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An Analysis of the Crush Environment for Light Weight Air Transportable Accident Resistant Containers

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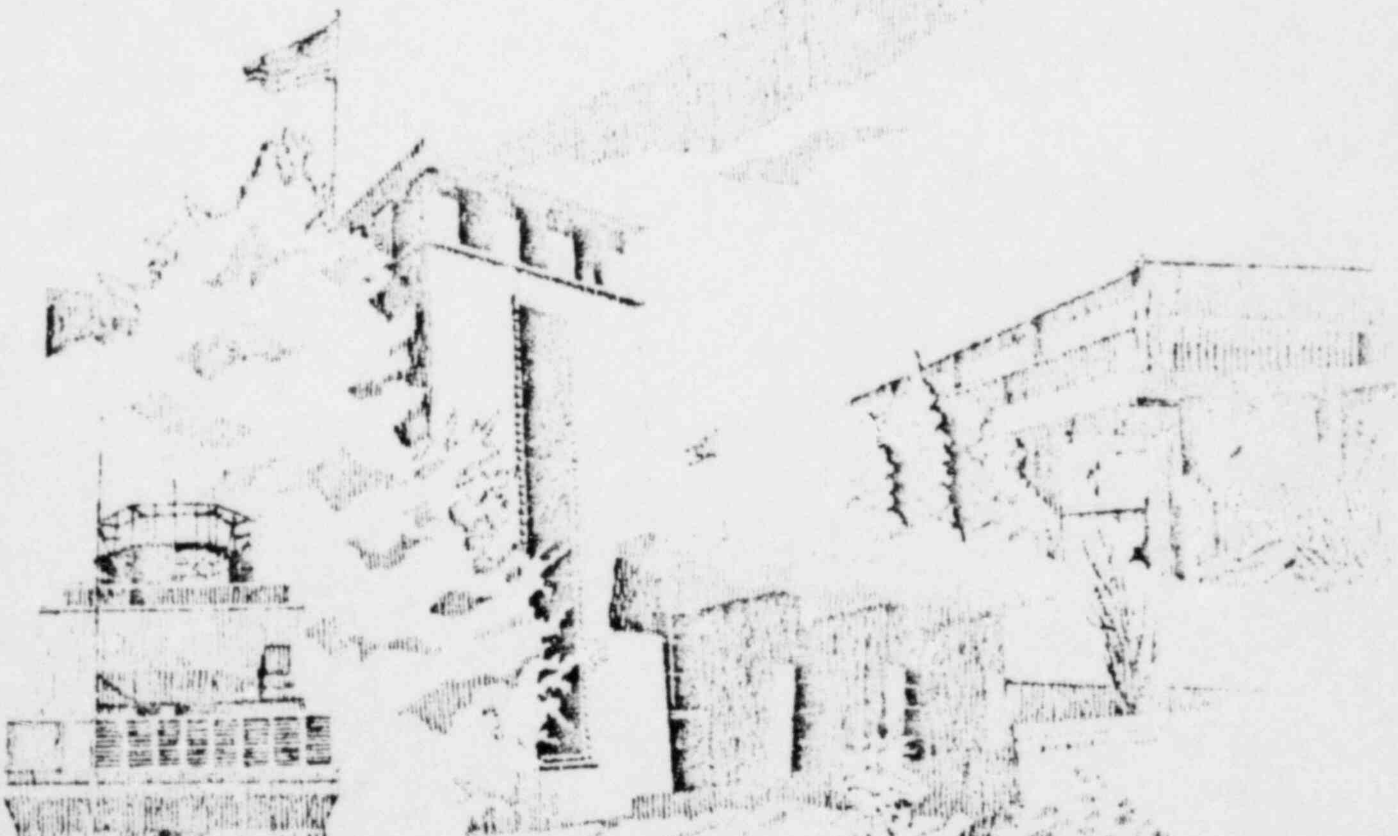

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AN ANALYSIS OF THE CRUSH ENVIRONMENT FOR LIGHTWEIGHT AIR-TRANSPORTABLE ACCIDENT-RESISTANT CONTAINERS

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ABSTRACT

This report describes the longitudinal dynamic crush environment for a Lightweight Air-Transportable Accident-Resistant Container (LAARC, now called PAT-2) that can be used to transport small quantities of radioactive material. The analysis of the crush environment involves evaluation of the forces imposed upon the LAARC package during the crash of a large, heavily loaded, cargo aircraft. To perform the analysis, a cargo load column was defined which consisted of a longitudinal prism of cargo of cross-sectional area equal to the projected area of the radioactive-material package and length equal to the longitudinal extent of the cargo compartment in a commercial cargo jet aircraft. To bound the problem, two analyses of the cargo load column were performed, a static stability analysis and a dynamic analysis. The results of these analyses can be applied to other packaging designs and suggest that the physical limits or magnitude of the longitudinal crush forces, which are controlled in part by the yield strength of the cargo and the package size, are much smaller than previously estimated.

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AN ANALYSIS OF THE CRUSH ENVIRONMENT FOR LIGHTWEIGHT AIR-TRANSPORTABLE ACCIDENT-RESISTANT CONTAINERS

Summary

The purpose of this analysis was to determine the magnitude of the crush forces that could be experienced by a small, accident-resistant package carried in the forward part of an aircraft cargo compartment during a severe aircraft accident. Two different analytical techniques were used. The first method attempted to establish the upper bound of the load on the package through consideration of the structural stability of the "cargo load column," i.e., that mass of cargo that inertially compresses the forward-positioned package under severe decelerations of the aircraft structure. The second analysis used a lumped-mass, plastically deformable model of the cargo load column to determine a realistic upper bound of the crush loads on the accident-resistant package. The results of this analysis are as follows:

1. The dynamic lumped-parameter model results in the largest estimate for the crush loads on the package. The magnitude of this crush force estimate is 210,000 pounds acting on a package the size of a Plutonium Air-Transportable, Model 2 (PAT-2), which is 14 inches in length and 15 inches in diameter.
2. The crush force estimate produced by a static stability analysis led to a maximum crush force of less than approximately 45,000 pounds acting upon a PAT-2-size package.
3. For the dynamic analysis, the magnitude of the crush force is governed primarily by the crush (yield) strength of the adjacent column of cargo and is independent of the cargo length. For the static analysis, the crush force is linearly dependent upon the total mass of the largest stable cargo load column and the maximum deceleration that the cargo load column is expected to experience.

Introduction

The nature of the environment associated with severe transportation accidents has already been studied in detail for relatively small packages.[1] The categories of environmental insult that can be applied to a radioactive-material (RAM) package have been divided into the categories of impact, fire, crush, puncture, and immersion. The severity or intensity level of these accident environment categories can be characterized by related parameters, e.g., the impact velocity of the package for the impact category. The temperature and fire duration can be used to characterize the fire and thermal environment. Similar characterizations of the other environmental categories can be made. The purpose of this analysis is to characterize the crush environment of the Lightweight Air-Transportable Accident-Resistant Container (LAARC), now also identified as the PAT-2 package.[2] An initial analysis of the crush environment for accidents involving U.S. commercial aircraft has been previously performed.[3] The analysis that is described in this report builds on the information in the earlier report and removes some of the conservative assumptions of the earlier analysis, partially by the use of additional information that has been obtained from a large commercial airfreight operation, the Flying Tiger Line.[4]

Extensive technical data was obtained from the Flying Tiger Line concerning cargo loading requirements and/or restrictions for two maximized cases: a large, wide-body air-freighter (747-100SF) with a 250,000-pound useful load and a very long, standard-body air-freighter (DC-8-63F) with a 100,000-pound useful load. Aircraft loading diagrams (see Appendix A) indicate maximum allowable cargo loadings for each case. The 747 cargo aircraft has 29 main deck positions for cargo containers or pallets; a main deck forward location in the nose for bulk cargo (individual items); 9 lower deck cargo positions; a lower deck bulk cargo zone; and an upper deck bulk cargo zone immediately aft of the flight deck and crew compartment. The maximum load for a standard 747 container or cargo pallet is 15,000 pounds; this maximum container loading cannot be cumulative for all containers (pallets), or the 250,000-pound useful load restriction would be exceeded. The DC-8 cargo aircraft has 18 main deck cargo positions for containers or pallets and two lower deck bulk cargo compartments (one forward, one aft). The maximum DC-8 pallet/container load is 13,300 pounds; again, this maximum load cannot be cumulative for all pallets/containers or the 100,000-pound useful load of the DC-8 would be exceeded. These facts and other information (see Reference 4) enabled the formulation of longitudinal crush models for this study.

The forces that act on the RAM package in the aircraft crash environment are represented by a cargo load column, as shown in Figure 1. The cargo load column is defined by the cross-sectional area of the package, the mass properties of the cargo, and a length that is the longitudinal extent of the cargo. The analysis that follows will be divided into two parts. First, a simple static analysis of the stability of a cargo load column will be presented. Second, a spring-mass computer model of an elastic-plastic cargo load column will be used to present a more detailed analysis of the dynamic load conditions on the RAM package under the assumption that no buckling of the cargo column takes place.

Each of these methods involves certain idealizations and deviations from a true description of the package loading, but the combination of the analyses should provide a reasonable bound on the magnitude of the loading forces. This combined analysis was performed specifically for the PAT-2 package. The stability analysis uses the geometry of the cargo load column, a maximum density of 20 lb/ft^3, and the assumed elastic properties of the cargo. The dynamic analysis uses a unit cross-sectional area for the cargo load column. The unit results of the dynamic analysis are applied to the geometry of the PAT-2 package and can also be applied to other packaging geometries.

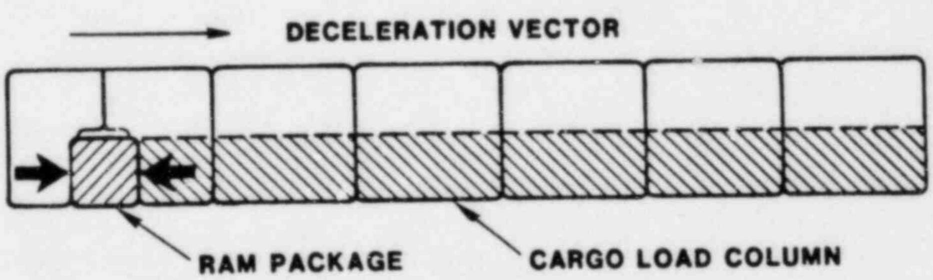


Figure 1. Longitudinal Crush Scenario

Mechanical Characterization of Aircraft Cargo

The effective modulus of elasticity of composite aircraft cargo is not accurately known. However, an estimate of this modulus can be made by examining the density and moduli of various materials such as those shown in Table 1.

Table 1

Density and Modulus Tabulation

Material	Density (lb/ft^3)	E ($lb/in.^2$) x 10^6
Aluminum	175	10
Cast Iron	480	13
Concrete	150	2
Steel	490	30
Wood	35	1.6

Note: Bulk aircraft cargo has a maximum density of 20 lb/ft^3 (see Reference 4).

Because the cargo density is relatively low compared to materials such as those shown in Table 1 and because E generally increases with increasing density, the modulus value for representative aircraft cargo was assumed to be in the range of 10^5 to 10^6 $lb/in.^2$. This range of values for the cargo modulus of elasticity was used to account for the variation in the actual materials that constitute general cargo.

Static Analysis--Cargo Load Column

The crush mode for a RAM package has been considered to be divided into two basic modes, vertical crush and horizontal or longitudinal crush. These crush modes have been analyzed in Reference 3, and the principal purpose of the present analysis is to reexamine the longitudinal crush mode. The rationale for the analysis in Reference 3 was that the analysis was an upper limit and assumed that the dynamic effects of all cargo aft of the package location were to be concentrated on a small hazardous-material package. On-the-scene observation of actual cargo containers and cargo loading and unloading operations[4] has led to the conclusion that this assumption is far too conservative. For example, the cargo containers for aircraft cargo operations require the "containerizing" of many small packages of assorted sizes and shapes. These containers are relatively thin-walled, are fabricated from sheet aluminum, and are easily deformable. The industry-wide average density for air cargo is about 8.5 lb/ft^3. Relatively dense cargo, such as a passenger car, is, on the average, around 20 lb/ft^3 (see Reference 4). These average values are used in the load-balance calculations performed by the air-cargo carriers. The thin-walled configuration of the air-cargo containers plus the low density of general cargo goods lead to the general conclusion that the relatively hard--and small--hazardous material package will deform the walls of an adjacent air-cargo container during longitudinal crush and be enveloped by the adjacent cargo as depicted in Figure 1.

The low stiffness provided by adjacent general cargo allows large deformations around the hard, small, hazardous-material package. These deformations produce the effect of cargo impinging upon cargo and cargo impinging upon and capturing a relatively hard hazardous-material package. This effect indicates that it is inappropriate to consider that all of the cargo aft of a hazardous material cargo location will be concentrated upon a single small package during a longitudinal deceleration. In effect, the relative ease with which a small, hard package can produce a cargo deformation, as envisioned in Figure 1, indicates that the dynamic crushing effects upon a hazardous-material package most probably will be produced by a "longitudinal column of cargo" aft of the package. For the purpose of this paper, the cargo load column is assumed to be a longitudinal prism with a cross-sectional area equal to the projected area of the package and a length equal to the longitudinal extent of the cargo. This loading configuration can be contrasted with that of the earlier worst-case analysis,[3] which essentially assumed that the package was sandwiched between a pair of nondeformable plates that transferred <u>all</u> of the inertial load from the aft cargo to the package. There is no known circumstance under which this loading model can occur.

The analysis that follows examines the structural stability of the cargo load column aft of the package that is being crushed, under the assumption that the cargo behaves elastically.

Observation of actual cargo loading operations indicates that containerized and palletized cargo volumes can be within 1.5 inches of the sidewalls of the fuselage on standard-body aircraft. Consequently, there is no access around containerized cargo in a standard-body cargo aircraft. Conversely, in wide-body cargo aircraft, such as the Boeing 747, a passageway exists for the length of the main cargo deck on both the left and right sides of the cargo positions. For both standard-body aircraft and wide-body aircraft, the longitudinal spacing between containerized and palletized cargo is approximately 1.5 inches. Pallet locks and cargo nets for palletized cargo help hold the cargo in a stable configuration.

Standard-body cargo aircraft contain a 9g barrier net with a million-pound capacity to contain the cargo and protect the crew from forward moving cargo in high-deceleration situations such as aircraft crashes. In nominal terms, aircraft crash loads experienced by the cargo can be represented by 9g longitudinal decelerations.[5] Aircraft structural limits are given by a 20g longitudinal deceleration.[5] Above approximately 20g of deceleration, the aircraft and the cargo load columns generally will disassemble.

A first-order analysis of the cargo load column can be performed by examining the free-body diagram of the cargo load column, Figure 2. For purposes of analysis, the cargo load column is assumed to have a cross-sectional area equal to the projected (frontal) area of the package. The cargo load column is of length ℓ and has a uniformly distributed weight of w pounds per linear foot. The deceleration of the aircraft during an aircraft crash is represented by the deceleration vector, which is a dynamic load factor, n, times the acceleration of gravity, g. The cargo load column, if subjected to the deceleration vector, (ng), would have an equal axial (longitudinal) force, F_D, applied to the package as shown in Figure 2.

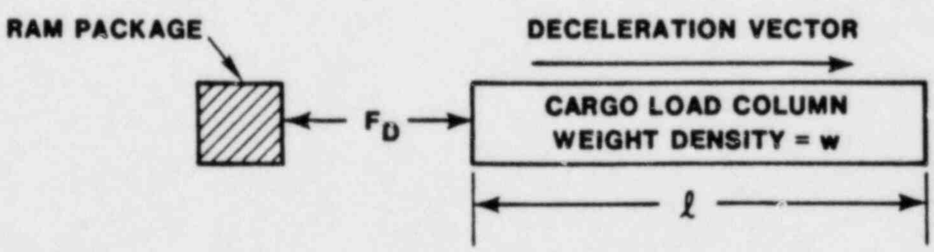


Figure 2. Free-Body Diagram--Cargo Load Column

The magnitude of the crush force created by the deceleration of the cargo load column is shown in Eq. (1).

$$F_D = \frac{w\ell}{g} (ng) \tag{1}$$

where

F_D = deceleration force

w = weight density of load column per foot

$w = \rho bh$

ρ = weight density of cargo (20 lb/ft^3)

b, h = cross-sectional dimensions of load column

g = acceleration of gravity (32.2 ft/s^2)

ℓ = length of cargo load column

n = dynamic load factor (number of g's deceleration)

If the cargo load column remains stable and intact, then the dynamic crush load on the package would be of magnitude F_D given by Eq. (1) and would involve the entire length of the cargo load column as governed by the geometry of a specific cargo aircraft. However, the length of the cargo compartments can be on the order of 100 feet or more,[4] and the question arises as to whether or not the mechanical disintegration of the aircraft during the crash process will provide the lateral confinement that will allow the prolonged existence of stable load column configurations and, hence, the prolonged application of longitudinal crush forces. In order to analyze this situation, it will be assumed that there is no lateral constraint of the cargo provided by aircraft structure during a crash, and the structural stability of the cargo load column geometry will be assessed using a simple stability model.

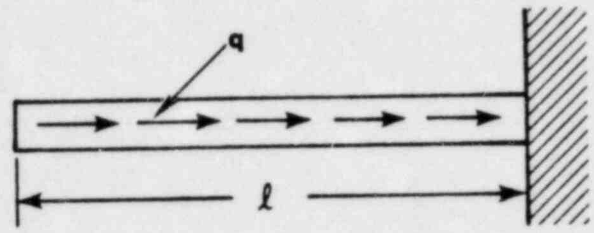
Because the longitudinal deceleration of the cargo load column provides a distribution of axial material inertial loads along the axis of the cargo load column, the stability model shown in Figure 3 will be used to analyze the stability of the cargo load column. It is further assumed that adjacent cargo can provide no lateral constraint of the cargo load column. Therefore, the stability analysis will determine the maximum stable length, ℓ_{cr}, of the cargo aft of the package. The determinination of such a stable length will give the physical limits of the magnitude of the longitudinal crush forces that can be applied to a package loaded in forward cargo locations. Once determined, the maximum stable length, ℓ_{cr}, if it is less than the entire length of the cargo compartment, can be substituted in Eq. (1) to estimate the magnitude of the longitudinal crush force.

The stability model shown in Figure 3 and Eq. (2) is from Timoshenko[6] and uses a fixed-end column with distributed axial loading similar to that which would be provided by the inertial loading of the cargo load column.

Eq. (2) is evaluated for two values of E and is shown in a graphic plot of the dynamic load factor, n, versus cargo column length, ℓ, in Figure 4. The value of n equal to 20g in Figure 4 represents the structural limits of the aircraft.[5] Values of n equal to 9g represent typical crash deceleration loads.[5] Referring to Figure 4, for the stiffest assumed cargo modulus, point A represents the maximum condition of deceleration, the 20g structural limit; point B is a representative cargo load column length, 100 feet. The maximum conditions associated with points A and B are evaluated using Eq. (1) and are given as follows:

Maximum Crash Loads--Cargo Load Column
(Based on structural stability of load column)

	Point A	Point B
n =	20	6.6 (from Eq. 2)
ℓ =	69 ft (from Eq. 2)	100 ft
w =	29.25 lb/ft	29.25 lb/ft
F_D =	40,300 lb	19,300 lb (from Eq. 1)
b =	15 in. (1.25 ft)	15 in. (1.25 ft)
h =	14 in. (1.17 ft)	14 in. (1.17 ft)



$q\ell$ = TOTAL AXIAL LOAD

$q = \frac{(\rho)(b)(h)}{g}(ng)$

$= nw$

ℓ_{cr} = STABLE LENGTH OF CARGO LOAD COLUMN

E = ELASTIC MODULUS OF CARGO

I = SECOND MOMENT OF AREA ABOUT BUCKLING AXIS

$I = \frac{bh^3}{12}$ (RECTANGULAR SECTION)

$$(\ell_{cr})^3 = \frac{7.837\ EI}{nw} \qquad (2)$$

Figure 3. Stability--Cargo Load Column

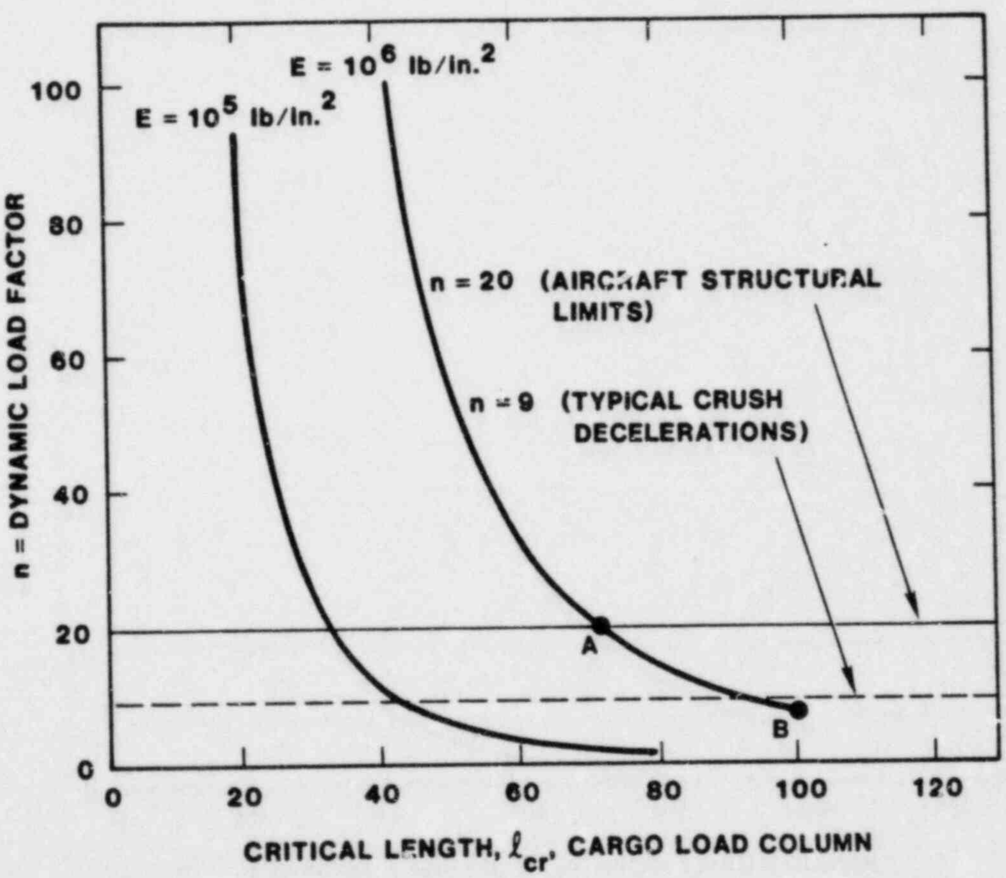


Figure 4. Dynamic Load Factor versus Critical Cargo Column Length [Eq. (2)]

Crush Analysis--Lumped-Parameter, Spring-Mass Model

This section of the crush analysis describes an elastic-plastic, lumped-parameter, spring-mass model that is used to determine the dynamic response of the cargo load column. The development of such a model is again not an exact representation of the crushing environment in an aircraft accident but is identified by the model as shown in Figure 5.

The dynamic model shown in Figure 5 consists of a fixed mass that represents the impact surface, the RAM package, and four discrete masses that represent the idealized cargo located aft of the package in the aircraft cargo space. The mechanical properties of the cargo are represented by hysteresis springs that model the loading and unloading modulus of the cargo and its ability to crush at predetermined loads that are related to the yield strength of the cargo.

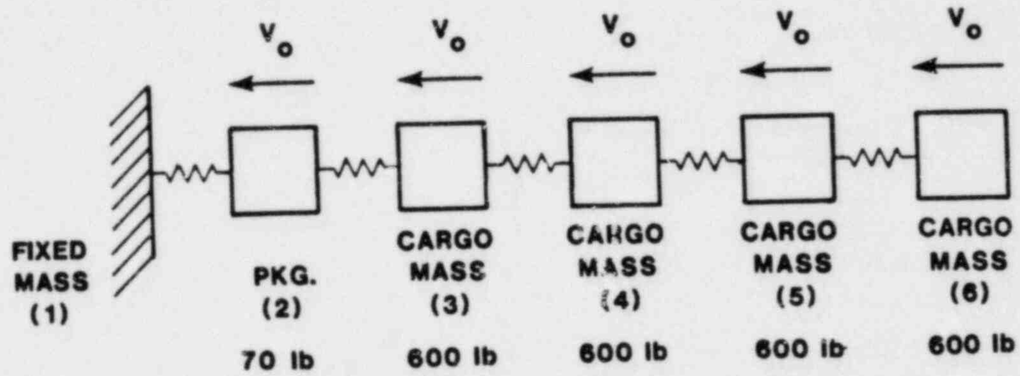


Figure 5. Lumped-Parameter Crush Model

The cargo load column, which is modeled by the configuration shown in Figure 5, is considered to be of unit cross-sectional area (1 ft^2) and 120 feet in length; it is assumed that no cargo buckling occurs. The 120-foot dimension is representative of the size of the aircraft that is currently the largest standard-body-width cargo jet, the Douglas DC-8-63F. The dynamic response for a unit cross-sectional area of cargo load column would have to be multiplied by the projected area of a package in square feet in order to obtain the total dynamic crush load on the package. The average weight density for air cargo is 8.5 lb/ft^3 (see Reference 4). The maximum density for air cargo, also from Reference 4, is approximately 20 lb/ft^3. A density of 20 lb/ft^3 was used in this analysis in order to establish a credible upper bound on the dynamic crush load on the package.

Two values of V_o were chosen for this analysis. The first value, 100 miles/hr, is representative of the preimpact velocity conditions described in full-scale crash tests of aircraft in Reference 5. The second value corresponds to the maximum impact velocity expected to be encountered in an actual aircraft accident, 288 miles/hr.

The mechanical characterization of the cargo was accomplished by using hysteresis springs in the lumped-parameter model. This type of spring model allows for the plastic yielding of the cargo rather than assuming that it remains elastic regardless of the magnitude of the load. The cargo was assumed to have a loading and unloading modulus of 1.0×10^5 lb/in.^{2} with a yield strength of 1,000 lb/in.^{2} (144,000 lb/ft^2). These values are believed to be representative of typical aircraft cargo, but, because the results of the calculation are dependent upon the actual magnitudes assumed, a few words of justification are in order. Aircraft cargo containers are very nonhomogeneous in density; the mass is usually localized in regions that are surrounded by empty space. Such variations in cargo density are difficult to model in a discrete fashion; therefore, for the purposes of this analysis, the cargo was modeled as a homogeneous volume of average density equal to 20 lb/ft^3. Materials with a 10- to 20-lb/ft^3 density typically have a modulus on the order of 10^4 to 10^5 lb/in.^{2} and characteristic yield stresses of approximately 1,000 lb/in.^{2} (Reference 7). The general description of the parameters involved with a spring-mass model, as generated by the computer program SHOCK, is presented in Reference 8; RAM package loading in this model is illustrated in Figure 6.

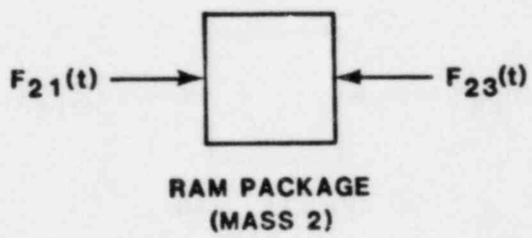


Figure 6. RAM Package Loading

Interpretation of Dynamic Analysis Results

The result of the dynamic analysis shown in Figures 7 through 10 is that the loading almost instantaneously rises to the yield strength of the cargo load column and levels off. This yield load of 144,000 pounds is dependent solely upon the yield strength of the adjacent cargo and is independent of the velocity of impact. The major difference that the impact velocity makes is to increase the duration of loading from about 75 ms for 100 miles/hr to 250 ms at 288 miles/hr.

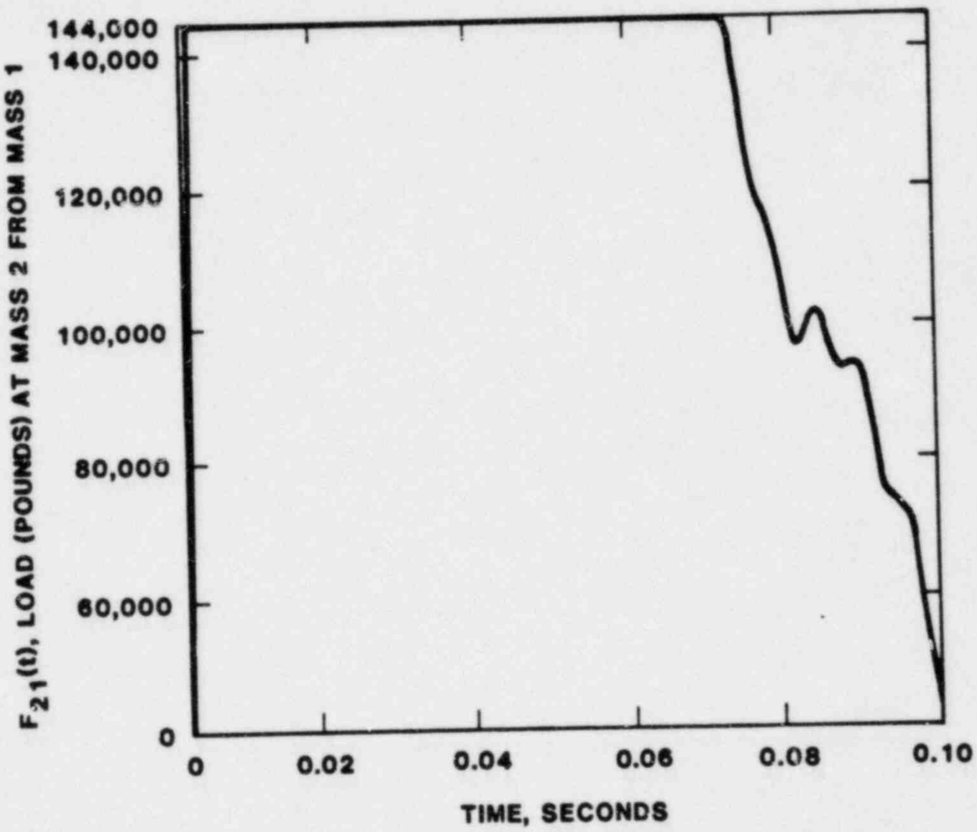


Figure 7. Dynamic Crush Load on RAM Package, $F_{21}(t)$

Some explanation of Figures 7 through 10 is helpful in understanding these plots. The output of the SHOCK code does not plot the net force on a specific mass but displays the force on a specific mass from an adjacent mass. This is depicted in Figure 7, which illustrates the action of the dynamic forces produced by an adjacent mass. $F_{21}(t)$ is the dynamic load on mass 2 from mass 1 (see Figure 6). A similar interpretation is used for $F_{23}(t)$. Both Figures 7 and 8 indicate that the column yield load magnitude is 144,000 lb/ft^2 and that these forces operate on the RAM package for essentially the same duration, approximately 0.07 second. Therefore, the crush load predicted by the data in Figures 7 and 8 would be the same as that which a one-square-foot container would experience if it were placed between the platens of a compression testing machine and subjected to 144,000 pounds for approximately 75 ms. For Figures 9 and 10, the load would again be 144,000 pounds, but the duration would increase to 250 ms.

Using the projected area (1.46 ft^2) of the PAT-2 package as an illustration, the maximum dynamic crush loading, as limited by the cargo yield strength, would equal (1.46) x (144,000) or 210,000 pounds.

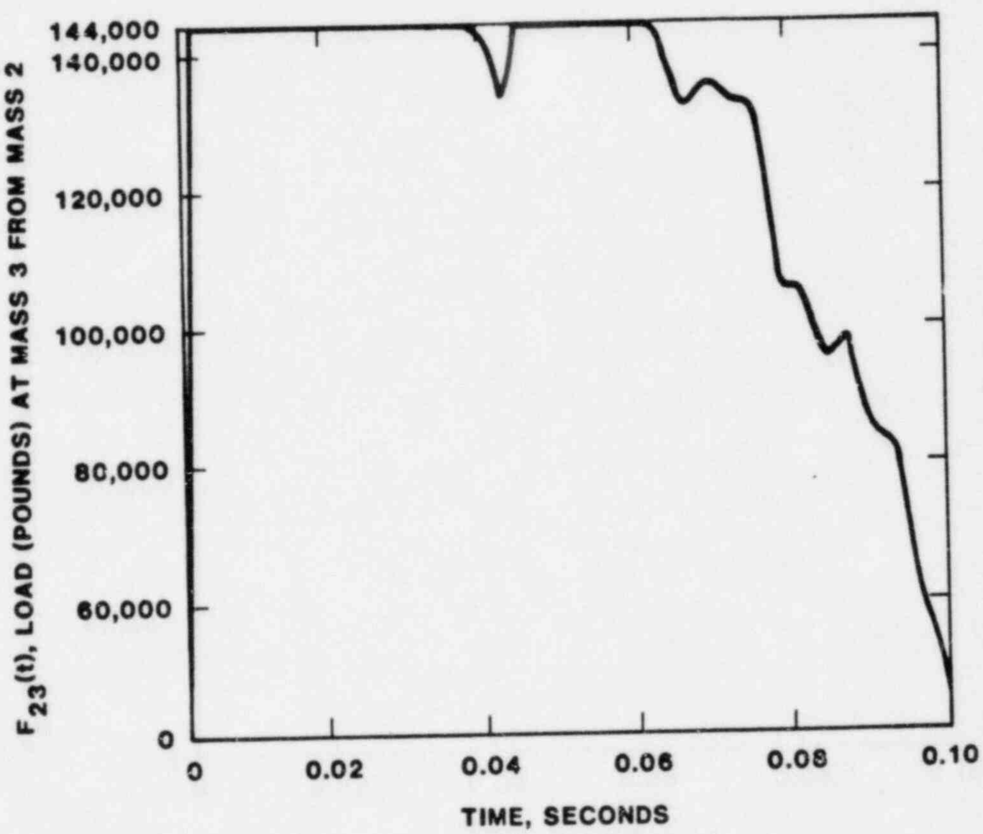


Figure 8. Dynamic Crush Load on RAM Package, $F_{23}(t)$

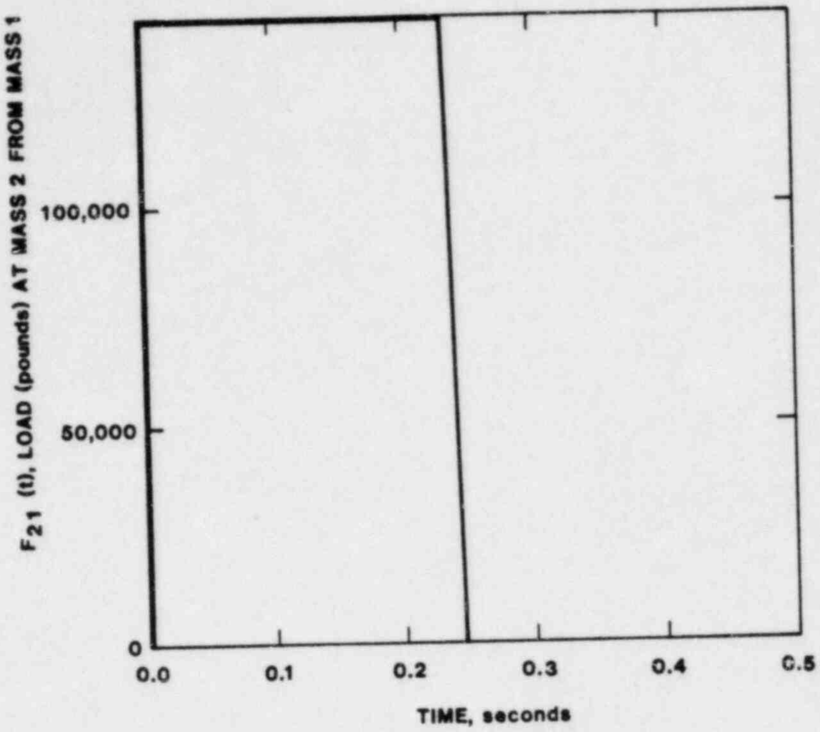


Figure 9. Dynamic Crush Load on RAM Package, $F_{21}(t)$

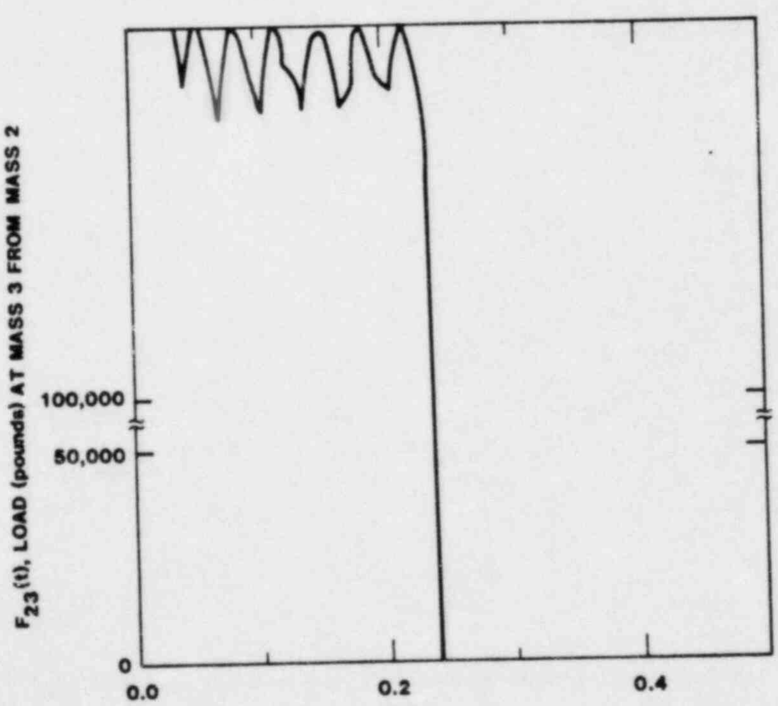


Figure 10. Dynamic Crush Load on RAM Package, $F_{23}(t)$

Conclusions--Lumped-Parameter Analysis

The analysis described above represents an attempt to determine the dynamic response of a cargo load column to an impact situation. The results of this analysis are very dependent upon how well the mechanical properties of general cargo are known. This analysis used an average representation of the cargo. The yield strength and material properties of general cargo are not known with great accuracy; however, the cargo properties used in this analysis are thought to be reasonably representative. In the dynamic lumped-parameter analysis, the cargo yield strength limited the magnitude of the crush load which was applied to the RAM package. It is concluded, therefore, that the determination (or estimation) of the cargo yield strength occupies a position of critical importance in the evaluation of the longitudinal crush loads which may be applied to the RAM packagings.

The model configurations used in this analysis are somewhat simplistic but give an insight into the loading that can be applied to hazardous-material cargo that is loaded in forward cargo stations or pallet positions. The loading on a hazardous-material package under the impact conditions is time varying as observed in Figures 7 through 10. The magnitude of the dynamic loading on the cargo column is limited by the yield strength of the cargo as represented by the hysteresis springs that were used to characterize the cargo. The dynamic crush load, as modeled in this study, was shown to be applied for a period of approximately 0.075 to 0.25 second; following this period, the load was reduced from this maximum value and oscillated to lower load values. The emphasis in these concluding remarks should be interpreted as being oriented toward the description of loading that can be applied to a generic hazardous-material (or radioactive-material--RAM) cargo package. The response of a particular packaging design to such a loading can only be determined by a detailed analysis or test of the packaging design when subjected to a loading as described herein.

Conclusions--LAARC Crush Analysis

This report has described two separate analyses; the purpose of these is to determine a reasonable upper bound of the dynamic loading conditions expected to be experienced by a hazardous-material package that is carried in a forward location in a cargo aircraft. The analysis reported here is somewhat generic in that the cargo was represented by a cargo load column that was assumed to represent cargo in general.

The first part of this analysis dealt with the structural stability of the cargo load column. The load that the cargo load column can impose on a package is a direct function of the effective length of the load column. The structural instability of the cargo load column working in combination with the disintegration processes that can occur in severe aircraft crashes will limit the dynamic crush loading on the hazardous-material package. Such physical limitations appear plausible based on the results of the stability analysis presented in the first section of this report.

The second portion of this report examined the dynamic loading that can be produced by the cargo load column as determined by a lumped-parameter, spring-mass model. Thus, two different analysis methods are given, both of which are approximate solutions to a complex problem. It has not been intended to offer these results as a definitive answer but rather to show that practical realistic limitations do exist. The judgment as to which of these methods most appropriately describes the crush environment probably does not need to be debated; the most important conclusion is that the maximum magnitudes of these forces on a package, using the size of PAT-2 as an example, are in the 100,000- to 210,000-pound range rather than an order of magnitude higher than this as was predicted by the initial, far more conservative analysis.[9] It is also important to note that the magnitude of the longitudinal crush load on the RAM package is a direct function of the size of the package, i.e., the projected area of the package crushed by the cargo load column.

The lumped-parameter analysis calculated the dynamic loading that could be applied to a hazardous material package in a forward cargo location. The maximum value of this loading is limited by the yield strength of the adjacent cargo. A reasonable maximum value of the loading developed by the cargo load column was 144,000 lb/ft^2. It must be remembered that this is the unit response for a cargo load column and that the total load applied to a package would be the unit response times the projected area of the package. For the current LAARC dimensions, this would be a projected area of approximately 1.46 ft^2; hence, the maximum dynamic crush load value as limited by the cargo yield strength is approximately 210,000 pounds. These crush loads may be large in magnitude, but they are of relatively short duration. In addition, it must be noted that the lumped-parameter model did not incorporate any structural stability arguments such as were presented in the analysis; if it were possible to include these effects, they would tend to decrease the maximum load that could be applied to the package.

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APPENDIX A

Aircraft Cargo Loading Drawings

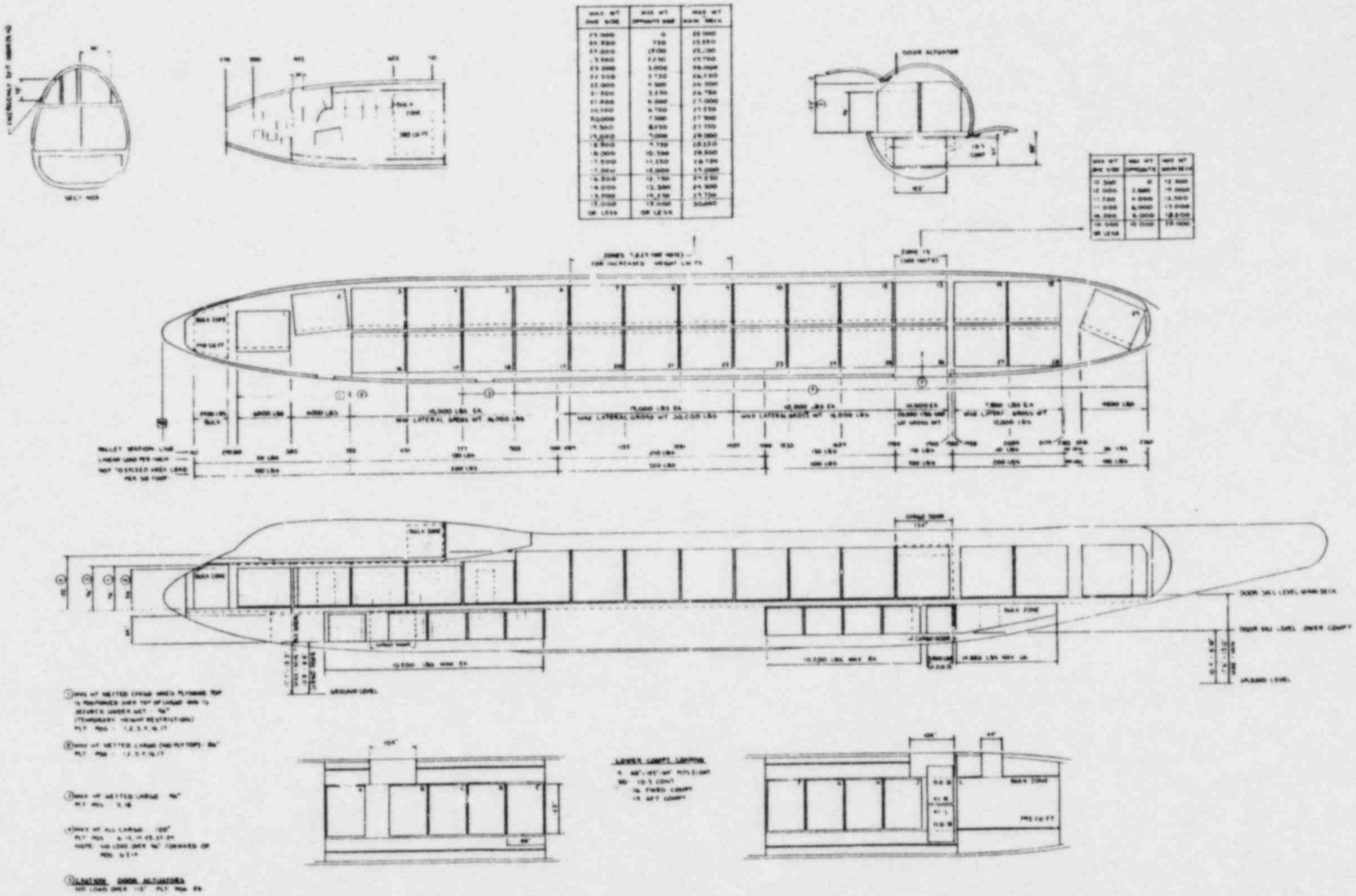

Figure A-1. 747 Cargo Configuration, Upper and Lower Decks. Scale: 1 in. = 80 in. (Flying Tiger Line drawing by T. J. Masterson, 25 May 1967.)

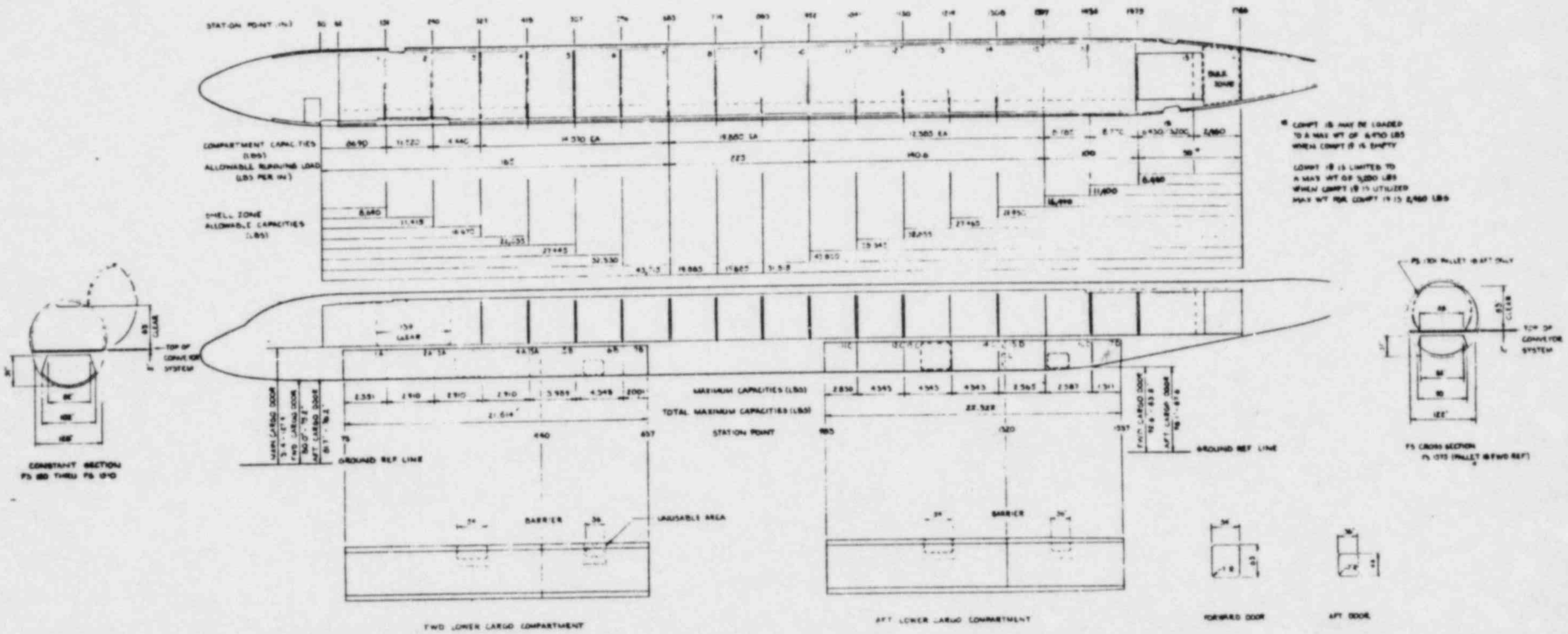

Figure A-2. DC-8 Cargo Configuration, Upper and Lower Decks. Scale: 1 in. = 80 in. (Flying Tiger Line drawing number 1534, by Masterson, revised 27 February 1979 RDF.)

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REF 8

Attachment I

Extended Crush Testing of the PAT-2 Package

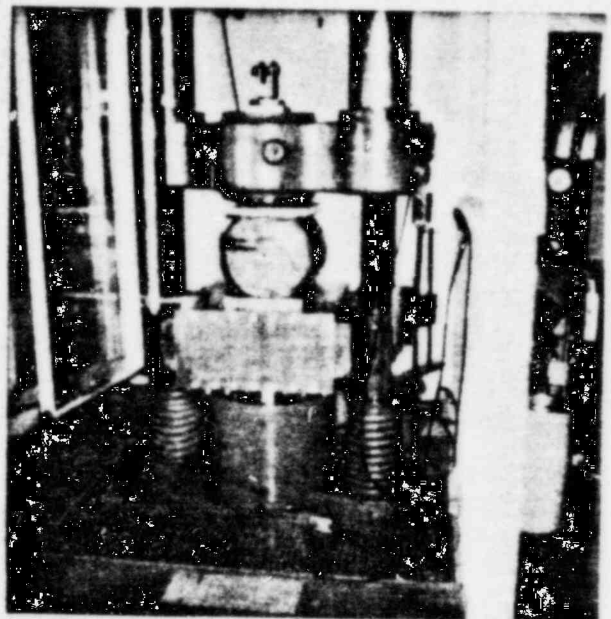
Reference: SAND80-0783, "An Analysis of the Crush Environment for Light Weight Air Transportable Accident Resistant Containers"

Background

The above referenced study assumes that the PAT-2 package (or any small package) is located in the most-forward possible location on the main deck of either the largest currently used standard body cargo aircraft (stretched DC-8, model DC-8-61F or DC-8-63F) or the largest currently used wide-body cargo aircraft (B-747F). The study assumes that the aircraft are loaded with the heaviest possible cargo load, and the makeup, composition, strength, rigidity, and other parameters of the cargo are characterized and maximized where appropriate. It is then assumed that the aircraft crashes onto its nose and that all the cargo is able to move forward and present a maximum crush threat to the package. Several mathematical (structural mechanics) models of column loading are defined: an Euler static buckling load, a dynamic buckling analysis, and a lumped-parameter dynamic analysis. The lumped-parameter dynamic analysis, made very severe by ignoring stability (buckling) considerations, produced the worst-case loading of 144,000 lb/ft^2 (6.9 MPa). Projected to the size of the PAT-2 package, this is a 210,000-pound (0.93-MN) crush load.

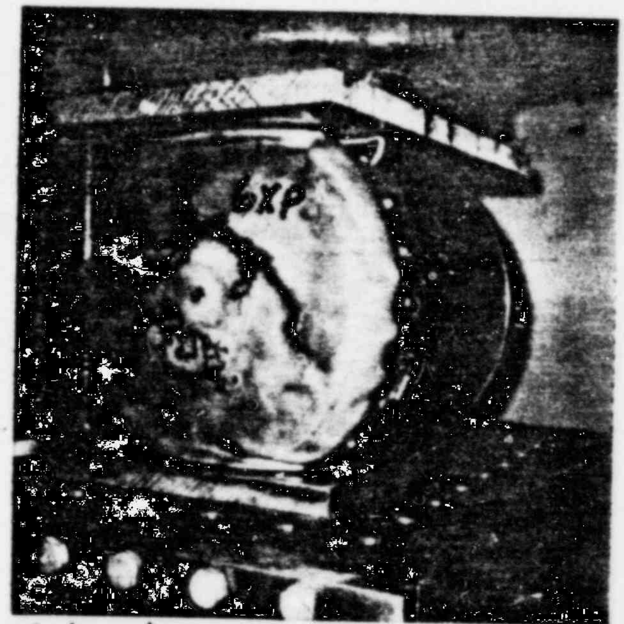
PAT-2 development model 6XP was crushed to the 210,000 pound (0.93 MN) load between rigid platens on a static test machine (Figure 1), resulting in a crushed height of approximately 13 inches (33 cm) (Figure 2). The package was then punctured (Figure 3) and double slashed (Figure 4) per NUREG-0360. A radiograph of this package after these tests is shown in Figure 5. The package was then burned and immersed per NUREG-0360. The post-test leak rate of the TB-2 containment vessel, which contained a plutonium sulfate surrogate, was $<10^{-10}$ cm^3/s helium; i.e., there was no detectable leak. The TB-2 containment vessel from 6XP contained a strong trace of helium when finally opened, confirming the validity of the helium leak-rate tests. The post-test condition of this package met all the NUREG-0360 acceptance criteria of containment, criticality, and shielding.

Another developmental PAT-2 package, X05, was subjected to a special test sequence beginning with extended crush. Two crush test goals were met: (1) to meet or exceed the recommended 210,000-pound (0.93 MN) load to qualify the forward-most location in any cargo aircraft, including the largest and heaviest aircraft, and (2) to produce at least as much total package deformation, as measured by the remaining package dimension in the direction of crush, that is produced in the NUREG-0360 high-speed impact test. These goals were met with a 500,000 pound (2.2-MN) load. The crush test was conducted between rigid steel platens on a Tinius-Olsen compressive test machine, which is shown in Figure 6. The package, originally 15 inches in diameter, was crushed to a thickness of 9-1/2 inches (24.1 cm), as shown in Figure 7. A radiograph of this test is shown as Figure 8. This package, which had been assembled with a severe surrogate $Pu(SO_4)_2 \cdot 4H_2O$ payload, was then sequentially tested to the NUREG-0360 criteria for puncture, double slash, and fire. The post-test leak rate of the TB-2 containment vessel was 2×10^{-9} cm^3/s air. The post-test condition of this package met all the NUREG-0360 acceptance criteria of containment, criticality, and shielding.



12/24/80 6XP Extended Crush Test 210,000 #

FIGURE 1



12/24/80 6XP Extended Crush Test 210,000 #

_Post Test

FIGURE 2

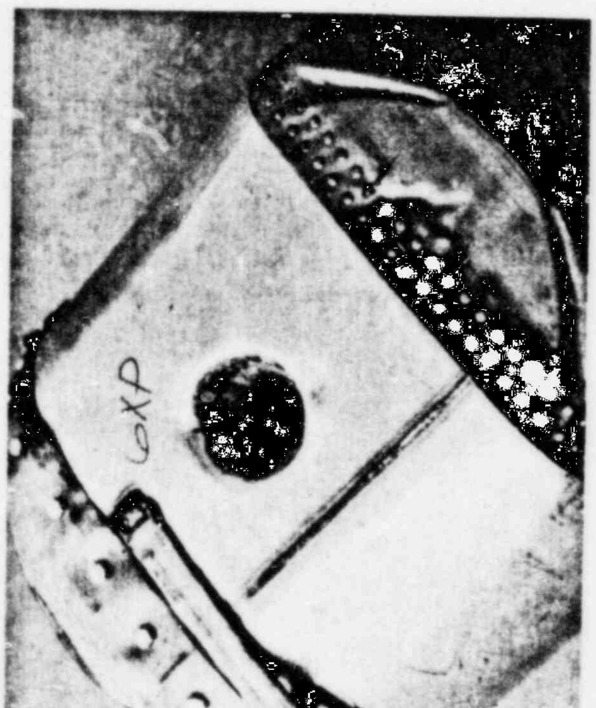


FIGURE 3

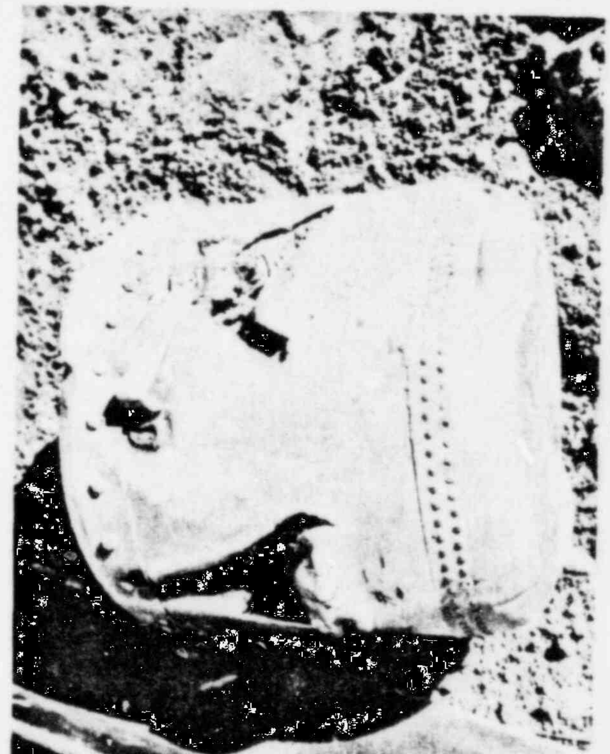


FIGURE 4

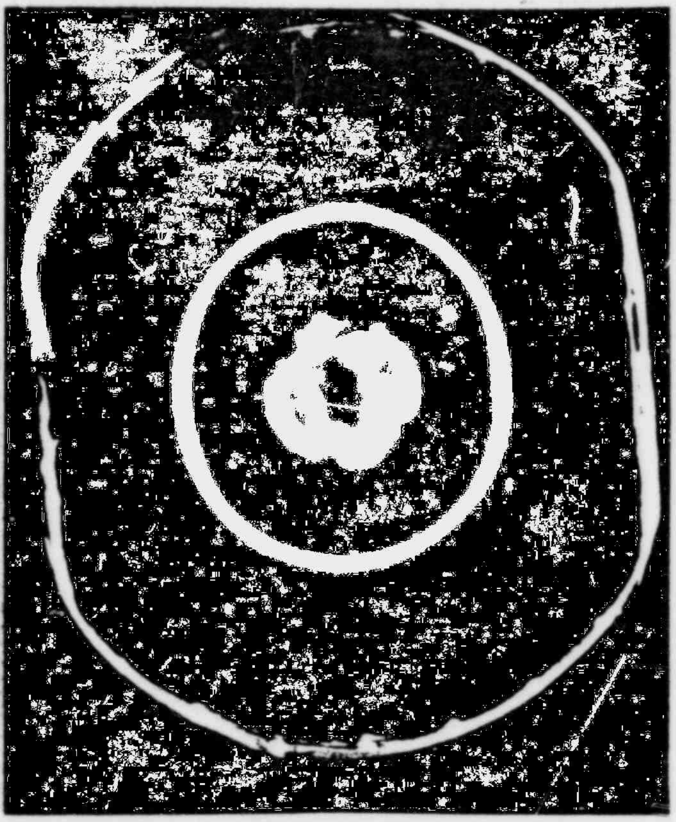
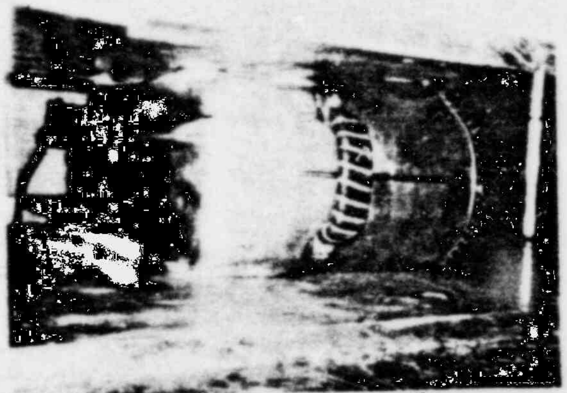


FIGURE 5



7-15-80 500,000# X05

Crush Test -tamper Simulation

FIGURE 6

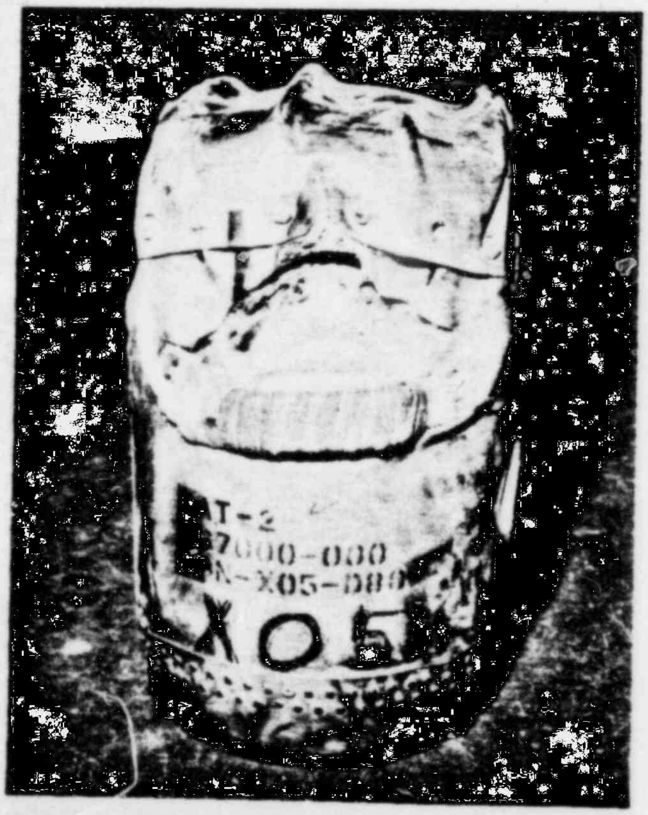


FIGURE 7

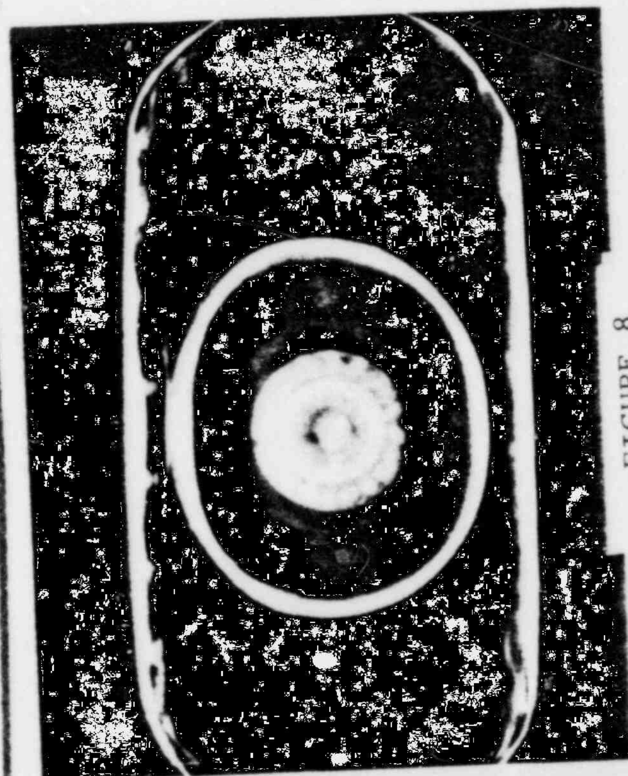


FIGURE 8