THE RESULTS OF A COORDINATED RESEARCH PROJECT INTO THE SEVERITY OF AIR ACCIDENTS

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ABSTRACT

An extensive study was carried out to determine whether the Type C hypothetical accident conditions were representative of real life. This study involved the analysis of all significant air accidents and comparing them to the test requirements. This paper presents a summary of this study.

INTRODUCTION

In order to investigate the effectiveness of the regulatory requirements, the IAEA established, in 1998, a CRP on *Accident Severity During Air Transport of Radioactive Material*. The overall objective of the CRP was:

"to study the issues related to aircraft accident forces by collecting and analyzing aircraft accident data to develop a better understanding of accident frequencies and severity." The objectives of the CRP included collection of additional relevant data and analysis of it so that the accident forces to which a package of radioactive material might be subjected can be further quantified. This quantified information should make the underlying data for decisions on regulatory test requirements more up to date and reliable. The expected result of the CRP was a better understanding of the technical basis of the regulatory test conditions. The CRP was not expected to make recommendations on test conditions.

Six Member States and two International Organizations agreed to undertake the research to support the project. These were Canada, France, Germany, Sweden, United Kingdom, United States of America, International Civil Aviation Organization, International Federation of Air Line Pilots' Associations

APPROACH TAKEN BY THE CRP

During the course of an aircraft accident, various accident environments are generated which impose stresses on packaging designed to contain radioactive material. These accident environments can be categorized as mechanical impact, thermal, and water immersion. The mechanical impact environment includes direct surface impact, puncture, and crush. In addition, the sequencing of accident environments is also important when considering the stresses imposed on packaging during an aircraft accident.

The assessment of the severity of the mechanical impact accident environment, as a result of an aircraft accident, is limited to analyzing the loading due to impact forces only. Although the puncture and crush loadings may also be present during an aircraft accident, this evaluation of the impact environment assumes that the dominant forces are due to the impact loads and, therefore, the puncture and crush environments are not evaluated. Additionally, it was concluded by the CRP members that the resources and time required to evaluate the puncture and crush environments would be considerable and the CRP should focus on other accident environments.

The CRP members collected, reviewed and analyzed the pertinent information on frequency and severity of air accidents related to the challenges of impact, fire and immersion posed to a package in severe air accidents and assessed it against the Type C packaging requirements. Aircraft accident data were taken from the ICAO accident data report (ADREP) and the accidents that were considered are those involving commercial aircrafts for weight classes corresponding to ICAO Category 4 and Category 5, that occurred from 1990 until 2000 and further limited to accidents that resulted in destruction of the aircraft and had a normal impact speed greater than 60 $m.s^{-1}$. However, for fire and water immersion all of the aircraft accidents that have occurred after 1990 were considered.

Actual data reported in accident reports were not readily available in a form enabling easy comparison to Type C package test requirements since the aircraft accident data are collected for purposes other than the purpose of this CRP. The emphasis of accident investigations and reports is to evaluate the cause of the aircraft accident and, particularly for passenger flights, to address safety-related issues. For example, fire fighting efforts are often reported as "effective" or "not effective." These recorded data needed to be supplemented with additional data that can be used to derive parameters that are comparable to packaging requirements.

The evaluations of available data involved

- interpretation and analysis by making quantitative inferences from generally qualitative data on accidents
- deterministic characterization of accidents
- assessments based on probability distributions and
- using results of previous analyses and best judgment.

The evaluations thus made were compared with Type C package test requirements.

Equivalent impact velocities were derived from the actual impact velocities on real targets normal to the surface. The equivalent impact velocity represents the velocity at which a package impacting an unyielding surface would suffer the same damage as it would impacting a real surface at the actual impact velocity.

Thermal stresses were considered due to thermal loading generated by fires internal to the aircraft prior to impact and by fires generated by the impact. Factors related to the magnitude and frequencies of aircraft thermal loads that were considered include: fire temperature, fire duration, fire size, and package location relative to the fire. Compared to impact velocity figures, available information on fire severity (intensity and duration) is sparse and inaccurate.

Water immersion environments can occur during both sea and air transport modes. Water immersion during the course of an accident imposes stress on a package through increased pressure and corrosion/deterioration of packaging seals. In the reports, the immersion depth is divided into three categories, deep water (depth > 200 m) which cover the oceans, shallow water ($200 \text{ m} \geq$ depth ≥ 15 m) which applies to ocean shelf and lakes etc and very shallow water (depth < 15 m).

Aircraft accident environments normally involve several stresses imposed on packaging in a sequential manner. To gain an understanding of these accident sequences, the data obtained from the ICAO ADREP (Accident/Incident Data Reporting) system for aircraft accidents that involve the destruction of the aircraft for the period, 1990 to 2000, were reviewed and evaluated. The data provided the following six events associated with aircraft accidents: Ground Impact; Impact in Flight / Collision; Post-impact Fire; Not post-impact Fire; Explosion; and Immersion. ADREP data categorizes aircraft accidents into accidents involving a single event, two events in a sequence, three event-sequence; and four or more events in the sequence.

AIRCRAFT ACCIDENT DATA COLLECTION

An extensive effort was conducted by the CRP to collect, review, and record pertinent worldwide aircraft accident data for use in developing accident environment severities. This effort included three phases of activity.

- The first phase was a review of the complete set of worldwide accident data to identify those accidents most pertinent to represent commercial aircraft operations and severe accident environments.
- The second phase involved collecting detailed accident data from aircraft accident reports, accident files and accident investigation organizations of countries where the accident occurred.
- The third phase included the development of an accident database that is used to evaluate accident environment severity.

The preliminary review of worldwide aircraft accidents since the end of Second World War identified over 5000 accidents involving all types of aircraft and aircraft operations. The CRP concentrated on identifying accidents representative of modern aircraft and involving the most severe accident environments. Accidents involving large commercial aircraft were considered to result in the most severe accident environments since these types of aircraft are normally used in cargo operations, have operating envelopes in the upper velocity range, and carry large amounts of fuel. Therefore, the evaluation of the data was limited to those accidents involving Civilian Commercial aircraft operation for two aircraft weight classes:

- aircraft with a maximum takeoff weight between 27,001 kg and 272,000 kg; and
- aircraft with a maximum takeoff weight over 272,000 kg.

These weight ranges correspond to ICAO Category 4 and Category 5, respectively, as defined in the ICAO ADREP reports. All types of aircraft are considered: jets; turbo-prop; and propeller driven aircraft.

Additionally, only those accidents that resulted in the destruction of the aircraft were identified. Accidents involving fatalities or serious injuries without related destruction of the aircraft were not considered. However, aircraft accidents were not restricted to those events that occur during the course of normal flight operations, accidents during ground operations were also included.

Initial efforts at collecting and evaluating data concentrated on accidents that have occurred since 1990. Further, it was agreed by the CRP to use a “coarse filter” for prioritizing the large number of accidents and for developing, in particular, a better understanding of the most serious air transport accidents. It was recognized that the application of this coarse filter would concentrate on only the most serious impact accidents in the spectrum of accidents involving total aircraft loss. The coarse filter was defined by using a normal impact velocity of greater than 60 $m.s^{-1}$. The normal impact velocity compares the recorded data to the relationship between calibrated air speed, altitude and true airspeed.

The application of the accident selection criteria and coarse filter resulted in identifying approximately 135 accidents that have occurred between 1990 and 2000 involving aircraft with a certified take-off weight greater than 27,000 kg and impact velocities greater than about 60 $m.s^{-1}$.

However, limiting the evaluation to high-speed accidents also eliminates accidents involving fire and immersion, therefore, data concerning fire and immersion from all of the aircraft accidents that have occurred between 1990 and 2000 is considered.

At the outset the CRP noted that there was data on 5000 aircraft accidents since the World War II. Upon determination of the aircraft categories and the period for which the data could be relevant to the CRP, the size of the accident database was 338. Of these accidents, two events included two aircrafts each. That is, the database included 336 accidents involving 338 aircrafts.

The criterion of high impact velocity, i.e., impact velocity > 60 m/s, resulted in 135 accidents to be considered. In response to the questionnaires sent to various States, 66 datasets were collected. Correcting for events involving two aircrafts yielded 64 accidents. Of these, one incident related to an aircraft of a category considered not relevant to the study. Of the remaining 63 accidents, 10 occurred (2 in the UK and 8 in the USA) during periods outside the range of dates considered in the study. Thus the sample size matching the selection criteria was 53 accidents. Due to the low probability of water immersion accidents, the analysis of water immersion was extended to the 64 accident database.

IMPACT

Impact data are corrected for normal impact velocity and for equivalent impact velocities for a real target. This data can be compared to the impact testing requirements for a Type C packaging on an unyielding surface. The equivalent impact velocity represents the velocity at which a package impacting an unyielding surface would experience the same damage as a package impacting the real surface at the actual impact velocity.

Given an accident, the most probable impact velocity occurs between 50 and 80 $m.s^{-1}$ indications are that there is a 90% probability that the impact velocity given an accident is less than or equal to ~160 $m.s^{-1}$. That is, there is a ~10% probability that the impact velocity is greater that 160 $m.s^{-1}$.

Translating these results to the 90 $m.s^{-1}$ impact velocity, the probability that the collected impact velocity is above 90 $m.s^{-1}$ is about 19.3%. That is, there is about a 19% probability that the impact velocity will be greater than 90 $m.s^{-1}$.

It should be noted that the calculated 19% probability does not consider a correction required for the equivalent impact velocity. For example a 100 m/s, at 60^o, impact onto a mixed surface (vehicles on the ground, structures, tall vegetation, etc.) was estimated by the CRP as resulting in the same impact loading as a 74 $m.s^{-1}$ vertical impact onto an unyielding surface.

When the collected impact velocity is adjusted for surface hardness and impact angle, the most probable equivalent impact velocity is less than about 60 $m.s^{-1}$ for the 90^{th} percentile. Due to the uncertainties with the correction factors the data are given based on mean (best estimate) value for equivalent velocity factors and also based on conservative 90th percentile values.

The cumulative probability of the equivalent impact velocities onto an unyielding target, given an accident shows that:

- for the mean adjustment factors there is about a 5% probability that the equivalent impact velocity is above 90 $m.s^{-1}$, and
- for the 90th percentile surface impact adjustment factors, there is about a 22% probability that the equivalent impact velocity is above 90 $m.s^{-1}$.

Accounting for the sample of collected data and assuming the results are representative of the sample, there is about:

- a 2% probability that the equivalent impact velocity given an accident will be above 90 m/s for the mean surface impact adjustment and
- a 9% probability that the equivalent impact velocity given an accident will be above 90 m/s for the 90th percentile surface impact adjustment.

The CRP carried out a variety of statistical analyses on this data and the other data below to validate it.

FIRE

The stresses imposed by the thermal accident environment are due to thermal loading generated by fires internal to the aircraft prior to impact and by fires generated by the impact. High thermal loads can lead to increased package internal pressure and deterioration of packaging seals, leading to loss of package containment.

Compared to impact velocity figures, available information on fire severity (intensity and duration) is sparse and inaccurate. In most accidents with long fire duration (>1h) there is a strong indication that secondary fires were involved. In these cases, the fire area grows and moves implying a low probability of long duration fixed location fire. Hence, there is only a low probability of engulfing a package in the fire for the total fire duration.

The average of reported (secondary) fire movement from the impact location is 200 m (range: 0 m– 600m). Hence, it is unlikely for a package to be involved in the fire scenario for the whole total fire duration. Furthermore the soil underneath and surrounding objects such as debris and other packages will reduce the package surface exposed to the fire.

The findings give support to the conclusion that most accidents even with reported fire duration above 1 h do not imply a higher thermal impact with respect to a possibly involved package in comparison with the IAEA fire test duration for Type C packages of 60 min. Furthermore, the combination of high speed impact and long duration fire is improbable.

AIRCRAFT ACCIDENT RATES

The establishment of reliable information on aircraft accident rates, covering world wide operations, has always been hindered by incomplete and unreliable reporting of both accidents and operational statistics. However, since the late 1980s, the UK based organization Airclaims has been collaborating with western aircraft manufacturers to collect data on all operational statistics and accidents involving western built turbine powered aircrafts over 5700 kg mass.

The analysis which follows is based on Airclaims data, supplied for this purpose by the UK Civil Aviation Authority.

- The data covers fatal accidents involving destroyed aircraft for all Western Jets in the period 1990 to 2000, inclusive.
- For each country and aircraft type, the data gives total hours, total flights for both cargo and passenger (i.e. non cargo) operations.
- Also given is a count of fatal accidents in each category of operation, together with a classification of the damage to the aircraft (Total Loss, Partial Loss, etc.)
- The data does not make a distinction between variants of the same aircraft type.
- The aircraft types of interest are those with maximum certificated aircraft mass of 27,000 kg or more. However, some variants of the Fokker F 28, of which significant numbers exist, have maximum mass just below 27,000 kg and the format of the data does not make it possible to distinguish between F28 variants. and so the mass cut off for this analysis was set at 25,000 kg in order to ensure that all F28s were included.

The World Wide Accident Rate (All Operations)for the period of 1990 to 2000 involving turbofan/turbojet powered aircraft build by western manufacturers and of a mass exceeding 25,000 kg for total loss fatal accident is 0.64 per million flights. Similarly, the total loss accident rate is approximately 0.8 per million flights.

CRP OUTCOME

The CRP started looking at data on 5000 aircraft accidents since the World War II. After applying some filters to make the data more manageable and to consider the accidents that were more relevant to Type C package testing requirements, the data that was analysed was reduced to 135 accidents for high impact energy, 53 accidents for fire and 66 for water immersion.

Fight Data Recorder (FDR)

The study shows that the test requirements and acceptance criteria for FDR and Type C package are different and no direct comparison of the impact test criteria can be made. The acceptance criterion for a radioactive material package is a very low level of leakage of the contents whereas FDR must allow retrieval of the data contained on the recording media.

The target hardness has a major influence on the survivability of the test specimen. The impact velocity for the performance specification of the FDR is higher than that for the Type C packages; however, the FDR specification does not require all the impact energy to be absorbed by the FDR. Because of the Type C impact of 90 m/s onto an unyielding target, the peak acceleration seen by the specimen is determined as about three times more than that required for the FDR specification. The level of damage is, therefore, seen to be greater when the specimen is subjected to the Type C requirements.

Impact velocity for a Type C package

Two approaches were considered to determine the probability of the equivalent impact velocity in an accident that may exceed 90 $m.s^{-1}$.

The first approach considers only the events, for which data was extracted from completed questionnaires. The mean and 90th percentile probabilities were calculated for this approach.

The second approach considers all the events, assuming that there is no correlation between the energy of impact of an event and the fact that the relating questionnaire has been filled out or not. The approach leads to the following conclusions:

- The most probable value of an impact exceeding 60 $m.s^{-1}$ is close to 11 %,
- A probability of an impact exceeding 60 $m.s^{-1}$ by about 10 % to 14 % cannot be rejected with a good confidence level
- A probability of an impact exceeding 60 $m.s^{-1}$ by less than 8 % or more than 18% can be rejected with a good confidence level.

Thermal environment

The information on fire severity (intensity and duration) was sparse and inaccurate. Based on the available information, it is estimated that the median value of the fire duration would be less than 1 h. For the adjusted fire duration the respective median values are 1.2 h for the fire cases and about 20 min for all accidents. The percentage of all accidents with adjusted fire duration of at least 1 h is approximately 45%.

Given that an aircraft accident fire is unlikely to be fully engulfing, a reported fire of duration above 1 h does not imply a higher heat input than the IAEA Type C regulatory fire test. Furthermore, the combination of high speed impact and long duration fire is improbable.

This statistical analysis of fire information from the 53 accident database can only give a rough estimate of major trends and dependencies. Further interpretation was needed to obtain conclusions with respect to equivalence to the IAEA Type C fire test requirements.

Water immersion environment

Only 5.6 % of the 338 accidents resulted in water immersion. It is estimated that in 16% of the accidents involving immersion the equivalent impact velocity is over 90 m/s. In these accidents the immersion depth was less than 200 m in 1/3 of the cases and more than 200 m in 2/3 of the cases. One of these accidents occurred over the Black sea in which the depth of immersion of major debris was 500 m.

For accidents resulting in an immersion depth over 200 m, it may not be possible to recover the package. Therefore, the consequences of the release of the radionuclides were investigated. It was concluded that the release would not result in any significant individual dose.

Accident Sequences

The following six air accident events were defined Ground impact, In-flight impact, Ground fire, In-flight fire, In-flight explosion and Water immersion. Of the 338 accidents which were reviewed, 49.4% involved single events, 46.5% involve two event sequences, 3.8% involve three event sequences, and 0.3% involves four event sequences.

Aircraft Accident Rates

Accident rate analysis carried out for other purposes has indicated that accident rates appear to vary according to geographical region, according to type of operation, and, also, according to aircraft size (with smaller aircraft appearing to suffer higher accident rates than larger aircraft). Accordingly, the analysis reported gives accident rates for cargo and non cargo operations separately by geographical region, as well as the world wide frequencies. However the probability that a package is involved in an aircraft accident in which the aircraft is destroyed is estimated as around 8×10^{-7} per flight

Estimation of Risk of Transporting Large Quantities of RAM by Air

The risk in transporting large quantity of RAM was estimated. On a per package basis, the probability that the package is involved in an aircraft accident in which the aircraft is destroyed is $\sim 8 \times 10^{-7}$ per flight.

The probability of a high speed ground impact is approximately 1.3×10^{-7} per flight and that of a high speed impact accident followed by fire is 5.4×10^{-8} per flight.

The accident rate of 1.3×10^{-7} per flight is the same as saying that the probability that a package will be subjected to a severe impact aircraft accident is about 1 in 8 million per flight.

CONCLUSIONS

This study provided an understanding of the technical basis of the regulatory tests. The accident frequency in air mode is very low. Even among this low number of accidents, the probability of an accident exceeding the severity of the regulatory tests is low. Further there is a low probability of a Type C package being on board. Even if an accident involving a package is more severe than the regulatory tests, it may not necessarily result in a significant, or any, release of the contents of the package.

Interesting anecdotal evidence was uncovered during the work, including details from one of the most significant aircraft impacts where excepted packages were involved, many being recovered without leakage.

An open question remains regarding the equivalence of Type C test requirements with those of the FDR. It is possible that the use of an unyielding target is over restrictive for some package types. Adjusting the Type C requirements would also permit greater comparison with FDR requirements. This is an area that could benefit from further research.

The relationship between potential fatality rates related to Type C package failure in an accident and fatality rates resulting from air accidents would seem to suggest that improvements in the aircraft industry to prevent fatal accidents will be the most effective means of improving safety of Type C packages. It would therefore appear from the results of the CRP that the current IAEA Regulatory test requirements for Type C packages are sufficiently bounding.

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