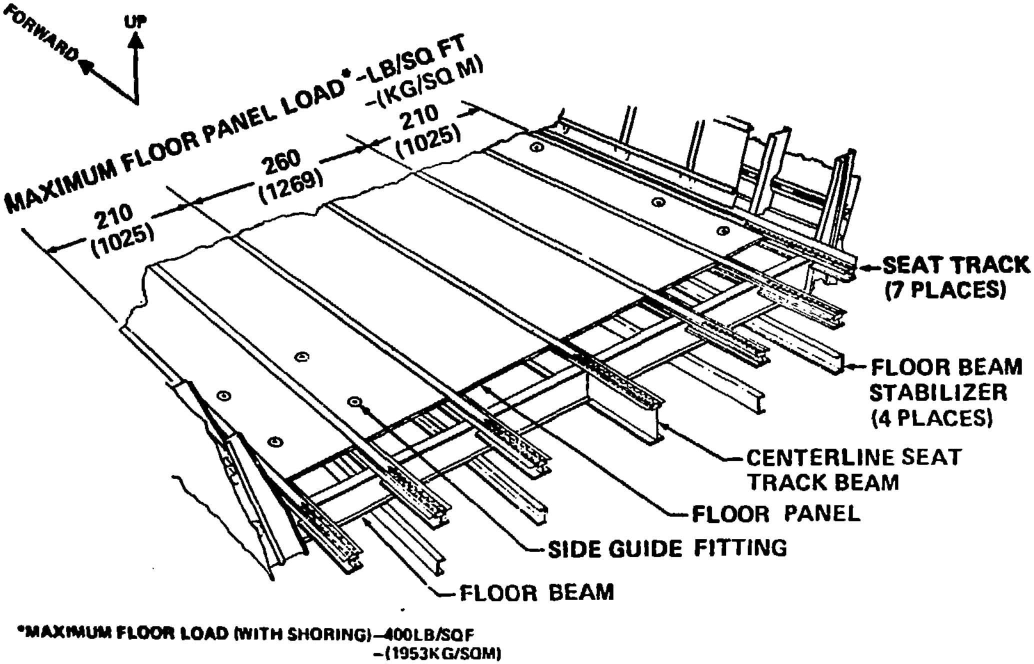


Figure A-4. Floor Structure, Boeing 707-320C (Reference A-5)

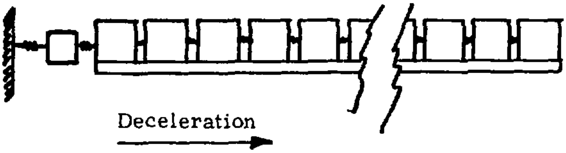


Figure A-5. Longitudinal Crush

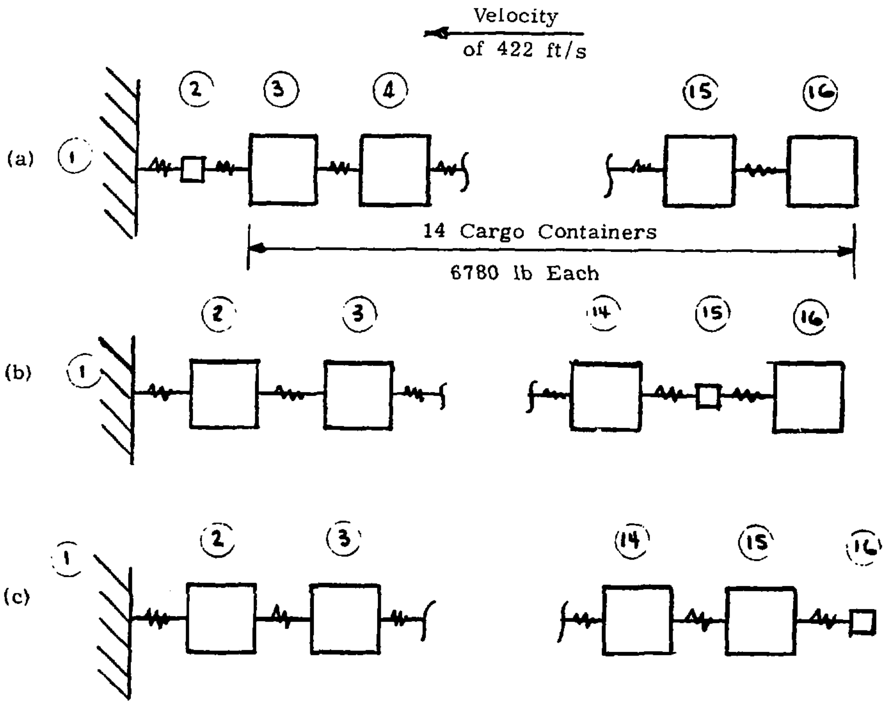


Figure A-6. SHOCK Model

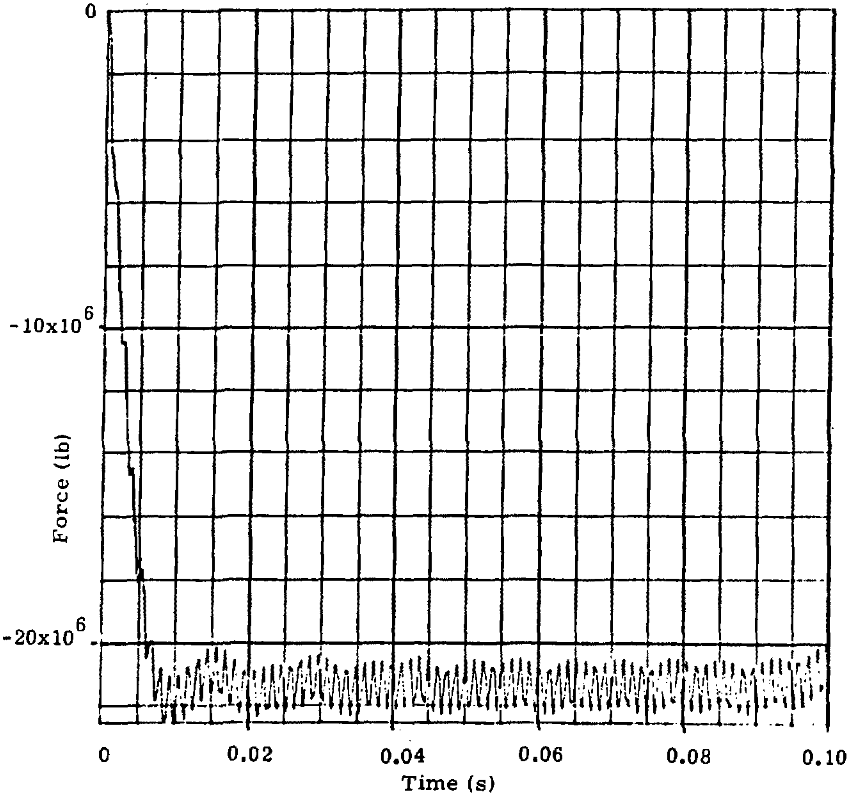


Figure A-7. Container in Forward-Most Position
K (Container) = 5.3×10^6 lb/in.
K (Cargo) = 1.0×10^6 lb/in.

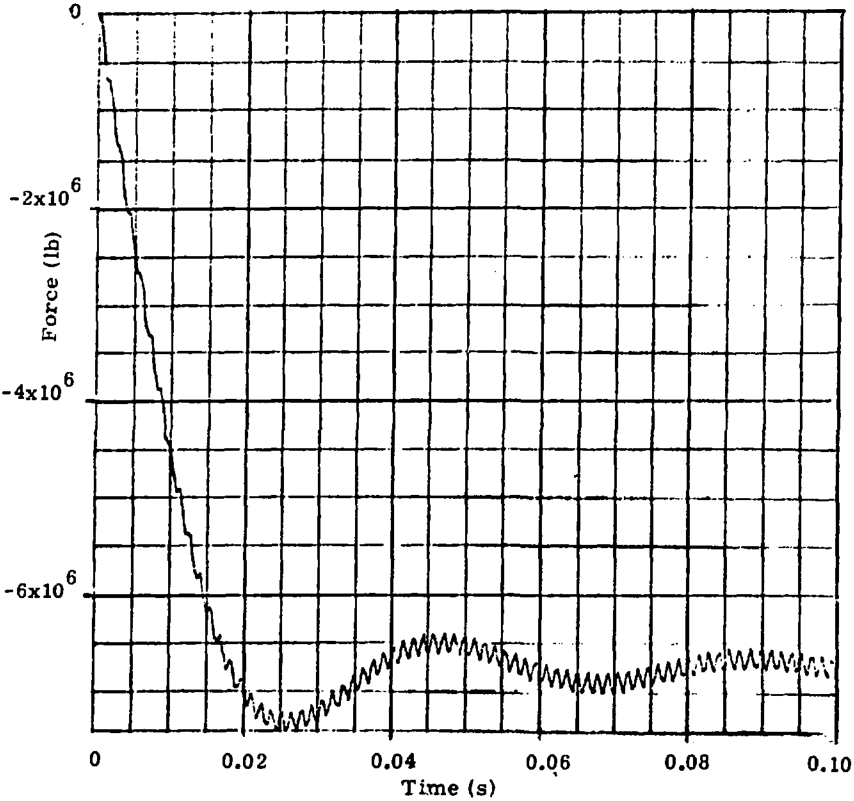


Figure A-8. Container in Forward-Most Position
K (Container) = 5.3 x 10^6 lb/in.
K (Cargo) = 1.0 x 10^5 lb/in.

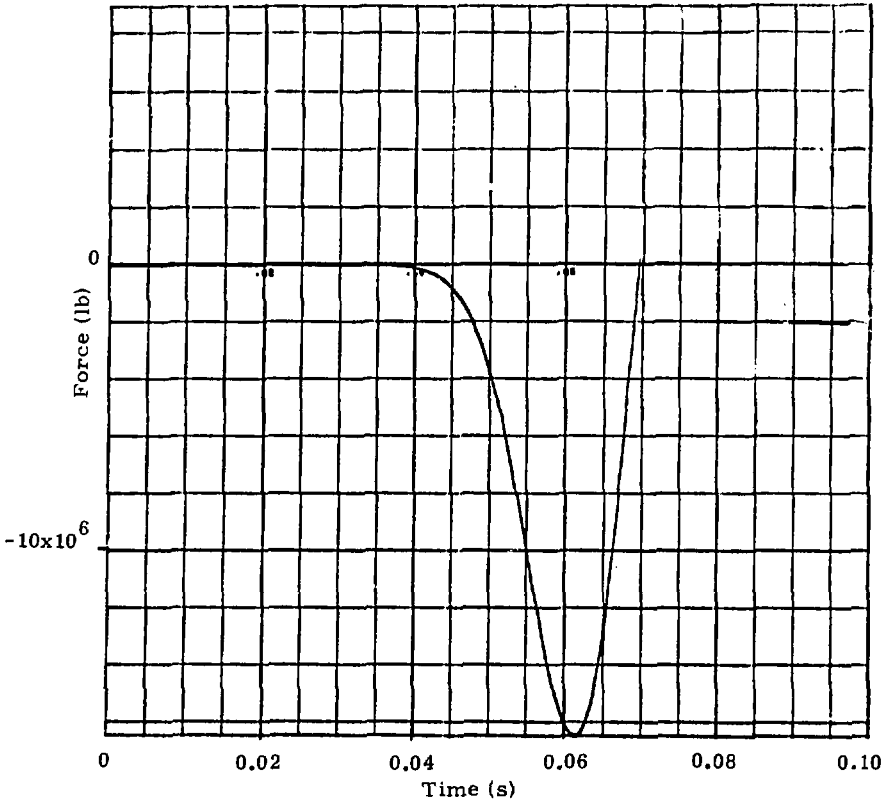


Figure A-9. Container at Mass Point 15
(one cargo mass aft of container)

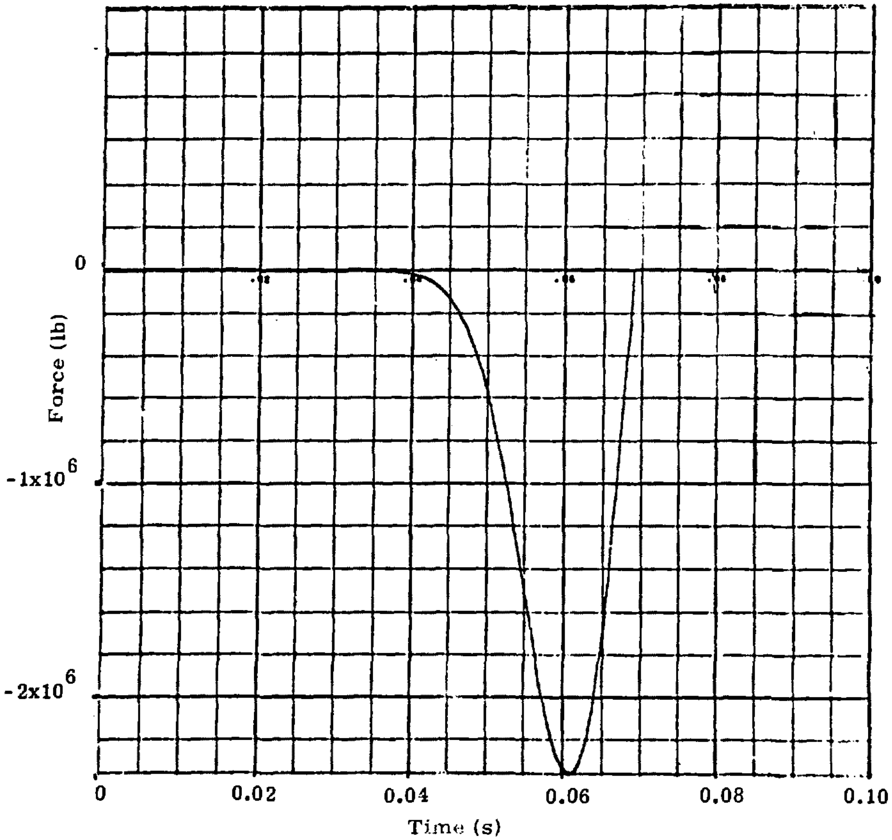


Figure A-10. Container at Aft Position

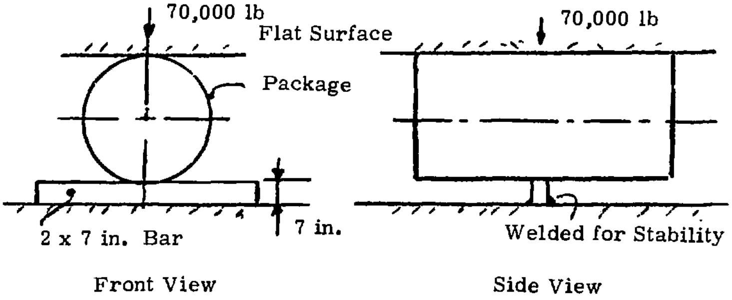


Figure A-11. Crush Test Proposal

References

A-1. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, "Severities of Transportation Accidents," SLA-74-0001, Sandia Laboratories, July 1976.

A-2. "Directory of Packagings for Transportation of Radioactive Materials," WASH-1279, USAEC, October 1973.

A-3. R. A. Davis, Boeing Commercial Airplane Company, letter (B8650-377) to W. A. Von Riesemann, Sandia Laboratories, dtd Jan 26, 1976.

A-4. M. Stone, Douglas Aircraft Company, letter (C1-25-595) to W. A. Von Riesemann, Sandia Laboratories, dtd Jan 26, 1976.

A-5. "Boeing 707-320C, General Description", Report D6-42002R4, Boeing Commercial Airplane Company, Seattle, January 1975.

A-6. Federal Aviation Regulation Part 25, Airworthiness Standards: Transport Category Airplanes.

A-7. V. K. Gabrielson and R. T. Reese, "SHOCK Code User's Manual - A Computer Code to Solve the Dynamic Response of Lumped Mass Systems," SCL-DR-69-98, Sandia Laboratories, Livermore, CA, November 1969.

A-8. J. T. Schamaun, Sandia Laboratories, private communication.

APPENDIX B

Engine Fragment Threat to Small Containers Carried on U.S. Commercial Jet Aircraft

CONTENTS

APPENDIX B

Engine Fragment Threat to Small Containers Carried on U.S. Commercial Jet Aircraft

W. A. Von Riesemann
Design Technology Division, 5431

and

W. F. Hartman
Applied Mechanics Division II, 1282

Introduction

This report is based on an analysis performed to predict the frequency of the threat to radioactive material containers resulting from fragments due to mechanical failure of high rotational velocity aircraft turbine engines. These are very infrequently occurring events. Impact and fire are far more probable events when severities such as those discussed in 10CFR71 are considered. Increases of impact severities to several hundred feet per second and fire durations to about one hour decreases the probabilities of container damage to such magnitudes that the probability of the loss of containment from rotor burst fragments needs to be considered. As will be seen here, penetration of the container by turbine rotor fragments is also on exceedingly infrequent occurrence.

Purpose of Study

Our purpose is to examine and analyze the possible potential threat to a small container, carrying radioactive materials, by engine fragments from a gas turbine engine which has failed. The aircraft examined were the Boeing 707, 727, 737, and 747, the McDonnell-Douglas DC-8, DC-9, and DC-10, and the Lockheed L-1011.

The report examines the past history of turbine failure occurrences and the current activities of industry, governmental agencies, and universities with regard to such failures. A digest of the statistics, to date, is presented. Based on these values and on aircraft geometries, the upper limit probability that a container will be in the path of an engine fragment is approximated.

Background

Turbine Engine Fragments

A failure of a rotating part of a gas turbine engine[*] which is not contained within the engine casing may cause potential difficulties if the part impacts and damages vital areas of the aircraft. An intensive study of the situation is being conducted by governmental agencies, universities, and industry.[†] "Although no major accidents have been attributed to rotor failures ..." (Reference B-1), there is a continuing effort in attempting to characterize the fragment (i.e., type, weight, dimensions, velocity, energy, etc.), its frequency of occurrence, and methods by which the incidence of failure can be reduced and ways to either contain the failed part or deflect it to a sector where it will do no additional damage.

Studies (References B-1 and B-2) of U. S. commercial aviation rotor failures have been made by the Federal Aviation Administration (FAA), the National Transportation Safety Board (NTSB), and the Naval Air Propulsion Test Center (NAPTC). For example, in 1974 (Reference B-3) there were 149 rotor failures in which fragments were generated and, of these, 17 were uncontained: "This represents an uncontained rotor burst rate[‡] of

2.8 per million gas turbine powered aircraft flight hours, or

0.9 per million engine operation hours.

Approximately 6 million and 18.5 million aircraft flight and engine operating hours, respectively, were logged by the U.S. commercial aviation fleet in 1974." Figures for previous years are similar. FAA statistics (Reference B-1) show that for a 12 year period beginning in 1962 through were 266 uncontained rotor and blade failures. The figure varied from a low of 11 a year to a high of 37.

---

[*] By definition gas turbine engines include turbofans, turbojets, turboprops and turbo shafts, and are frequently referred to as jet engines.

[†] The list of references is indicative of this activity.

[‡] An uncontained rotor burst is defined as a rotor failure that produces fragments which penetrate and escape the confines of the engine casing.

Although these values are low, there is an effort underway to reduce the incidence rate. For several years there has been a combined program to establish statistics, perform experiments, and develop analytical methods at NASA Lewis Research Center, Cleveland, Ohio; the Naval Air Propulsion Test Center, Trenton, New Jersey; and Massachusetts Institute of Technology, Cambridge, Massachusetts (References B-2 to B-27). In addition, the engine manufacturers and airframe manufacturers are expending considerable effort and resources on the problem (see, e.g., References B-28 to B-31).

In Reference B-31, which is a study by Rolls-Royce (Rolls engines are used, for example, on the Lockheed L-1011), the statement is made that the " ... probability of this once-per-million-hour event (rotor failure) causing an aircraft accident, defined as penetration of fuselage or damage to wings or vital services, has proved to be about 1 chance in 8.5. [This value appears to be based on an angular probability calculation.] In other words, aircraft accidents due to noncontained engine failure have occurred, on the average, less than once per 8.5 million engine hours. The statistics ... show that 97.2% of all aircraft accidents and 99.9% of all fatalities have been the result of events other than noncontained engine failure."

Nevertheless, there is a vigorous program to reduce this incidence rate; however, "... ultimately a balance must be struck between weight increase and the effect upon an already low probability of hazard" (Reference B-31).

In the next sections the size of the fragments, their energy and path are discussed. No detailed study will be given here, rather only a brief review of available information will be presented. For additional details the referenced literature should be consulted.

Fragment Size and Weight

Little definitive information is available as to the size and weight distribution of fragments. A Boeing study (Reference B-28) concluded that, in about 90% of the cases studied, the fragments were less than 25 inches in size, and in 52% of the cases the maximum dimension was less than 10 inches. The Rolls-Royce study (Reference B-31) shows that, except for the turbine disk, the maximum weight is 50% of the weight of the disk. For the turbine section, the maximum weight was 100% of the disk, but these failures did not result in an aircraft accident.

Fragment Energy

Upon leaving the engine casing, the fragment has both rotational and translational energy. This energy depends on the size of the fragment and the distribution of the two energies depends on, among other things, the included angle of the failed sector (Reference B-31). Kinetic energies on the order of 0.6 to 5.5 million inch pounds are available in 1/3 of a rotor disk, before penetration of the engine casing (Reference B-32).

Path of Fragments

The heavier and higher energy particles are confined to a volume within several degrees fore and aft of the path of the particle before it fails. The FAA (Reference B-1) recommends that the probable impact area be that area within 15 degrees fore and aft of the plane of rotation of the various rotor assemblies. This appears to be conservative since Reference B-31 shows that the heavier fragments are confined to a ± 5 degree region.

Number of Fragments

A study (Reference B-28) has shown that as high as 10 major fragments are produced in a particular failure, but in about 80% of the cases there will be 4 or less. The mean of all the bursts is 3 major fragments.

Analysis

Method

Since the character of the fragment is random in nature, it is very difficult (if not impossible) to analyze the failure modes and provide protection to the aircraft (Reference B-1) or to its contents. (Even controlled tests are difficult to perform. One problem, for example, is the fact that the fragment has both rotational and translational energy.) Because of this, an analysis will be performed to determine the probability of a container aboard a plane being in the path of a fragment.

Probability Analysis

The probability of a container being struck while carried aboard a commercial jet aircraft is equal to the probability of an unconfined engine failure times the probability that the container is in the path of a fragment. This latter value is a geometrical factor and depends on the size of the container and fragment, and the particular aircraft being considered. It is important to note that the analysis does <u>not</u> consider the resistance to penetration of <u>any</u> intervening structure or cargo. Also, assuming the fragment strikes the container, the calculation assumes that the penetration probability is unity. This assumption implies that any fragment which intercepts the critical area is of consequence while in reality the penetration capability is highly dependent upon impact angle and fragment energy. If all of these factors (intervening structure, cargo impact geometry, and residual energy threshold) could be quantitatively included they would significantly reduce the calculated threat.

There are several ways in which the probabilities may be calculated, since values for failure may be based on engine operating hours, on aircraft operating hours, or on departures of aircraft. The choice was made to perform the analysis on the basis of engine operating hours since it would then be possible to include the effect of the location of the engines and could also be a useful indication of the potential threat. To cast the results in terms of the probability per shipment, a flight duration of 5 hours was conservatively chosen; the average flight duration for commercial air carriers is between 1 and 2 hours.

The equation used in the analysis is as follows:

$$P_G \times P_{FR} = P_c$$

where

P_G = geometric probability

P_{FR} = failure rate probability/flight

P_c = probability container is in path of fragment/flight.

A typical size container--2R, the one in the 6M package--was used in the calculations; it has a length of 12 inches and a diameter of 4.5 inches.

The longitudinal probability is calculated on the assumption that the container is in the probable impact area (Reference B-1), times the ratio of the probable impact area to the length of the cargo compartment. The probable impact region is that area covered by a 15 degree projection, fore and aft, of the engine. Thus its length is equal to

$$L_e + 2D_e \tan 15° ,$$

where

L_e = length of engine.

D_e = distance from centerline of the engine to the centerline of the fuselage.

The probability of the container being in the path of a fragment is

$$P_c = \left[\frac{L_c + 2(2)}{L_e + 2D_e \tan 15°}\right]\left[\frac{L_e + (2)(D_e \tan 15°)}{L_{cab}}\right] ,$$

where L_c = length of container, 12 inches. An assumed width of 2 inches was used for the fragment and L_{cab} is the length of the cabin. Note that as long as $L_e + (2)(D_e \tan 15°)$ is less than L_{cab}, the former quantity does not enter into the final calculation for the longitudinal probability.

The number of fragments used in the analysis was 3, and the number of engines used are given in Table B-I.

TABLE B-I

Calculated Probabilities

Aircraft	Distance(1) ℄ Fuselage to ℄ Engine (in.)	Geometric Probability				Probable(2) Failure Rate, Failures/Engine Flight	= Expected Intercept Rate/Flight/Set of Engines x 10^{-6}	Expected Intercept Rate/Flight/Aircraft x 10^{-6}	Expected Flights per Event x 10^{6}
		Angular x	Longitudinal x	3 Fragments x No. of Engines	= x				
Boeing 707	391	.0100	.0120	6	.00072	5.9 x 10^{-6}	.0042	.0069	144
	610	.0064	.0120	6	.00046	5.9 x 10^{-6}	.0027		
727	122	.0320	.0183	6	.0035	5.9 x 10^{-6}	.0207	.0207	48
737	191	.0204	.0214	6	.00262	5.9 x 10^{-6}	.0154	.0154	65
747	470	.0083	.0072	6	.00036	5.9 x 10^{-6}	.0021	.0033	303
	825	.0047	.0072	6	.00020	5.9 x 10^{-6}	.0012		
McDonnell-Douglas									
DC-8	310	.0126	.0131	6	.00099	5.9 x 10^{-6}	.0058	.0092	109
	535	.0073	.0131	6	.00057	5.9 x 10^{-6}	.0034		
DC-9	110	.0354	.0239	6	.00507	5.9 x 10^{-6}	.0300	.0300	33
DC-10	330	.018	.0098	6	.00069	5.9 x 10^{-6}	.0041	.0041	244
Lockheed L-1011	415	.0084	.0099	6	.00056	5.9 x 10^{-6}	.0033	.0033	303

(1) Only engines overlapping the pressurized fuselage are considered.

(2) See text.

The aircraft dimensions used in the calculations for the various aircraft are given in Table B-II. The information is based on data in "Jane's All the World's Aircraft" and from telephone conversations with D. S. Warren, Douglas Aircraft Co., Long Beach, California, and Robert A. Davis, Boeing Commercial Airplane Co., Seattle, Washington. It should be realized that due to the variety of combinations of aircraft types and engines, the information given here is considered to be typical. Certainly there are variations in the dimensions; however, their effect on the results is negligible.

Geometric Probability

The geometric probability consists of four terms:

- the angular probability
- the longitudinal probability
- the number of fragments
- the number of engines

TABLE B-II

Commercial Airplane Data

Aircraft	Distance From ℄ Fuselage to ℄ of Engine (in.)			Length(1) of Cabin (in.)	Length of Engine (in.)	Comments
	Inboard	Outboard	Aft			
Boeing						
707	390	610	--	1338	136	707-320C
727	--	--	122(2)	872	119	727-100C
737	191	--	--	746	119	737-100
747	470	825	--	2220	154	
McDonnell-Douglas						
DC-8(3)	310	535	--	1225	119	Series 50
DC-9	--	--	110	669		Series 10
DC-10	330	--	Beyond Pressure Bulkhead	1632	193	Series 10, 20, and 30
Lockheed						
L-1011	415	--	Beyond Pressure Bulkhead	1621	119	L-1011-1

(1) Excluding flight deck.

(2) Two engines overlap pressurized fuselage, third engine is beyond pressure bulkhead.

(3) Production of this aircraft ended during 1972.

The angular probability is calculated on the assumption that the fragments are distributed randomly over 360 degrees. (In reality, deflectors are used on some aircraft to throw the fragments away from the plane.)

In addition, a maximum fragment size of 10 inches was used. Hence the probability of a fragment being thrown in the proper direction radial to the engine center line is equal to

$$\frac{D_c + 2\,(10)}{2\pi D_e} .$$

Failure Rate

The average yearly value of unconfined failures for a 13 year period (References B-1 and B-3) is 21.8. Assuming, as mentioned previously, a flight time of 5 hours and using 18.5×10^6 engine operating hours per year[*] (Reference B-3), the failure rate is

$$\frac{21.8 \text{ failures}}{18.5 \times 10^6 \text{ engine hours}} \times \frac{5 \text{ hours}}{\text{flight}} = 5.9 \times 10^{-6}\, \frac{\text{failures/engine}}{\text{flight}} .$$

Calculated Values

Using nine different jet aircraft, the calculated values are tabulated in Table B-I. The rate at which a container is in the path of a fragment varies, according to aircraft type, from a high value of 33 million container flights to a low value of over 300 million container flights. The flight hours can be obtained by multiplying these figures by 5.

Limitations of Analysis

As discussed previously, the analysis used a single container with a length of 12 inches and a diameter of 4.5 inches and assumed that the container was randomly positioned along the length of the cargo compartment. In addition, a maximum fragment size of 10 inches, 3 fragments per failure, and a flight time of 5 hours were assumed. Two major conservatisms--there is no intervening material in the path of the fragment, and a fragment entering the spatial area occupied by the 2R container is tantamount to loss of protection--suggest that the predicted probabilities are considerably higher than in actuality.

---

[*] This value is for 1974 and varies slightly from year to year.

Summary

The analysis in this appendix determines the probability of a small container (4.5 inches in diameter and 12 inches long) being in the path of a fragment from a failure in a gas turbine engine. The calculated values show that, depending on aircraft type, the incidence rate varies by about one order of magnitude from a low of once per 33 million flights to a high of once every 300 million container flights for a flight of 5 hours duration.

The analysis does not include the resistance of any cargo or structure between the engine and container, nor does it include the fragment energy or angularity restrictions that must be satisfied to penetrate the container. Hence the above values are conservative.

References

B-1. "Design Considerations for Minimizing Damage Caused by Uncontained Aircraft Turbine Engine Rotor Failures," Dept. of Transportation, FAA, Order 8110.11, Nov 19, 1975.

B-2. G. J. Mangano and R. A. DeLucia, "Rotor Burst Protection Program: Statistics on Aircraft Gas Turbine Engine Rotor Failures That Occurred in U.S. Commercial Aviation During 1973," ASME Reprint 75-GT-12, 1975.

B-3. R. A. DeLucia and G. J. Mangano, "Rotor Burst Protection Program: Statistics on Aircraft Gas Turbine Engine Rotor Failures That Occurred in U.S. Commercial Aviation During 1974," NASA CR-134855 (NAPTC-PE-67), Naval Air Propulsion Test Center, Trenton, NJ, Sept 1975.

B-4. "Special Study - Turbine Engine Rotor Disk Failures," NTSB-AAS-74-4, National Transportation Safety Board, Washington, DC, Dec 18, 1974.

B-5. R. A. DeLucia and G. J. Mangano, "Rotor Burst Protection Program: Statistics on Aircraft Gas Turbine Engine Rotor Failures That Occurred in U.S. Commercial Aviation During 1973," NASA CR-134854 (NAPTC-PE-61), Naval Air Propulsion Test Center, Trenton, NJ, Aug 1975.

B-6. R. W-H. Wu and E. A. Witmer, "Finite-Element Analysis of Large Transient Elastic-Plastic Deformations of Simple Structures, With Application to the Engine Rotor Fragment Containment/Deflection Problems," NASA CR-120886 (ASRL TR 154-4), Aerospace Safety Research and Data Institute, NASA Lewis Research Center, Jan 1972.

B-7. T. P. Collins and E. A. Witmer, "Application of the Collision-Imparted Velocity Method for Analyzing the Responses of Containment and Deflector Structures to Engine Rotor Fragment Impact," NASA CR-134494 (ASRL TR 154-8), Aerospace Safety Research and Data Institute, NASA Lewis Research Center, Aug 1973.

B-8 P. T. Chiarito, "Status of Engine Rotor Burst Protection Program for Aircraft," NASA SP-270, NASA Aircraft Safety and Operating Problems Conference, Langley Research Center, May 4-6, 1971, Vol. 1, pp. 75-88. (See also Reference B-22.)

B-9. A. A. Martino and G. J. Mangano, "Turbine Disk Burst Protection Study, Phase I--Final Report on Problem Assignment NASA DPR R-105," NAEC-AEL-1973 (NASA CR-80962), U.S. Navy, Mar 1965.

B-10. A. A. Martino and G. J. Mangano, "Turbine Disk Burst Protection Study, Phases II and III--Final Report on Problem Assignment NASA DPR R-105," NAEC-AEL-1848 (NASA CR-84967), U.S. Navy, Feb 1967.

B-11. A. A. Martino and G. J. Mangano, "Rotor Burst Protection Program Initial Test Results, Phase IV--Final Report, NASA DPR R-105," NAPTC-AED-1869 (NASA CR-95967), U.S. Navy, Apr 1968.

B-12. A. A. Martino and G. J. Mangano, "Rotor Burst Protection Program, Phase V--Final Report, Problem Assignment NASA DPR R-105," NAPTC-AEC-1901 (NASA CR-106801), U.S. Navy, May 1969.

B-13. R. P. Yeghiayan, E. A. Witmer, and J. W. Leech, "Theoretical and Experimental Studies of the Ineraction Forces and Responses of Structural Rings Subjected to Engine Rotor Fragment Impact," ASRL TR 154-5, Aeroelastic and Structures Research Laboratory, Massachusetts Institute of Technology, in preparation.

B-14. R. B. McCallum, J. W. Leech, and E. A. Witmer, "On the Interaction Forces and Responses of Structural Rings Subjected to Fragment Impact," ASRL TR 154-2 (NASA CR-72801), Aeroelastic and Structures Research Laboratory, MIT, Sept 1970.

B-15. W. A. Loden and E. A. Witmer, "A Limited Parametric Study of Large Elastic-Plastic Dynamic Response of Single-Layer Circular Rings to Sequential External Forces," Tech. Memo 1604, Picatinny Arsenal (or ASRL TR 122-3, Aeroelastic and Structures Research Laboratory, MIT), Feb 1965.

B-16. R. B. McCallum, J. W. Leech, and E. A. Witmer, "Progress in the Analysis of Jet Engine Burst-Rotor Containment Devices," ASRL TR 154-1 (NASA CR-107900), Aeroelastic and Structures Research Laboratory, MIT, Aug 1969.

B-17. "Rotor Burst Protection Program," Progress Reports, study for NASA Lewis Research Center on NASA DPR R-105 and NASA Interagency Agreement C-41581-B, Naval Air Propulsion Test Center, Philadelphia, PA, Sept 1969 to Apr 1973.

B-18. R. M. Zirin and E. A. Witmer, "Examination of the Collision Force Method for Analyzing the Responses of Simple Containment/Deflection Structures to Impact by One Engine Rotor Blade Fragment," ASRL TR 154-6 (NASA CR-120952), Aeroelastic and Structures Research Laboratory, MIT, May 1972.

B-19. R. A. DeLucia and G. J. Mangano, "Rotor Burst Protection Program: Statistics on Aircraft Gas Turbine Engine Failures That Occurred in Commercial Aviation During 1971," NAPTC-PE-12 (NASA CR-121151), U.S. Navy, Feb 1973.

B-20. G. J. Mangano, "Rotor Burst Protection Program, Phases VI and VII--Exploratory Experimentation to Provide Data for the Design of Rotor Burst Fragment Containment Rings," NAPTC-AEC-1968 (NASA CR-120962), U.S. Navy, Mar 1972.

B-21. A. A. Martino, "Rotor Burst Protection Program, Phase VI--Progress Report No. 7 on Problem Assignment NASA DPR R-105," Mar 19, 1969.

B-22. P. T. Chiarito, "Status of Engine Rotor Burst Protection Program for Aircraft," J. Aircraft, 9, 7 (July 1972), pp. 449-450.

B-23. R. W-H. Wu and E. A. Witmer, "Approximate Analysis of Containment/Deflection Ring Reponse to Engine Rotor Fragment Impact," J. Aircraft, 10, 1 (January 1973).

B-24. T. R. Stagliano, R. L. Spilker, and E. A. Witmer, "User's Guide to Computer Program CIVM-JET 4B to Calculate the Transient Structural Response of Partial and/or Complete Structural Rings to Engine-Rotor-Fragment Impact," ASRL TR 154-9 (NASA CR-134907), Aeroelastic and Structures Research Laboratory, MIT, in preparation.

B-25. R. W-H. Wu, E. A. Witmer, T. R. Stagliano, and R. L. Spilker, "User's Guide to Computer Programs JET 5A and CIVM-JET 5B to Calculate the Large Elastic-Plastic Dynamically Induced Deformations of Multilayer Partial and/or Complete Structural Rings," ASRL TR 154-10 (also as NASA Contract Report), Aeroelastic and Structures Research Laboratory, MIT, in preparation.

References (cont)

B-26. J. E. Leech, E. A. Witmer, and R. P. Yeghiayan, "Dimensional Analysis Consideration in the Engine Rotor Fragment Containment/Deflection Problem," ASRL TR 154-3 (NASA CR-120841), Aeroelastic and Structures Research Laboratory, MIT, Dec 1971.

B-27. R. W-H. Wu and E. A. Witmer, "Computer Program JET 3 to Calculate the Large Elastic-Plastic Dynamically Induced Deformations of Free and Restrained, Partial and/or Complete Structural Rings," ASRL TR 154-7 (NASA CR-120993), Aeroelastic and Structures Research Laboratory, MIT, Aug 1972.

B-28. R. B. Clarke, "Rotor Disk Burst Characteristics Data Analysis," S&A 73-1 (internal report), Boeing Commercial Airplane Co., Feb 28, 1973.

B-29. M. N. Aarnes and J. L. White, "Propulsion System and Airframe Structural Integration Program," J. Aircraft, 12, 4 (April 1975), pp. 234-242.

B-30. J. H. Gerstle, "Analysis of Rotor Fragment Impact on Ballistic Fabric Engine Burst Containment Shields," J. Aircraft, 12, 4 (April 1975), pp. 388-393.

B-31. D. McCarthy, Rolls-Royce, Ltd., "Definition of Engine Debris and Some Proposals for Reducing Potential Damage to Aircraft Structure," paper presented at the AGARD Specialty Meeting on the Impact Tolerance of Structures, Ankara, Turkey, Sept 1975.

B-32. F. G. Campbell, Pratt and Whitney Aircraft, East Hartford, CT, letter to W. A. Von Riesemann, Sandia Laboratories, dtd Mar 22, 1976.

APPENDIX C

Probabilistic Estimate of Frequency of Extremely Severe Aircraft Impact Accidents

APPENDIX C

Probabilistic Estimate of Frequency of Extremely Severe Aircraft Impact Accidents

W. F. Hartman
Applied Mechanics Division II, 1282

The data reported on aircraft impact accidents in SLA-74-0001 (Reference C-1) shows that nearly one-half of these impact accidents are more severe than the present 30 ft drop (44 ft/s) qualification test. Even though aircraft accidents are relatively infrequent events, this finding suggests that more stringent specifications for air-carried packages should be considered. To provide the technical information required to establish new qualification test levels, it is necessary to define the frequency of impact accidents at the high severity end of the distribution curve, i.e., at velocities well in excess of 44 ft/s.

The data analysis procedure used to derive the impact curves in Reference C-1 was not intended to define accurately the velocity distribution near either the high or low velocity extremes. In addition, two other aspects of the SLA-74-0001 treatment call for additional effort if a more tenable decription is to result. One of these is that, at lower velocities, the response of typical small packages is nearly independent of target properties. However, at velocities above 200 ft/s or so, the target hardness becomes increasingly important. The desired description, therefore, is one that predicts how frequently an accident produces an environment more severe than it might experience in some prescribed impact tests in which the container velocity, impact orientation, and the surface impacted are all specified.

The second problem concerning the applicability of the Reference C-1 data to defining the severe aircraft impact problem relates to the source of the data. The military cargo aircraft accident data statistics used were influenced by several factors which suggest their inappropriateness for analysis of civilian cargo aircraft accidents: low altitude impact at high velocities into mountains (in Vietnam), the lower cruise velocities of military cargo aircraft, and lost-at-sea and refueling accidents.

Based upon these concerns, it was judged that the best approximation of the severe aircraft impact accident distribution would result from a detailed examination of the National Transportation Safety Board (NTSB) accident digests. There are 417 of these digests for the years 1962 to 1972 and they cover all accidents involving substantial aircraft damage or serious personnel injury to U.S. registered fixed-wing civilian aircraft over 12,500 pounds. Each of these digests was individually reviewed and a subjective estimate made of the probability that a package on board the aircraft would have experienced an environment more severe than that which exists in an impact test at some velocity, v, into an essentially unyielding target. No attempt to predict container orientation at impact was made.

Since much of the information which is desirable in making judgments regarding severity may not be available in each of the digests, several guidelines were established:

- For an impact accident to threaten the hardened container, it has to be severe enough that most of the persons on board are fatally injured.
- Accidents which occur during final landing approach or during takeoff before an altitude of 200 feet has been reached have low normal components of velocity with respect to the ground and hence will not create an environment of concern.
- If estimates or implications are not included in the accident digest, it is assumed that the aircraft velocity for impacts into mountains is 80% of the planes cruise velocity and the impact angles are 50 to 70 degrees. These observations result from the Air Force data used in SLA-74-0001.

Using these general guidelines, each of the individual accidents was reviewed and the probability of an environment whose severity exceeds the test environment was established for each accident. The total probability of exceeding an impact at some velocity, v, into the essentially unyielding target employed in impact tests then results from summing these individual contributions and normalizing with respect to the total number of accidents (417).

Table C-I shows a condensed listing of the more serious accidents and the estimated probabilities of exceeding 425 ft/s. All accidents in the NTSB listing which possessed any realistic possibility of threatening a hardened container are included in Table C-I.

While the estimation of the probabilities is to some extent judgmental, there are some [illegible]nical considerations which are of value to making these determinations. Prominent among the[illegible] are calculations of free-fall velocities of packages and cargo sections and the work of Bonzon and Schamau (Reference C-2) on the variation of impact velocities required to achieve equivalent package damage as a function of target rigidity.

Summing up these predicted probabilities leads to an expected value of .62/417 or .0015 that an aircraft accident will experience an environment which is more severe than that resulting from a 425 ft/s impact into an essentially unyielding target. In other words, the stresses felt by the container in an impact test of this velocity onto a hard unyielding target exceeds those observed in 99.85% of the aircraft accidents in this sample.

The accuracy of this prediction is certainly open to question. Based upon judgments of others looking at the same data, variations by as much as a factor of 5 appear plausible; the estimated limits on the 425 ft/s, unyielding target event are therefore, 99.2 to 99.97%.

It is both interest and value to compare the predictions from the civilian data with the somewhat less applicable Air Force data used as the basis for SLA-74-0001. Depending upon how one analyzes these latter data, at most 4% of the military accidents have a normal velocity into a general target in excess of 425 ft/s. If the assumption is made that accidents of the severity under consideration here will only occur during the inflight phase of the flight profile, data presented in SLA-74-0001 indicates that about 5% of these accidents will, assuming independence of accident occurrence and target, impact against something representing the essentially unyielding target. Therefore, Air Force data suggests that the 425 ft/s, unyielding target test will cover at least 99.8% of the accidents. This is consistent with the one based upon the probabilities from the NTSB data.

It is probable that, if anything, even a higher percentage of accidents will be covered than the calculated numbers predicted--there has been no consideration of the mitigating effect of aircraft structure or other cargo and no credit has been taken for the fact that the container will not always impact in the most damaging orientation as is usually specified for impact testing of radioactive material packages.

To be of maximum usefulness, it is helpful to have the complete spectrum of accident severity versus the normal impact velocity rather than the single point (425 ft/s) just calculated. One way this could be done is to go back through the accident digests, repeating the estimation procedure for 250 ft/s, 300 ft/s, and so forth. This method proved far more difficult to use at lower levels than it was at 425 ft/s. The alternative (which was used) was to scale the 425 ft/s point estimate based upon (1) the aircraft data in SLA-74-0001 and listed in Reference C-3, (2) the predicted impact surfaces for inflight accidents, and (3) the package damage equivalence information discussed in Reference C-2.

With these types of arguments, the data shown in Figure C-1 results. For convenience, the same information is presented in tabular form in Table C-II. While the results are self-consistent, it must be recognized that the data is approximate; the estimated predicted error is also shown in Figure C-1.

TABLE C-I

Estimated Probabilities of Exceeding 425 ft/s Impact Velocity Into an Essentially Unyielding Target for the Most Severe U.S. Civilian Aircraft Accidents From 1962 to 1972

Description of Accident	Probability of Exceeding 425 ft/s Normal Impact Velocity Onto Unyielding Surface	Rational for Probability Estimate
	Accidents Resulting From Meterological Conditions (clear air turbulence (CAT), wind, lightning, fog)	
720B lost wings due to CAT at unknown inflight altitude, impacted level flat terrain near Miami, Florida in uncontrolled impact.	.05	Value probably too high, terminal velocity of 800 ft/s or greater is required.
707 hit by lightning at 5000 ft, left outer wing disintegrated by explosion of fuel-air, near Elkton, Maryland.	.01	Plane under partial control, soft target.
Impact into Mt. Rainer at 10,200 ft, zero visibility, disorientation, 115 knot speed at 60°.	0	Insufficient velocity.
Impact into mountain near Alamosa, Colorado at 13,000 ft altitude, in heavy snow, Super Constellation, impact angle 60°, pilot disoriented.	.05	Cruise speed of Super Constellation is 485 ft/s. (485) (.8) (sin 60°) = 336 ft/s. Disorientation probably decreases velocity even more.
CAT, right wing, right tailplane, and fin failed, British Aircraft, from 5000 ft onto rolling terrain.	0	Insufficient velocity.
L-188 wing failure during attempted recovery from turbulence at 6750 ft, (v = 330 knots), hit rolling land near Dawson, Texas.	.02	Velocity probably too low.
F-27B lost right wing due to CAT at 11,500 ft, impacted hilly terrain near Pedro Bay, Alaska, at 280 knots.	.02	Velocity too low for target.
FH-227 hit 1960 ft mountain near Glen Falls, New York, due to heavy winds.	.02	Velocity should be less than 425 ft/s at this altitude.
	Accidents Resulting From Midair Collisions	
Collision at 2600 ft, near Jones Beach, impacted water.	0	Insufficient velocity with water target.
Collision at 11,000 ft near Carmel, New York, partially controlled landing, 4 of 112 persons killed.	0	Insufficient severity.
C-46 midair collision with general aviation craft over Indiana, impacted rolling terrain at 910 ft, no indication of collision altitude.	.02	General aviation craft in Indiana probably flying no higher than 5000 to 6000 ft, therefore, insufficient velocity for soil target.
DC-9 with general aviation aircraft at 4525 ft, speed 323 knots.	0	Altitude too low to achieve required velocity.
727 collided at 8132 ft with general aviation plane, impacted in forest in North Carolina at 2000 ft altitude.	0	Velocity too low.
DC-9 midair near Indianapolis, at 3575 ft (v = 256 knots at time of collision).	0	Insufficient velocity.
DC-9 collided with fighter during climb to cruise at 15,150 ft near Duarte, California.	.3	Most probable accident to challenge container, too little known to make good estimate. Estimate includes probability of hitting granite, of complete loss of control after collision, and having required velocity.
Convair-580 collided with general aviation plane at 2500 ft in Wisconsin, impacted water.	0	Insufficient velocity for water impact.

(cont)

TABLE C-I (cont)

Description of Accident	Probability of Exceeding 425 ft/s Normal Impact Velocity Onto Unyielding Surface	Rationale for Probability Estimate
	Aircraft Problems (separation in flight, electrical, fire, rotor or engine failure, icing)	
Viscount-745, fire in cargo compartment, cockpit, cabin, uncontrolled forced landing, 90° impact, during descent from inflight but no altitude given, impact at 1400 ft into hilly terrain (Tennessee).	.05	Plane probably under some control, not hard target.
Convair-340 had prop failure at 8000 ft over Ohio, led to airframe failure.	.02	Altitude too low to threaten container for this target.
British 1-11 aircraft suffered inflight fire which damaged control systems during climb to cruise, impact angle into dense trees about 40° at 1900 ft near Blossburg, Pennsylvania.	.01	Probability low that altitude high enough, 40° angle indicates some degree of control.
F-27 iced over, hit mountain at unspecified velocity at 5049 ft altitude near Klamath Falls, Oregon, 1080 ft stopping distance.	.01	Velocity should be less than 425 ft/s at this velocity; also long stopping distance.
727 had electrical failure in Los Angeles fog, impacted at unknown velocity and angle into Pacific in uncontrolled fashion.	.02	Velocity probably too low with water impact.
	Pilot Error or Disorientation	
707 impacted mountain at 2760 ft in British West Indies, due to disorientation, 90° impact, thunderstorm, during descent from inflight.	.01	Velocity too low at this altitude.
DC-9 hit mountain at 3830 ft near Emme, Oregon, descended below clearance to avoid rain squall.	.01	Assumed below 425 ft/s at this altitude.
L-1011, pilot inattention to altimeter while preoccupied with landing gear warning, descended too rapidly, hit level ground at low angle, 50% of people survived.	0	Not nearly severe enough.
	Passenger Action and Unknown	
DC-7 lost at sea off Alaska, for undetermined reason, no evidence.	0	Water impact.
Passenger (suicidal) shot pilot, copilot at 5000 ft, F-27, 1050 ft stopping distance, hilly terrain at 800 ft.	0	Insufficient altitude to achieve required 800 ft/s impact for soil target; long stopping distance implies relatively nonviolent impact.

TABLE C-II

Probability of Exceeding an Impact Velocity v Onto an Essentially Unyielding Surface in an Aircraft Accident

Velocity, v (ft/s)	Probability of Exceeding v
150	.1
200	.038
250	.021
300	.014
350	.008
400	.003
450	.0008

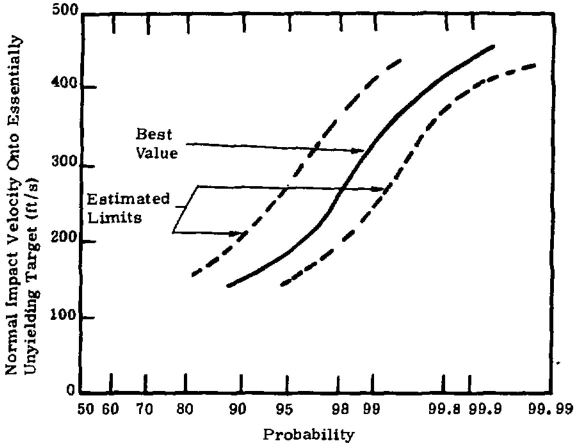


Figure C-1. Probability That an Aircraft Accident Results in an Impact Environment Less Severe Than an Impact Test at Velocity v Onto Unyielding Surface

References

C-1. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, "Severities of Transportation Accidents," SLA-74-0001, Sandia Laboratories, July 1976.

C-2. L. L. Bonzon and J. T. Schamaun, Sandia Laboratories, "Container Damage Correlation With Impact Velocity and Target Hardness," IAEA-SR-10/21, August 1976.

C-3. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, Sandia Laboratories, "Accident Environments Expected in Air Force C-5, C-141, and C-130 Aircraft Accidents," AFWL-TR-75-247, Air Force Weapons Laboratory, Air Force Systems Command, Kirtland AFB, NM, January 1976.

APPENDIX D

Severe Thermal Environments in Aircraft Accidents

APPENDIX D

Severe Thermal Environments in Aircraft Accidents

W. F. Hartman
Applied Mechanics Division II, 1282

The question which this appendix addresses is "how frequently will radioactive material packages carried aboard an aircraft experience an environment which is more severe than some specified fire test?" The answer to this question has an immediate bearing on decisions regarding the levels at which fire tests should be conducted to properly qualify radioactive material packages for aircraft transport.

A probabilistic description of the fire environment expected in aircraft accident is presented in Reference D-1 (SLA-74-0001). That report develops arguments regarding probable fire temperatures and durations; it does not attempt to estimate how frequently a package might be in the fire or how probable it is that the size of the fire is large enough that the thermal environment experienced by the package approximates that of a fire test. As an example of this latter concern, long aircraft fires sometimes result from the slow leak of a fuel tank in the proximity of the package. Even though the duration might be very long, the threat to the package will be considerably less under these conditions than it would be if the package were suspended above a large fuel fire as occurs in the typical fire test. The distribution curves from Reference D-1 are therefore a severe overprediction of the thermal environment if they are used per se to define fire test parameters. As was done for severe aircraft impact accidents, this requires a re-review of accident records in an attempt to predict, for each accident:

- The probability of the duration exceeding some time t.
- The probability that the package will be exposed to the fire.
- The probability that the extent of the fire, if the package is in it, approximates a staged fire test for the duration t or longer.

The NTSB data, which was used for the description of severe impact accidents in Appendix C, does not include sufficient information to make the necessary judgments about the fire environment. The military accident records, Reference D-2, because of their extensive narrative and the occasional detailed quantitative information regarding fires, permit estimates to be made. In using the military data, it should be recognized that commercial aviation fires may be more severe because of (1) the larger amount of on-board fuel carried by commercial planes and (2) the use of rear-engine aircraft in the commercial sector (these aircraft have fuel lines running along the fuselage which represent an enhanced fire danger). To apply the military data to a description of commercial aviation fire accidents, all military aircraft accidents involving tanker aircraft were excluded from the sample and fire-fighting efforts were assumed to be similar in the military and commercial sectors.

One hundred and seven of the 305 military accidents involved fire. As was done in the severe impact accident analysis, the procedure adopted for the fire description was to attempt to predict the probability that the package would experience in an accident an environment more severe than that in a particular qualification test. Of the 107 fire accidents, have a duration of no more than 10 minutes and another 6 last between 10 and 30 minutes. All of the remaining 51 are assumed to have some probability of being of significant duration with respect to package capability.

The judgments on each accident were made for two different durations, 30 minutes and 60 minutes. The estimates for each accident are shown in Table D-I. The accident number corresponds to the accident listing in Reference D-2. P_1 is the probability of the package, after the accident, being so located that it will be threatened by the fire. P_2 is the probability that, if the package is in the fire for t minutes, it will experience a thermal environment similar to that it would see in a fire test of the same length. P_3 is the probability that this fire lasts for t minutes or longer.

From these estimates, 3.66/305 or 1.2% of the aircraft accidents are expected to have environments in excess of those a package would see in a 30 minute fire test; the corresponding number for 60 minutes is .88/305 or 0.3%. Stated in another manner, if an aircraft accident occurs with a package on board, a package qualified by a 60 minute fire test is estimated to see a fire environment exceeding these levels in 3 out of every 1000 accidents.

It is desirable to develop a continuous fire duration probability spectrum around the 30 minute and 60 minute values. About 17% (51 of 305) accidents involve fires lasting longer than 10 minutes.* Using these three values and scaling them by the ratios of fire durations predicted in SLA-74-0001 results in the curve shown in Figure D-1.

---

*This assumes P_1 and P_2 are both 1.0 for these short fires and hence the 0.17 values is a reasonable upper limit.

The type of analysis employed to create Figure D-1 obviously does not lend itself to a statistical prediction of probable error. The judgment made concerning P_1, P_2, and P_3 were intentionally chosen to overestimate the probability of exceeding a given fire duration; in this sense the prediction is conservative. The only way of arriving at any appraisal of the possible error is through consideration of the potential errors in the estimates of P_1, P_2, and P_3. It is difficult to believe that the total (.88) of these individual probabilities at 60 minutes could be in error by more than a factor of 5. This predicts the lowest probability of the 60 minute fire environment of .985 with realistic expectation that it is even greater than .997.

There is one other aspect of the aircraft fire situation which suggests that a 60 minute fire will cover more than 99.7% of the aircraft fire environments. This has to do with the experimental difficulties involved in fire testing. It is extremely difficult to conduct a precise fire test the pool size must be properly controlled, the packages must be suspended somewhat above the liquid fuels, and there must be practically no wind. Deviation from any of these conditions will result in a less threatening thermal environment and all three conditions will usually not occur in concept in a typical aircraft accident. These variations from the idealized fire test in the actual aircraft accident will have some unquantifiable but significant effect on the thermal response of the package, and increase the percentage of accidents covered by a given specification.

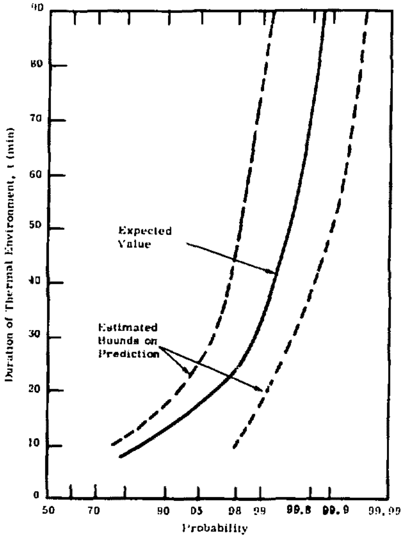


Figure D-1. Estimated Probability That an Aircraft Accident Results in a Thermal Environment Less Severe Than That Experienced in a Fire Test of Duration, t

TABLE D-I

Probabilities of Aircraft Accidents Exposing Packages to Fire Environments More Severe Than Those in Fire Test of t Minutes Duration

Accident Number	P_1	P_2		P_3		$P_4 = P_1 \times P_2 \times P_3$	
		30 min	60 min	30 min	60 min	30 min	60 min
900-4	.4	.6	.3	.8	.5	.19	.06
800-1	.2	.3	.05	1.0	1.0	.06	.01
800-2	.3	.4	.2	.7	.4	.08	.02
800-3	.3	.4	.2	.9	.5	.11	.03
800-5	.2	.3	.1	.6	.3	.03	.01
800-11	.2	.3	.1	.8	.5	.05	.01
800-14	.4	.2	.1	.6	.3	.05	.01
800-23	.2	.2	.1	1.0	.6	.04	.01
800-26	.3	.6	.3	.8	.5	.14	.05
800-27	.2	.2	.1	.4	.2	.02	-
800-36	.1	.3	.1	.3	.1	.01	-
800-40	.1	.4	.2	.3	.1	.01	-
800-43	.3	.3	.1	.7	.3	.06	.01
800-51	.2	.2	.1	.6	.3	.02	.01
800-52	.1	.3	.1	.9	.5	.03	.01
800-53	.5	.2	.1	.6	.3	.06	.02
800-54	.2	.2	.1	.5	.2	.02	-
800-67	.8	.4	.2	.6	.3	.02	-
800-73	.2	.2	.1	.7	.3	.03	.01
700-3	.3	.4	.2	.8	.5	.1	.03
600-4	.2	.1	.02	1.0	1.0	.02	-
600-27	.2	.2	.1	.5	.3	.02	.01
600-36	.1	.1	.01	.9	.5	.01	-
600-47	.2	.4	.2	.9	.5	.07	.02
600-58	.05	.3	.1	.7	.4	.01	-
600-60	.9	.3	.1	1.0	.7	.27	.06
600-72	.4	.5	.2	.6	.3	.12	.02
600-74	.1	.2	.1	.1	.01	-	-
600-73	.3	.5	.2	.7	.3	.11	.02

(cont)

TABLE D-1 (cont)

Accident Number	P_1	P_2		P_3		$P_4 = P_1 \times P_2 \times P_3$	
		30 min	60 min	30 min	60 min	30 min	60 min
600-76	.9	.04	.01	.2	.05	.01	-
600-77	.5	.5	.2	.6	.4	.15	.04
600-78	.3	.3	.2	.4	.2	.04	.01
600-85	.3	.3	.1	.4	.2	.04	.01
600-95	.3	.2	.1	.2	.1	.01	-
600-96	.7	.1	.05	.4	.2	.03	.01
600-97	.3	.2	.1	.5	.2	.03	.01
600-100	.4	.5	.2	.6	.4	.12	.03
600-121	.5	.3	.2	.4	.2	.06	.02
600-122	1.0	.4	.2	.8	.4	.32	.08
600-138	.5	.4	.1	.8	.4	.16	.02
600-141	.3	.2	.1	.4	.2	.02	.01
100-2	.6	.5	.2	.8	.4	.24	.05
500-2	.5	.6	.3	.9	.5	.27	.08
500-12	.2	.2	.05	.5	.2	.02	-
500-14	.6	.1	.05	.4	.2	.02	-
500-16	.9	.4	.2	.6	.3	.22	.05
400-5	.3	.1	.05	.4	.2	.01	-
500-15	.2	.05	.02	.3	.1	-	-
500-18	.2	.2	.1	.9	.5	.04	.01
400-20	.3	.3	.1	.6	.3	.05	.01
400-21	.3	.2	.1	.6	.3	.04	.01
						$\Sigma P_4)_{30}$=3.66	$\Sigma P_4)_{60}$=.88

Note: A dash means that the estimated value is less than .005.

References

D-1. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, "Severities of Transportation Accidents," SLA-74-0001, Sandia Laboratories, July 1976.

D-2. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, Sandia Laboratories, "Accident Environments Expected in Air Force C-5, C-141, and C-130 Aircraft Accidents," AFWL-TR-75-247, Air Force Weapons Laboratory, Kirtland AFB, NM, January 1976.

APPENDIX E

Probability of Impact Followed by Fire

APPENDIX E

Probability of Impact Followed by Fire

J. D. McClure
W. F. Hartman
Applied Mechanics Division II, 1282

Introduction

The purpose of this appendix is to describe the methodology used to perform the probability analysis required to describe in a quantitative manner the frequency at which a package will experience conditions more extreme than those of a specified impact-followed-by-fire environment. These calculations are needed to evaluate the relative protection levels provided by various combined impact-fire test sequences. It is assumed, for the tests described herein, that the impact tests will be on an unyielding target and that the fire severities will be described in terms of the duration of an 1850°F fire.

The basic ingredients of the probability analysis are concerned with the calculation of the probability that the severity level imposed by a given environmental test parameter (either impact velocity or fire duration) will be exceeded. These probability values are then combined in such a way that a statement can be made as to the percentage of all accidents of a given transportation mode that are protected by a specified impact-fire test sequence.

This probability analysis will consider the impact-followed-by-fire environment which may be imposed by an aircraft accident. The same analytical methdology could be applied to all transport modes--truck, rail, or air. This section will describe only the impact-fire test for the air transport mode since earlier sections of this report have shown that existing test standards, with some modifications, provide what is judged to be adequate protection for the material package in surface transport.

Impact and Fire Probability Values

Estimates must first be made of the individual probabilities that the impact and fire severities will be exceeded. These estimates are depicted graphically in Figures E-1 and E-2 and tabulated values of these probabilities are shown in Tables E-I and E-II. It must be emphasized that the probability values shown in the tables are, in fact, engineering estimates of the real occurrence of exceeding the severity levels. The impact estimates were made from a reexamination of the National Transportation Safety Board (NTSB) accident digests for 1962 through 1972 (see Appendix C), and the fire probability estimates were made from a review of 305 military accidents (see Appendix D). These probability estimates will be used as input to the probability calculations for several impact-fire test sequences which will be used as examples.

Probability Calculations

The probability calculations described in this appendix will be used to determine what percentage of aircraft accidents will provide an environment more severe than the impact-fire severity levels imposed on the radioactive material package by a specified test sequence. From these results the complementary argument can also be made, i.e., a known percentage of aircraft accidents will provide severity levels equal to or less severe than those imposed on the radioactive material package by a specified impact-fire test sequence.

Any number of proposed impact-fire test sequences can be proposed from the data in Tables E-I and E-II. A probability value for the test array in both of the above-mentioned forms will be calculated for each of the proposed test sequences. An examination of several proposed test sequences and their respective probability values will provide the basis for a judgment that leads to a final selection of a test sequence that can be used for the licensing of a RAM package with respect to the impact-fire environment. The probability analysis and the comparison of several proposed impact-fire test sequences plays a role of special importance in the case of the aircraft accident since SLA-74-0001 showed that the environments of impact and fire were of primary influence for the air mode of transportation. The results of the present study have indicated that increased protection should be provided for containers shipped by the air transport mode by providing more severe qualification criteria for air-shipped packages.

A survey of U.S. commercial air carriers which is described in SLA-74-0001 shows the following breakdown of the impact and fire environments for aircraft accidents:

Impact:	41% of all aircraft accidents involved impact
Fire:	34% of all aircraft accidents involved fire

Impact and Fire:	22% of all aircraft accidents involved both impact and fire
No Impact or Fire[*]:	47% of all aircraft accidents were accidents in which no impact or fire threat existed with respect to the cargo.

Restating this information in a slightly different form one obtains the following graphical view of the component environments of the aircraft accident environment.

Recognizing that aircraft accidents may involve impact and fire singly or in combination, one can express the probability of exceeding the severity of a test sequence as shown in Eq. (1).

$$\underbrace{\mathrm{PTOT}}_{\substack{\text{Total probability}\\ \text{of exceeding}\\ \text{impact-fire test}\\ \text{array}}} = \underbrace{(\mathrm{PIO})(\mathrm{PV})}_{\substack{\text{Probability}\\ \text{of exceeding}\\ \text{impact severity only}}} + \underbrace{(\mathrm{PFO})(\mathrm{PF})}_{\substack{\text{Probability}\\ \text{of exceeding}\\ \text{fire severity}\\ \text{only}}} + \underbrace{\mathrm{PJT}}_{\substack{\text{Joint probability}\\ \text{of exceeding}\\ \text{impact and fire}\\ \text{severity}}} \tag{1}$$

PTOT = total probability of exceeding an impact-fire test array

PIO = probability of an impact environment only

PV = probability of exceeding impact severity (Table E-I)

PFO = probability of a fire environment only

PF = probability of exceeding fire severity (Table E-II)

PJT = joint probability of exceeding impact-followed-by-fire environment.

Equation (1) represents the probability that a real aircraft accident will furnish environment levels more severe than those specified in an impact-fire test sequence. The form of Eq. (1) recognizes the fact that aircraft accidents include individual occurrences of impact or fire as well as the combined environment. The coefficients PIO, PFO, and PIF shown in Figure E-3 will be used in the valuation of Eq. (1). The terms of Eq. (1) may also be written in dimensional terms as follows:

(Impact Only) Component

(PIO) (PV) = (Probability of exceeding impact severity/given aircraft accident)

= (Probability of an impact accident/given an aircraft accident) times

(Probability of exceeding impact severity/given an impact accident)

---

[*] This 47% includes such accidents as ground operations and taxiing and ground roll collisions in which no threat to the package exists.

TABLE E-I

Impact Probability Tabulations[*]
(given an aircraft impact accident)

v	Prob.	v	Prob.
0	1.000	200	.100
10	.917	210	.095
20	.840	220	.090
30	.757	230	.085
40	.677	240	.078
50	.600	250	.073
60	.560	260	.068
70	.518	270	.062
80	.480	280	.057
90	.440	290	.052
100	.400	300	.045
110	.370	310	.040
120	.340	320	.035
(125)	.320	330	.030
130	.310	340	.025
140	.278	350	.020
150	.250	380	.0136
160	.218	425	.004
170	.178	450	.002
180	.163	475	.001
190	.100	500	.0002

---

[*] These probability values, multiplied by 0.41, yield the probabilities shown in Figure C-1 and Table C-II.

TABLE E-II

Fire Probability Tabulation[*]
(given an aircraft fire accident)

t (min)	Prob.	t (min)	Prob.
1	.920	33	.034
2	.837	34	.033
3	.758	35	.031
4	.670	36	.030
5	.600	37	.029
6	.560	38	.028
7	.518	39	.027
8	.475	40	.026
9	.438	41	.025
10	.400	42	.024
11	.360	43	.023
12	.320	44	.022
13	.280	45	.019
14	.235	46	.018
15	.200	47	.018
16	.180	48	.017
17	.160	49	.016
18	.140	50	.015
19	.121	51	.015
20	.100	52	.013
21	.095	53	.012
22	.088	54	.011
23	.083	55	.010
24	.075	56	.010
25	.070	57	.010
26	.063	58	.010
27	.058	59	.009
28	.050	60	.008
29	.045	70	.0065
30	.038	80	.005
31	.036	90	.004
32	.035		

[*] These values, multiplied by 0.34, yield the probabilities shown in Figure D-1.

(Fire Only) Component

(PFO)(PF) = (Probability of exceeding fire severity/given an aircraft accident)

PFO = (Probability of fire accident/given an aircraft accident) times

(Probability of exceeding fire severity/given a fire accident)

(Impact and Fire) Component

PJT = (PIF)(PEIF) = (Probability of exceeding impact and fire severity/given an aircraft accident)

= (Probability of an impact and fire accident/given an aircraft accident) times

(Probability of exceeding impact and fire severity/given an impact and fire accident).

The remainder of this section will deal with the calculation of the joint probability, PJT, and these results will be combined with the probability values for the individual environments of impact and of fire to assess the total probability of an accident exceeding the severity of an impact-fire test array.

In order to explain the methodology of the joint probability calculation it is convenient to visualize the severities of the impact and fire environments on the same graph which has coordinate axes of impact velocity versus the duration of an 1850°F fire. A sample of this type of display is shown in Figure E-4a.

v_{150} represents the severity of an impact test of 150 ft/s into an unyielding target. t_{60} represents the severity of a fire test, that is, an 1850°F fire lasting 60 minutes. The joint test would be impact of severity 150 ft/s followed by a 60 minute 1850°F fire.

Figure E-4b shows a companion plot to the velocity-fire duration diagram. Pv_{150} represents the probability of exceeding the impact test severity of 150 ft/s. PF_{60} represents the probability of exceeding the severity represented by a 1850°F fire lasting 60 minutes.

The choice of a 150 ft/s, 60 minute joint impact-fire test was chosen as a convenient example for illustrative purposes, other values could have been chosen. The impact velocity/fire duration diagram is very descriptive but the probability diagram of the type shown in Figure E-4b will be used to illustrate the joint probability calculation.

It should be noted that, in Figure E-4a, coordinate scales of impact velocity and fire duration are as large as required to accommodate the maximum impact velocities and fire durations that will be considered in the impact-fire probability calculations. In contrast, the ordinate and abcissa in Figure E-4b ranges from 1.0 to 0.0. The meaning of the probability values is that Pv_o represents the probability of any aircraft impact velocity exceeding the impact severity of zero velocity, i.e., 1.0. There is some ultimate impact severity, v_{max}, its exact magnitude unknown, where there is zero probability, Pv_{max}, that the severity of v_{max} will be exceeded in an impact accident.

A similar line of reasoning can be used with probabilities associated with the fire test. PF_o represents the probability, 1.0, that any aircraft fire will exceed the severity of a zero duration fire. Likewise, there is some maximum duration fire, T_{max}, its exact duration unknown, such that there is zero probability, PF_{max}, that an aircraft fire of severity T_{max} will be exceeded. It can be observed that the probability plot is a square of unit area since both axes have probability values of 1.0.

The joint probability calculation for a 150 ft/s-60 min fire is performed as follows:

$$PJT = (PIF)(PEIF) \tag{2}$$

Referring to Figure E-4b, the probability of exceeding the severity of the impact and fire environments, given an aircraft accident, is

$$PEIF = (Pv_{150})(PF_o - PF_{60}) + (Pv_o)(PF_{60}) \tag{3}$$

$$PEIF = \text{Area A} + \text{Area B (see Figure E-4)} .$$

Noting the values of PF_o and Pv_o from Figure E-4b, Eq. (3) can be restated as

$$PEIF = (Pv_{150})(1.0 - PF_{60}) + (1.0)(PF_{60}) \tag{4}$$

Evaluating Eq.(4) using the values of Pv_{150} and PF_{60} from Tables E-I and E-II, the joint probability of exceeding the severity of the impact and fire environments when both occur in the same accident can be calculated. This probability PEIF is multiplied, in Eq.(2), by the probability of occurrence of the combined environment, PIF, to produce the joint probability of exceeding the severity of 150 ft/s and a 60 min fire. The joint probability is used in Eq. (1) to produce the total probability of exceeding the severity imposed upon a package by individual occurrences of impact or fire or their combined occurrence.

A graphical interpretation can be made of Eq. (4). The values of Pv_{150} and PF_{60} are measured from the zero probability coordinate location on the axes of Figure E-4b, hence the terms in Eq. (4) can be represented in Figure E-4b by the shaded areas A and B. The corner established by the coordinates (PF_{60}, Pv_{150}) designates two areal components of a probability square of unit area, i.e., $(Pv_0) \times (PF_0)$. The shaded areas A and B are proportional to the probability of an aircraft accident exceeding the severity of a combined impact-fire environment of 150 ft/s-60 min. Similarly, the complementary area, which is unshaded in Figure E-4b, represents the probability of having an accident less severe than the combined impact-fire environment of 150 ft/s-60 min. Hence, the sum of both probabilities add up to unity, the set of all impact and fire probabilities, which is equal to the area of the probability plot.

Example Test Sequences

SLA-74-0001 indicated that environments of impact and fire are of first-order significance in the aircraft accident. Noting this fact, and employing the probability method discussed above for analyzing a sequence of environmental tests, the rationale for a proposed impact-fire qualification test standard will now be discussed.

The basic elements for a sequenced set of impact and fire tests are displayed in Figure E-5. We have discussed the fact that aircraft accidents can produce both single and combined occurrences of impact and fire. It is assumed that in the combined impact-fire environment that impact occurs first and is followed by fire. The basic proposal for an impact-fire test sequence is shown in Figure E-5.

For illustrative purposes, consider some very severe environmental levels, i.e., an impact velocity of 425 ft/s onto an unyielding target followed by 60 min fire of 1850°F. The test proposal shown in Figure E-5a constitutes a very severe environment. While it may be argued that the violent nature of extreme velocity impacts should lead to fuel dispersal over a wide area (and, consequently, short duration fires) and that less severe fires should be of longer duration, no such correlations could be found in the accident statistics. The most appropriate assumption, therefore, is that the impact velocity and fire duration are independent parameters. If the probability of exceeding a given impact velocity is small and the probability of having a fire whose duration is longer than some given time is also small, then the probability of having a single event in which both environments are surpassed is far less than the probability of having an event in which only one environment is present (and of a severity greater than a specified value); this then logically suggests that it is appropriate to choose a combined environment of lesser severity and more in concert with the contributions of the individual probabilities as given in Eq. (1). Stating this in another way, requiring a package to satisfy in a sequential test both the severe impact and the severe fire environments, the severities of which are based on the severity of individual tests, can seriously increase the environmental requirements without a corresponding increase in the percentage of the accidents covered.

Figure E-5b displays a number of sequenced test combinations which do not incorporate both environmental extremes in the same test. The sequenced testing shown in Figure E-5b can be represented by a single environmental coordinate pair or at most several environmentally intermediate coordinate pairs.

Six cases which represent viable test options for the impact-fire test sequence will be discussed in the examples which follow. The probability calculations as described above will be used to evaluate these test options which include the severe impact-fire environment of 425 ft/s and 60 min. The main point to be made in analyzing the test options is to determine how much protection is provided by a severe impact-fire test proposal and how this protection level compares with a series of more moderate impact-fire tests.

The basic components of an impact-fire test sequence have now been assembled. From the review of real aircraft accidents it has been observed that aircraft accidents include separate occurrences of impact or fire and combined environments of impact and fire. The physical processes which accompany an aircraft accident suggest that it is very improbable that these environmental components of primary significance occur sequentially and at their maximum severities; in fact, it is more consistent with the studies of aircraft accidents to consider a sequential test at some intermediate severity level. Single and multiple sets of sequenced environmental tests will be evaluated in the following examples.

An additional question needs to be considered in the evaluation of the test proposals and that deals with the economics of testing. How many tests need to be conducted in order to assess a given level of protection? The number of tests must be minimized for economy yet be sufficient to adequately assess protection levels. This question is raised here because it is an important concern in the following examples, but it will be discussed in greater detail later in this appendix.

A number of examples of test sequences have been formulated to illustrate the proposed test concepts just presented. A probability analysis of these test sequences will be performed. The total probability of exceeding the severity imposed by a test sequence will be used as a figure of merit in evaluating each proposed test sequence. Probability values from Tables E-I and E-II will be used as input data for the calculations. The individual and sequenced test parameters for the test proposals are shown in Table E-III. The test proposals are identified by case numbers 1 through 6. A synopsis of these is as follows:

Case 1 - Severe environment for individual tests and sequenced tests

Case 2 - Severe environment for individual tests and multiple set of (intermediate severity) sequenced tests

Case 3 - Severe environment for individual tests and single set of (intermediate severity) sequenced tests

Case 4 - Severe environment for individual tests and single set of (intermediate severity) sequenced tests

Case 5 - Severe environment for individual tests and single set of (intermediate severity) sequenced tests

Case 6 - Severe environment for individual tests and single set of (intermediate severity) sequenced tests.

TABLE E-III

Test Proposal Protection Levels

	Individual Tests		Sequential Tests		Protection Levels*	
Case	Impact Velocity (ft/s)	Fire Duration (min)	Impact Velocity (ft/s)	Fire Duration (min)	P_T	P_E
1	425	60	425	60	99.56	.44
2	425	60	425 350 250 200	15 25 40 60	99.41	.59
3	350	60	250	30	98.35	1.65
4	350	60	300	40	98.74	1.26
5	425	60	300	30	99.25	.75
6	500	90	300	40	99.63	.37

*Percent of all aircraft accidents.

P_T - The percent of all aircraft accidents equal to or less severe than the designated impact-fire test sequence.

P_E - The percent of all aircraft accidents more severe than the designated impact-fire test sequence.

Impact velocity-fire duration plots for each of the fire cases are shown in Figures E-6 through E-10. The minimum protection level offered by these individual cases is shown by the solid line indicating the domain of environmental protection provided by a package design surviving the test sequence and meeting the acceptance criteria. The total probability of exceeding the severity of the test sequence is a function of the severity of the individual and sequenced tests. Table E-III lists the calculated probabilities for these cases.

It is not normally feasible in the design process to produce a design so refined that a set of qualification or acceptance standards will be met with no margin for acceptance beyond the limits stated by the standards. For this reason the solid lines in Figures E-6 through E-10 represent a minimum or baseline of protection which one can feel confident has been demonstrated by testing.

However, using Case 3, Figure E-8 as an example, if a package design can survive the individual and the sequenced tests for Case 3, then it seems reasonable to expect that the design can also survive additional sequenced test combinations. If a package design can survive the individual impact test of 350 ft/s with no subsequent fire, then one might expect that a package of the same design might be able to sustain a less severe impact environment, say 300 ft/s, and a fire environment of 10 min. These environmental coordinates are shown in Figure E-8 and are not the only such pair one might construct. The dashed lines in Figure E-8 represent a linear, hence the simplest, bounding of such environmental combinations.

The high cost of fabrication and testing will favor a set of qualification criteria which includes a single (or at most a few) sequenced tests of intermediate environmental severity rather than a large array of such tests. Refined calculations have been performed which evaluate the increased protection level provided by the dashed boundary in Figure E-8. The refined calculations consist of using the probability calculation described earlier and applying it to a step-wise approximation of the protective domain described by the dashed lines. Figure E-11 shows such a step-wise process and the refined calculations, while approximate, evaluate a higher level of protection. In addition, the area added to the protective domain by the linear bounding (dashed lines) includes, in a conservative fashion, some additional impact-fire test combinations which it appears the package design should be able to successfully sustain if the design can pass the specified individual and sequential tests.

It is suggested that an individual impact test, an individual fire test, and a single impact-fire sequential test represent an assessment of the protective domain bounded by the dashed lines in Figure E-11 (or a similar representation). From the package designer's viewpoint the more sequential test combinations of intermediate severity that are performed the more confidence one can have that a specified level of protection has been demonstrated by actual test.

Another test approach exists if the desire is to achieve even greater protection than say, Case 1, or Case 5. Case 6 was formulated by increasing the impact velocity to 500 ft/s and the fire duration to 90 min for the individual tests. A sequential test of 300 ft/s followed by a 40 min fire is specified. Thus, performing the joint probability calculation it is determined that, if an aircraft accident occurs, only 0.37% of all aircraft accidents should be more severe than this environment (a 99.63% protection level) as shown in Table E-III.

Observations and Concluding Remarks

The purpose of this appendix has been to describe the methodology used to perform the probability analysis required to describe in a quantitative manner a series of qualification test sequences which can be used to license a radioactive material package design against a specified impact-followed-by fire environment.

The basic reference for this study, SLA-74-0001, shows that the aircraft accident environment can be described in terms of specified levels of severity for the environmental categories of impact, fire, crush, puncture, and immersion. In a sensitivity analysis of the various environmental categories for the aircraft accident, SLA-74-0001 indicates that impact and fire are of first-order significance and crush, puncture, and immersion are of secondary importance. The main emphasis of this appendix has been to examine the individual and sequenced (combined) effects of the two environments of primary importance.

The basic outline for a test plan to qualify a package design against the severe environment of an aircraft crash would be to test the environments of primary importance (impact and fire), individually and in a logical sequence (impact followed by fire). Environments of lesser or secondary importance (crush, puncture and immersion) would be tested individually to a specified level of severity. The test plans for the secondary environments will be more fully discussed in other sections and these concluding remarks and observations will focus on the appropriate package qualification test sequence for impact and fire environments.

The limits of severity for the impact environment were placed at impact velocities of 500 ft/s and for the fire environment at a duration of 90 min. Values somewhat higher or lower might have been chosen but, upon examination of Tables E-I and E-II, we see that the severity of these respective environments are expected to be exceeded in only 4 of every 1000 aircraft accidents for impact, and 8 times out of every 1000 for fire. In addition, 422 ft/s (250 knots) is the maximum permissible air speed for aircraft at altitudes lower than 10,000 ft. Hence, these limits of severity appear to be reasonable after an examination of actual accident records and federal regulations.

Several test sequences for the impact-followed-by-fire environment were formulated in terms of the options shown as Case 1 through Case 6 in this appendix. The probability calculation for each case was an attempt to assign a numerical value to the protection level offered by a package design that could sustain the environmental severity of the test sequence and subsequently demonstrate a specified level of integrity of the package envelope.

At this point, it must be mentioned again, for emphasis, that the probability values in Tables E-I and E-II which were the input to the probability calculations are engineering estimates. To the best of the authors' knowledge, no better or more pertinent estimates of these distributions exist. Therefore, one must not be under the impression that some algorithim or physical principle was available which produced the probabilities in Tables E-I and E-II. The use of these estimated probabilities of environmental severity was the only way the calculation of the total probability of exceeding the severity of the test sequences could proceed and hence permit a determination of the relative protection offered by each of the test sequences.

It is judged that, for the purposes of this study, Case 6 represents a set of qualification criteria that can serve as a reference datum with respect to the severity of the impact-followed-by-fire accident. Case 6 is the most severe combination of the impact-fire test parameters considered in the evaluation of the protection levels by joint probability analysis.

The value of the probability calculations can be shown by examining the results given in Table E-III: All of the cases considered offer a considerable amount of environmental protection; for example, Case 4 offers enough protection that only 1.26% of all aircraft accidents provide environmental combinations of impact and fire more severe than those provided by its test sequence. Examining this table, one can see that Case 6 offers the highest protection level of all those considered; only 3.7 out of 1000 aircraft accidents would offer an environment more severe than Case 6.

It is the judgment of the authors that, while Case 6 offers the highest degree of protection, Case 1 is environmentally more severe because it offe[illegible] the most severe combination of impact followed by fire.

Case 2 offers a protec[illegible] level close to the protection level of Case 1. This is due in part to the fact that the individu[illegible] are at the Case 1 levels (425 ft/s impact and 60 min fire) and in part to the multiple set of sequenced tests. Case 2 would have the disadvantage of being a more costly test sequence--requiring more test specimens.

Cases 3, 4, and 5 offer a protective level in the 97 to 98% range and the refined calculations, which present a more realistic assessment of the protection levels for these cases, show values of 98 to 99%. In fact, Case 5 has a protective level of 99.25%, which is very near the protection level of Case 1, the limiting case.

An important point to be made here concerns the accuracy of the probability calculations and assumptions about the input probabilities. All of the total probability values were calculated using the estimated probability values for impact and fire and the total probabilities were expressed to an accuracy of two decimal places. While this accuracy may be questioned the important factor to note is the consistent use of the estimated input data and the relative protection provided by the test options with respect to each other. Since Case 1 is a very severe environmental sequence and the high protection level (99.56%) associated with it is indicative of the protection levels one would expect on an absolute scale, it is judged that the calculated total probabilities for the test options represent not only a relative but an absolute indication of protection provided by the test options.

The quantification of the protection levels which has been discussed in this appendix allows a comparison of the various test options on a rational and a technical basis rather than on a purely subjective basis. Recommendations for specific test options based upon the results of this appendix will be found in the main body of the report.

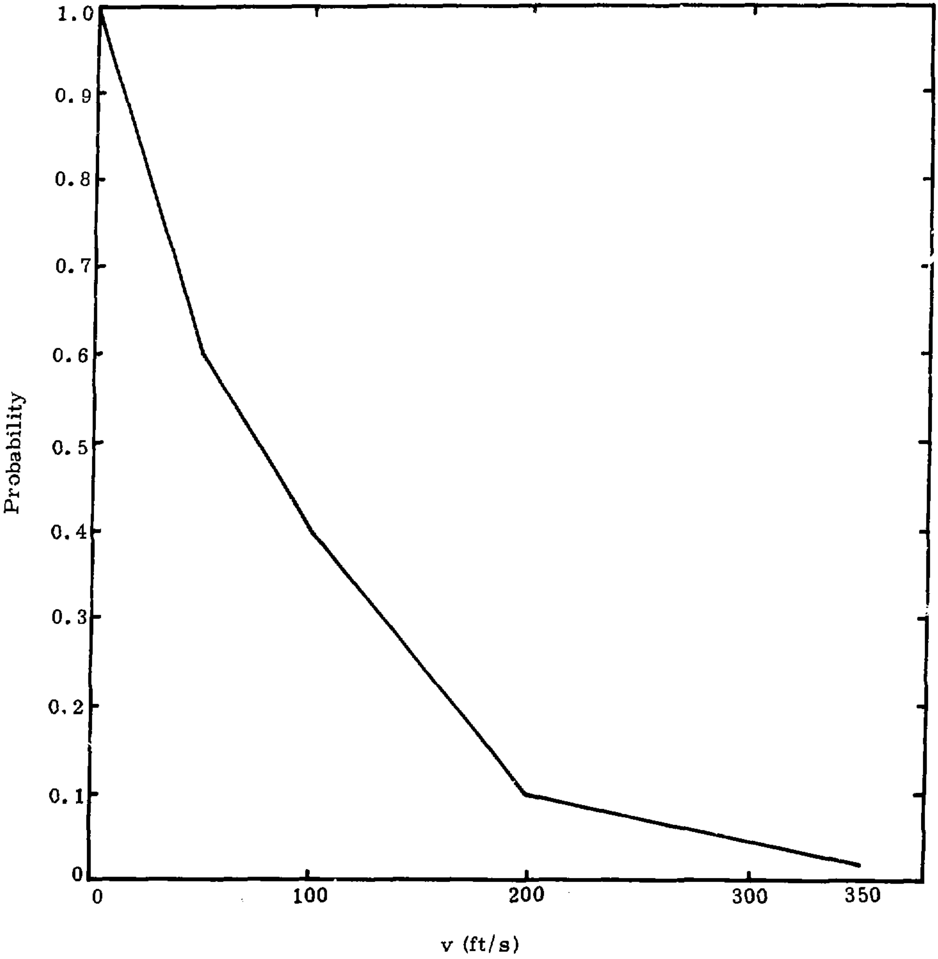


Figure E-1. Probability That the Impact Severity Exceeds Velocity v (ft/s)

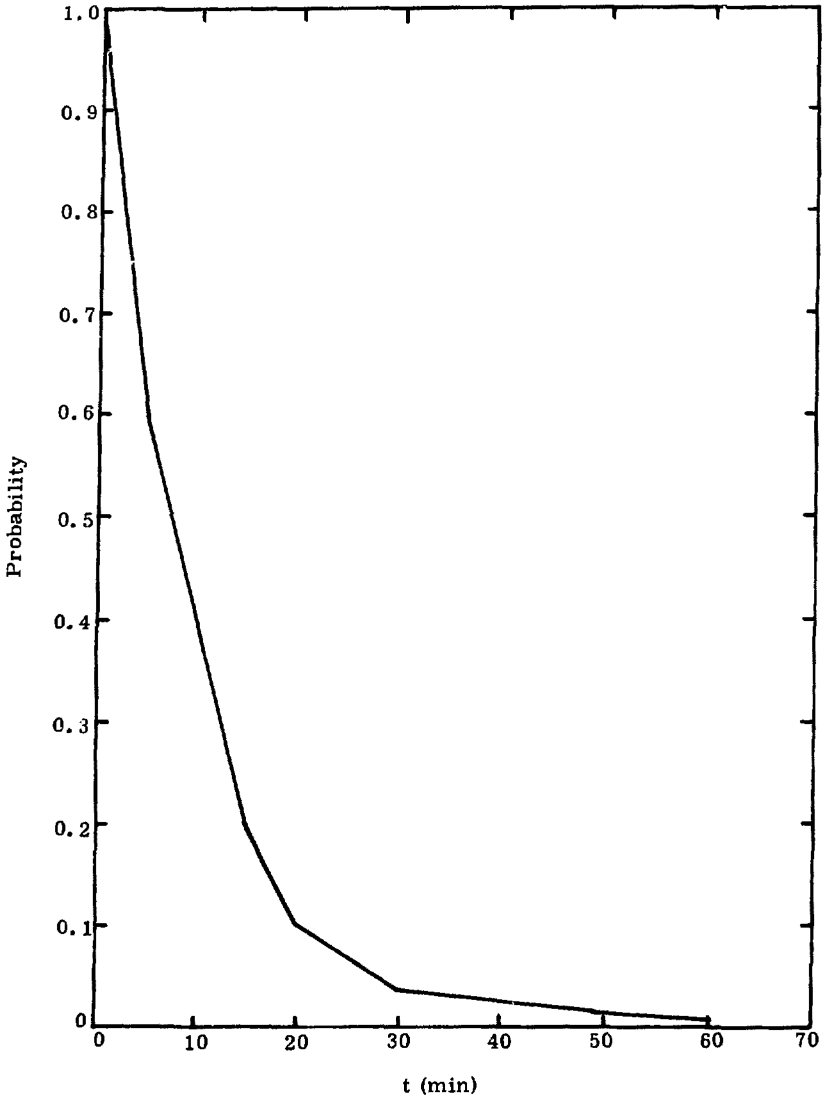


Figure E-2. Probability That the Fire Lasts Longer Than t Minutes

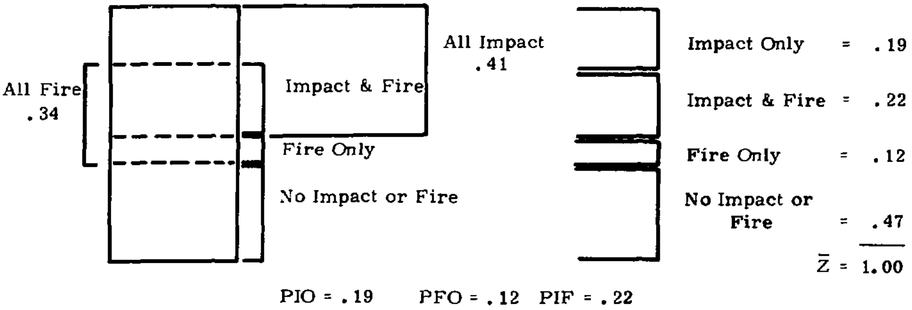


Figure E-3. Environmental Components of the Aircraft Accident

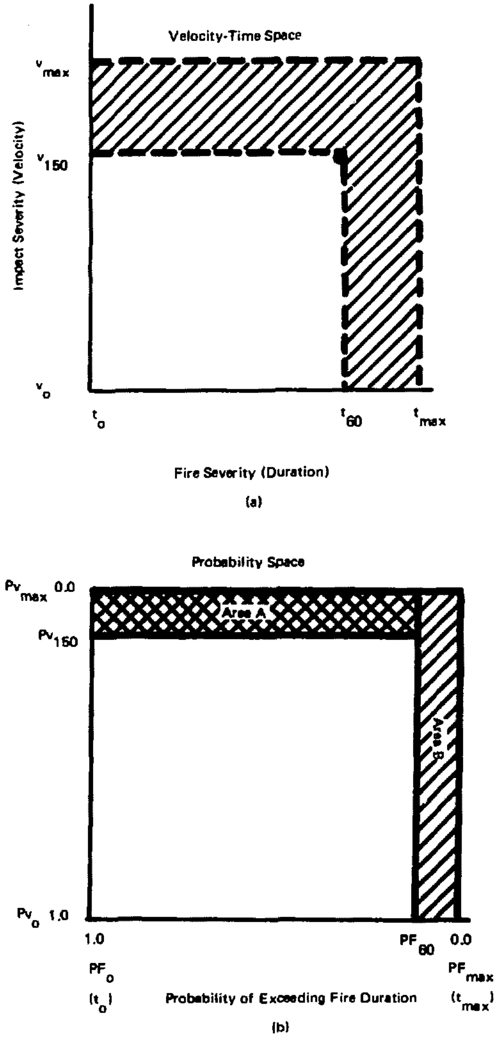
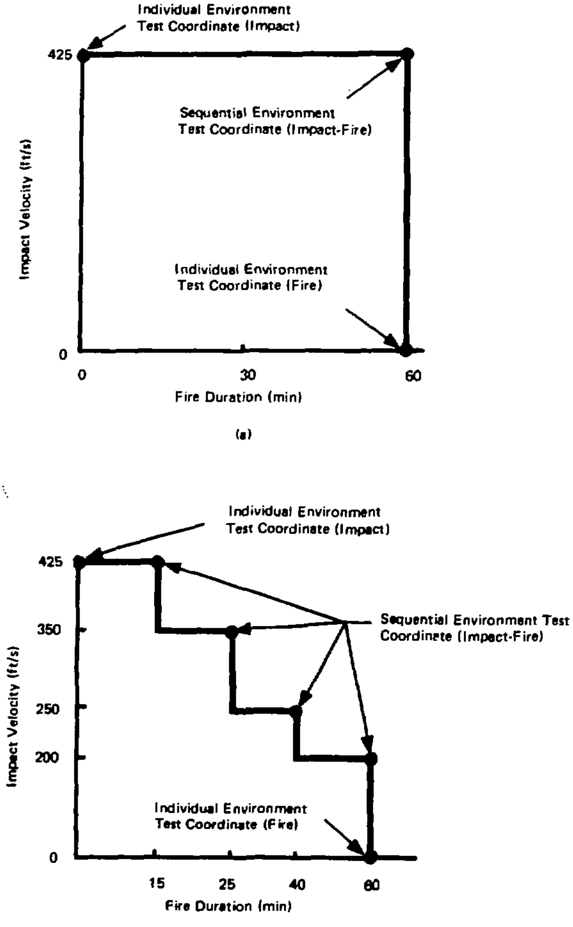


Figure E-4. Impact-Fire Severity/Probability Display



(a)

(b)

Figure E-5. Impact Fire Test Sequences

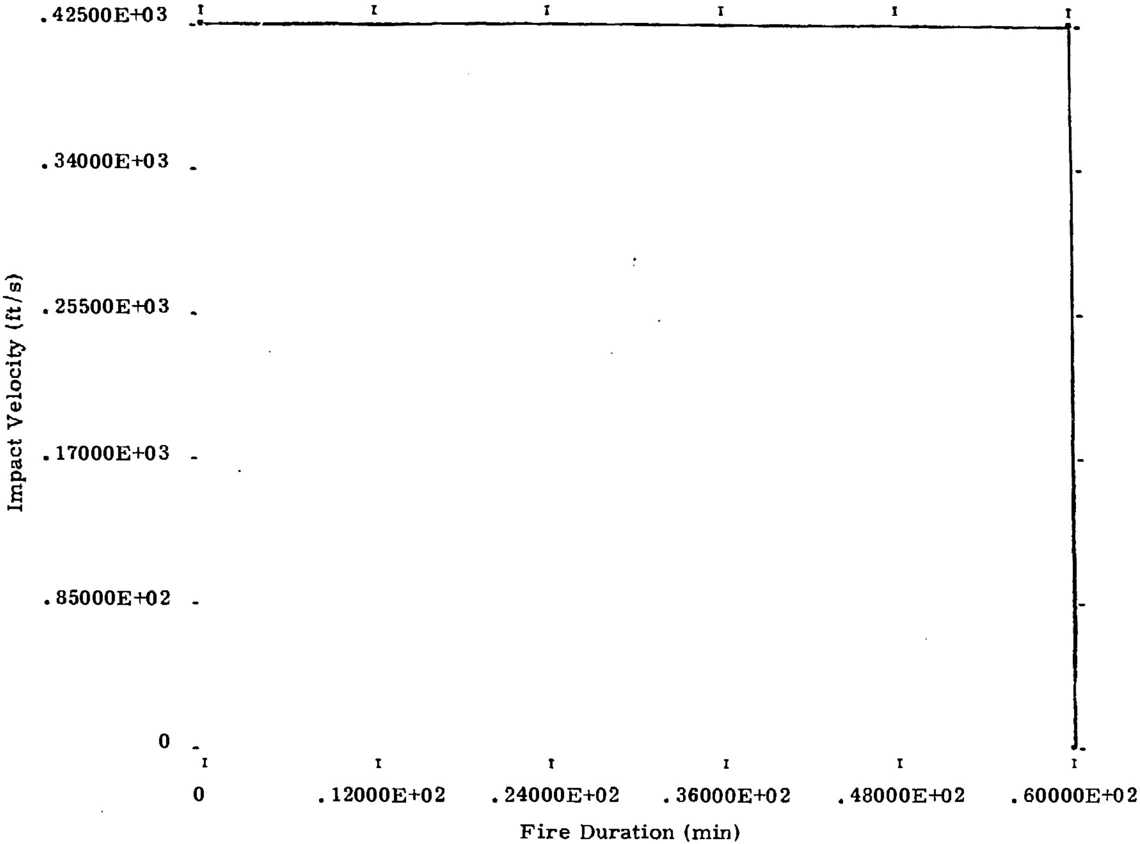


Figure E-6. Impact Velocity-Fire Duration Plot - Case 1

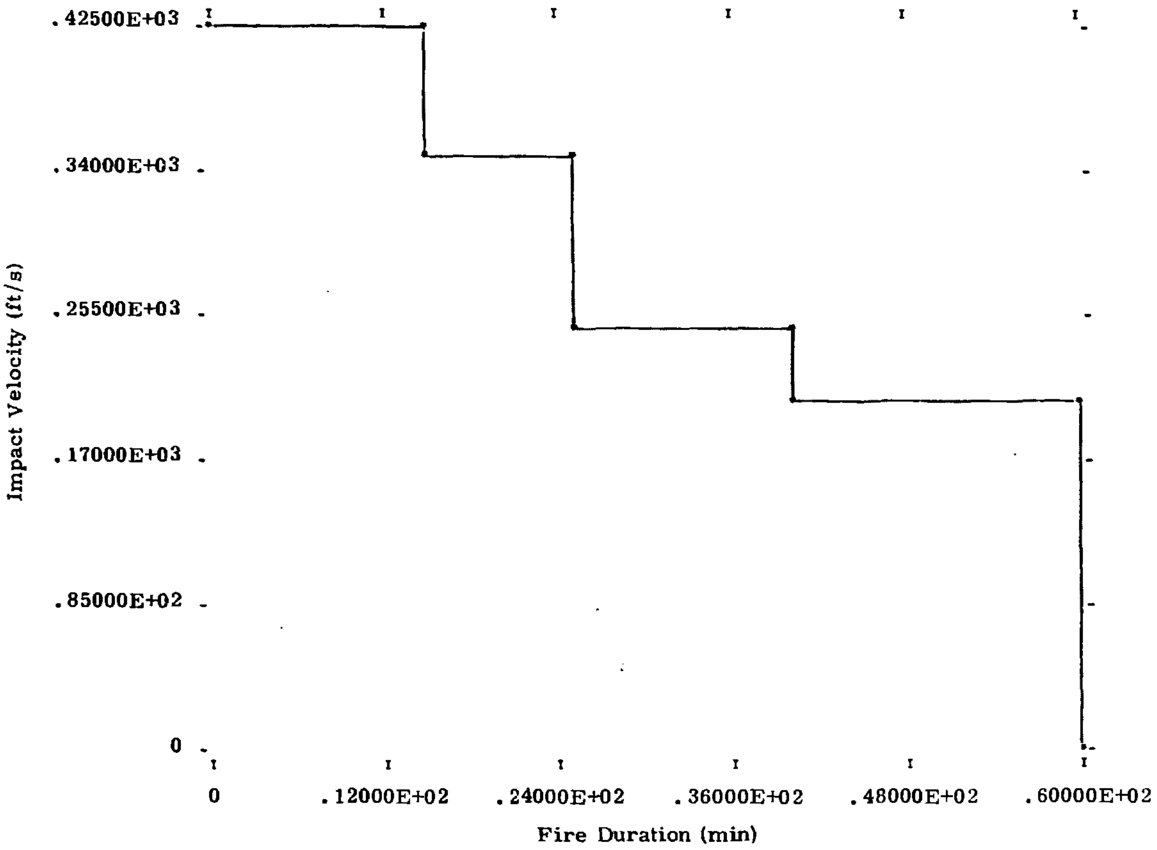


Figure E-7. Impact Velocity-Fire Duration Plot - Case 2

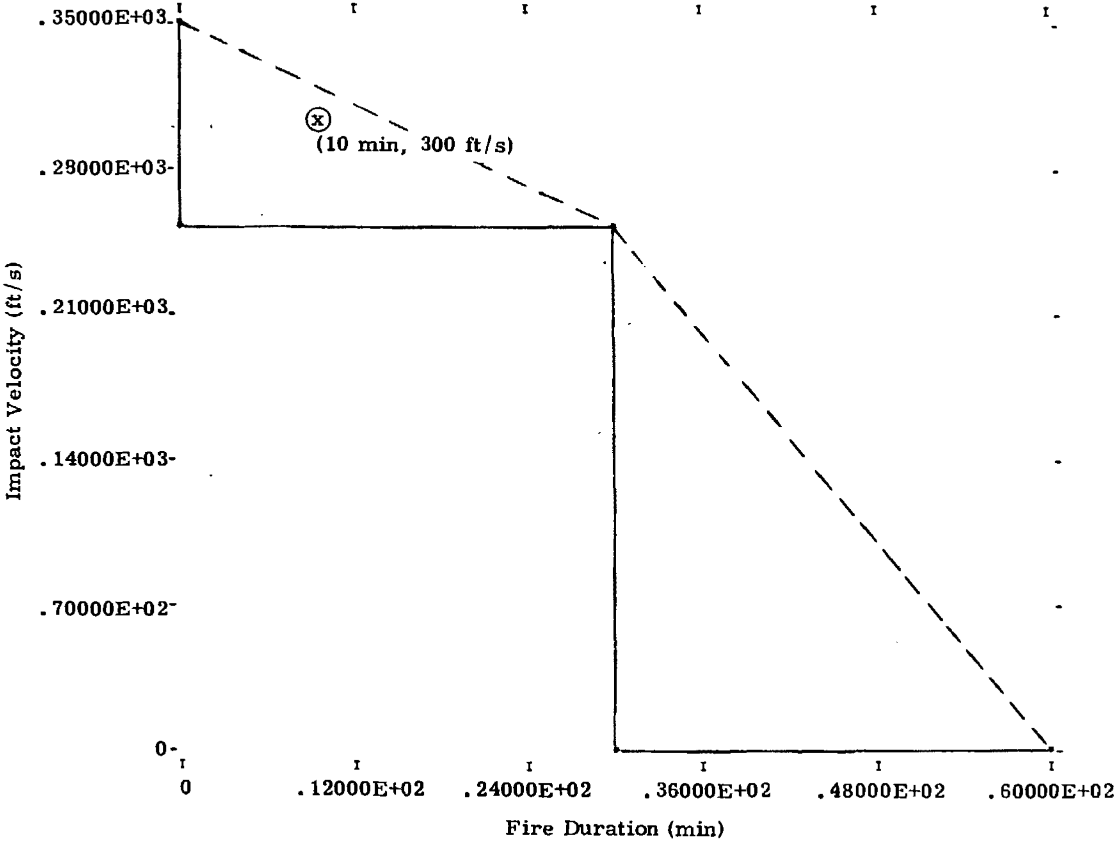


Figure E-8. Impact Velocity-Fire Duration Plot - Case 3

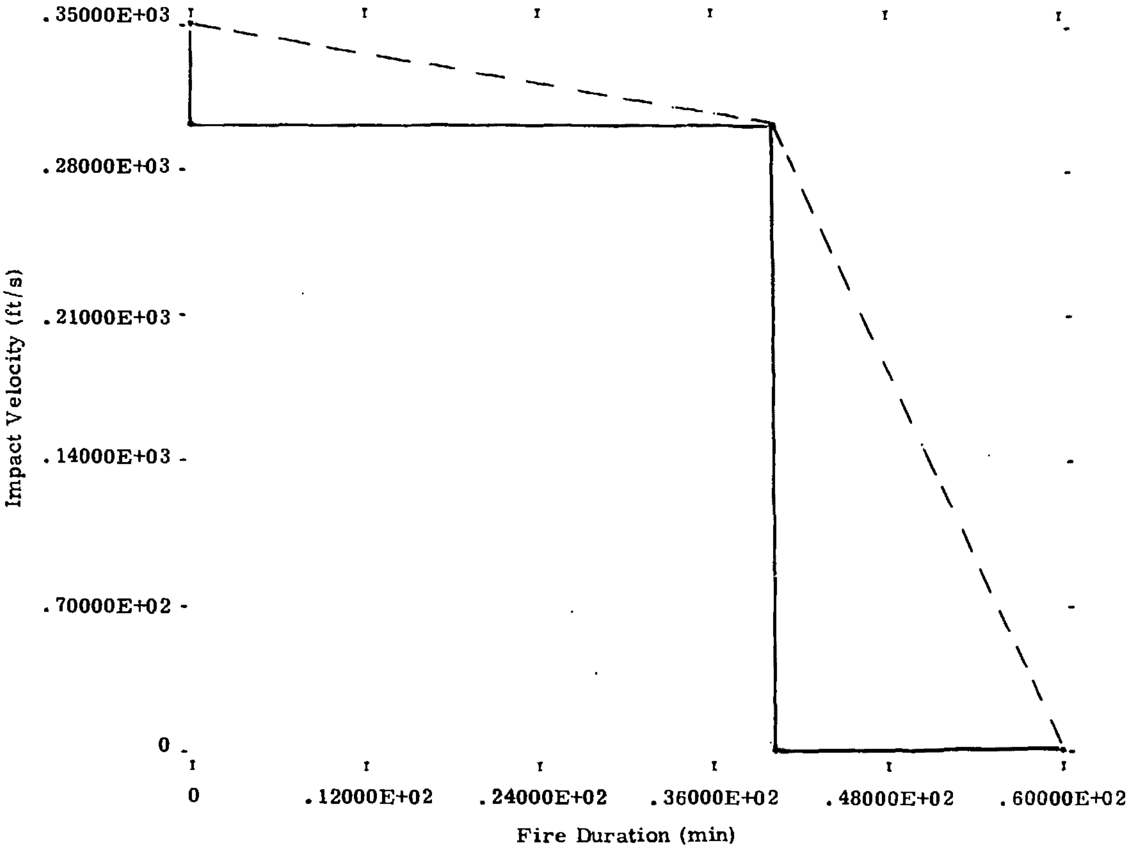


Figure E-9. Impact Velocity-Fire Duration Plot - Case 4

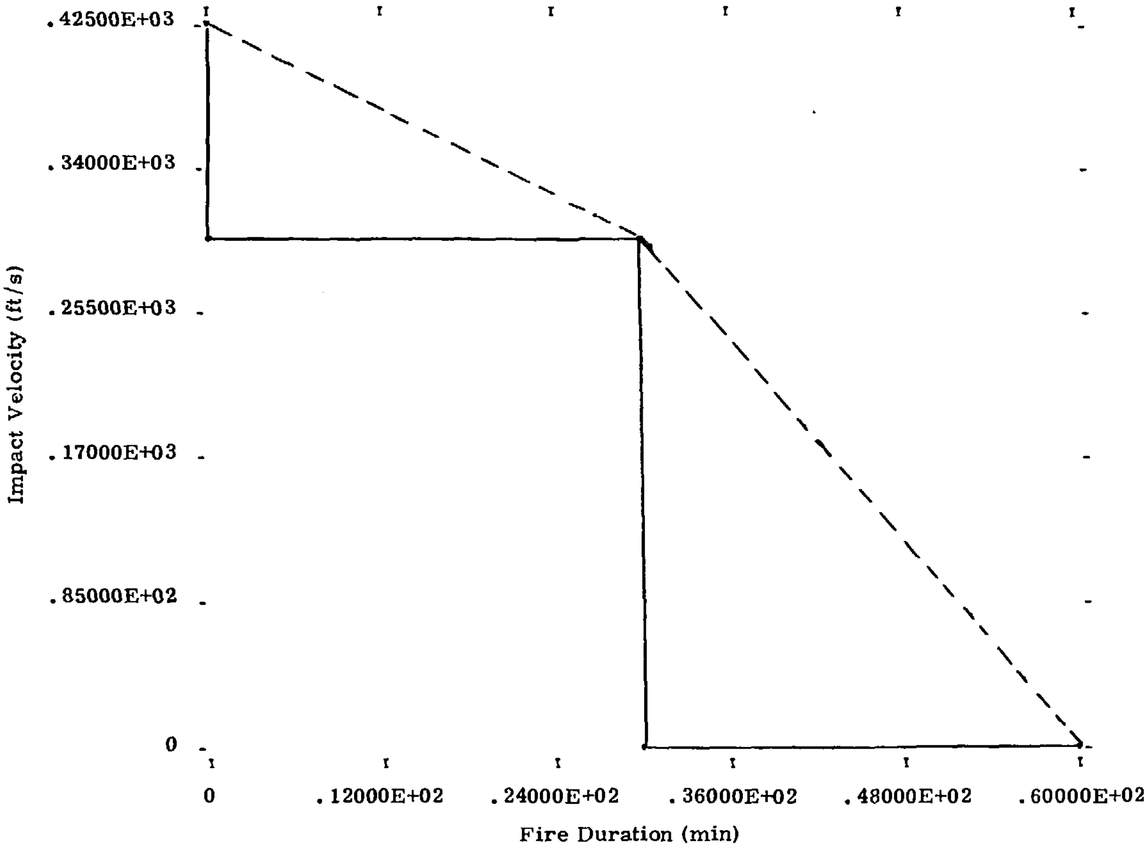


Figure E-10. Impact Velocity-Fire Duration Plot - Case 5

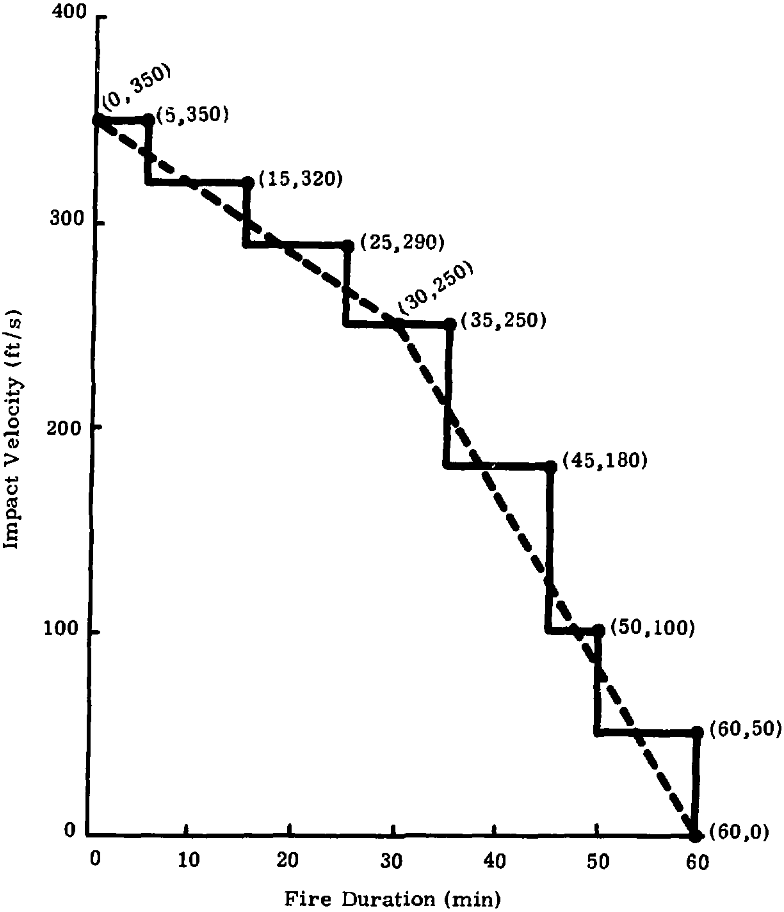


Figure E-11. Refined Calculations - Impact-Fire Tests

APPENDIX F

Existing Qualification Test Standards

APPENDIX F

Existing Qualification Test Standards

J. D. McClure
Applied Mechanics Division II, 1282

The regulatory basis for the integrity of packages which are used to ship radioactive materials are U.S. Nuclear Regulatory Commission Rules and Regulations, Title 10, Chapter 1, Code of Federal Regulations Energy, Part 71, commonly referred to as "10CFR71," and Department of Transportation Regulations, Title 49, Code of Federal Regulations, Parts 170-178. These standards have undergone continual evaluation and improvement and are consistent with the regulations developed by 70 foreign countries in the International Atomic Energy Agency.

Appendices A and B of 10CFR71 refer, respectively, to the Normal Conditions of Transport, and to the Hypothetical Accident Conditions--which we applied to a package designed to contain a specific quantity and type of radionuclide. The emphasis in this study is on the qualification criteria stated in Appendix B of 10CFR71, the Hypothetical Accident Conditions relating to Free Drop (impact), Puncture, Thermal (fire), and Water Immersion.

The basic accident environment categories considered in SLA-74-0001 were impact, fire, crush, puncture, and immersion. The crush environment is not presently included as an accident environment in Appendix B of 10CFR71. The crush environment was considered in detail in Appendix A of this report.

For information purposes the qualification criteria stated in Appendices A and B of 10CFR71 are quoted:

APPENDIX A

Normal Conditions of Transport

> Each of the following normal conditions and transport is to be applied separately to determine its effect on a package.

1. Heat--Direct sunlight at an ambient temperature of 130°F in still air.

2. Cold--An ambient temperature of -40°F in still air and shade.

3. Pressure--Atmospheric pressure of 0.5 times standard atmospheric pressure.

4. Vibration--Vibration normally incident to transport.

5. Water Spray--A water spray sufficiently heavy to keep the entire exposed surface of the package except the bottom continuously wet during a period 30 minutes.

6. Free Drop--Between 1-1/2 and 2-1/2 hours after the conclusion of the water spray test, a free drop through the distance specified below onto a flat essentially unyielding horizontal surface, striking the surface in a position for which maximum damage is expected.

Free Fall Distance

Package Weight (pounds)	Distance (feet)
Less than 10,000	4
10,000 to 20,000	3
20,000 to 30,000	2
More than 30,000	1

7. Corner Drop--A free drop onto each corner of the package in succession, or in the case of a cylindrical package onto each quarter of each run, from a height of 1 foot onto a flat essentially unyielding horizontal surface. This test applies only to packages which are constructed primarily of wood or fiberboard, and do not exceed 110 pounds gross weight, and to all Fissile Class II packagings.

8. Penetration--Impact of the hemispherical end of a vertical steel cylinder 1-1/4 inches in diameter and weighing 13 pounds, dropped from a height of 40 inches onto the exposed surface of the package which is expected to be most vulnerable to puncture. The long axis of the cylinder shall be perpendicular to the package surface.

9. Compression--For packages not exceeding 10,000 pounds in weight, a compressive load equal to either 5 times the weight of the package or 2 pounds per square inch multiplied by the maximum horizontal cross section of the package, whichever is greater. The load shall be applied during a period of 24 hours, uniformly against the top and bottom of the package in the position in which the package would normally be transported.

APPENDIX B

Hypothetical Accident Conditions

The following hypothetical accident conditions are to be applied sequentially in the order indicated to determine their cumulative effect on a package or array of packages.

1. Free Drop--A free drop through a distance of 30 feet onto a flat essentially unyielding horizontal surface, striking the surface in a position for which maximum damage is expected.
2. Puncture--A free drop through a distance of 40 inches striking in a position for which maximum damage is expected, the top end of a vertical cylindrical mild steel bar mounted on an essentially unyielding horizontal surface. The bar shall be 6 inches in diameter, with the top horizontal and its edge rounded to a radius of not more than one-quarter inch, and of such a length as to cause maximum damage to the package, but not less than 8 inches long. The long axis of the bar shall be perpendicular to the unyielding horizontal surface.
3. Thermal-- Exposure to a thermal test in which the heat input to the package is not less than that which would result from exposure of the whole package to a radiation environment of 1475 °F for 30 minutes with an emissivity coefficient of 0.9, assuming the surfaces of the package have an absorption coefficient of 0.8. The package shall not be cooled artificially until 3 hours after the test period unless it can be shown that the temperature on the inside of the package has begun to fall in less than 3 hours.
4. Water Immersion (fissile material packages only)-- Immersion in water to the extent that all portions of the package to be tested are under a least 3 feet of water for a period of not less than 8 hours.

In addition to the detailed provisions of the actual qualification tests described in the regulations cited above, the "Air Freight Guide for Hazardous Materials," put out by the Flying Tiger Line, 7401 World Way West, Los Angeles, CA 90009, describes the interaction of the various regulations from an air shipper's point of view.

APPENDIX G

Test Descriptions

APPENDIX G

Test Descriptions

J. D. McClure
Applied Mechanics Division II, 1282

The purpose of this appendix is to provide a detailed, yet brief, description of how the proposed qualification tests should be conducted. The test descriptions will deal with the accident environmental categories of impact, fire, crush, puncture, and immersion for the surface and air transport modes.

Pretest Package Preparation

- The candidate RAM package shall be prepared in accordance with any packaging or other specifications required for its proper functioning.
- The test package shall contain a substitute radioactive material in a quantity similar to the amount of radioactive material which is to be carried by the candidate RAM package.
- To help identify any posttest leakages, standard health physics swipe tests shall be performed during various phases of the RAM package closure process to provide pretest verification of the absence of substitute radioactive material on selected surfaces.

Surface Transport Qualification Tests

Impact Testing

The impact test shall be a 13.4 m/s (44 ft/s) impact onto an unyielding target surface. This impact velocity can be provided by a 9 m (30 ft) free-fall drop of the package. The height of the free-fall drop shall be measured from the point of lowest elevation on the package to the impact surface.

The interpretation of what constitutes an unyielding target is that the mass of the target be at least 10 times the mass of the package and that it be faced with steel to prevent indentation and spalling of the concrete during the impact process, (Reference G-1, p.77).

Fire Testing

The general requirements for surface transport fire testing are as follows:

a. The RAM package shall be subjected to a 1000°C (1832°F) fire for a duration of 30 minutes.

b. JP-4 aviation fuel shall be burned for the heat source.

c. The dimensions of the pool of fuel shall be such that the RAM package will be engulfed in an optically thick fire. To meet these requirements the RAM package must be centrally located above the pool of JP-4 fuel and the pool shall be of such dimensions that the RAM package will be completely surrounded by a fire thickness of at least 1.5 m (4.9 ft).

d. The burning of JP-4 fuel produces a recession of the fuel surface at the rate of 41 mm/min (0.16 in./min)(References G-2 and G-3) and the recession of the fuel shall be used to control the fire duration. For the specified 40-minute fire duration, the fuel depth in the burn pit shall be 4.1 mm/min x 40 = 164 mm. Thus, a 16 cm JP-4 fuel depth is recommended. The point of lowest elevation on the RAM package shall be positioned 1.2 m (4 ft) above the middepth (8 cm) of the JP-4 fuel.

e. A chimney shall be centered over the burn pit to help provide the optically thick dimensions of the flame volume and help reduce the effects of wind on the flame geometry. The diameter of the chimney shall be at least the maximum dimension of the RAM package plus 2.4 m (8 ft). For many small packages a chimney 3.5 m (11.5 ft) in diameter will be adequate. The chimney shall be constructed of 25 mm (1 in.) mild steel or a similar material. The chimney shall stand on 0.5 m (1.5 ft) vertical legs as shown in Figure G-1. The 0.5 m opening at the chimney base provides draft for the fire.

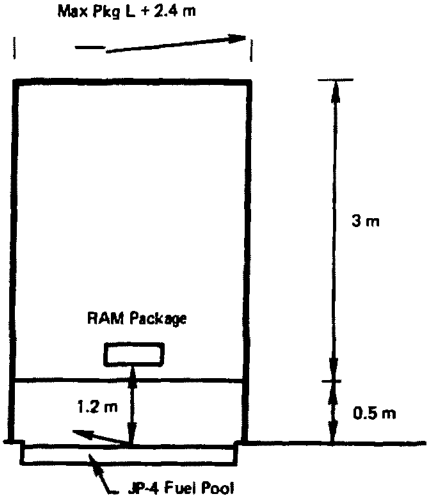


Figure G-1. Fire Test Schematic

f. A noncombustible fence about 1.5 m high shall be constructed approximately 1 m from the draft opening and around the perimeter of the chimney base, to reduce the effects of wind on the flame characteristics. Wind velocity or local air currents in the general area surrounding the test facility must be less than 2.6 m/s (5 knots) during the test (exclusive of the posttest cool down period).

g. If there is an orientation or face of the RAM package which is more vulnerable or easily threatened by fire, this face should be so oriented that it is adjacent to the burning JP-4 fuel surface.

h. The RAM package support structure should be constructed so as not to prevent direct exposure of any significant area of the package to the radiative and convective heating. These supports should not provide a significant heat path away from the package. The support structure should survive the test and be intact at the end of the test.

i. The flame temperature must be measured in at least two locations in the immediate vicinity of the RAM package and must exceed 870°C (1600°F) during at least 90% of the test duration and must exceed 980°C (1800°F) during at least 50% of the test duration.

j. The fire duration shall be controlled by the burnout of a measured fuel depth (see paragraph d) and, following burnout, the RAM package shall not be artificially cooled for a period of hours (to allow for the combustion of outer layers of package materials, and to simulate the denial of fire-fighting efforts in remotely located accident sites). No precipitation should occur during the test or the cool down period (24 hours).

Crush Testing

A static crush level of 310 000 N (70,000 lb) shall be applied to the RAM package by placing it between the platens of a compression testing machine. The load shall be applied gradually so that the loading is static and not dynamic. The RAM package shall be so oriented that its most vulnerable direction is being crushed (if such an orientation can be determined). The maximum crush load shall be held for a period of 5 min and then removed from the RAM package.

Puncture Testing

The RAM package shall be dropped through a distance of 1 m (40 in.) in order to strike a puncture probe. The package shall be oriented in such a way as to sustain maximum puncture damage. The puncture probe shall consist of a mild steel cylindrical bar, 15 cm (6 in.) in diameter with its top edge rounded to a radius of not more than 60 mm (1/4 in.), and mounted on an essentially unyielding surface. The probe shall be long enough to inflict maximum damage to the RAM package and not less than 20 cm. The long axis of the probe shall be perpendicular to the unyielding surface.

Immersion Testing

The RAM package shall be hydrostatically tested to a pressure of 146 950 Pa (21.3 psig), which is equivalent to a submerged depth in water of 15 m (49.2 ft). The duration of the test shall be 8 hours.

Acceptance Criteria

The acceptance criteria to be used following the individual and sequential tests are those specified in 10CFR71, and the compliance with these criteria is outlined in U.S. Nuclear Regulatory Commission Regulatory Guide 7.4.

Air Transport Qualification Tests

The following procedures are based in part on the development testing described in Reference G-4.

Impact Testing

The impact test shall consist of a minimum specified impact velocity onto an essentially unyielding target surface. Two impact tests are specified in the air transport mode, an impact of 110 m/s (360 ft/s) and a sequential test of impact, 90 m/s (295 ft/s) followed by a 40-minute fire.

A statement similar to that made for the surface transport mode can also be used to describe an "essentially unyielding target" in the impact testing for the air transport mode. Reference G-1 states that the mass of the impact target must be at least 10 times the mass of the impacting body. More elaborate impact target designs use piers so that the impact loads applied to relatively massive concrete pads are transferred through the piers to bedrock formations. In addition, a steel facing on the impact target is provided to prevent, or at least reduce, the spalling and penetration of the target by the impacting body.

Fire Testing

The general requirements for fire testing are similar to the fire tests described for surface transport but with different durations specified. The general requirements for air transport fire testing are as follows:

a. The RAM package shall be subjected to the following fire tests:

Individual	1000 °C (1832 °F) for 60 minutes.
Sequenced	Impact 90 m/s (295 ft/s) followed by 1000 °C (1832 °F) for 40 minutes.

b. JP-4 aviation fuel shall be burned for the heat source.

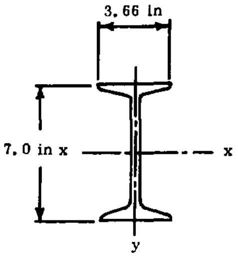
c. The dimensions of the pool of fuel shall be such that the RAM package will be engulfed in an optically thick fire. To meet these requirements the RAM package must be centrally located above the pool of JP-4 fuel and the pool shall be of such dimensions that the RAM package will be completely surrounded by a fire thickness of at least 1.5 m (4.9 ft).

d. The burning of JP-4 fuel produces a recession of the fuel surface at a rate (References G-2 and G-3) of 4.1 mm/min (0.16 in./min) and the recession of the fuel shall be used to control the fire duration. For the specified fire tests the fuel depths shall be as follows:

Fire Duration	Fuel Depth
40 min	16 cm
60 min	25 cm

The point of lowest elevation on the RAM package shall be positioned 1.2 m (4 ft) above the middepth of the JP-4 fuel.

e. A chimney shall be centered over the burn pit to help provide the optically thick dimensions of the flame volume and help reduce the effects of wind on the flame geometry. The diameter of the chimney shall be at least the maximum dimension of the RAM package plus 2.4 m (8 ft). For many small packages a chimney of 3.5 m (11.5 ft) will be adequate. The chimney shall be constructed of 25 mm (1 in.) mild steel or a similar material. The chimney shall stand on 0.5 m (1.5 ft) vertical legs as shown in Figure G-1. The 0.5 m opening at the chimney base provides draft for the fire.



AMERICAN STD. I BEAM EXTRUSION
7075-T6 Aluminum Wt. 5.27 lbs/ft.
Cross-Sectional Area = 4.48 in^2
I_{xx} = 36.69 in^4 I_{yy} = 2.63 in^4
Ref. Alcoa Structural Handbook
Table 41, 1960

Figure G-2 Beam Section for Puncture Test

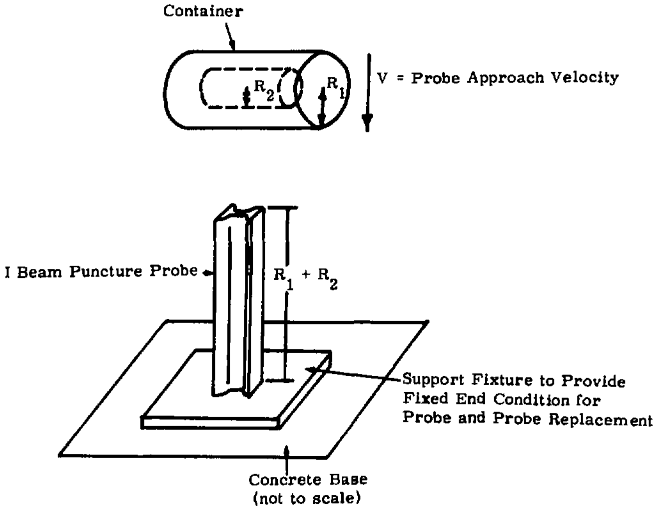


Figure G-3 Proposed Puncture Test

f. A noncombustible fence about 1.5 m high shall be constructed approximately 1 m from the draft opening and around the perimeter of the chimney base, to reduce the effects of wind on the flame characteristics. Wind velocity or local air currents in the general area surrounding the test facility must be less than 2.6 m/s (5 knots) during the test (exclusive of the posttest cool down period).

g. If there is an orientation or face of the RAM package which is more vulnerable or easily threatened by fire, this face should be so oriented that it is adjacent to the burning JP-4 fuel surface.

h. The RAM package support structure should be constructed so as not to prevent direct exposure of any significant area of the package to the radiative and convective heating. These supports should not provide a significant heat path away from the package. The support structure should survive the test and be intact at the end of the test.

i. The flame temperature must be measured in at least two locations in the immediate vicinity of the RAM package and must exceed 870°C (1600°F) during at least 90% of the test duration and must exceed 980°C (1800°F) during at least 50% of the test duration.

j. The fire duration shall be controlled by the burnout of a measured fuel depth (see paragraph d) and, following burnout, the RAM package shall not be artificially cooled for a period of 24 hours (to allow for the combustion of outer layers of package materials, and to simulate the denial of fire-fighting efforts in remotely located accident sites). No precipitation should occur during the test or the cool down period (24 hours).

Crush Testing

A static crush level of 310 000 N (70,000 lb) shall be applied to the RAM package by placing it between the platens of a compression testing machine. The load shall be applied gradually so that the loading is static and not dynamic. The RAM package shall be so oriented that its most vulnerable direction is being crushed (if such an orientation can be determined). The maximum crush load shall be held for a period of 5 min and then removed from the RAM package.

Puncture Testing

The puncture testing sequence shall consist of an individual puncture test and a sequential test of puncture followed by a fire. The details of the puncture test are outlined in Figures G-2 and G-3. The aluminum I-beam puncture probe simulates the type of probe that can be developed by broken aircraft structural members. The individual puncture test uses an approach velocity 30 m/s (100 ft/s) onto the aluminum I-beam probe. The sequential test of puncture followed by fire consists of a puncture test with a 12 m/s (40 ft/s) probe approach velocity followed by a 1000°C (1832°F) fire of 40 minutes duration.

Immersion Testing

The RAM package shall be hydrostatically tested to a pressure of 2 MPa (300 psig). The duration of the test shall be 8 hours.

Acceptance Criteria

The acceptance criteria to be used following the individual and sequential tests are those specified in 10CFR71, and the compliance with these criteria is outlined in U. S. Nuclear Regulatory Commission Regulatory Guide 7.4.

References

G-1. "Cask Designers Guide," ORNL-NSIC-68, Oak Ridge National Laboratory, February 1970.

G-2. D. W. Larson, Sandia Laboratories, private communication.

G-3. Thermal Fire Test Specification, unclassified letter, H. C. Hardee, D. W. Larson, R. H. Nilson, Sandia Laboratories, February 25, 1977.

G-4. J. A. Anderson, Sandia Laboratories, "Test Protocol, Plutonium Air Transportable (PAT) Package," November 2, 1976.

APPENDIX H

Target Rigidity and Its Effect on Impact Testing

APPENDIX H

Target Rigidity and Its Effect on Impact Testing

J. D. McClure
Applied Mechanics Division II, 1282

Introduction

The purpose of this appendix is to discuss the role played by impact target rigidity in the impact testing which is specified as a part of the qualification criteria for radioactive material packages. In particular, the relationship of target rigidity to the response of the RAM package will be discussed. Impact is one category of accident environment and the severity of this contributing element of the accident environment has been discussed for each of the transportation modes, air, truck, and rail.

The impact environment can be specified by an impact velocity, impact orientation, and an impact target description. The existing impact test is specified by the impact velocity associated with a 9 m (30 ft) free-fall drop test of the package in its most damaging orientation onto an unyielding target. A level of severity is associated with a test of this type and the location of this severity level within the impact accident environmental spectra for the air, truck, and rail transportation modes has been discussed in the second section of the report proper. The purpose of an impact test is to produce an impact environment with a severity equal to that of an extreme transportation accident and thereby demonstrate that a given package design can sustain the specified environmental severity levels and maintain its integrity.

Impact Target Description

The provision of a specified severity level in the case of the impact test is accomplished by not only specifying the impact velocity but, in addition, by specifying the impact target. An unyielding target is specified for the following reasons:

- There is some finite possibility that a target equivalent to an unyielding target can be impacted.

- Unyielding targets can be constructed more readily with preproducible quality and rigidity than can soft targets. Also, such targets can be reused.

If one considers all the possible types of surface conditions upon which an impact can occur, they can be divided into the categories of water impact (oceans, lakes, rivers), soil impacts, and "hard target" impacts with aircraft runways, road surfaces, and natural outcroppings of rock. From the data reported in Reference H-1, there is a probability of about .18, that the impact from inflight accidents will be with water, .65 with soil targets and the remaining probability, .14, will be for an impact with "hard" targets.

The results of several investigations are available that discuss the structural damage associated with impact (References H-2 through H-4). Reference H-3 indicates that concrete acts as a rigid target provided that it does not break up or pit during impact, and Reference H-2 provides isodamage information between rigid (steel), concrete, and soil targets. The definition of an unyielding target has come to mean a steel-faced concrete target with the mass of the target at least ten times the mass of the impacting body. The steel face prevents cracking, subsequent breakup, and indentation of the target. Damage to the impacting body can be reduced (Reference H-3) if the target can be cracked, pitted, and cratered during the impact process.

The Impact Process

Unyielding Targets

A simplified model of the damage-producing mechanism can be formulated if one examines the average force which is applied to a body during the impact process. The model will only approximate the complex phenomenon of impact and we will neglect the energy losses due to the generation of elastic waves in the impacting bodies, the generation of sound energy, and the generation of heat at the contact point. For the first case we shell consider a RAM package impacting an unyielding target, and this model is shown in Figure H-1. The package approaches the target with velocity v, the weight of the package is W, and the kinetic energy is $W v^2/2g$.

The preimpact condition is shown in Figure H-1a. In Figure H-1b the first impact is shown taking place. Following any rebound the package is finally at rest. All of the deformation is assumed to be taking place in the package. For small impact velocities, the deformation of the package could be elastic but for any reasonable value of the impact velocity the kinetic energy of the body will probably require that plastic (permanent) deformations be sustained by the package. The average force applied to the body would be of such magnitude that this force magnitude acting through a displacement of magnitude equal to the maximum deformation Δ sustained by the package would be equal to the preimpact kinetic energy, i.e.,

$$(F_{avg})(\Delta) = 1/2\ W/g\ v^2 .$$

Soft Targets

Let us now examine the impact of a RAM package after a relatively soft target. A schematic of this process is shown in Figure H-2.

Prior to impact the body possesses velocity v and kinetic energy $1/2\ W/g\ v^2$. During impact, since the target is relatively soft, the target captures the impacting body. The body is slowed to zero velocity by an average force, F_{avg}, over a distance Δ. The impacting body may sustain some deformation depending on the stiffness of the body and the forces applied during the penetration of the target. Depending on the stiffness of the target material, the penetration distance, Δ, may be of the order of several multiples of the major dimensions of the impacting package.

An important point to note is that, for the case of impact against an unyielding target, the average force applied to the target was large because we had by definition an unyielding target; therefore, all of the deformation Δ was a deformation of the impacting body. For a given amount of kinetic energy and small body deformations, the average force applied to the body will be large. For soft targets it is possible for the body to deform during impact but these deformations were small compared to the penetration distance, Δ, into the soft target. Thus, for a given amount of kinetic energy and relatively large values for Δ, the corresponding values of average force will be small. Hence, based on the relative magnitude of the applied forces, the impact into a soft target should be <u>much</u> less damaging than for a hard target.

The main purpose in describing the extremes in the representation of an impact environment in Figures H-1 and H-2 is to show the importance of the stiffness of the target. Figure H-1 represents the type of test currently being specified for impact testing. Figure H-2 represents what might be called a "realistic" target.

The disputed point which is sometimes raised is that it is recognized that aircraft, for example, travel at high rates of speed and can impact into mountain faces or in a high-altitude midair collision radioactive material package might be expelled from the aircraft. The question is, then, how can a 9 m (30 ft) drop test stimulate such a condition? The answer is that 9 m (30 ft) drop test cannot simulate extremely severe impact environments; for small packages it is, however, able to simulate a large fraction of the aircraft impact accidents (see Table V).

Let us discuss the high-speed aircraft impact further. The existing 9 m (30 ft) drop test onto an unyielding target equals or exceeds in severity the impact environment of about 79% of all aircraft accidents. If the severity level of the impact test is increased, then the percentage of the aircraft accidents that are protected by the increased severity level is correspondingly increased. The fraction of the aircraft accidents that have impact severity levels corresponding to several hundreds of feet per second impact velocity onto an unyielding target is exceedingly small (see Appendix C). However, the only certain way to provide the simulation of a high-velocity impact into a mountain face is to do high-velocity impact testing onto unyielding targets. The information on impact presented in Appendix C was with respect to hard unyielding targets.

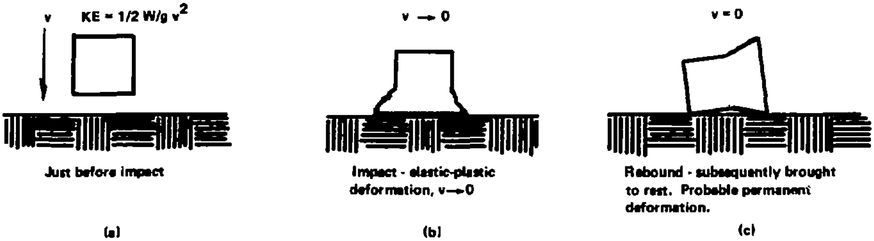
Let us now consider high-altitude RAM package ejection. From the point of view of the impact environments, the package will experience some magnitude impact during the collision of the aircraft. After ejection the package will experience a free fall. Depending on the collision altitude, the package may accelerate until it reaches a terminal velocity which is a function of the local viscous properties of the air, the package velocity, and the geometric properties of the package. If the collision altitude is high enough a terminal velocity will be reached; if not, the body will continuously increase in velocity until impact. For a high-altitude collision the greater probability is for a soil impact, although impacts onto hard rock or water are possible.

Reference H-4 describes a test series wherein a RAM package design was subjected to a 9 m (30 ft) drop test and a separate package of the same design was dropped 610 m (200 ft) in a free-fall drop from a helicopter onto hard prairie soil. The 610 m drop test provided an impact velocity 8 times greater than that provided by the 9 m test. However, in the 610 m test, the package penetrated the soil 2.4 m (8 ft) and was otherwise undamaged whereas the same package sustained broken welds, lead slump, and localized bulging after the 9 m drop onto an unyielding target. It was concluded in Reference H-4 that the 9 m drop test was onto the unyielding target was more severe than the 610 m drop onto hard soil.

The designation of an unyielding target is recommended for several reasons:

- Impact accidents can occur over a wide range of impact velocities and impact surface conditions. High-speed impacts onto essentially unyielding targets can occur.
- Impact tests onto unyielding targets at even moderate velocities can provide a more severe environment than is provided by high-altitude drops onto soil targets.
- A precise, controllable, and repeatable impact target condition can be provided by the engineered construction of an unyielding target.

Recognizing the importance of an unyielding target as discussed in this appendix, the re-examination of the National Transportation Safety Board (NTSB) accident digests which is presented in Appendix C describes the aircraft impact accident in terms of the impact into an unyielding target.



Just before impact

(a)

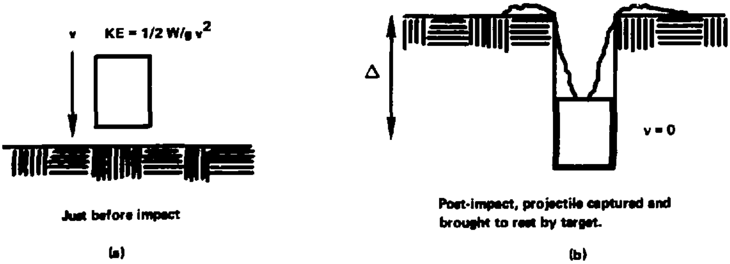
Impact - elastic-plastic deformation, v → 0

(b)

Rebound - subsequently brought to rest. Probable permanent deformation.

(c)

Figure H-1. The Impact Process (Unyielding Targets)



Just before impact

(a)

Post-impact, projectile captured and brought to rest by target.

(b)

Figure H-2. The Impact Process (Soft Targets)

References

H-1. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, "Severities of Transportation Accidents," SLA-74-0001, Sandia Laboratories, July 1976, p. 43.

H-2. L. L. Bonzon and J. T. Schamaun, Sandia Laboratories, "Container Damage Correlation With Impact Velocity and Target Hardness," IAEA SR 10/21.

H-3. J. T. Schamaun and W. A. Von Riesemann, "Effects of Target Rigidity on Impact Behavior of Shipping Containers," SAND76-0207, Sandia Laboratories, June 1976.

H-4. I. G. Waddoups, "Air Drop Test of Shielded Radioactive Material Containers," SAND75-0276, Sandia Laboratories, September 1975.

DISTRIBUTION:

U. S. Department of Energy (20)
Washington, DC 20545
Attn: Col. R. E. Lounsbury, Safety & Facilities
H. Lyons, Div. of Safeguards & Security
H. Hollister, Div. of Safety, Standards,
and Compliance
J. W. Crawford, Asst. Adm. for Nuclear Energy
W. A. Brobst, Transportation Br. (15)
J. A. Sisler, Transportation Br.

Transnuclear, Inc. (6)
Suite 700
1 North Broadway
White Plains, NY 10601
Attn: L. Macklin

U. S. Department of Transportation
Materials Transportation Bureau
Washington, DC 20590
Attn: J. Curtis, Director

Office of Hazardous Materials Operations (6)
U. S. Department of Transportation
Materials Transportation Bureau
Washington, DC 20590
Attn: A. W. Grella

U. S. Nuclear Regulatory Commission (6)
Office of Nuclear Regulatory Research
Fuel Cycle Research Branch
Division of Safeguards, Fuel Cycle,
and Environmental Research
Washington, DC 20555
Attn: W. Lahs

U. S. Nuclear Regulatory Commission (6)
Office of Nuclear Material Safety
and Safeguards
Washington, DC 20555
Attn: K. R. Chapman, Director

Battelle-Northwest (3)
Pacific Northwest Laboratory
P. O. Box 999
Richland, WA 99352
Attn: L. D. Williams

Deputy Assistant Administrator
for Radiation Programs
Environmental Protection Agency
401 M Street, S.W.
Washington, DC 20460
Attn: W. D. Rowe

U. S. Nuclear Regulatory Commission (6)
Office of Standards Development
Washington, DC 20555
Attn: R. B. Minogue, Director

DISTRIBUTION (continued)

International Atomic Energy Agency (IAEA) (50)
Division of Health, Safety and Waste Management
Vienna, Austria
Attn: G. E. Swindell

1000	L. C. Guynes
1200	L. D. Smith
1262	D. W. Larson
1280	T. B. Lane
1282	T. G. Priddy
1282	A. W. Dennis
1282	W. F. Hartman
1282	J. D. McClure (20)
1282	J. T. Foley, Jr.
1284	R. T. Othmer
1713	J. T. Risse
5400	A. W. Snyder
5430	R. M. Jefferson
5431	W. A. Von Riesemann
5433	R. B. Pope
5433	J. M. Freedman

Second Printing May 1983