An Analysis of Severe Air Transport Accidents*

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INTRODUCTION

The objective of this paper is to analyze the severity of aircraft accidents that may involve the air transport of radioactive materials (RAM). One of the basic aims of this paper is to provide a numerical description of the severity of aircraft transport accidents so that the accident severity can be compared with the accident performance standards that are specified in IAEA Safety Series 6, the international packaging standards for the safe movement of RAM.

The existing packaging regulations in most countries embrace the packaging standards developed by the IAEA. Historically, the packaging standards for Type B packages have been independent of the transport mode. That is, if the shipment occurs in a certified packaging, then the shipment can take place by any transport mode. In 1975, a legislative action occurred in the U.S. Congress which led to the development of a package designed specifically for the air transport of plutonium. Changes were subsequently made to the U.S. packaging regulations in 10CFR71 to incorporate the plutonium air transport performance standards. These standards were used to certify the air transport package for plutonium which is commonly referred to as PAT-1 (U.S.NRC). The PAT-1 was certified by the U.S. Nuclear Regulatory Commission in September 1978.

*This work performed at Sandia National Laboratories, Albuquerque, New Mexico, supported by the United States Department of Energy under Contract No. DE-AC04-76DP00789.

**A United States Department of Energy Facility

The IAEA is in the preliminary phase of considering whether special regulations for the air transport of plutonium should be added to Safety Series 6. In this analysis we will present information on the severity of air transport accidents and relate the severity of these environments to the performance standards which are used to certify Type B RAM packages.

DESCRIPTION OF AIRCRAFT ACCIDENTS

The efficacy of the IAEA packaging regulations has been demonstrated through the historical safety record of RAM packagings. Packagings certified to these standards have survived actual accident conditions without release of contents. In addition, the packaging regulations are under almost continual study which includes the comparison of the package qualification standards with the severity of actual accidents.

A description of aircraft accidents is given in Figure 1. Figure 1 describes the various components of an aircraft transport accident. For example, the main elements of an aircraft accident can be divided into take-off accidents, approach accidents, landing accidents, inflight accidents and ground operations accidents. Percentages of aircraft accidents which represent these various components are given in Figure 1. Therefore, Figure 1 represents a description of aircraft accidents that have occurred. We shall use Figure 1 to provide a basis for the probability analysis of aircraft accidents presented in the next section.

Another characteristic of aircraft accidents is that the principal environmental threats come from impact and fire (Clarke). Recognizing this characteristic, we shall describe a typical aircraft accident in terms of these environmental threats. It is assumed that although puncture, crush, and other environmental forces such as immersion can be presented to a RAM package in an aircraft accident, the dominant forces are due to impact and fire. Table 1 displays the relative probability that a RAM package in an aircraft accident will encounter impact and fire (Clarke). From Table 1 we can observe that the possibilities are combinations of impact only, impact and fire and fire only. Furthermore, 47 percent of aircraft accidents do not involve either impact or fire.

In this analysis we assume that the accident velocity sustained by the RAM packaging is the aircraft velocity. We take no credit for any mitigation of the aircraft structure during the accident.

Figure 2 displays the velocity distributions for take-off, approach, and landing accidents. Similarly, Figure 3 (Clarke) shows the velocity distribution of in-flight aircraft accidents in general which ranges to approximately 150 m/s. The information in Figure 3 was extrapolated to sonic velocity, approximately 321 m/s (1052 ft/s), in order to provide a reasonable bound on impact velocity for the aircraft accident problem. Table 2 (Clarke) shows the cumulative probability of fire durations for aircraft accidents. In this analysis we shall consider three fire duration intervals in our calculations: 30, 60 and 120 minutes. Other fire durations could be used but these intervals represent the present regulatory fire duration interval and multiples of the basic regulatory interval.

Table 1

Distribution of Impact and Fire Components In Aircraft Accidents

Environment	Probability
Impact only	0.19
Impact and fire	0.22
Fire only	0.12
No impact or fire	0.47
	1.00

Table 2

Cumulative Probability Distribution (Aircraft Fires)

Fire Duration (Minutes)	Cumulative Probability
0-20	0.67
20-30	0.78
30-60	0.91
60-100	0.96
100-120	0.97
120-140	0.98
140-160	0.99
160-180	1.00

PROBABILITY ANALYSIS OF AIRCRAFT ACCIDENTS

In this section we develop an expression for the probability that the impact velocity in the various accident components (take-off, landing, in-flight etc.) will be less than some specified magnitude. In addition, we include the probability that the fire duration shall be less than some specified magnitude. The expression will use events presented in Figure 1 and additional information about the occurrence of impact and fire environments that was presented in Table 1. Specific combinations of impact velocity and fire duration will be evaluated in the probability equation. Assuming a RAM package has been certified to these environmental levels, the probability that a RAM package in an aircraft accident would be exposed to these environmental magnitudes (or lesser magnitudes) is a numerical measure of the protection provided by the RAM package.

The expression representing the probability discussed above is presented in Eq. 1. Since we will be thinking in terms of protection levels, we shall use the symbol PL to represent the expression. Therefore,

$$PL = 0.19[0.124(AVTO) + 0.266(AVA) + 0.209(AVL) + 0.368(AVIF) + 0.033(AVGO)]$$

(impact only component)

$$+0.22[0.124(AVTO)(AFD) + 0.266(AVA)(AFD) + 0.209(AVL)(AFD) + 0.368(AVIF)(AFD) + 0.033(AVGO)(AFD)]$$

(impact and fire component)

$$+0.12[0.124(AFD) + 0.266(AFD) + 0.209(AFD) + 0.368(AFD) + 0.033(AFD)]$$

(fire only component)

$$+ 0.47 \tag{1}$$

(no impact or fire component)

AVTO	=	cumulative distribution of velocity for take-off accidents
AVA	=	cumulative distribution of velocity for approach accidents
AVIF	=	cumulative distribution of velocity for in-flight accidents
AVL	=	cumulative distribution of velocity for landing accidents
AVGO	=	cumulative distribution of velocity for ground operation accidents
AFD	=	cumulative distribution of fire duration for aircraft accidents
PL	=	protection level for aircraft accidents for a specified impact velocity, fire duration pair

The protection level for aircraft accidents, PL, can be evaluated for specific magnitudes of impact velocity and fire duration. The magnitude of the variables AVTO, AVA, AVIF, and AFD can be taken from Figures 2, 3 and Table 2. It is assumed that there are no ground operations impact velocity magnitudes, AVGO, that can severely damage a package thus AVGO is assumed to equal 1.0.

THE CONSIDERATION OF TARGET HARDNESS IN ACCIDENT ANALYSIS

There are a number of categories of natural material on which RAM package can impact during an accident. We have broadly grouped these into the categories of water, soft soil, hard soil, soft rock, and hard rock. The estimates of the occurrence of water, soil and rock targets along major airline routes in the U.S. have been investigated and are shown in Table 3 (Clarke). Intercontinental flights will have larger components over water.

The unyielding impact target specified in the IAEA packaging regulations is thought to occur only on an infrequent basis in actual accidents. Earlier work (McClure, Gonzales) has discussed the wide range of impact velocities that can be presented to RAM packages in accident situations.

Table 3
Calculated Probability Of Impacting
Surfaces of Differing Hardness
Under Flight Paths Between Major US Air Hubs

Target Material	Probability
Water	0.18
Soft soil	0.28
Hard soil	0.40
Soft rock	0.09
Hard rock	0.05

In order to include the possibility that an unyielding impact target can be encountered, the probabilities in Table 3 will be altered slightly to change the hard rock value to 0.04 and to assume the probability that an unyielding impact target can be encountered in one percent (0.01) of the aircraft accidents.

In impact accidents, it is possible to have much larger impact velocities on softer targets such as soft soil, soft or hard rock etc. and have essentially the equivalent damage that would occur with a much smaller impact velocity onto an unyielding target. Approximate values of these velocity ranges were presented in McClure. The magnitude of these impact velocity ratios and the probability of impacting targets of varying hardness are shown in Table 4.

Table 4

Correction for Impact Target Hardness
(Example: Take-off accident, VEF = 100 ft/s, (30.5 m/s)

SURFACE	VR	VEF	PVEF	PI	NP
Water	4.5	450	1.0	0.18	0.18
Soft Soil	7.0	700	1.0	0.28	0.28
Hard Soil	3.0	300	1.0	0.40	0.40
Soft Rock	2.5	250	0.500	0.09	0.045
Hard Rock	2.2	220	0.340	0.04	0.0136
Unyielding	1.0	100	0.06471	0.01	0.0006471

Sum of NP column equals = 0.9192471 weighted probability of accident velocity equal to or less than the accident velocity of 100 ft/s (30.5 m/s) (weighted for target hardness).

where:

VR	=	equivalent velocity ratio for specified target material
VEF	=	impact accident velocity magnitude
PVEF	=	probability that velocity is equal to or less than the impact velocity magnitude (obtained from cumulative distribution curves).
PI	=	probability of impacting the specified target medium (soft rock, hard rock, etc.)
NP	=	the probability (product) of PVEF and PI.

In the aircraft accident probability expression, Eq. 1, each of the individual terms, AVTO, AVA, AVIF, AVL must be corrected (weighted) according to the example shown in Table 4. These corrected or weighted values for the variables AVTO etc., are used to calculate the the protection level, PL, for air transport. The calculated value of the protection level will include the effects of target hardness.

COMPARISON OF EXISTING REGULATIONS WITH THE SEVERITY OF AIRCRAFT ACCIDENTS

Figure 4 displays the protection levels calculated according to the procedures described above. The characteristic of the curves in Figure 4 is that the protection level rises sharply from small impact velocities and bends over to form a "knee" and asymptotically approaches complete protection of 100 percent. Superimposed on the protection level curves are the protection levels associated with the current regulatory tests for impact, 13.4 m/s (44 ft/s) and a fire duration of 30 minutes. In addition, the protection level associated with the regulatory tests for the U.S. air transport regulations for plutonium of 129 m/s (422 ft/s) for impact and 60 minutes for fire and the current IAEA proposal of 85 m/s (279 fps) and a one hour fire are also superimposed onto Figure 4.

From a regulatory viewpoint, increases in the severity level of the certification tests would cause movement to the right along the protection level curve. Above the "knee" of the curve such movement could cause increases in package development costs without significantly increasing the level of protection.

The existing regulatory level of protection for a Type B package (9.3 m/s accident velocity and a 30 minute fire) is somewhat below "knee" of the protection level curve for air transport accidents. The protection level for Type B packages is well above the knee for surface transport but not nearly as protective in the air transport mode.

A relatively large zone of high protection levels exists for impact velocities greater than approximately 45 m/s (147.6 ft/s) It is worth noting that extension of the regulatory fire duration interval extended to 120 minutes and achieves the same protection level for air transport offered by the NUREG-0360 criteria but at a lower impact velocity.

CONCLUDING REMARKS

In this analysis we have attempted to place a numerical value or figure of merit on the protection offered in air transport accidents for RAM packages certified to specified values of aircraft impact velocity and fire duration. Comparison of the protection levels with the impact and fire parameters associated with them allows regulatory working groups to consider changes to the packaging and transport regulations in the area of air transport of RAM.

The character of the protection level curves in Figure 4 is such that there is a distinct "knee" or zone of curvature as the curves transition from small impact velocities to larger velocity magnitudes. It is in this domain that the impact velocity approaches large magnitudes and higher and higher protection levels in an asymptotic manner. From a regulatory viewpoint, it is prudent to have the regulatory values for impact test velocity located above the "knee" of the protection level curve, but the asymptotic character of the protection level curve means that large increases in impact velocity standards (and package costs) yield very little increase in public safety.

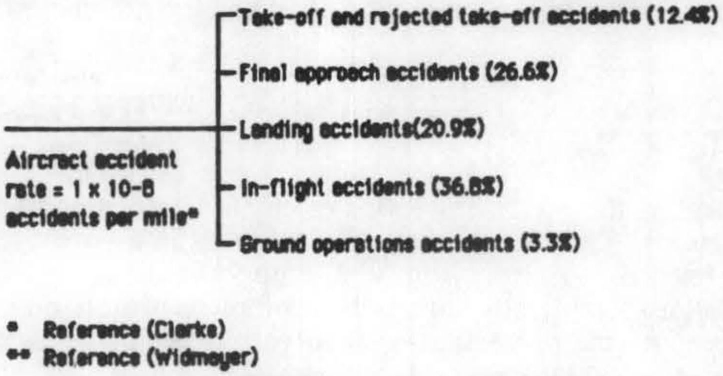

Figure 1
Aircraft Transport Accident Logic Diagram **

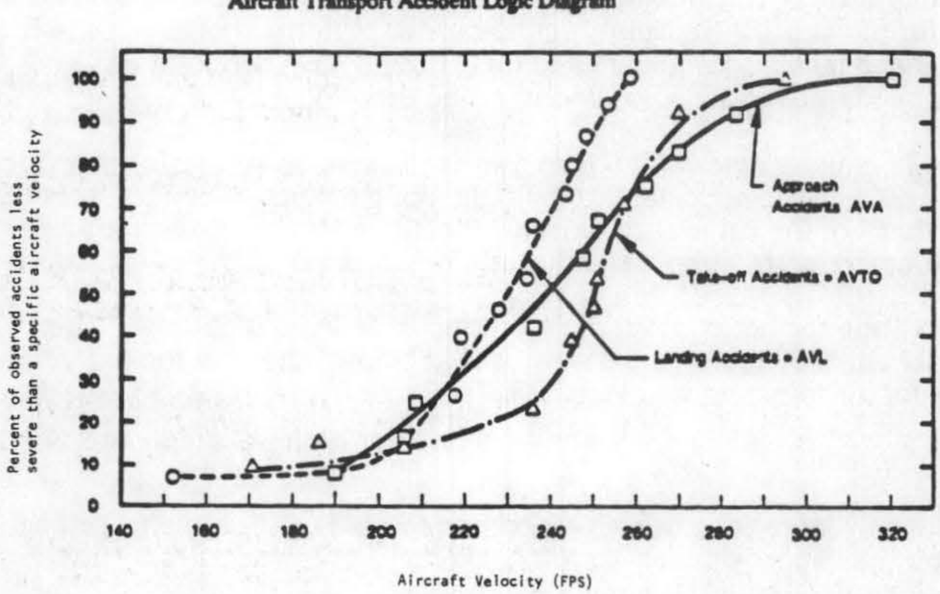

Figure 2
Cumulative Velocity Distributions For
Take-Off, Approach, Landing Accidents

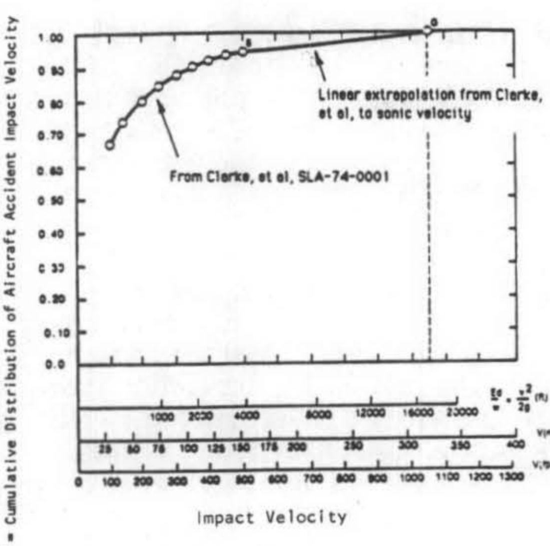

Figure 3
Cumulative Velocity Distributions For In-Flight Aircraft Accidents

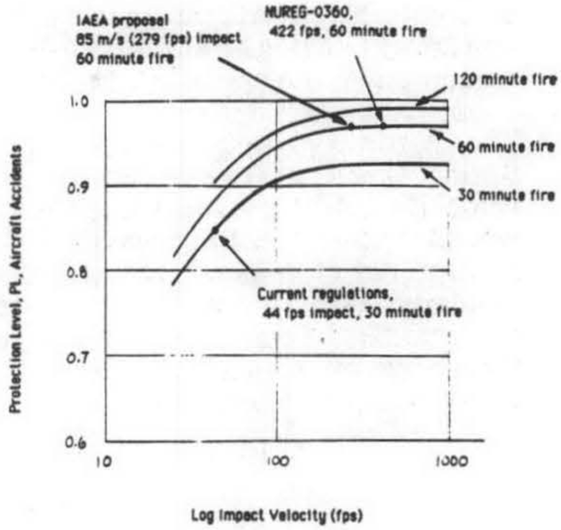

Figure 4
Protection Level versus Impact Velocity
Aircraft Accidents

REFERENCES

Clarke, R.K., Foley, J.T., et al, "Severities of Transportation Accidents," SLA-74-0001, Sandia National Laboratories, (July 1976).

Gonzales, A., "Comparison of the IAEA Unyielding Surface to Various Yielding Targets," SAND 86-2802, TTC-0708, Sandia National Laboratories, (1987).

IAEA, Safety Series No. 6, Regulations for the Safe Transport of Radioactive Material, International Atomic Energy Agency, (1985).

McClure, J.D., Yoshimura, H.R., et al, Relative Response of Type B Packagings To Regulatory and Other Impact Environments, Vol. II, Proceedings, PATRAM-80, (1980).

U.S. NRC, "Qualification Criteria To Certify A Package For Air Transport Of Plutonium," NUREG-0360, Office of Nuclear Material Safety and Safeguards, (January 1978).

Widmayer E., Brende, O.B., Commercial Jet Crashworthiness, Boeing Commercial Airplane Co., prepared for NASA-Langley, NASA-CR-165849, DOT-FAA-CT-82-68, National Aeronautics and Space Administration, (1982).