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EVALUATION OF AIRCRAFT CRASH HAZARDS ANALYSES FOR NUCLEAR POWER PLANTS

by

C. A. Kot, H. C. Lin, J. B. van Erp,
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ARGONNE NATIONAL LABORATORY

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EVALUATION OF AIRCRAFT CRASH HAZARDS ANALYSES FOR NUCLEAR POWER PLANTS

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ABSTRACT

The state of knowledge concerning aircraft crash hazards to nuclear power plants is critically evaluated. This effort is part of a study to analyze the potential effects of offsite hazards upon the safety of nuclear power plants and to develop a technical basis for the assessment of siting approaches for such facilities. The evaluation includes the deterministic modeling of aircraft crash scenarios and threat environments, the estimation of the effects on and the response of the vital plant systems, and the probabilistic aspects of the crash problem, i.e., data bases and statistical methodologies. Also critically reviewed are past licensing experience and regulatory practice with respect to aircraft crash hazards.

In general it is found that the data bases, methodologies and modeling approaches are adequate to estimate the threat and plant response. However, this knowledge is not always fully used in specific applications. Siting of nuclear power plants relative to aircraft hazards is a risk based procedure that considers both probabilities of crash occurrence and their consequences. In this context it appears feasible to improve the site screening procedures and to develop exclusion zones from controlled air spaces (airports, airways, etc.) based solely on local aviation statistics and independent of plant design. Methodologies for treating complex aviation environments such as multiple airports and overlapping airways are needed, as are guidelines for crash target calculations. Further investigations of crash scenarios, particularly those that could lead to multiple or propagating failures, should be pursued.

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EXECUTIVE SUMMARY

This report provides a review and evaluation of aircraft crash hazards analyses for nuclear power plants. Of particular concern are the policies, both past and proposed, and regulatory experience of the U.S. Nuclear Regulatory Commission regarding the siting and design of these plants. The U.S. Code of Federal Regulations currently requires that the site location and engineered safety features of a nuclear power plant should insure a low risk of public exposure to accidental radioactive releases, and that design basis events used to ensure this should not be exceeded by any accident considered credible. NRC standard review practice considers credible potential exposure events as those having an expected rate of occurrence greater than from 10^{-6} to 10^{-7} per year depending upon the nature of the data and assumptions. Both the Code of Federal Regulations and NRC policy provide for engineering safeguards to compensate for unfavorable site characteristics. The NRC has recently instituted a formal policy to screen future site selection on the basis of proximity criteria to concentrations of commercial and military aircraft activities.

It has been suggested that the present rules and regulations may result in an over-reliance on engineering solutions, unnecessary exposure, and de-emphasis of siting as a defense-in-depth factor to aircraft hazards. In addition to specific plant design features to mitigate aircraft crash-induced consequences, alternate siting approaches have been advanced and are summarized as follows:

- minimum standoff distances
- exclusion distances
- site acceptance limits - exclusion threshholds
- site acceptance floors - approval threshholds
- screening distance values
- screening probability levels

As mentioned, recent NRC review procedures establish screening distance values which are independent of specific plant design.

In general, extensive aircraft data bases and statistical crash rate models have been developed. The latter are judged here to be accurate on a national basis to within about one order of magnitude with variations arising from the definition of crashes potentially threatening to nuclear power plants and the classification of aviation characteristics and activities. Deficiencies do, however, exist with regard to military aviation, delineation of phases of operation, and important parameters of

aircraft crash scenarios. These difficulties are usually surmounted through analytical models, probability distribution function constructions, and conservative assumptions.

Aircraft crash rates correspond to groupings of aircraft type, aviation activity, airport characteristics, and air space usage (e.g., airway, restricted air space, and background air activities). The rates scale with the number of operations; other possible scaling effects have not been adequately studied. A value of 10^{-4} events per year per square mile is representative of the crash rates of background light aircraft and of heavy aircraft in the immediate vicinity of heavily traveled airways and within about five miles of a major airport. Although detailed crash rates in actual situations will vary widely, this representative value demonstrates that siting and plant design features are important and necessary considerations in meeting federal safety requirements for nuclear power plants relative to aircraft hazards. More specifically, sites nearby heavy aircraft aviation spaces, which concentrate air traffic, increase crash rates, and multiply the types of aviation activities, must be thoroughly scrutinized, and plants should be relatively nonsusceptible to light aircraft crashes.

Crash probabilities corresponding to various aviation groupings have been calculated for a number of plants. These results depend principally upon the number of annual operations occurring locally in each aviation group, respective crash rates, assumed accident scenario parameters such as aircraft type and crash path, and plant parameters. The latter includes the identification of susceptible safety-related features and computation of their effective target areas. These calculations typically depend upon considerable local data gathering, site-specific representations, accident parameter modeling, and conditional probability estimations of certain event occurrences. In particular, conditional probabilities of having a radioactive material release exceeding NRC guidelines given an aircraft crash are usually implicitly made as follows: a value of unity for structures used in the effective target area evaluation and zero for those excluded.

The results obtained are often near to or marginally within the frequency of occurrence safety guidelines. Considerable conservatism is apparently included in the cases reviewed. However, not enough attention has been paid to certain specialized aspects of the problem and especially the sensitivities of results to variations in the key parameters which are important in any marginal situation. For example, the impact phenomena of aircraft and aircraft missiles on substantial concrete structures has been extensively studied, but other crash scenarios have not been pursued in any similar detail. Aircraft crashes may result in multiple failure initiating events, and a propagating failure orginating with a nonsafety system malfunction may be possible. Fire and explosion hazards associated with the aircraft fuel have not been treated in sufficient detail, and, while these threats may be relatively less hazardous than the direct aircraft impact threat, this has not been adequately demonstrated.

Further, there is a lack of clear and supported statements on many important underlying assumptions and of comprehensive treatments of the overall hazard. From the perspective of risk analysis methodology, the calculation experience is generally rather simplified with gross and often implied relationships used to represent the complex couplings among the many variables of the problem. It is important to state, however, that this does not necessarily imply that the results are misleading or invalid or that significantly different estimates can be made, but that improved treatments of aircraft hazard scenarios and more advanced methodologies are generally desirable.

Major findings are that, in addition to the types of improvements in analyses and methodologies outlined above, certain alternate regulatory approaches are worthy of pursuit. Specifically, the recently instituted site screening approach can be further refined, and the establishment of minimum standoff and/or exclusion distances relative to airports, airways, and complex aviation environments appears both feasible and practical to develop. The principal advantages of the latter would be (1) to clearly emphasize site selection over engineering solutions in those cases where safety design features are costly and heavily relied upon to reduce the risk of power generation to the public, and (2) to significantly streamline and simplify the regulatory process.

1. INTRODUCTION

In recent years the effects of offsite hazards have become an important consideration in the siting and design of nuclear power plants. The objective of the current study is to provide NRC with technical background for possible rulemaking on the siting of nuclear power plants with regard to a number of offsite hazards. One of the considered hazards is the crash of an airplane on the power plant site. As with all hazards the ultimate concern is the safety of the general public, which in turn implies the avoidance of substantial radioactive releases. Such releases may arise either directly through the damage or breaching of a plant component containing radioactive materials or indirectly through the malfunction of plant systems and components, which in turn result in substantial damage to the reactor core and primary heat transport system.

The major threats associated with an aircraft crash are the impact loads resulting from the collision of the aircraft with power plant structures and components and the thermal and/or overpressure effects which can arise due to the ignition of the fuel carried by the aircraft. While the damage mechanisms depend on the plant system affected by the crash, credible accident scenarios must consider both the direct release of radioactivity due to breaching of barriers and the delayed release associated with damage to core and other vital plant systems. In the latter category of prime importance are safety systems which are needed for safe shutdown and long-term heat removal.

Since offsite hazards to nuclear power plants arise from accidental events, the stochastic aspects of the problem must also be considered. This maxim holds particularly for aircraft crashes because it is not possible a priori to exclude the presence of aircraft from any particular location. The purpose of the current study is to critically review and evaluate the state-of-the-art of both deterministic and probabilistic knowledge concerning the hazards to nuclear power plants from aircraft crashes. The effort is not only intended as a review of past practices, but represents an independent evaluation of the data bases and methodologies used in estimating the hazards to nuclear power plants. Both the strong points and the inadequacies of past practices are identified, and where possible remedial approaches are recommended. Possible regulatory approaches are discussed in light of these evaluations.

To provide the proper perspective, present policies, practices, and regulatory experience are briefly reviewed in the next section. This is followed by an overview of the literature survey. Aircraft hazards analysis and the safety related power plant systems and protection barriers are discussed in the next sections. This is followed by a detailed evaluation of the methods used to estimate crash loads, structural response, and fire/explosion hazards. The final sections of the report concern the overall evaluation of methodologies and recommendations concerning analysis improvements as well as possible regulatory approaches. Brief summaries of most of the reviewed papers, reports and documents are provided in the Appendix.

2. BACKGROUND

Past practice in nuclear power plant siting has been to address the problems associated with offsite hazards on a case-by-case basis. The approach consisted of (i) identification of significant hazards, (ii) an analysis and evaluation of the hazard level by the applicant using recommended or his own methodologies, and (iii) a demonstration of techniques and engineered design features for mitigating the consequences if the level of hazard is found to be excessive. In the past all of these efforts were directed to meet the nuclear reactor siting criteria which are contained in the Code of Federal Regulations - Part 100 of Title 10 (10 CFR 100) [1] and which constituted the primary mandate for NRC evaluation of proposed sites.

While new criteria may be developed in conjunction with future siting rulemaking, several aspects of 10 CFR 100 are important to this study since they have historically not only influenced the site selection and reactor plant design processes but have provided the objectives of most of the subject analyses to be evaluated here. Specifically, "... the site location and the engineered features included as safeguards against the hazardous consequences of an accident, should one occur, should insure a low risk of public exposure." Provision is made for the derivation of an exclusion area, a low population zone, and population center distance assuming a fission product release from the core and expected demonstrable leak rate from the containment utilizing exposure guidelines described for these regions. The fission product release assumed is suggested to follow from calculations based upon a major accident having potential hazards not exceeded by those from any accident considered credible. It is further stated that such accidents are generally assumed to result in substantial core meltdown and release of appreciable quantities of fission products. Site acceptability factors to be taken into account include, among others, unique or unusual features having a significant bearing on the probability and consequences of accidental radioactive release and appropriate and adequate engineering safeguards that compensate for unfavorable physical characteristics of the site. Thus, 10 CFR 100 predicates consideration of the following topics:

- definition of physical characteristics of the site;
- the appropriateness and adequacy of engineering safeguards;
- the factors that define probability and consequence estimation and their senstivity;
- failure modes of radioactive material barriers and subsequent uncontrolled release;
- failure modes of safe shutdown and decay-heat-removal systems;

- accident scenarios, mechanisms, and credibilities;
- risk estimations.

Review procedures are used by the NRC in interpreting 10 CFR 100 and other applicable regulations; these are contained in the Standard Review Plan (SRP), NUREG-0800 [2]. These procedures establish criteria which must be complied with in specific licensing cases before a license is issued. The SRP Sections having a direct bearing on aircraft hazards are:

<u>2.2.1-2.2.2</u> Identification of Potential Hazards in Site Vicinity
<u>2.2.3</u> Evaluation of Potential Accidents
<u>3.5.1.6</u> Aircraft Hazards

Section 2.2.1-2.2.2 is primarily concerned with the locations and separation distances from the site of industrial, military, and transportation facilities and routes in the vicinity and during the lifetime of the plant. It suggests review of all identified facilities and activities within 8 km (5 miles) and at greater distances if the potential for affecting plant safety-related features exists. Section 2.2.3 provides for review of the identification of potential accident situations, their completeness, and the bases of design accomodation. Included, where appropriate, is the review of probability analyses - data bases and analytical models - and consequence analyses of accidents identified as design basis events. In the past design basis events had to include each accident having an expected rate of occurrence of potential exposures in excess of the 10 CFR 100 guidelines exceeding approximately 10^{-7} per year using site-specific or representative information and assumptions, i.e., realistic estimations. A rate of 10^{-6} per year is acceptable if conservatism can be demonstrated. The effects of those design basis events on safety-related features must be analyzed, and measures to mitigate their consequences must be taken. It is recognized in the SRP that the aggregate probability of individual classes of external man-made hazards may exceed the acceptance criteria even though the individual rates are in themselves acceptably low, and that additional design features may be warranted.

Section 3.5.1.6 is specifically concerned with aircraft hazards and establishes review procedures to ensure that they are eliminated as a design basis concern or that appropriate accident events have been chosen and properly characterized relative to impact and fire hazards. The SRP review procedure identifies the following situations:

1. Sites having an adequately low probability of occurrence (less than about 10^{-7} per year) of radiological consequences in excess of the 10 CFR 100 guideline. This condition is assumed to occur by inspection if the distances from the plant meet the requirements below:

   (a) The plant-to-airport distance D is between 5 and 10 statute miles, and the projected annual number of operations is less than 500 D^2, or D is greater than 10 statute miles, and the projected annual number of operations is less than 1000 D^2,

   (b) The plant is at least 5 statute miles from the edge of military training routes, including low-level training routes, except those associated with a usage greater than 1000 flights per year, or where activities (e.g., practice bombing) may create an unusual stress situation,

   (c) The plant is at least 2 statute miles beyond the nearest edge of a federal airway, holding pattern, or approach pattern.

2. Sites not meeting the above proximity criteria or if sufficiently hazardous military activities are identified. In this situation a detailed review of aircraft hazards must be performed. If any, aircraft accidents which could lead to radiological consequences in excess of 10 CFR 100 exposure guidelines with an occurrence probability greater than about 10^{-7} per year should be considered in the design of the plant, subject to the design basis acceptance criteria regarding aircraft impacts (missiles) and fires.

This section of the SRP also addresses review procedures in some detail relative to aviation uses, holding patterns, designated airspaces, and airways. For these cases the crash probability depends upon flight altitude and frequency, the airway location and characteristics, in-flight crash data (crashes per aircraft-mile flown per year), and plant features. Also addressed are civilian and military airports and heli-ports. Here the crash probability will depend upon the types of aircraft, number of flight paths affecting the site, airport crash statistics (crashes per movement per square mile) of the aircraft types, traffic data for the aircraft and flight paths, and plant features. The total aircraft hazard probability must be integrated over all potentially threatening aviation situations. The effective plant area is recognized to depend upon a shadow area based on the assumed crash angles of the various aircraft and failure modes, a skid area based on aircraft and topographical characteristics, and the susceptible features of the plant relative to structural or fire damage.

The current nuclear power plant siting policy and practice, in which an applicant selects a single proposed site using factors presented in 10 CFR 100 and submits it for NRC staff review, has encountered significant criticism and has been under review by NRC for some time. One outcome was the formation by NRC of a Task Force to develop a general policy statement on nuclear power reactor siting. Their findings were presented in 1979 in the "Report of the Siting Policy Task Force," NUREG-0625 [3]. The major conclusion of this study is that past siting practice has stressed the employment of engineered safety systems and has tended to deemphasize site isolation leading to the acceptance of reactor sites with unfavorable characteristics. Recommendation 2 of the Report, which deals specifically with offsite hazards, states that 10 CFR 100 should be revised to require consideration of potential hazards posed by man-made activities by establishing minimum standoff distances for specific threats. This recommendation is in line with the overall goals set by the Task Force, namely:

- To strengthen siting as a defense in-depth factor by establishing requirements for site approval that are independent of plant design considerations.

- To take into consideration in siting the risk associated with accidents beyond the design basis by establishing population density and distribution criteria.

- To require that sites selected will minimize the risk from energy generation.

With respect to the hazard of aircraft crashes, the Task Force felt that some practicable standoff distances can be set and recommended specifically that major or commercial airports be no closer than 5 miles from a nuclear power plant.

While not all recommendations of the Task Force have been generally accepted by the NRC, serious consideration has been given to changes in the siting policy as evidenced by the Advance Notice of Rulemaking 7590-01: Revision of Reactor Siting Criteria [4]. While the Notice discusses many specific aspects of nuclear power plant siting, its major thrust is to emphasize site isolation, i.e., siting new plants away from highly populated areas and major industrial facilities. At the same time more uniform national criteria for plant siting are stressed. One approach suggested for the implementation of such uniformity is the so-called "three-tier" approach. This would involve the specification of two thresholds for each parameter. One would be the acceptance limit which would exclude any site not meeting it. The other would be an acceptance floor — any site that did not exceed that floor would be approved with respect to this criterion. Between these extremes would be a middle ground where residual risks would be considered in deciding whether to approve a site. In the case of offsite hazards the establishment of minimum standoff distances is again proposed. These suggestions have by no means gained general acceptance as evidence by some of the ACRS comments incorporated into the Notice.

To provide technical backup for some aspects of this proposed rule-making NRC - Office of Nuclear Reactor Regulatory Research requested that Argonne National Laboratory review, evaluate, and where possible improve and recommend methodologies and approaches for addressing offsite hazards to nuclear power plants. At the same time a somewhat similar effort was launched by Sandia National Laboratories under the auspices of NRC/NRR [5].

A review of past nuclear power plant siting experience indicated that hazards arising from aircraft crashes were analyzed in at least 12 cases in the U.S.A. The preferred approach in the evaluation of the aircraft hazard is through probabilistic techniques. However, deterministic studies addressing primarily impact loading and the structural response of concrete structures are also part of past experience. As with other offsite hazards the current approach has led to a variety of solutions to mitigate the aircraft crash problem. In the vast majority of cases the hazard is simply excluded on the basis of the statistical data. In some cases the vital power plant systems, in particular the containment structures, are hardened to resist the impact of certain types of aircraft, e.g., Three Mile Island [6]. It appears that for all U.S. plants currently under construction it has been found that it is not necessary to require containments designed to take the impact of a large commercial jet aircraft.

This practice is contrasted by the experience in the Federal Republic of Germany where it has been found necessary to design essentially all nuclear containments to withstand the crash of certain types of military and commercial aircraft [7,8]. A systematic approach to the problem of aircraft hazards is also recommended by the International Atomic Energy Agency [9]. During the site survey stage it is recommended that either a Screening Distance Value (SDV) or a Screening Probability Level (SPL) approach be used to determine if aircraft hazards require further considerations. Steps to be followed in a detailed evaluation of the hazards are also outlined in the

IAEA Safety Guide and include the determination of probabilities for crashes of all pertinent types of aircraft. When it is necessary to protect the plant against aircraft crashes, the design basis crash, i.e., the crash giving the most severe consequence, is defined. Effects which are included in the evaluation are impact and secondary missiles as well as possible fire and explosion caused by fuel ignition. The document also recommends careful consideration and procedures for the determination of design basis parameters, i.e., aircraft type, aircraft speed, load time functions, and amount and type of fuel.

3. LITERATURE SURVEY

The literature survey can be categorized into the following four areas:

- NRC Documents: NUREG reports, regulatory guides, standard review plan, regulations, past siting experience (SAR's, SER's, Dockets),
- IAEA Documents: Safety guides, Safety Standards, recommendations, and procedures.
- Government Documents: DOE, DOT, DOD, EPA, etc.
- Open Literature.

The NRC documents provide the background of current regulations, criteria, and procedures for licensing and approval of nuclear power plant sites, as well as the past siting experience which is contained primarily in the various SAR and SER reports. In addition, some pertinent information is contained in specific plant Dockets. The Docket material is poorly referenced and is available only in microfiche form, making the survey of this information rather difficult. On the other hand, the IAEA documents are readily available and much of the information is also contained in other U.S. publications. Concerning other U.S. Government documents, National Transportation Safety Board reports were collected since they provide the data base for low probability accident events in the past. Most of the structural response and analysis of aircraft crash on the nuclear power plants can be found in the published open literature.

Computer searches were used to locate much of the material and provided a large number of titles; e.g., in the category of structural response alone, several hundred papers surfaced as published in the last decade. After screening and collection of these original papers from various journals and reports, a summary sheet was prepared for each relevent paper. These are presented in the Appendix of this report. In each summary sheet, the title, author's name, origin, and a brief description of the contents are given for the convenience of later referral. As can be seen from the References, most of the pertinent open literature appears in the Journal of Nuclear Engineering and Design, which collects papers from various international conferences such as SMiRT and the International Extreme Load Conference on Nuclear Power Plants. Some pertinent structural literature can be found in the area of seismic analyses s' .e many air crash responses have been compared with the consequences of a earthquake.

4. AIRCRAFT HAZARDS ANALYSES

4.1 Sources of Information

Literature relevant to aircraft hazards was identified, collected, and evaluated. In addition to the NRC documents discussed in Section 2, the literature consists of

- data bases, e.g., air traffic/accident reports,
- probabilistic/deterministic methodologies and applications,
- nuclear power plant and other site-specific aircraft risk estimations.

Extensive data bases exist for virtually all aspects of air travel, both civilian and military. In particular, excellent compilations are maintained on a routine basis of aircraft by type, usage, flights, etc., and of airports including movements and traffic patterns. The air space over the United States is rather well defined; an extensive network of air corridors is maintained for air carrier traffic, and restricted air spaces are enforced for special purposes such as military applications in addition to airport activities. The principal source of civilian aviation records and statistics is the Federal Aviation Administration (FAA), Department of Transportation. Specialized statistics that may be required in general or for a particular site will be provided to the extent possible by the FAA Management Services Division and airport records. Military flight information can be obtained from the appropriate branch of the Department of Defense, military airports, and other command . Unique problems exist, however, in the case of military aviation; in particular, these relate to unavailability, reliability, and variability of the data bases as exemplified by classified operations and data and the statistical significance of much of the flying experience and especially short duration missions.

Accident data for U.S. Civil Aviation are thoroughly compiled on a case-by-case basis as well as statistically by the National Transportation Safety Board (NTSB). It can be assumed that the data base of accidents potentially threatening to a nuclear power plant is complete and accurate to the extent possible. Unfortunately, however, the nature of an accident scenario usually precludes the accurate gathering of certain data that would be useful to nuclear power plant applications, for example, the aircraft trajectory from normal flight to point of impact, the inclination of the final crash path to the ground, and the ability or inability to control the descent and point of impact. Details of the air traffic/accident data bases are presented in Section 4.2.

Probabilistic methodologies, both generic and special application, have been developed for aircraft crashes, crash impact characteristics, nuclear power plant characteristics, and the risk estimation process. In general, the various aspects of the problem can be treated with reasonable confidence given a particular site. Results of the relevant analyses are presented in Sections 4.3 and 4.4.

Deterministic (and experimental) studies have been made for the aircraft impact loading and structure-component response for certain structures and systems. In addition to impact loading, fire and possible explosion provide other loading mechanisms. These results are very important to (1) define the range of consequences and bound the risk estimation, and (2) provide for some measure of control via engineered safety features over both the consequences and level of risk. These results are presented in Sections 6 and 7.

The results of analyses made for the aircraft hazards to nuclear power plants and other sites are summarized here to illustrate in some detail the nature of the problem and past practices. It should be remembered that aircraft hazards, like most other offsite hazards, belong to that class of low probability-potentially high consequences events.

4.2 Air Traffic/Accident Data Base

The necessary data to estimate crash probabilities includes both normal air traffic and accident statistics. The most general statistical categories are

- Air Carrier
- General Aviation
- Military Aviation

Air Carriers operate under 14 CFR 121 and include certified route and supplemental (charter) carriers and commercial operators of large aircraft* (over 12,500 pounds). The types of services provided by Air Carriers are typically passenger, cargo, training, and ferry operations.

*Commercial operators were included in the General Aviation category prior to 1975.

General Aviation refers to the operation of all U.S. Civil Aircraft other than Air Carrier operations. The aircraft are classified according to type, maximum gross takeoff weight, the number and type of engines, etc. The types of flying include instructional, noncommercial, commercial, and miscellaneous flying. Military Aviation includes aircraft and air/air-ground operations unique to military applications and military airports.

4.2.1 Air Carrier Statistics

Air Carrier accidents are defined to occur [10] when any person, passenger, crewmember, or other person in direct contact with the aircraft, suffers death or serious injury or the aircraft receives substantial damage. Accordingly, such accidents are tabulated by the NTSB by injury - fatal, involving serious injury, involving minor injury - and by aircraft damage - destroyed or substantial damage. The type of accident relates to the circumstances surrounding the accident such as collision with ground/water, engine failure, overshoot, etc., and two separate types may be recorded, i.e., first and second types. The first phase of operation - static, taxi, takeoff, in-flight or en route, landing, unknown - is recorded for each type. Finally, causes/factors categories such as pilot, weather, power plant, etc. are tabulated from the accident data.

For the ten year period 1967 to 1976* there was an average of 40 accidents per year with an average of 6 per year with fatalities [10]. For this period fatal accidents were, therefore, about 15 percent of all Air Carrier accidents, and from 1971 to 1976 about 25 percent of the aircraft in accidents were destroyed. Over 50 percent of all fatal accidents from 1967 to 1976 had collision of some kind including midair as the first type of accident, whereas, for all accidents, collisions represented less than 20 percent (turbulence is cited in about one-third of all accidents). The principal causes/factors cited in both fatal and all accidents are pilot, personnel, and weather; these are reported on the average about seven times more frequently than other causes/factors such as airframe, landing gear, power plant, systems, instruments/equipment, airports/airways/facilities, and miscellaneous. For the ten years 1967 to 1976, about 20 percent of all accidents are during the static or taxi phases of operation; landing accidents at about 25 percent are nearly four times more prevelant than takeoff accidents, and nearly 50 percent occur in-flight. The first phase of operation statistics for fatal accidents involve landings slightly more

*Unless otherwise stated, the from-to notation is inclusive.

often than in-flight (both around 40 percent) and landings about five times more than takeoffs.

From 1971 to 1975 an average of 2.6×10^9 aircraft-miles were flown annually by Air Carriers excluding commercial operators (about 2 to 3 percent of total miles flown). The average accident rate for that period was 0.018 per million aircraft-miles flown, and the average fatal accident rate was 0.003 per million aircraft-miles flown.

4.2.2 General Aviation Data Base

General Aviation accidents are also defined [11] on the basis of injury and damage indexes. In addition to the type of accident, phase of operation, and causes/factors, the kind of flying and type of aircraft are statistically analyzed. Kinds of flying are instructional; noncommercial, including pleasure, business, and corporate/executive operations; commercial, such as air taxi and aerial application; and a miscellaneous category. The types of aircraft are small fixed-wing having maximum gross takeoff weight less than 12,565 pounds, large-fixed wing heavier than 12,565 pounds, and rotorcraft.

From 1969 to 1978 there was an average of 4,427 accidents per year (more than 100 times that of the Air Carriers) with an average of 696 fatal accidents per year or about 16 percent of the total accidents [11] - note that the fatal to total accident percentage is essentially the same for both Air Carrier and General Aviation. During 1977 and 1978, about 26 percent of the aircraft damaged were destroyed, again roughly the same percentage as for Air Carriers, and virtually all the others received substantial damage, i.e., damage normally requiring major repair or replacement of the affected component. From 1973 to 1978 the most prevalent first accident type was engine failure/malfunction, accounting for 24 percent of all accidents. Uncontrolled collision with ground/water accounted for 17 percent of fatal accidents followed by controlled collision with ground/water at 13 percent and engine failure/malfunction at 12 percent. The most frequently cited causes and related factors for both fatal and all accidents were pilot, weather, and terrain.

From 1973 to 1978 the in-flight phase of operation accounted for about one-third of all accidents and two-thirds of fatal accidents. For all accidents, landings at about 42 percent occur more often than in-flight and about twice as often as takeoff accidents; landing and takeoff phases of operation occur in about 16 and 12 percent of all fatal accidents, respectively. Pleasure, aerial application, and instructional flying accounted for 81 percent of all accidents from 1975 to 1978, and pleasure, aerial application, and air taxi accounted for 75 percent of fatal accidents.

Of 793 fatal accidents in 1978 about half of the aircraft were beyond 5 miles from an airport (for all phases of operation); of the 4,494 total accidents (4,554 aircraft) in 1978, less than 30 percent were beyond 5 miles of an airport. Chelapti, Kennedy, and Wall [12] analyzed ten- and four-year periods up to and including 1968 and found that on the average about two-thirds of the fatal accidents occurred beyond 5 miles of an airport for small and large General Aviation aircraft and for Air Car-riers. Small fixed-wing aircraft accounted for 90 percent of both all and fatal accidents during 1978. Large fixed-wing aircraft accounted for 1 to 2 percent of these accidents, specifically, 14 fatal and 48 total acci-dents during 1978. Rotorcraft and miscellaneous types account for the remainder.

From 1969 to 1978 an average of 3.9×10^9 aircraft-miles was flown annually, ranging from 3.1×10^9 (1971) to 4.9×10^9 (1978) miles flown per year. The total and fatal accident rates both exhibited decreasing tendencies during that period. On the average (1969 to 1978) 1.2 accidents occur per million aircraft-miles flown, ranging from 1.48 (1971) to 0.90 (1978), and 0.18 fatal accidents occur per million aircraft-miles flown, ranging from 0.211 (1971) to 0.159 (1977 and 1978).

4.2.3 Military Aviation Statistics

Comparable accident statistics for U. S. Military Aircraft are not published. It is widely assumed, e.g., by Solomon and others, that the accident rate of military aircraft on noncombat missions that could cause the aircraft to crash or collide with any structure not at the airport is comparable to the similar accident rate for Air Carriers. An accident data compilation published by the NRC, "Aircraft Impact Risk Assessment Data Base for Assessment of Fixed Wing Air Carrier Impact in the Vicinity of Airports," NUREG-0533, June 1979, by Akstulewicz, Read et al. found that military air transport, "...when operating as an air carrier, has accident rates approximately the same as those of civilian non-scheduled air carrier service." The accident and traffic experience used in the compilation included military aircraft similar to types flown by civilian Air Carriers - specifically, C5A, C141, E4A aircraft. It has been the practice in certain cases where military aviation is involved to adopt a rate equal to the Air Carrier accident rate multiplied by an integer greater than one (to allow for uncertainty) as the military transport accident rate when the acquisition of specialized data appears to be unwarranted.

4.2.4 Airport Statistics

Niyogi, Boritz, and Bhattacharyya [13] analyzed the characteristics of critical accidents, i.e., accidents resulting in fatalities or a destroyed aircraft, of civil aviation occurring within 5 miles of an airport for the years 1966 to 1970. The ratio of these critical accidents to fatal accidents is 1.6. Their statistical results are of interest because of the breakdown by aircraft type and power plant, phase of operation, and airport type. The airports listed are those covered in the 1972 National Airport System Plan and are characterized in the table below:

Designation†	Airport Type (Operations/Yr.)	Number of Airports	Annual Number of Total Operations
A	<2,000	6,632	33.2×10^6
B	2,000 - 10,000	1,702	28.4×10^6
C	10,000 - 40,000	1,047	78.1×10^6
D	>40,000 (non FAA)	299	85.4×10^6
E	>40,000 (FAA)	330	192.5×10^6
Totals		10,010	417.6×10^6

†(assigned here)

Table 1 gives the number of critical accidents during the 1966 to 1970 period for several types of aircraft. Table 2 shows the relationship between types of airport and power plants for small fixed-wing aircraft. Table 3 gives the distribution of small fixed-wing aircraft accidents according to phase of operation and distance from the airport for each airport type.

Godbout [14] studied takeoff and landing accidents that produced fatalities of serious aircraft damage for heavy aircraft (gross weight more than 18,000 pounds) for the years from 1960 to 1973 in the vicinity of Canadian airports. He found that most of these accidents occur within 10 miles of an airport but included data out to 30 miles in the airport-related, e.g., takeoff and landing, statistics. Figure 1 is a polar representation of the landing accidents that have occurred. Very few heavy aircraft accidents were found to occur off the runway axis as indicated in the figure; this may, in part, be due to Canadian airport traffic pattern procedures. Figure 2 shows the accident histograms for landing (A), takeoff (B), and combined (C) accidents. These statistics are interesting since they are analyzed in a manner that clearly illustrates landing and takeoff direction correlations.

Table 1. Critical Civil Aviation Accidents within 5 Miles of an Airport 1966-1970 [13]

Type of Aircraft	Critical Accidents
Large Fixed-Wing (more than 12,500 lb)	35
Small Fixed-Wing - jet	20
Small Fixed-Wing - 2 propeller	260
Small Fixed-Wing - 1 propeller	1640
Other	110
Total	2065

Table 2. Critical Civil Aviation Accidents of Small Fixed-Wing Aircraft, 1966-1970. [13]

Airport Designation	Type of Power Plant			
	Jet	2 Propeller	1 Propeller	Any
A	4	52	661	717
B	2	38	241	281
C	5	57	346	408
D	2	38	178	218
E	7	75	214	296
Total	20	260	1640	1920

Table 3. Nature of Small Fixed-Wing Aircraft Accidents, 1966-1970. [13]

Air-port Type	Phase of Operation†	Frequency of Accidents: Distance from Airport (miles): Traffic Pattern	0-1	1-2	2-3	3-4	4-5	Total	Phase Fraction
A	TO	113	65	9	5	1	0	193	0.269
	IF	29	109	70	61	55	17	341	0.476
	IL	1	1	2	1	1	0	6	0.008
	OL	124	40	3	5	3	2	177	0.247
	Total	267	215	84	72	60	19	717	1.000
B	TO	33	17	3	2	3	1	59	0.210
	IF	8	39	42	34	27	10	160	0.569
	IL	0	1	0	0	0	0	1	0.004
	OL	39	14	3	1	2	2	61	0.217
	Total	80	71	48	37	32	13	281	1.000
C	TO	44	28	7	0	0	1	80	0.196
	IF	16	48	48	39	41	15	207	0.507
	IL	3	3	2	1	0	1	10	0.025
	OL	82	21	1	4	2	1	111	0.272
	Total	145	100	58	44	43	18	408	1.000
D	TO	25	20	1	1	0	0	47	0.215
	IF	12	19	29	22	12	8	102	0.468
	IL	3	2	0	2	0	0	7	0.032
	OL	38	17	5	0	0	1	62	0.284
	Total	78	58	35	25	13	9	218	1.000
E	TO	22	19	1	4	1	0	47	0.159
	IF	7	26	26	18	30	7	114	0.385
	IL	20	3	9	4	1	1	38	0.128
	OL	65	17	11	2	1	1	97	0.328
	Total	114	65	47	28	33	9	296	1.000
Any	TO	237	149	21	12	5	2	426	0.222
	IF	72	241	215	174	165	57	924	0.481
	IL	27	10	13	8	2	2	62	0.032
	OL	348	109	23	12	9	7	508	0.265
	Total	684	509	272	206	181	68	1920	1.000
Fraction of aircraft crashes			0.412	0.220	0.167	0.146	0.055		

†TO = Takeoff, IF = In-flight, IL = Instrument Landing, OL = Other Landing.

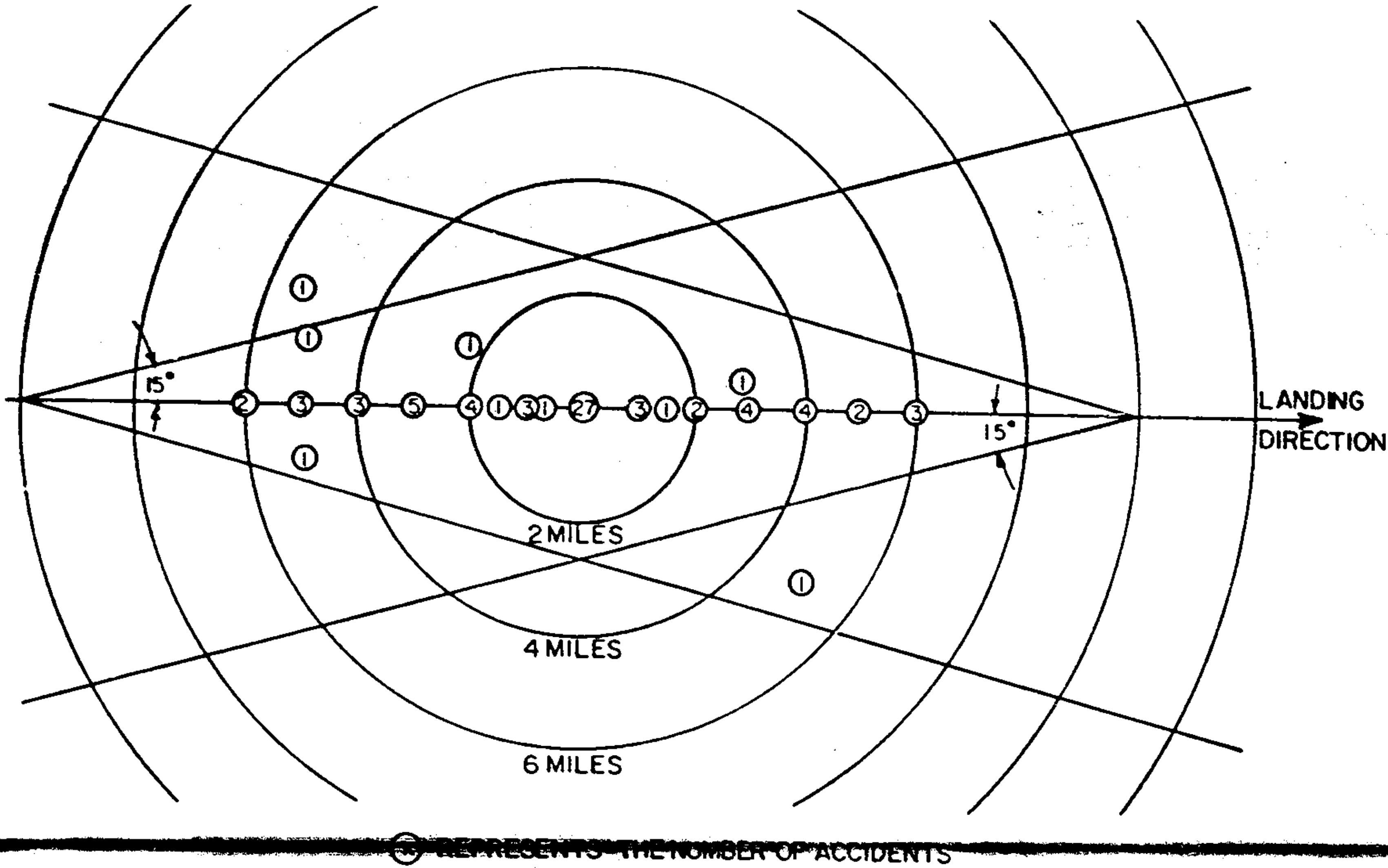

Fig. 1 Polar Plot for all Canadian Landing Accidents for Aircraft Above 18,000 Pounds during 1960-1973 [14]

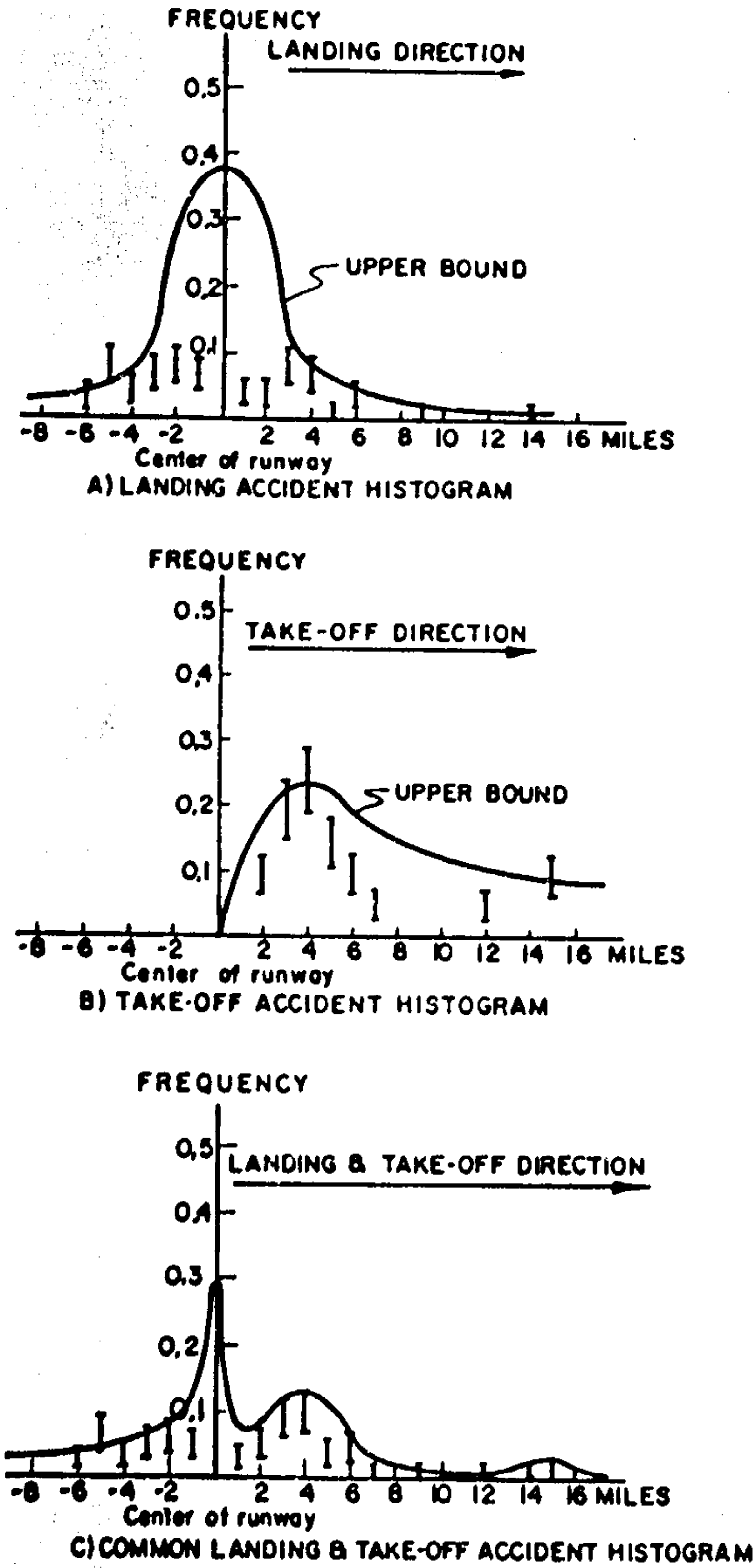

Fig. 2 Canadian Accident Histograms, 1963-1973 [14]

For any of the aviation categories and characteristics discussed above, as much specific detail as desired is generally available. Once a site location is selected the presence of nearby airports, federal airways, controlled air spaces, and military activities can be identified and appropriate site-specific statistics can be gathered and analyzed. This information is necessary to (1) identify the appropriate crash rates, (2) determine whether specialized statistical crash models require development, and (3) compute the desired crash probabilities for aircraft hazards to the nuclear power plant. In Section 4.3 existing crash rate models are presented.

4.3 Aircraft Crash Rate Models

Several definitions of an aircraft accident potentially hazardous to a nuclear power plant have been used, e.g., fatal and critical accidents defined in the preceding section. Other definitions include incidents that result in fatalities or malfunctions serious enough to force the aircraft to land at other than its planned destination and accidents that could cause the aircraft to crash or collide with any structure not at an airport. In the following crash rate models, the definition involved will be presented as used with no serious attempt at quantitative correlation since, in general, the difference between fatal and major accident subsets and all accidents is less than one order of magnitude. The three most common normalizing factors applied to the accident data are the number of aircraft-miles flown, the surface area over which flights are made, and the number of airport operations or movements.

4.3.1 Crash Rates per Aircraft-Mile

As derived in Section 4.2.1, the average fatal Air Carrier accident rate is about 3×10^{-9} per aircraft-mile. NRC Standard Review Plan [2] cites a value of 4×10^{-10} commercial aircraft en route crashes per aircraft-mile as having been used and references H.E.P. Krug, "Testimony on Aircraft Operations in Response to a Request from the Board," Docket Nos. 50-275 and 50-323. This crash rate is based on the assumption that one catastrophic in-flight failure will occur in the U.S. per year, an event characterized by loss of altitude with no pilot directional control of the aircraft. This is certainly an accident subset smaller than the total fatal accident subset, and, although no accident data base analysis was presented, the value of one en route catastrophic aircraft event per year appears plausible. However, it is not obvious that only catastrophic aircraft failures are threatening to nuclear power plants in view of the record that cites most first causes of accidents as weather, personnel, and pilot (e.g., pilot failed to follow procedures and directions, misjudged speed and distance, etc.). Thus, it would appear that calculating the in-flight crash rate per aircraft-mile on the basis of the smallest accident subset, i.e., catastrophic accidents, yields the lower bound for the Air Carrier en route accident rate.

The SRP also cautions that heavily traveled corridors (more than 100 flights per day) may require a more detailed analysis. This is important since it recognizes that the above value is an average over all corridors. To our knowledge Air Carrier crash rates have not been derived as a function of air corridor characteristics such as identity, traffic density, location, altitude, etc.

Godbout and Brais [15] have calculated the following en route crash rates for heavy aircraft in several countries for the years 1969 to 1973:

Country	Crash Rate per Billion Aircraft-Miles	Uncertainty
United States	2.1	30%
United Kingdom	24	58%
France	50	50%
West Germany	32	100%
World Average	9.5	12%

These rates are based upon all accidents serious enough to force the aircraft to land, but include only accidents that occur farther than 30 miles from an airport. In the U.S. it has been observed that about one-third of fatal accidents occur within 5 miles of an airport (see Section 4.2.2). Thus, their value of 2.1×10^{-9} potential crashes per aircraft-mile reflects the increasing effect of using an accident data base larger than the fatal subset and the decreasing effect of the 30-mile data exclusion zone around an airport. For heavy Canadian aircraft they have computed an in-flight serious accident rate of 8.0×10^{-9} per aircraft-mile.

Solomon [16,17,18] derived the following average Air Carrier crash rates for three classes of accidents for the period 1967 to 1972:

Accident Class	Accidents per Aircraft-Mile
All Accidents	23×10^{-9}
Major Accidents†	11×10^{-9}
Fatal Accidents	4×10^{-9}

†Potential crash or collision with any structure not at an airport

For major Air Carrier accidents Solomon derived the following crash rates for three phases (modes) of operation:

Phase of Operation	Major Accidents per Aircraft-Mile
Takeoff	116×10^{-9}
Inflight†	5.2×10^{-9}
Landing	450×10^{-9}
Average	11×10^{-9}

†Includes climb and descent

Gottlieb [19] determines a fatal accident rate of 0.045×10^{-8} per mile "by averaging the rates for the years 1970 to 1975 as reported by the NTSB." This value is an order of magnitude lower than other similar calculations, and since the supporting data base is not presented, it is not clear how the calculation is made.

Subject to possible air corridor traffic variations, a value of 3×10^{-9} for the in-flight heavy aircraft crash rate per aircraft-mile along air corridors appears to be a reasonable compromise among variations due to phase of operation and accident definition. Site analyses in the vicinity of an airport may duplicate from one-third to one-half of these accidents in the airport-related hazard rates, and an expanded accident data base no more than about 1.5 to 3 times the fatal accident data could be justified based upon reviews of accident types and scenarios that could be postulated as potentially threatening to nuclear power plants.

For the General Aviation category, crash rates per aircraft-mile have been developed by Solomon [16,17] with kind of flying as an additional parameter;

these results are summarized below for major accidents and the phases of operation:

Flight Category	Major Accidents per Aircraft-Mile (x 10^{-9}) All	Takeoff	In-flight†	Landing
All	530	2440	318	2440
Instructional	330	1530	198	1010
Business/Corporate	370	1710	222	1210
Pleasure	940	4230	564	6350
Aerial Application	790	2370	474	1740
Air Taxi	320	1470	192	1230

†Includes climb and descent

The ratio of the major accident and fatal accident crash rates is about the same for both Air Carrier and General Aviation, slightly less than a factor of 3. (This ratio is significantly larger than three for instructional and aerial application flights.)

Niyogi et al. [13] derived crash rates for critical accidents of small fixed-wing General Aviation aircraft as a function of distance from the airport; these are presented below for the five-year period 1966 to 1970:

Accident Location	Average Critical Accidents per Year	Critical Accidents per Aircraft-Mile
On airport	87	-
0-1 miles	190	2370 x 10^{-9}
1-2 miles	76	950 x 10^{-9}
2-3 miles	55	690 x 10^{-9}
3-4 miles	44	560 x 10^{-9}
4-5 miles	19	230 x 10^{-9}
> 5 miles	514	160 x 10^{-9}
All accidents	985	280 x 10^{-9}

Clearly, the crash rate of small fixed-wing aircraft reaches the beyond-5-mile asymptotic value shortly after the 5-mile distance. This value is computed using an average of 3.12 x 10^9 aircraft-miles flown beyond 5 miles; the miles flown within 5 miles of an airport is one order of magnitude less.

Critical accidents defined by Niyogi et al. are 1.6 times larger than the fatal subset; therefore, the average fatal crash rate is 175×10^{-9} per aircraft-mile consistent with the values of 180×10^{-9} and 187×10^{-9} per aircraft-mile given in Section 4.2.2 and by Solomon, respectively. Gottlieb [19] gives fatal crash rates for twin-engine aircraft of 69×10^{-9}, 6.4×10^{-9}, and 14×10^{-9} per aircraft-mile for pleasure, business, and air- taxi flying, respectively, derived from data for 1975 and 1976.

These crash rates are used in computing crash probabilities for sites in the vicinity of flight paths or airways (see Section 4.4). A statistical measure of the crash distribution normal to the flight path or airway is needed to define the crash accidents per aircraft-mile per mile normal to the flight path or per flight operation per square mile.

4.3.2 Crash Rates per Square Mile

There is an absence of statistical data required to correlate the distribution of crash impact locations with aircraft and flight path characteristics. Analyses that construct models to do this are discussed in Section 4.4. However, two cases can be developed from statistical data and correspond to the extremes in which the flight path is either irrelevent or relatively fixed. The first represents statistically random flights which closely approximate much of General Aviation, and the second represents the immediate vicinity of airports.

Using the data of Niyogi et al. from 1966 to 1970, there is an average of 898 critical accidents per year of small fixed-wing aircraft (not including aircraft on the airport), which gives an average of 3.0×10^{-4} accidents per square mile per year over the Continental U.S.* during the reference 5-year period. Niyogi et al. derive a value of 2.3×10^{-4} crashes per square mile per year for these accidents occurring more than 5 miles from an airport assuming 10,010 airports; the average airport rate, i.e., within 5 miles, is 4.9×10^{-4} accidents per square mile per year, and this rate increases rapidly as the distance to the airport decreases. The Canadian light aircraft en route average crash rate is derived by Godbout et al. to be about 4×10^{-5} per square mile per year during 1974.

*Continental U.S. area is 3.023×10^{6} square miles (source: 1978 Hammond Almanac).

These rates assume that a crash can occur anywhere with equal likelihood and independent of flight path. They may be viewed as nonconservative in the sense that they represent gross averages of statistical data and do not take into account flight traffic density. The Canadian crash rate could well reflect this type of variation. Thus, the area of susceptible targets of a nuclear power plant to small fixed-wing aircraft must be exceedingly low for the probability of an unacceptable crash event to be less than 10^{-7} per year. This will be discussed in more detail in Sections 4.4 and 8.

Several analyses have been made for airport crash rates utilizing statistical data on the distribution of crashes occurring in the vicinity of an airport. Eisenhut [6] analyzed fatal crashes that "occurred within a 60 degree reference flight path symmetric about the extended centerline of the runway." His results are based upon 8×10^7 Air Carrier, 5.5×10^7 Navy/Marine Corps, and 3.9×10^7 Air Force movements and are given in Table 4. Eisenhut [6,20] also derived fatal crash rates for General Aviation as a function of distance from the airport using a data base of 3993 fatal accidents resulting from 3.2×10^8 movements from 1964 to 1968. These are given in Table 5 and range from 3.75 to 6.46 times higher than the corresponding rates for Air Carriers with an average of 5:1.

Boonin [21] performed a similar analysis of data for the years 1966 to 1970 assuming that all accidents (fatal) occurred within the 60 degree cone used by Eisenhut. Results were obtained for small (less than 12,500 pounds) and large (more than 12,500 pounds) aircraft in General Aviation and Air Carrier categories and are given in Table 6. They agree closely with Eisenhut's results for General Aviation but exhibit some differences with regard to Air Carriers.

From Tables 5 or 6 for General Aviation the fraction of fatal aircraft crashes occurring in each radial zone can be computed after multiplying by the respective zone areas. The resulting distribution of fatal accidents agrees closely with that of Niyogi et al. for critical small fixed-wing aircraft accidents operating out of any airport (see Table 3). The radial variation of crash rate strongly decreases due to (1) the decrease in the number of accidents with increasing distance from the airport, and (2) the geometric divergence of the radial zones.

Solomon et al. [22,23] derive an average crash rate of 2.0×10^{-8} per operation per square mile by considering all fatal crashes occurring at all commercial airports from 1965 to 1972 over the 10 square miles immediately adjacent to the runways. In addition a fatal crash rate of 15×10^{-8} per

Table 4 Fatal Crash Rates for Air Carrier - Military Aviation [6,20].

Distance from end of runway (miles)	Probability ($x 10^8$) of a fatal crash per square mile per aircraft movement		
	U.S. Air Carrier	USN/USMC	USAF
0 to 1	16.7	8.3	5.7
1 to 2	4.0	1.1	2.3
2 to 3	0.96	0.33	1.1
3 to 4	0.68	0.31	0.42
4 to 5	0.27	0.20	0.40
5 to 6	0.0*	NA†	NA†
6 to 7	0.0	NA	NA
7 to 8	0.0	NA	NA
8 to 9	0.14	NA	NA
9 to 10	0.12	NA	NA

*No crashes occurred at these distances within a 60° flight path.
†Data not available.

Table 5 Fatal Crash Rates for General Aviation [20]

Distance from airport, miles	Probability of a fatal crash per $mile^2$ per aircraft movement
0 to 1	84×10^{-5}
1 to 2	15×10^{-5}
2 to 3	6.2×10^{-5}
3 to 4	3.8×10^{-5}
4 to 5	1.2×10^{-5}

Table 6 Detailed Crash Rates - Fatal Accidents per Operation per Square Mile [21]

Aircraft Categories	Distance from Airport				
	1/2-1 mile	1-2 mile	2-3 mile	3-4 mile	4-5 mile
All aircraft	4.098×10^{-7}	1.438×10^{-7}	6.232×10^{-8}	3.857×10^{-8}	1.149×10^{-8}
Small aircraft	4.755×10^{-7}	1.561×10^{-7}	7.199×10^{-8}	4.404×10^{-8}	1.291×10^{-8}
Large aircraft	6.902×10^{-8}	2.076×10^{-8}	2.076×10^{-9}	4.448×10^{-9}	2.307×10^{-9}
General Aviation (total)	4.283×10^{-7}	1.400×10^{-7}	6.271×10^{-8}	3.958×10^{-8}	1.220×10^{-8}
General Aviation (small)	4.534×10^{-7}	1.483×10^{-7}	6.271×10^{-8}	4.203×10^{-8}	1.220×10^{-8}
General Aviation (large)	2.976×10^{-7}	3.809×10^{-8}	----	5.952×10^{-9}	----
Air taxi (total)	1.188×10^{-6}	4.291×10^{-7}	2.447×10^{-7}	9.574×10^{-8}	5.319×10^{-8}
Air taxi (small)	1.100×10^{-6}	4.291×10^{-7}	2.447×10^{-7}	9.574×10^{-8}	5.319×10^{-8}
Air taxi (large)	1.415×10^{-6}	----	----	----	----
Air Carrier (total)	7.639×10^{-8}	1.910×10^{-8}	7.639×10^{-9}	1.091×10^{-8}	8.488×10^{-9}
Air Carrier (small)	2.425×10^{-6}	6.190×10^{-7}	1.905×10^{-7}	3.809×10^{-7}	1.905×10^{-7}
Air Carrier (large)	2.604×10^{-8}	6.135×10^{-9}	4.090×10^{-9}	2.761×10^{-9}	4.090×10^{-9}

operation per square mile over the "most dangerous" square mile located at a distance of one mile and along the centerline of the runway is derived. These values are independent of aircraft category and are in general agreement with the all aircraft values in Table 5.

Godbout and Brais [15] found that for light aircraft (gross weight less than 18,000 pounds) the crash point distribution in the vicinity of Canadian airports exhibits no angular dependence with respect to the runway direction. Further, the number of accidents decreases very rapidly with distance such that the presence of a light aircraft airport becomes unimportant after about 2 to 5 miles as shown in Fig. 3. Corresponding crash rates would appear to drop off faster with distance than the U.S. data indicate; however, the en route value for light aircraft exists in both cases in the neighborhood of 5 miles from the airport.

The dependence of the heavy aircraft crash rate on the polar coordinates (r,θ), r being the radial distance and θ the angle to a crash location measured relative to an airport runway, is derived by Godbout and Brais [15] on the basis of Fig. 2 for takeoff and landing r-variations and the Solomon et al. model [22] for the θ-variation, i.e., given a relative crash rate $C(\theta) = 1.0$ between 0 and 1 degree of the runway,

$$C(\theta) = \begin{cases} 1.0 \, , & 0^\circ < \theta < 1^\circ \, , \\ 1/\theta \, , & 1^\circ < \theta < 90^\circ . \end{cases} \tag{4.1}$$

Making use of the conservative assumption that all takeoffs of heavy aircraft are made in the same direction along a runway, independent of meteorological or other conditions, the crash rate* distribution for heavy aircraft in the vicinity of Canadian airports is shown in Fig. 4 for an airport having 300,000 annual movements from a single runway.

The crash rate model of Solomon et al. also exhibits both radial and angular dependence about a runway for takeoff and landing accidents. Solomon and Godbout both considered airports with more than one runway and potential crash sites near particular airports for which additional relevant data were gathered. In such actual situations, statistics on takeoff and landing patterns and practices, either from airport and FAA records or through direct observation, are necessary to define the traffic levels and define

*Godbout's results presented for the crash probability on a site of 0.01 mi^2 are converted to crash rates per square mile here.

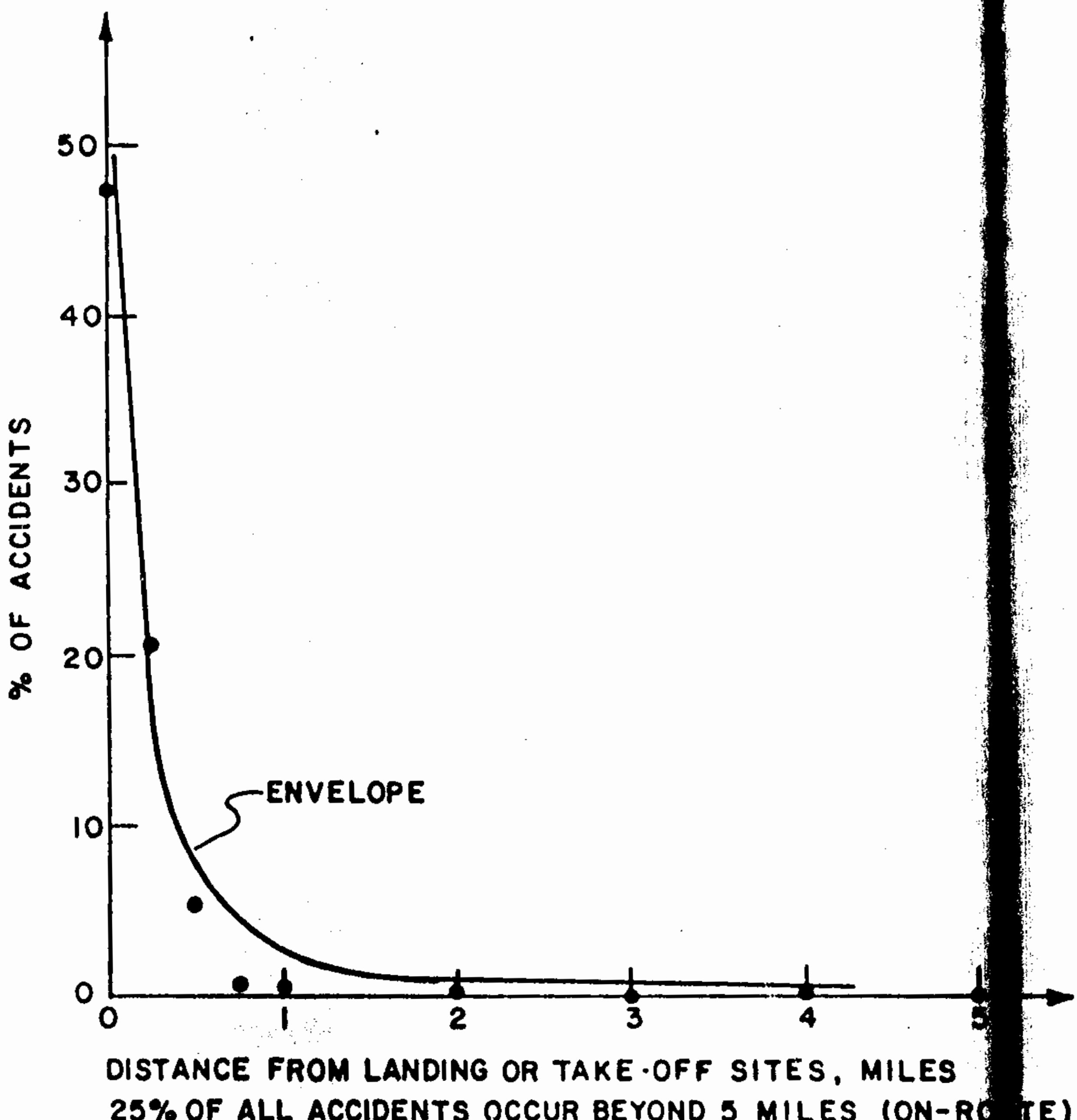

Fig. 3 Canadian Crash Point Histogram for Distance to Landing or Takeoff Site for Light Aircraft [15]

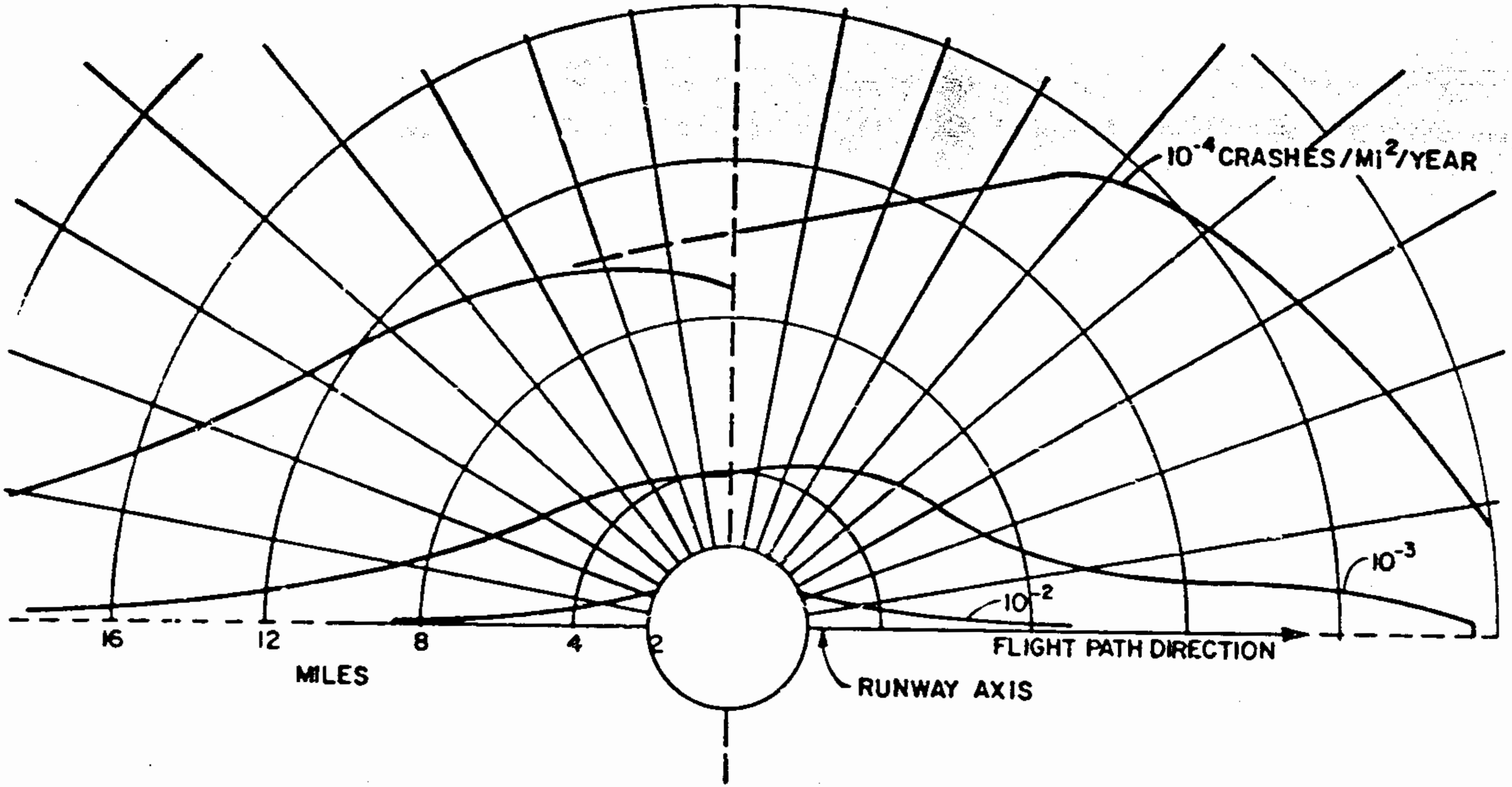

Fig. 4 Crash Rate Contour Lines for Heavy Aircraft in the Vicinity of a Hypothetical Canadian MOT Airport with 150,000 Landing and 150,000 Takeoff Annual Movements [15]

the calculations where desirable. Hornyik et al. [24,25,26] derived crash rate distributions for military aircraft flying target-bombing flight patterns, again utilizing available site-specific information (in this case military data were obtained).

4.4 Aircraft Crash Probability Methodologies

The aircraft crash rates of Section 4.3 are used to determine the probabilities of crashes at any specific site. In general a set of probability estimates must be generated corresponding to groupings of the following parameters: (i) type of aircraft, (ii) type of aviation activity, (iii) airport characteristics, (iv) air corridor, restricted air space, and background air activity overhead or within crash range, and (v) site features. These parameters appear explicitly in the probability estimation process and implicitly through the selection of the appropriate crash rate statistics and modeling methodologies.

The sensitivity of these calculations is such that the results will depend principally upon the frequency of flights, the crash rate, and the potentially susceptible targets at the site for each grouping. Obviously site-specific data must thus be used in any numerical crash probability evaluation. It should be mentioned at this point, however, that past experience indicates that, for the siting of nuclear power plants, the presence of nearby airports having a relatively large number of annual movements, nearby air corridors, and the flights of light (single engine) aircraft usually dominate the overall crash probability valuation. In these instances it has been found that the engineered safety features of a nuclear power plant are importantly drawn into the risk estimation procedure, and the individual hazard groupings above become quite significant in themselves in addition to their contribution to the overall crash probability.

4.4.1 Crash-Probability Models

The probability P_G of an aircraft crash per year for a particular grouping described above is given by

$$\begin{aligned} &(I) \quad P_G = NAC \\ &(II) \quad P_G = NAC/W \end{aligned} \qquad (4.2)$$

where N is the number of annual operations, e.g., airport movements or aircraft flights, A is the effective target area at the site, C is the crash rate per movement per square mile in Eq. 4.2(I) or the crash rate per aircraft-mile in Eq. 4.2(II), and W is the effective crash width extent centered on the aircraft's flight path (when C is given per aircraft-mile). All of these variables depend upon the identities of the parameters chosen to belong to the various possible groupings (subscripts to indicate the five principal parameters are omitted for clarity with the single subscript G affixed to P to emphasize this dependence). The values of the variables in Eq. 4.2 are, of course, site-specific, and their variability depends upon the level of detail represented by the parameter groups chosen.

Note that although crash rates can vary considerably depending upon their parameter composition, they are derived on the basis of the national accident data base - a statistical requirement in view of the rarity of aircraft crashes at any given site location. Additionally, certain conditional probabilities are required as they affect potential target areas and aircraft crash consequence models. These relate to the aircraft crash path and its orientation relative to the plant features, the aircraft impact speed and weight, and the likelihood of fuel fire and explosion events, given that the crash of a particular type of aircraft occurs. The discussion in the following subsections will examine the formulation and evaluation of the pertinent conditional probabilities.

4.4.1.1 Aircraft Crash Path

Crash trajectories from the flight point where trouble (first) develops to the impact point are implicitly represented by the statistical distribution of crash points for airport-related activities and treated as randomly occurring events for uncontrolled (general) aviation. For in-flight traffic along prescribed routes such as air corridors and traffic patterns where a flight line exists, for example, military air maneuvers such as weapons delivery or navigation practice [25], probability distributions can be constructed for both the normal traffic deviations and crash trajectories. The latter will depend upon such factors as altitude, attitude, type of aircraft and other characteristics such as speed.

Hornyik et al. [24,25] construct a normal air traffic density function in order to compute a collision probability, that is, collisions resulting from deviations from the intended flight path and the presence of plant structures. These accident types are included in the statistical data base and can be usually ignored as an important separate class of events except in very special cases of low flying aircraft in aerial application and military aviation. For most low flying aircraft, e.g., pleasure flying, the deviations from "intended" routes are usually so large that the routes are virtually nonexistent relative to the present application, and collisions are equivalent to random crash events. For high altitude flights along air corridors, flight path deviations are assumed negligible in extent and implicitly included within the crash trajectory distribution orthonormal to the flight path.

Crash site probability distribution functions have been constructed by Hornyik et al. [24] and Solomon [16]. Figure 5 illustrates the geometric relation between the crash site and (straight) intended flight path, e.g., air corridor centerline. Associated with the crash site to flight path distance x is the conditional probability of a crash occurring along the line x equal to a constant, given that a crash occurs. Solomon assumes this conditional probability to be a negative exponential function that decays (symmetrically) as x increases and gives the following subjective estimates for the decay constant as a function of aviation category:

Aviation Category	Exponential Decay Constant (mi^{-1})
Air Carrier	1.6
General Aviation-Aerial Appliction	1.0
General Aviation-Other	2.0
Military Aircraft	1.0

Gottlieb [19] increased certain of these values to account for lower air-corridor altitudes in his site-specific analysis.

In general, air corridors may not be straight, and there are often multiple corridors having different directions and different altitudes over a given site. Gottlieb modeled such an instance by dividing the air space into half-mile wide strips and superimposed the negative exponential density functions for each strip. He found that the orthonormal conditional probability becomes negligible beyond x equal 3 miles for a decay constant of 2/mile.

The value of W^{-1} in Eq. 4.2 is this conditional probability of orthonormal crash site location and is a function of the distance from the plant to the air corridor centerline. SRP Section 3.5.1.6 suggests using for the value of W the air corridor width when the site is under it, and this width plus twice the distance from its edge to the site when the site is beyond the airway. The product of Δh and ΔL shown in Fig. 5 corresponds to the value of A in Eq. 4.2.

The effective plant area A is the equivalent ground surface area such that a crash probability computed on the basis of A accounts for all crashes that could affect susceptible targets at the plant site for each parameter grouping. The calculation of A will, in general, involve aircraft, crash related, and target characteristics. Most analyses treat A as the sum of a skid area, shadow area, and true target area. The shadow area is very significant since it allows for target height; it depends strongly upon the crash angle and is illustrated in Fig. 6. The shadow area varies inversely with tan ϕ where ϕ is the crash angle shown in the figure. Solomon uses values for ϕ of 15° [16] and 20° [22]; Niyogi [13] quotes values of 10° for landings and 45° for takeoffs. Cravero and Lucent [28] conclude from their study of international aviation that of 34 accidents from 1962 to 1966 over half resulted in vertical dives (ϕ equal to 90°), and for the remainder ϕ is greater than 45°; they arrive at similar conclusions from their study of European private aviation for the years 1968 to 1970. Joerissen and Zuend [29] assume an average value for ϕ of 45°.

The skid area is shown by Solomon [16] to vary proportionally with the square of the aircraft's initial horizontal velocity, and inversely with a friction factor that depends on the ground terrain. From a review of accident reports and other studies, Solomon [16] lists possible skid lengths, viz.: 0.6 mile for high velocity military aircraft; 0.3 mile for Air Carrier aircraft; 0.06 mile for General Aviation aircraft; and an upper distance of one mile for high velocity military aircraft on very smooth terrain. Hornyik and Grund [25] state that the choice of skid length should fall into the category of conservatism due to "partial/total ignorance".

In many analyses, skid area is not factored into estimations of A; this may be due to the corresponding decrease of the aircraft's impact kinetic energy as the skid distance increases. However, Solomon notes that skid area tends to dominate the evaluation of total effective area, more so than the choice of ϕ, and is, therefore, important.

In general, the calculation of effective plant area can become rather complex. The effective aircraft diameter is of the same order of magnitude as plant structure dimensions and must be included; this is usually done by simply increasing the dimensions of the target. Accordingly, A is a direct function of the aircraft type. Crash related characteristics other than ϕ can be important such as crash orientation relative to the plant and accident failure modes. The targets at the plant have complex geometries

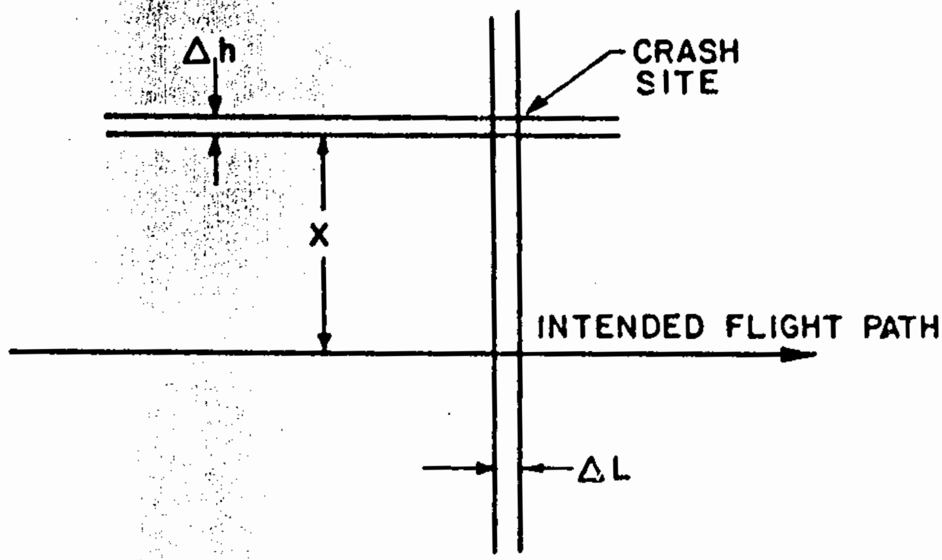

Fig. 5. Crash Sites Orthonormal to a Flight Path [16]

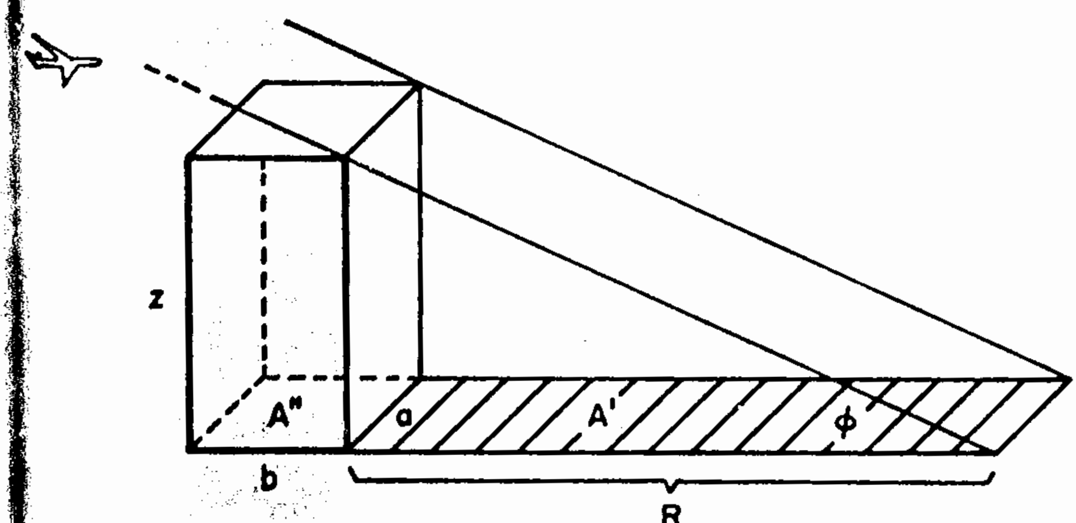

Fig. 6 Shadow Area of a Plant Structure [16]

especially in relation to one another (shielding possibilities arise and vary with crash orientation), and terrain features (both natural and man-made) strongly affect skidding.

4.4.1.2 Aircraft Impact Characteristics

From 1973 to 1976, 19 different aircraft makes and models were involved in 88 percent of all and 90 percent of fatal Air Carrier accidents [10]. Including both piston and turbine engines, there were over 118,000 small (lighter than 12,500 lbs) and 5,100 large (heavier than 12,500 lbs) aircraft in 1968 [12]. Chelapati et al. note that the size, weight, and speed of an aircraft are direct functions of its horsepower and use the 1967 annual FAA census and other data to construct frequency distributions for small and large aircraft speeds and engine weights and thus their effective diameters and weights. A typical speed of 140 percent of stall was assumed within 5 miles of an airport, and 75 percent of power, 140 percent of stall, and maximum power were assumed beyond 5 miles.

Niyogi et al. [13] analyzed the characteristics of small fixed-wing aircraft and observed that length, maximum takeoff weight, stalling velocity, and maximum horizontal velocity (for at least single-engine aircraft) all scale with empty weight, w_o. They developed idealized aircraft parameters as functions of w_o for single-engine (1000 lb $\leq w_o <$ 2200 lb) and twin-engine (2800 lb $\leq w_o <$ 8000 lb) aircraft, and they suggest several probability distribution models to account for fleet mixes. Solomon et al. [22] base selection of aircraft characteristics upon the aircraft flight data for two specific airports; e.g., wide-body jet aircraft account for one-third of all operations at Los Angeles International Airport.

Godbout and Brais [15,27] have constructed probability density functions for the crash characteristics of a large number of individual light and heavy aircraft (e.g., average crash speeds of 80 and 150 mph, respectively). Modeling the conditional probability of an impacting aircraft having any given set of characteristics is necessary to the realistic estimation of possible crash consequences, e.g., the conditional probability of a particular structural failure mode occurring. Information on the fleet mix appropriate to a given site locale can be subsequently used to yield overall conditional probabilities defining the aircraft crash consequence environment.

4.4.1.3 Aircraft Fires

In their study of accident data, Cravero and Lucenet [28] found that for 44 accidents from 1962 to 1966, 26 fires commenced after impact against the ground (about 60 percent of the accidents) while 9 aircraft "were in fire at the moment of the impact on the ground." Joerissen and Zuend [29] report that an engine catches fire in about a third of all fatal accidents, according to statistics. Wall [30] reviewed NTSB reports of accidents and found that about 30 percent of General Aviation and 50 percent of Air Carrier crashes involved postaccident fire.

4.4.2 Crash Probability Calculations

The immediate objective of calculating an aircraft crash probability at a given nuclear power plant site is to obtain the annual frequency of the condition "given a crash occurs" corresponding to each or any combination of groupings of the aircraft accident and plant parameters defined in Section 4.4.2 and selected from site-specific criteria. This can then be combined with suitable conditional probabilities (see Sections 4.4.1.1 to 4.4.1.3) and deterministic relationships (see Sections 6 and 7) to estimate the possibilities that various modes and magnitudes of crash-induced plant-related consequences will exist.

However, the crash probability is itself a conditional probability, conditioned by the particular parameter grouping, that is, accident scenario characteristics and, more importantly in the current context, the effective target features. Since the nature of the target in the present application depends itself upon the assumed accident scenario, e.g., light or heavy aircraft, the calculation process can be rather involved; further, potential nuclear power plant (safety-related) targets are complex and varied (see Section 5). The procedure requires identification and quantification of likely accident scenarios and evaluation of corresponding target features on the basis of deterministic and judgmental methodologies and consequences criteria.

It is important to view the results of various investigations discussed below with this perspective in mind since the necessary detail supporting both scenario and plant feature assumptions and sensitivity calculations are extremely difficult to find and evaluate. Furthermore, crash probabilities must be multiplied by appropriate conditional probabilities of a radioactive material release exceeding 10 CFR 100 guidelines to obtain the consequence probabilities for such a release. This is usually implicitly done by assuming a release conditional probability of unity for all structures used in the effective plant area evaluation and of zero for those excluded. The first assumption is in many cases very conservative for the type of structures and range of both accident and plant response scenarios

involved. Sensitivity to the second assumption can be estimated by using all potentially relevant plant features (and their shadow, skid, and shielding characteristics) as an upper-bound calculation, but total effective plant area evaluations are generally unavailable.
Niyogi et al. [13] discuss this aspect of the problem in more detail and numerically weight the effective areas of their identified susceptible targets by assumed conditional release probabilities as follows: a value of 1.0 for the containment, fuel storage building, and control room; 0.1 for the primary auxiliary building and equipment vault; 0.01 for the diesel-generator building, cooling tower, waste-processing building, refueling water storage tank, circulating-water pump house, and service water pump house; and 0.0 for the turbine building.

Joerissen and Zuend [29] present probabilities of crash-induced radioactive releases and refer to detailed studies of system/component susceptibilities and reactor response for both BWR and PWR plants, but do not cite references or provide details. They estimate the conditional probability of equipment damage in a room inside a penetrated building as generally greater than 30 percent. Selvidge [31] considers damage scenarios for an aircraft missile penetrating a building containing plutonium and computes probabilities (Rocky Flats Plant) of various forms of plutonium escaping in different quantities. These scenarios all involve fire of the aircraft fuel as the primary release mechanism.

Table 7 presents various crash probability and related results for nuclear power plants [20] and is based on calculations by Eisenhut [6] and the Surry SAR and AEC Regulatory staff evaluations. Chelapati et al. [12] and Wall [30] derive the following crash probabilities for a "typical" BWR plant located relative to an "average" airport using crash rates and traffic data averaged over the entire U.S.:

Aircraft Size	Aircraft Strikes per Year†	
	Within 5 miles	Beyond 5 miles
Small	3.3×10^{-5}	1.4×10^{-5}
Large	1.1×10^{-6}	4.6×10^{-7}

†Does not consider air corridors

These results assume effective target areas ($\phi = 10°$) as follows: 0.093 mi^2 for the reactor building, 0.026 mi^2 for the turbine building, and 0.018 mi^2 for the switchyard (0.137 total square miles for a BWR plant). Note that the switchyard target area is as large as the entire target areas given in Table 7. These results do not include any conditional probabilities

Table 7. Crash Probabilities for Various Sites [6,20]

	Three Mile Island (2 units)	Shoreham (1 unit)	Rome Point (2 units)	Surry units 3 and 4 (2 units)
Usage (movements/year)				
Air cariers	80,000*		3,000	40,000
Navy		8,000	97,000†	40,000
Miscellaneous		3,000‡		
Location (plant-airport distance in miles)	2.5	4.5	3.5	5
Target area (used in probability analysis)	0.02 mi^2	0.01 mi^2	0.02 mi^2	0.01 mi^2§
Probability of a potentially damaging crash (per year)	5×10^{-7}	2×10^{-7}	4×10^{-7}	1×10^{-6}

*The facility is designed to withstand the crash of all but 2400 of these movements.

†The facility is designed to withstand the crash of all these 97,000 movements.

‡Air-carrier statistics were used for these movements.

§For small aircraft, area used was 0.005 mi^2

representing crash consequences, but they derive adjustments to the strike probabilities based upon calculations of the perforation failure mode for varying thicknesses of concrete and two aircraft types. Additionally, they derive the conditional probability of striking any specific safety-related equipment within a building to be 0.01.

Niyogi et al. [13] derive the following crash probabilities from normal background aviation crashes into safety-related structures for a typical two-unit nuclear power plant having a total projected area of about 0.01 mi^2:

Aircraft Type	Two-Unit Crash Probability (yr^{-1})
Air Carrier	2.0×10^{-8}
Small Fixed-Wing (2 Engine)	2.0×10^{-7}
Small Fixed-Wing (1 Engine)	1.1×10^{-6}
Any	1.3×10^{-6}

The effective plant area does not appear to be conservatively calculated, and the conditional damage probabilities discussed above have been applied to obtain these results. Further, the background aviation used does not explicitly take into account airport and airway effects.

Solomon [16] derives effective plant areas* for the Palo Verde Nuclear Generating Station of 0.017 mi^2 for General Aviation aircraft, 0.1 mi^2 for an F-104 Starfighter Jet, and 0.067 mi^2 for a DC-10 using shadow and skid areas for the containment, fuel, and radwaste buildings. These areas are significantly larger than those used in most such studies. The PVNGS is near some military aviation and approximately 5 miles from an air corridor having about 100,000 flights per year. The crash probability for the air corridor hazard (strongly dependent upon separation distance) is derived to be about 6×10^{-8} per year and represents the largest aircraft hazard at this site. Solomon [17,18] also has developed a generalized methodology for calculating the crash-probability at an arbitrarily located site, but, since his sample results are hypothetical in nature, they will not be presented here.

Gottlieb [19] treated a specific site near several air corridors, a large airport 50 miles away, a large number of small airports, and at least six

*Adjusted here from a three-unit plant to an average single-unit plant.

large ones within 75 miles. His analysis clearly illustrates the importance of deriving crash probabilities on the basis of the parameter groupings discussed previously. The crash probabilities for single-engine and twin-engine General Aviation aircraft are given as 3.9×10^{-5} and 1.0×10^{-6} per year, respectively.

4.5 Aircraft Hazards Summary

Excellent information sources exist and are readily available for establishing aircraft-related data bases and statistics. All aircraft accidents are investigated and reports filed containing as much detail as possible under the circumstances. The absence of or difficulties involved in generating certain types of accident parameters can usually be compensated for by analytical procedures, conservative assumptions, or probability distribution functions. Major aircraft crashes at any given site represent very low probability events. Aircraft crash rates that scale with the number of operations and based upon the data bases can be estimated with a reasonably high degree of confidence. However, except primarily for a cursory treatment in the Canadian reports [14,15,27], other scaling effects have not been adequately studied. Niyogi et al. [13] found, however, that the airport-related accident rate for small fixed-wing aircraft varies from about one-third to almost five times the average rate in going from large FAA airports to very small airports (see Table 3). The possibility of regional and air corridor variations in the crash rates for all types of aviation, both nonrouted and in airways, has not been adequately investigated in regard to the present application. Also, not enough attention is given in general to the particularly threatening scenarios posed by small but relatively heavy and fast (e.g., twin-engine) aircraft.

There are three primary effects of airports, airways, and other restricted air spaces: (1) to concentrate the level of air traffic, (2) to increase the crash rates as distance to these zones decreases, and (3) to increase the number of different types of aviation activities (for example, takeoffs, landings, and the concentration of large commercial aircraft; others include military applications, etc.). It is reasonable to conclude that the combined effects of these controlled regions represent a significantly increased hazard to nuclear power plants than the true or even averaged background aircraft hazard.

For small (General Aviation) aircraft it would appear from the available analyses that the airport effect merges into background crash rates at about 5 miles for airports having say 10,000 operations per year and probably at only a slightly larger distance, say 6 miles, for any size airport; a significantly increased rate would only begin to appear very close in, say within 2 to 3 miles. For large (Air Carrier) aircraft a nominal background crash rate on the order of 10^{-9} major crashes per flight per square mile can be assumed along the affected strip of ground under a single air corridor (assume a crash rate of 3×10^{-9} per aircraft-mile and a mean crash-width dimension of 3 miles). For heavily traveled corridors, more than 100,000 flights per year, the heavy aircraft crash rate in the <u>immediate</u> vicinity of air corridors will vary from about the same to significant., greater than the background light aircraft rate.

The heavy aircraft crash rate per square mile 5 miles from an airport is not significantly larger than that near an air corridor <u>per operation</u>. If it is assumed that one-third of all Air Carrier crashes occur within 5 miles of an airport and one-half of all crashes are "airport related," then the airport effect on crash rate will extend for some, possibly considerable, distance beyond 5 miles. This distance-airport effect relationship cannot be examined further at present using only the analyses and data evaluated here.

Crash probability calculations for the specific sites previously studied involved considerable data gathering and modeling of site features and accident parameters. Results are strongly dependent upon these factors and invariably reflect derived and in most cases assumed conditional probability estimations of certain event occurrences. In general, the aircraft accident hazard cannot be eliminated solely on the basis of the crash probability being less than 10^{-6} to 10^{-7} per year without taking into account the inherent hardness and identity of safety-related features of the plant. Even doing so often leads to results that are near to or marginally within 10 CFR 100 guidelines; however, considerable conservatism is apparently included in the radioactive release conditional probabilities typically used.

The aircraft hazards studies that have been made are important to more general considerations of reactor safety, siting, and risk estimation. These procedures are essentially risk-based concepts [32,33,34] in that both probabilities of occurrence and consequences as the result of occurrence, i.e., all aspects of a possible event, are considered. Finally it should be noted that there are no explicit requirements on the frequency of occurrence of aircraft crashes per se on nuclear power plants provided that the risk is acceptably small. The low risk value is, of course, tantamount to a low crash probability in cases where the conditional probability of having a radioactive release given a crash is taken as unity, e.g., for large commercial aircraft. At the other extreme of zero conditional probability, e.g., light single engine aircraft crashing into the containment structure, no such relationship exists.

5. SAFETY-RELATED SYSTEMS

Safety-related systems may be subdivided in (1) criticality control systems, (2) heat removal systems, (3) support systems, (4) containment system(s), and (5) mitigation systems. In the following we shall address primarily the first three types of systems.

5.1 PWR Safety-Related Systems

5.1.1 PWR Criticality Control Systems

For PWRs the criticality control systems consist of: (1) control rods and drives, and (2) safety injection systems (SIS). Rapid shutdown by dropping the control rods does not require the availability of electric power. However, it should be recognized that in PWRs the control rods do not constitute a complete shutdown system, in that the reactivity worth of the rods is only sufficient to bring the plant from full power to hot stand-by conditions. To bring the plant to cold shutdown requires injection of boron by means of the safety injection system, which does require electric power if the primary system remains pressurized. Note that both these criticality control systems are quite well protected against direct impact in case of an aircraft crash.

5.1.2 PWR Heat Removal Systems

These systems may be subdivided into two groups:

(1) PWR Heat Removal Systems for Normal Operation

- primary heat transport system (PHTS), including: pressure vessel, primary coolant piping and pumps, steam generators, and pressurizer,
- main feedwater system and steam lines,
- condenser and condenser cooling system,
- residual heat removal system (RHRS),
- water intakes and ultimate heat sink(s) (UHS).

Of these systems, the condenser and condenser cooling water system, parts of the feedwater system and the steam lines, as well as the water intakes and ultimate heat sink(s) are not protected inside hardened structures; they are thus vulnerable to direct impact. Moreover, though the residual heat removal system itself is fully contained in the hardened containment and auxiliary buildings, its intermediate heat removal circuit and ultimate heat sink are not protected in that way.

(2) Heat Removal Systems for Off-Normal Conditions

- emergency core cooling system (ECCS), with its injection and recirculation mode,
- auxiliary feedwater system,
- steam dump system,
- containment cooling system (PAHR),
- systems for the feed-and-bleed cooling mode,
- residual heat removal system (RHRS),
- water intakes and ultimate heat sink(s) (UHS).

Most of the above systems are contained inside hardened structures, except for water intakes, ultimate heat sinks, and some of the support systems.

5.1.3 PWR Support Systems

The support systems play an extremely important role, in that many safety-related systems would fail without their correct performance. Among these support systems should be named

- component cooling water system (CCWS),
- service water system (SWS)
- electric power system (EPS), including (a) onsite power, (b) offsite power, (c) emergency diesel generators, and (d) batteries.

Though the CCWS and SWS are well protected in hardened structures, some of their subsystems are not (e.g., water intakes and conduits from the water intakes). Furthermore, the offsite power is quite vulnerable to direct impact in case of an aircraft crash.

5.2 BWR Safety-Related Systems

5.2.1 BWR Criticality Control Systems

In the BWRs the reactivity worth of the control rods is sufficiently large to shut the reactor down from full power to cold conditions. The rods have to move against gravity; however, each rod is provided with an independent energy source (compressed nitrogen), and is not dependent on outside electrical power for rapid reactor shutdown. Furthermore, the entire reactor shutdown system is well protected against direct impact in case of an aircraft crash, being fully inside the containment structure.

5.2.2 BWR Heat Removal Systems

As for PWRs, the BWR heat removal systems may be subdivided into two groups:

(1) BWR Heat Removal Systems for Normal Operation

- PHTS (part inside the containment building),
- main feedwater system and steam lines,
- condenser and condenser cooling water system,
- residual heat removal system (RHRS),
- water intakes and ultimate heat sink(s).

As for PWRs, the condenser and condenser cooling system, parts of the feedwater system and steam lines, the condenser and condenser cooling system, as well as the water intakes and ultimate heat sink(s) are vulnerable to direct impact in case of an aircraft crash. Note that for BWRs the PHTS includes the steam lines, the condenser, and the main feedwater system.

(2) BWR Heat Removal Systems for Off-Normal Conditions

- high pressure core spray system (HPCS),
- low pressure core spray system (LPCS),
- low pressure coolant injection (LPCI),
- residual heat removal system (RHRS).

As for the PWRs, most of the above systems are contained inside hardened structures, except for the water intakes for the service water systems and the ultimate heat sinks.

5.2.3 BWR Support Systems

The BWR support systems are similar in nature to those in a PWR facility which are discussed above.

5.3 Accident Sequences Involving Safety-Related Systems

5.3.1 General Aspects

The results of an aircraft crash on a nuclear power plant are not limited to the effects of the impact of heavy parts (such as a jet engine) on civil engineering structures. Numerous systems are required in order to provide reactor shutdown and adequate long-term cooling of the core. Although many of these safety-related systems are well protected within hardened structures (containment system, auxiliary building), some are not. In particular, certain systems, which are not formally designated as safety systems but which may indirectly affect safety systems, are quite exposed. The plant's electric switchyard may serve as an example: A crash of an aircraft on a switchyard would very likely eliminate the plant's offsite power. Furthermore, although there exist protective design features against propagation of electrical failures from the switchyard into the rest of the plant, the probability for such electrical failure propagation is not zero: Past experience has shown that electrical failures may propagate unexpectedly from nonsafety systems to safety systems (examples: San Onofre, Rancho Seco, Crystal River).

Therefore, in an overall risk evaluation, the possibility of exceeding the 10 CFR 100 probability guidelines due to an aircraft crash on the switchyard of a nuclear power plant merits investigation. Should massive electrical failure leading to total loss of power be possible (with the diesel generators failing or unable to deliver power because of short circuits or other equipment failures) it would leave the plant vulnerable to core melt. The only way left to cool the core would be natural circulation combined with atmospheric steam dump. The latter cooling mode depends on the availability of a turbine-driven auxiliary feedwater pump.

Additional ways in which a nuclear power plant could be seriously affected, different from a direct impact on a hardened structure, would be by impact on systems affecting long-term heat removal capability such as the turbine hall (severing the steam lines) and the water intakes. It should be kept foremost in mind that the combined effects of impact and fire due to an aircraft crash open the possibility for numerous multiple failures; the detailed evaluation of this is not easy and well beyond the scope of the present study.

5.3.2 Accident Sequences Involving PWR Safety-Related Systems

5.3.2.1 Accident Sequences Involving PWR Criticality Control Systems

An aircraft crash on a PWR nuclear power plant resulting in rapid depressurization of the plant's secondary cooling system, combined with total loss of electrical power (impact on the turbine building and the switchyard), would result in an accident sequence in which the fission power in the core would remain at some considerable level: Initially, upon dropping of the control rods, the fission power would decrease; however, the rapid depressurization of the secondary system would result in a rapid cooldown of the primary system, thus resulting in recriticality since the primary system would remain pressurized (preventing discharge of the accumulators with borated water), and since the safety injection system (SIS) would not be functioning due to loss of electric power, there would be no way to shut down the reactor. Furthermore, since the loss of electrical power and the damage to the secondary system would preclude any cooling other than short-term boil-off of the primary coolant inventory, the core would most probably be headed for serious damage if not total meltdown. Core meltdown, without the availability of electric power, would probably result in containment overpressurization and release of radioactive materials to the environment far in excess of 10 CFR 100 guidelines.

Note that the above sequence of events does not depend in any way on the breach of a hardened structure due to the impact of a heavy segment of the aircraft at some optimum (i.e., most-damaging) angle, which seems up to now to have had the greatest attention in the evaluation of nuclear power reactor safety with respect to aircraft crashes. Note further that this accident scenario requires the occurrence of multiple failures, many of which are strongly plant-dependent. As an example, the location (inside or outside hardened structures) of the auxiliary transformer (used for reducing the voltage of the offsite power lines) and the associated breakers strongly affects the probability of losing all electrical power. A detailed probabilistic evaluation of this accident scenario is beyond the scope of this study; such a study is, however, recommended if the initial event (aircraft crash) has a probability of occurrence larger than required.

5.3.2.2 Accident Sequences Involving PWR Cooling Systems

Long-term cooling capability is an important requirement for preventing core damage or meltdown. An aircraft crash could compromise long-term cooling capability in numerous ways. Systems, or parts of systems, most susceptible to aircraft impact are those not (or not fully) enclosed in hardened structures. Among these should be named: The main feedwater system, the condenser cooling water system, the steam lines, the ultimate heat sink (cooling tower, water intakes, etc.)

(1) Rupture of either the steam lines or the main feedwater lines (aircraft crash on the turbine building) could compromise the normal means for cooling down the core and depressurizing the PHTS to the point where the RHR system can be employed. If the feedwater line rupture can be isolated, the use of the auxiliary feedwater system would provide an adequate means of cooling the core and depressurizing the PHTS to the level of the RHRS. If the auxiliary feedwater system is not functional, the feed-and-bleed cooling mode would constitute the only long-term method of cooling the core; this

would, however, not allow it to depressurize the PHTS to the level of the RHRS.

(2) A multiple failure, resulting in rupture of the main feedwater lines combined with loss of electrical power, would require the correct performance of the turbine-driven auxiliary feedwater pump.

(3) An aircraft crash affecting the ultimate heat sink (cooling tower, water intakes, etc.) would leave core cooling dependent on the feed-and-bleed cooling mode, provided a sufficient water supply and electrical power remain available.

5.3.3 Accident Sequences Involving BWR Safety-Related Systems

Since BWR criticality control systems are well-protected against direct external impact on the plant, and since their performance is independent of the availability of electrical power, it seems that these systems can be omitted as contributors to accident causes in case of an aircraft crash.

The availability of the large suppression pool (heat sink) inside the hardened containment structure makes BWRs in general less susceptible than PWRs to loss of cooling capability. However, since the PHTS includes the steam lines and feedwater lines, a direct impact in the area of the containment penetration of the steam line(s) and feedwater line(s) could conceivably cause blowdown of PHTS into the environment, if both steam line isolation valves in the steam lines, or the check valves in the feedwater line, were to be damaged simultaneously.

6. STRUCTURAL RESPONSE

To understand the phenomena of nuclear power plant structural response subjected to aircraft impact, it is necessary to discuss first the impact loading function. Without proper definition of impact load, the structural response calculation may lead to erroneous conclusions. In dealing with structural response, one has to examine the material description and its modeling technique. In Section 6.2 some typical constitutive equations for concrete and structural steel will be given together with the effects of material nonlinearities on the structural response. The local response of the structure will then be presented in terms of its failure mechanism and corresponding failure-mode analysis. The structural system may fail through either its local or global response. The nuclear power plant equipment response can be correlated to the floor response spectra which depends upon the structural system response to the impact. The severity of equipment response is then compared to a modest earthquake-induced vibrational effect. Since a variety of approaches is used in the published analyses, a comparison of modeling techniques is also made.

6.1 Aircraft Impact Loads

The impact of an aircraft upon a relatively rigid or hard structure will generally result in the gross collapse or crushing of the aircraft structure. Some components of the aircraft, such as outboard mounted engines, which are relatively solid substructures, can impose severe local impact loads upon the structure and may lead to local puncture of the plant structure. Still other aircraft components, such as the fuel, can be expected to behave in yet another response mode. Since the plant structures are generally hard structures, their gross motions in the vicinity of the impact will be small compared to those of the aircraft structure. Thus, the response of the aircraft can be uncoupled from that of the plant structure, and the impact load can be evaluated under the condition that the aircraft impacts a rigid surface.

It is reasonable to expect that the motion of all the mass of the impacting aircraft, at least for impact normal to the structure, will be completely arrested (without any significant rebound) by the impact event such that the momentum transferred to the plant structure is well defined and is equal to the product of the mass of the aircraft and its speed at the onset of the impact process. Since the aircraft is, in its simplest geometric form, a line source (along its flight path), the impact process will take place over a short period of time which, to a first approximation, can be calculated as the quotient of the length of the aircraft and the aircraft speed. Thus, the total impulse imposed upon the plant structure is known and the approximate load duration can be estimated. An adequate treatment of the response of a hard power plant structure to an aircraft impact will generally require a more definitive description of the impact load. Specifically, the time details of the force acting over a nominal impact area are needed. In addition, for certain aircraft configurations, a spacewise or multiple source representation may be appropriate. This would be the case for any aircraft which has relatively massive outboard engines.

Considerable effort has been expended over the past decade in order to define the load details resulting from the impact of an aircraft on a hard structure. The recent Canadian report [27] presents a comprehensive summary and evaluation of this aspect of the aircraft crash problem. Two models for the soft missile (aircraft frame and distributed mass representation as differentiated from the relatively solid engine sub-structure, the so-called rigid missile) impact treatment warrant discussion. Both models are relatively simplistic and treat the aircraft as a line source of distributed mass and crushing strength. The time dependent reaction force is represented as the sum of two terms; the first represents the force acting upon the (still) uncrushed portion of the aircraft, and the second represents the influence of the crushed portion of the aircraft adjacent to the rigid impact surface. The first model of interest was developed in 1968 by Riera [35]. In this model the uncrushed portion of the aircraft is decelerated as a result of the imposed crushing load, and the second term contributing to the reaction force represents the momentum flux entering the crushed region. The reaction is given as a function of the distance from the nose of the aircraft. This distance is converted to time by assuming that the crushed region is very small; however, this assumption also leads to a velocity discontinuity at the wall (rigid boundary) or at the crushing front. This apparent nonphysical feature is the primary weakness of the Riera model [27]. In 1975, Rice et al. [36] developed a somewhat different model which eliminated the velocity discontinuity and represented the two terms that contribute to the reaction force directly as a function of time. These two models allow the distributed character of the aircraft (i.e., its mass and crushing strength) to be included into the load definition. The mass distribution is generally well known; however, the axial crushing strength of the aircraft is not well known.

The Rice model was used [37,38] to analyze the aircraft crash problem for the Seabrook Nuclear Station. The specific application dealt with the impact of the FB-111 aircraft traveling at 200 mph. The weight and crushing strength distributions are presented in Fig. 7 and the resulting load details are presented in Fig. 8. Since the crushing strength was uncertain

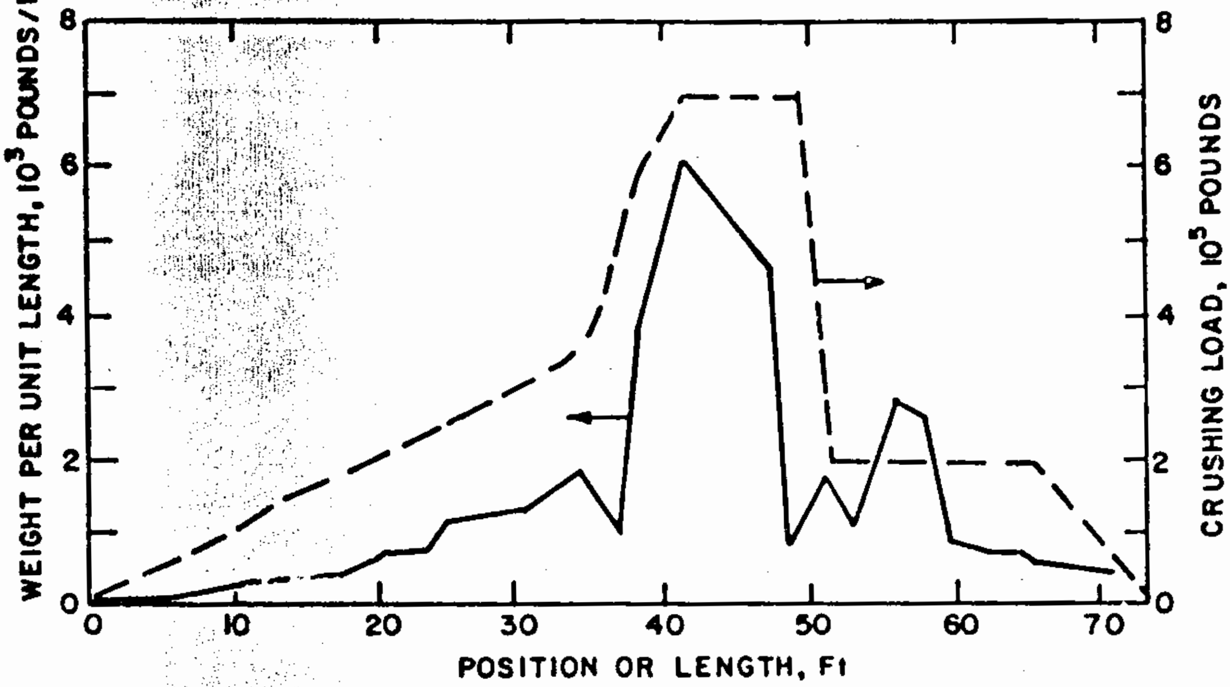

Fig. 7 Weight Distribution and Crushing Load Distribution, FB-111 [37]

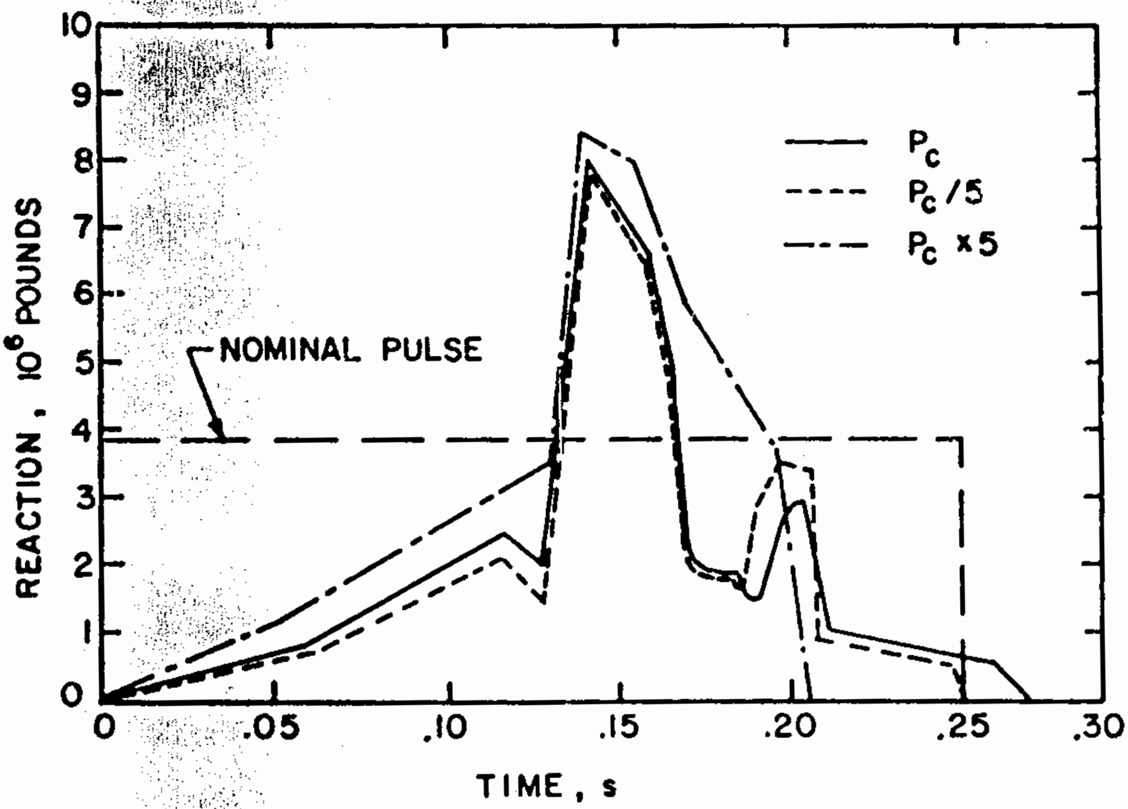

Fig. 8 Reaction-Time Relationship for FB-111 with Impact Velocities of 200 mph. P_c denotes the scale crushing load used in the calculation. $P_c/5$ and $P_c \times 5$ denote that one-fifth and five times the crushing load were used, respectively [37]

the calculations were repeated with crushing strength variations differing by a factor of five (both larger and smaller). The results of these calculations are also presented in Fig. 8 and show that, for this case at least, the crushing strength is not an influential parameter in the impact load specification. The aircraft weight is 107,440 lbs and its length is 73.8 ft; thus, the total impulse is 9.79×10^5 lb-sec with an approximate load duration of 0.252 sec. The corresponding uniform reaction force pulse is also presented in Fig. 8. It is clear that the total impulse of the load history computed by the Rice model is significantly smaller (by approximately 40 percent) than the correct impulse; however, the durations are generally in the correct range.

The Canadian report examined Riera's model and compared its load prediction with the predictions from a number of more sophisticated models [39,40,41]. These comparisons are presented in Fig. 9 and show that the various models yield similar results. They also note that sensitivity analyses for typical commercial aircraft indicate that the momentum term (of Riera's model) contributes approximately 80 percent of the impact force. Thus, the crushing strength details should not be an influential parameter in these cases. The Canadian report concludes that Riera's model yields results which are "pessimistic in nature" due to its treatment of the behavior of the crushed portion of the aircraft. It used Rice's model to evaluate the above reference weakness of Riera's model and notes that peak loads predicted by the Rice model are approximately 40 percent lower than those predicted by Riera's model. They further conclude that "even if the RIERA approach may be in error by at least 40% it represents a reasonable formulation for the upper bound."

The current evaluation examined the Riera model for a simple soft missile which consisted of a uniform mass and crushing strength distribution. The results demonstrated that the total impulse was conserved and that for the limiting case of zero crushing strength the load is a simple constant reaction force whose duration is equal to the approximate (i.e., idealized) value defined in the initial portion of this section. A similar limiting treatment of Rice's model yielded a uniform pulse shape; however, the amplitude was only one-half of the proper value and thus, 50 percent of the total impulse was lost. The current evaluation also examined a continuum model for a simple uniform rigid-perfectly plastic material. In such a model a plastic wave exists across which the particle velocity changes discontinuously. This detail, although not explicitly defined in Riera's model, can be used to infer the correctness of the model. This continuum model indicated that the compression ratio which occurs across the plastic front is the only parameter involved (it is relatable to the crushing

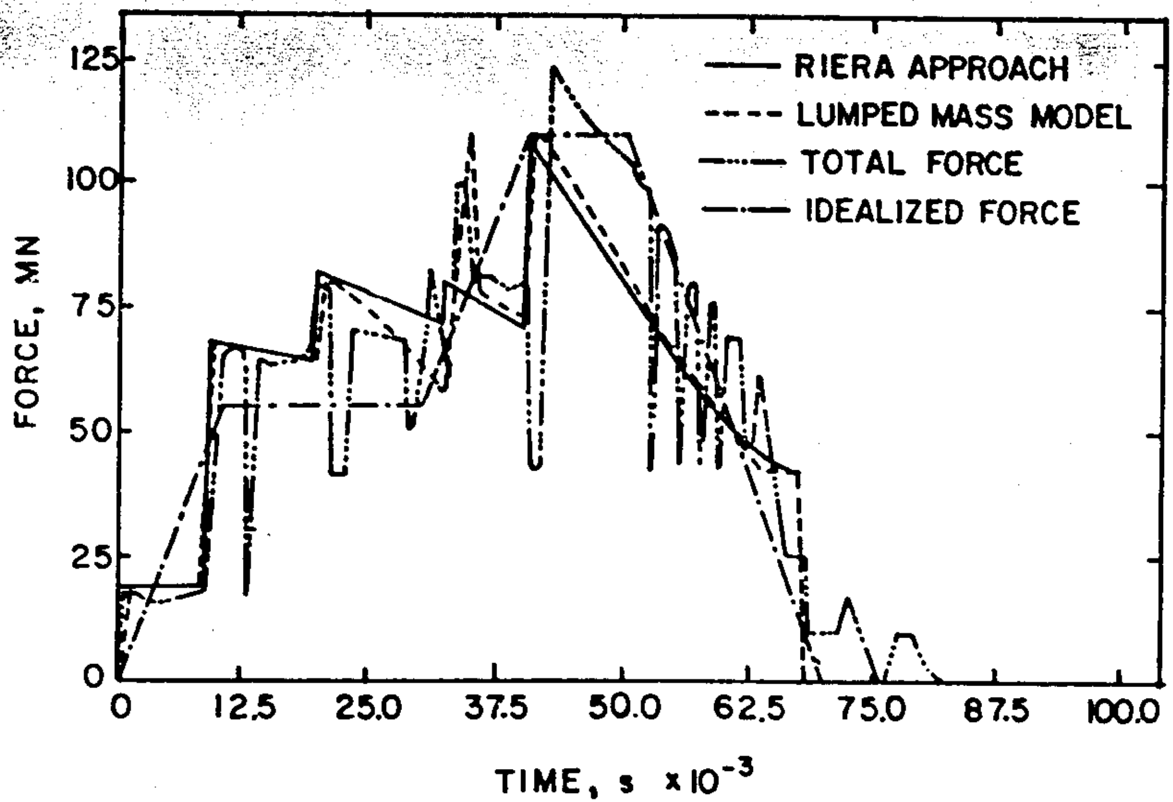

Fig. 9 Force-time Diagrams for Phantom at 215 m/sec [38]

strength). The reaction load for this idealized case is uniform in magnitude, and its duration is shortened as the compression ratio is reduced. Since the total impulse is conserved, the amplitude must increase. For typical values of the compression ratio, the influence of the crushing strength is relatively small. It is clear that Rice's model is not correct and that Riera's model is adequate.

The total impulse is proportional to the speed of the aircraft at the onset of impact; hence, it is important to specify the value of this parameter with considerable care. The Canadian report presents an excellent statistical treatment of this aspect of the aircraft crash problem. Finally, the appropriate representation of the aircraft as a single line source or as a series of additional masses to model any significant outboard features of the aircraft is important. Again, the Canadian report presents a comprehensive summary of the methodologies needed to treat the hard missile problem. The level of sophistication used to define the impact load should be consistent with the level of sophistication being applied to the response of the plant structure.

6.2 Constitutive Relationship of Structural Materials

6.2.1 Material Models

The response of containment structures subjected to aircraft impact depends on the material properties of the structures. The material models for reinforced concrete in general include a fracturing, spalling, and yielding of concrete and steel components. There are three types of concrete failure: (i) failure by tension, (ii) failure due to shear deformation, and (iii) failure due to compressional crushing. Concrete can be considered as an isotropic material in a three-dimensional state of strain. In tension and for moderate compression, a linear elastic constitutive law can be applied. In the domain of higher compressive stress, a nonlinear stress-strain relationship should be used. The failure criterion can be expressed as a function of stress invariants, specified in the spatial coordinates of the three principal stresses. The same failure criterion governs the failure in tension (cracking) and compression (crushing).

The nonlinear behavior of concrete is described by a variable shear modulus μ as a function of the second stress invariant I_2, such as shown in Fig. 10(a) taken from [42]. The failure surface, shown in Fig. 10(b) is a general cone centered along the average axis of the principal stresses. Any state of stress which is on or outside the surface represents a failure. The loading-unloading behavior of concrete is shown in Fig. 10(c). For reinforcing steel, the elastic-plastic behavior applies. Yielding of the

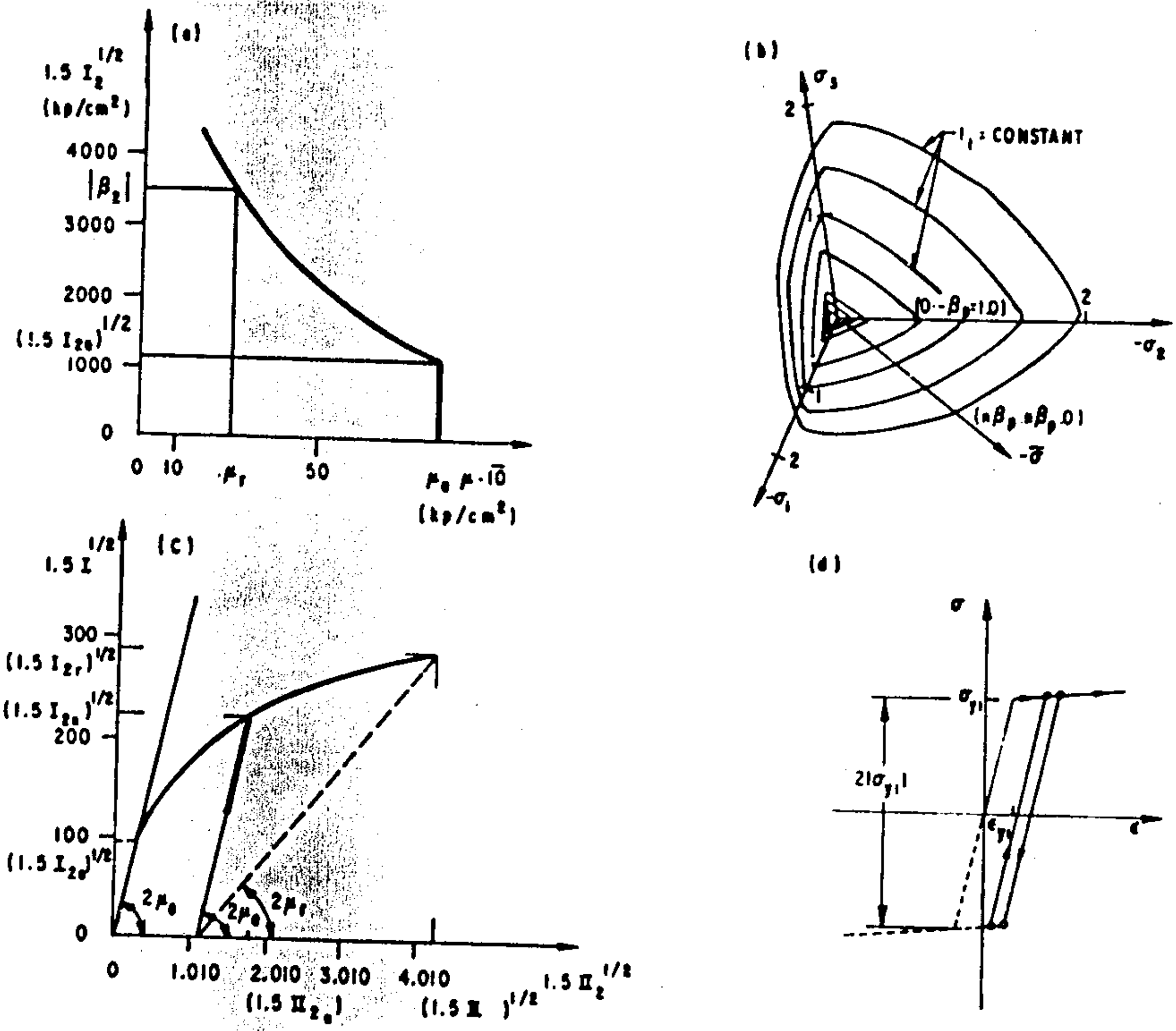

Fig. 10 Constitutive Laws (a) Concrete Shear Modulus, (b) Concrete Failure Surface, (c) Concrete Hysteresis, (d) Steel Hysteresis [42]

steel is determined, for example, by the von Mises criterion: $I_2 - \frac{2}{3}\bar{\sigma}^2(k) = 0$, where $\bar{\sigma}(k)$, the uniaxial tensile yield stress, is a function of a hardening parameter k. Figure 10(d) shows a typical curve for kinematic hardening. Failure in steel bars occurs when the ultimate tensile strain is reached.

6.2.2 Material Nonlinearity Effects on Structural Response

Zimmermann et al. [42] investigated the effects of material nonlinearities on response spectra resulting from the impact of a Boeing 707-320 on the secondary containment of a BWR reactor such as shown in Fig. 11. They used a finite-element model which considered concrete cracking and crushing as well as steel yielding for the analysis. The resulting displacement time histories are shown in Fig. 12. Comparison of the nonlinear and linear displacement time histories shows a significant increase in the vertical displacement (28%) in the vicinity of impact zone, which fades out rapidly away from the impact point as expected, since the response far away from the impact area is primarily elastic behavior. Therefore, if the impact loading is sufficient to produce any permanent deformation, a more complicated constitutive equation must be used in order to obtain the real structural response. Since there is no consensus theory which can predict all material behavior of concrete, such as tension, compression, crushing, microcracking, creeping, etc., the choice should depend on the most important.

6.3 Local Structural Response

6.3.1 Local Failure Mechanisms

The impact of an aircraft upon a concrete containment of a nuclear power plant generally may result in the damage to concrete walls. The damage may be local or may produce an overall dynamic response of the target wall. Kennedy [43] presented a detail review of procedures for the analysis and design of concrete structures to withstand missile impact effects. Missile velocities generated by aircraft crashes may be between 100 and 1500 ft/sec. The local damage due to aircraft impact consists of spalling of concrete from the front (impacted) surface and scabbing of concrete from the rear surface of the target together with missile penetration into the target as shown in Fig. 13. If the damage is sufficient, the missile may perforate and pass through the target.

As the velocity of the impacting missile increases, pieces of concrete are spalled off from the impacted surface of the target. This spalling creates a spall crater that can extend over an area substantially greater than the

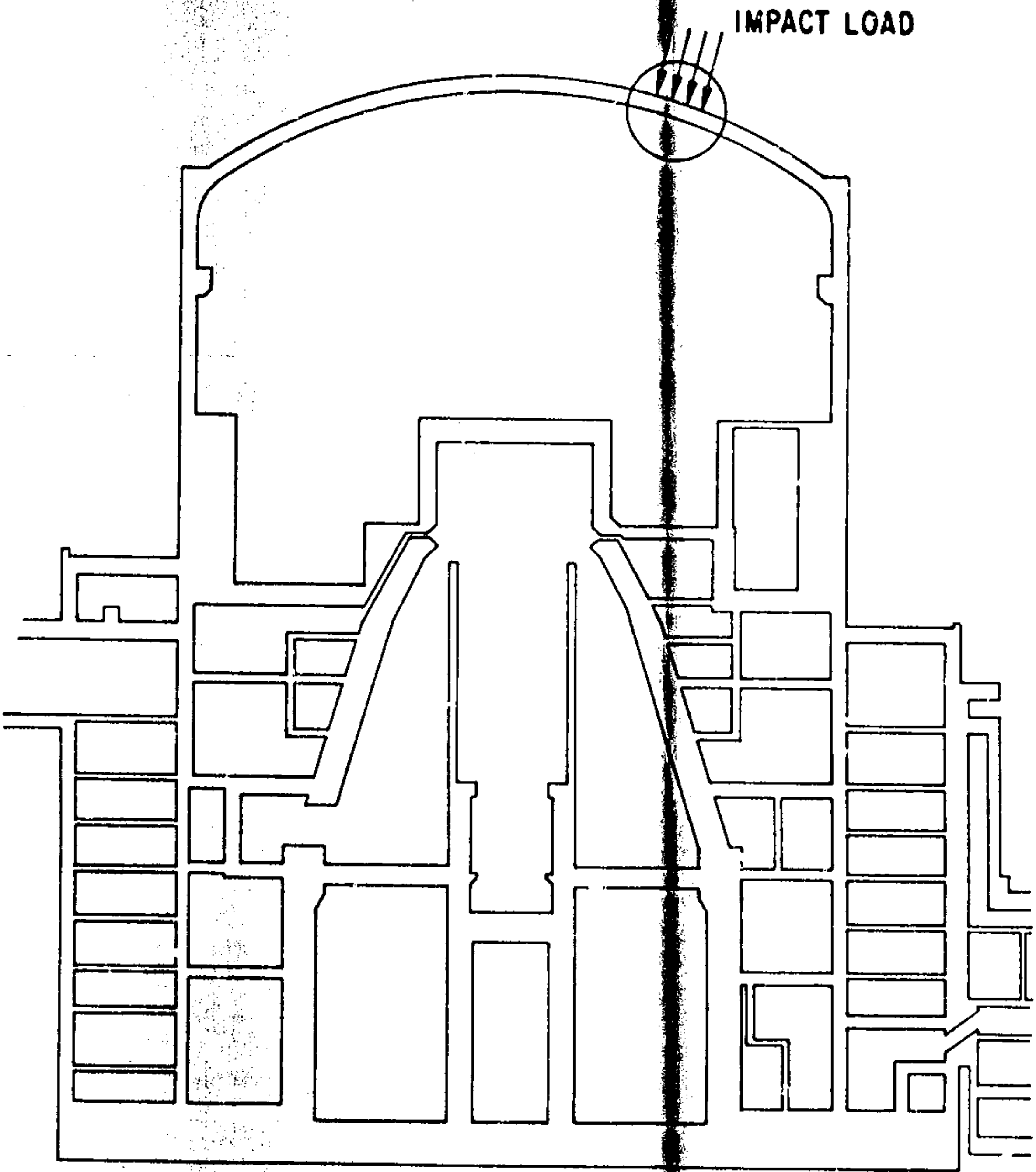

Fig. 11 Impact on Reactor Building [42]

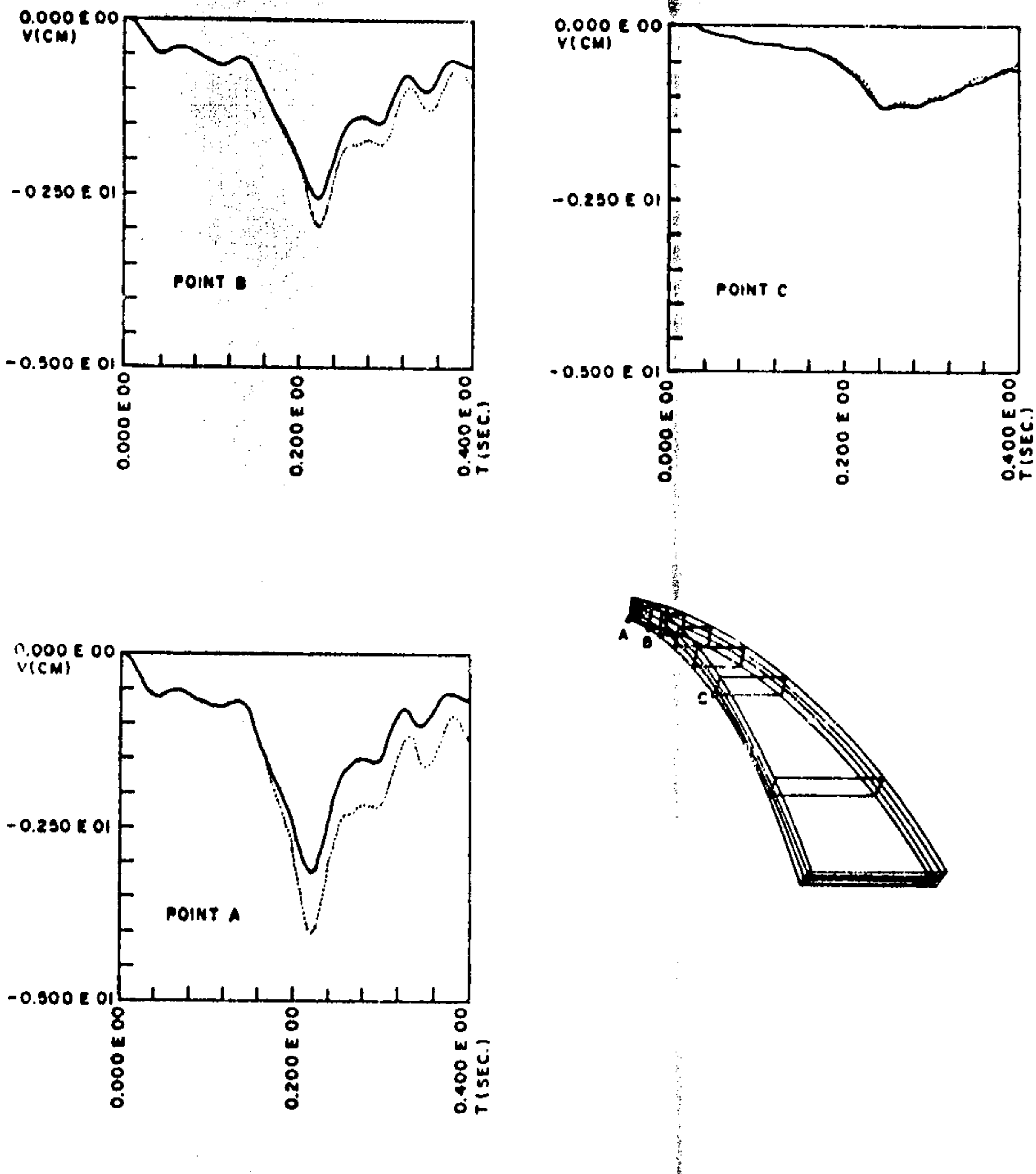

Fig. 12 Displacements-Time-Histories [42]

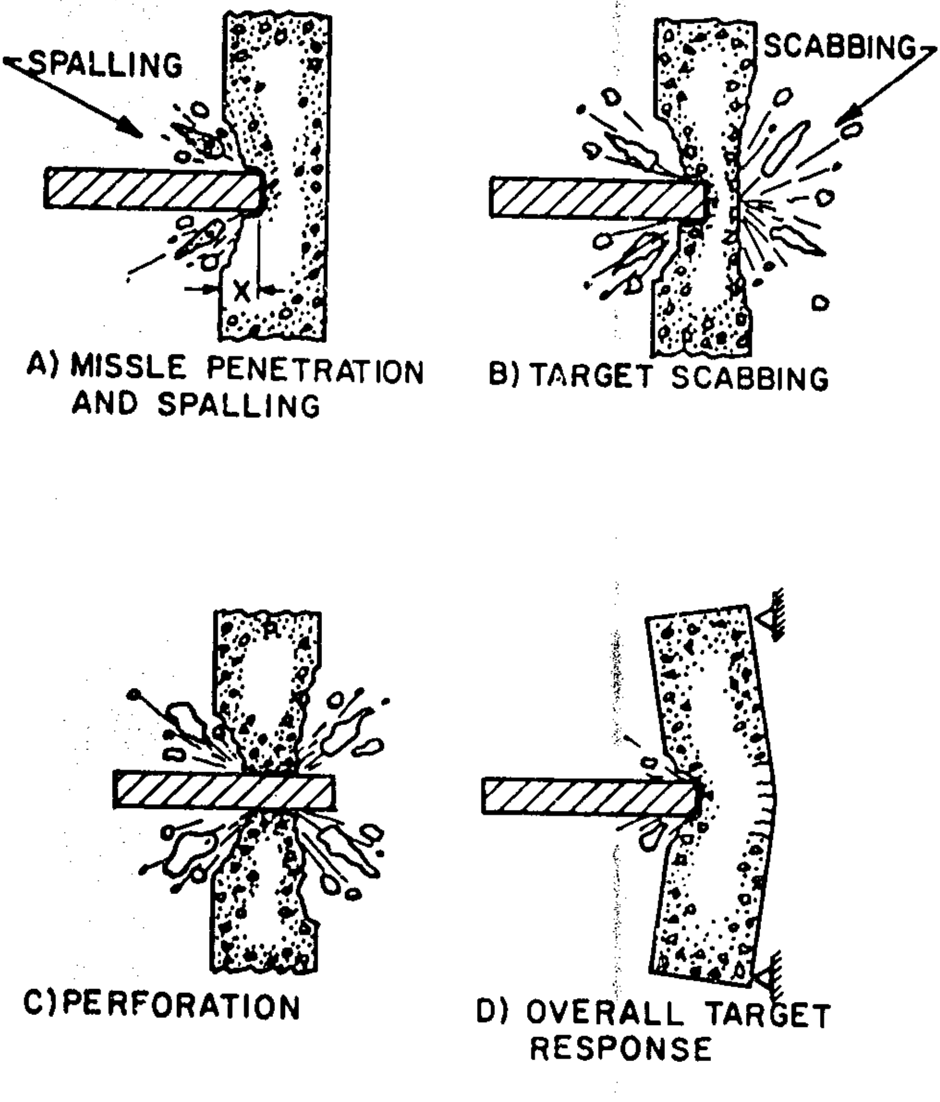

Fig. 13 Missile Impact Phenomena [43]

cross-sectional area of the striking missile. As the velocity increases, the missile will penetrate the target to depths beyond the depth of the spall crater, forming a cylindrical hole with diameter slightly greater than the missile diameter. As the penetration continues, the missile will stick to the concrete target; this is called plastic impact. Further increases in velocity produce cracking of the concrete on the rear surface followed by scabbing of concrete from this rear surface. The zone of scabbing will generally be much wider, but not as deep as the front surface spall crater.

Once scabbing begins, the depth of penetration will increase rapidly. For barrier thickness to missile diameter ratios less than five, the pieces of scabbed concrete can be large and have substantial velocities. As the missile velocity increases further, perforation of the target will occur as the penetration hole extends through to the scabbing crater. Still higher velocities will cause the missile to exit from the rear surface of the target. Upon plastic impact, portions of the kinetic energy of the impacting missile are converted to strain energy associated with deformation of the missile and energy losses associated with target penetration. The remaining energy is absorbed by the impact target. This absorbed energy results in an overall target response that includes flexural deformation of the target barrier and the subsequent deformation of its supporting structures. A review of commonly used empirical procedures for determining local missile impact effects such as penetration depth, perforation thickness, and scabbing thickness for concrete targets subjected to hard-missile impact can be found in [43]. Note that these empirical formulas were developed by the Army Corps of Engineers, the National Defense Research Committee, and others many years ago based on experimental observation. Today, with the advent of the finite-element method and after intensive research in fracture mechanics, it is possible to predict these phenomena analytically. The above discussion deals with concrete structures only. If the aircraft impact on a steel structure, then only penetration, perforation, and overall response will occur. The numerical approach to various target geometries of this type can be found in [44].

6.3.2 Failure-Mode Analysis Using Plastic Shells of Revolution Theory

Degen, Furrer, and Jemielewski [45] have investigated the effects of a large commercial airplane crashing perpendicularly on the surface of a spherical reactor building dome. They obtained the carrying capacity of the structure under an equivalent static load using the yield-line theory of circular plates, and calculated the sectional forces using linear-elastic shell theory. They then calculate the failure load and distribution of sectional forces using the plastic shell theory. The analysis was performed using the computer code STARS-2P developed by Svalbonas and Levine [46]. This code performs plastic analysis of shells of revolution. Plastic effects are approximated using the initial strain appproach, and different modes of hardening may be taken into account. From the results, they obtained the failure zone mechanism at the apex of a spherical shell subjected to aircraft impact over a finite loading area. The results are shown in Fig. 14.

Degen et al. [45] also presented failure mode analysis by the finite-element program TRIDI [47] which utilizes three-dimensional elements for concrete and one-dimensional elements for reinforcing steel. This program considered nonlinear stress-strain relationships for concrete under multiaxial stress, cracking and crushing under a triaxial stress state, and elastic-plastic behavior for reinforcing steel. The calculation of collapse load using yield-line theory for plates, STARS-2P for shell of revolution, and three-dimensional TRIDI are in the pressure range of p = 11 to 25, 30 to 35, and 25 to 30 kg/cm^2, respectively as reported by Degen et al.

Since the calculated collapsed load was assumed to be distributed over a certain contact area, the impacting total load corresponding to a range of 30-35 kg/cm^2 results in 28,000-33,000 tons, using the peak load-velocity relationship; the crushing velocity of a large commercial airplane which the structure under consideration could still sustain may be between 480 and 530 km/hr. If the impact velocity further increases, part of the energy (not absorbed by the structure) will be retained in the falling object. Figure 15 shows the maximum remaining loads as a function of crash velocity. Within the velocity range of 480 to 750 km/hr, only part of the peak load may act on the structure, but over 750 km/hr the total peak load must be used. Carlton and Bedi [48] and Gupta and Seaman [49] also studied the local response of reinforced concrete to missile impacts using a different computer code. The analysis appears to be adequate for the description of failure mode mechanisms.

6.4 Structural System and Equipment Response

There are many studies [50-58] concerning the comparison of the dynamic response of a typical nuclear power plant subjected to a modest earthquake and to the impact of aircraft crashes. Ahmed et al. [50-51] used a finite-element beam model and modal superposition techniques to obtain the time history response and the corresponding floor response spectra of the structure/component. The effect of soil-structure interaction is considered in that study. Figure 16 shows the structural idealization of the nuclear power plant in the finite-element model. Figure 17 shows the comparison of

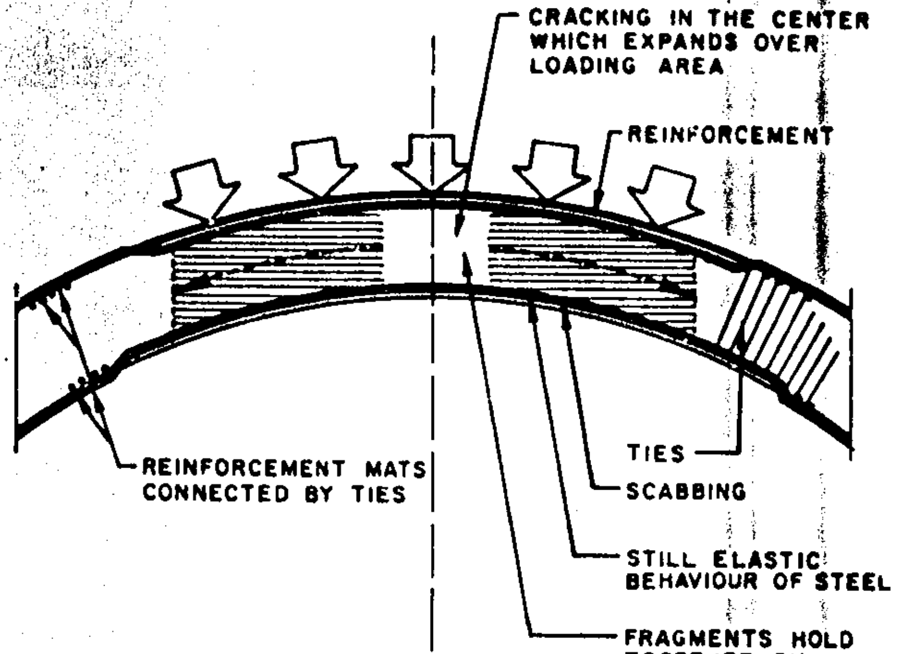

Fig. 14 Failure Zone at the Apex [45]

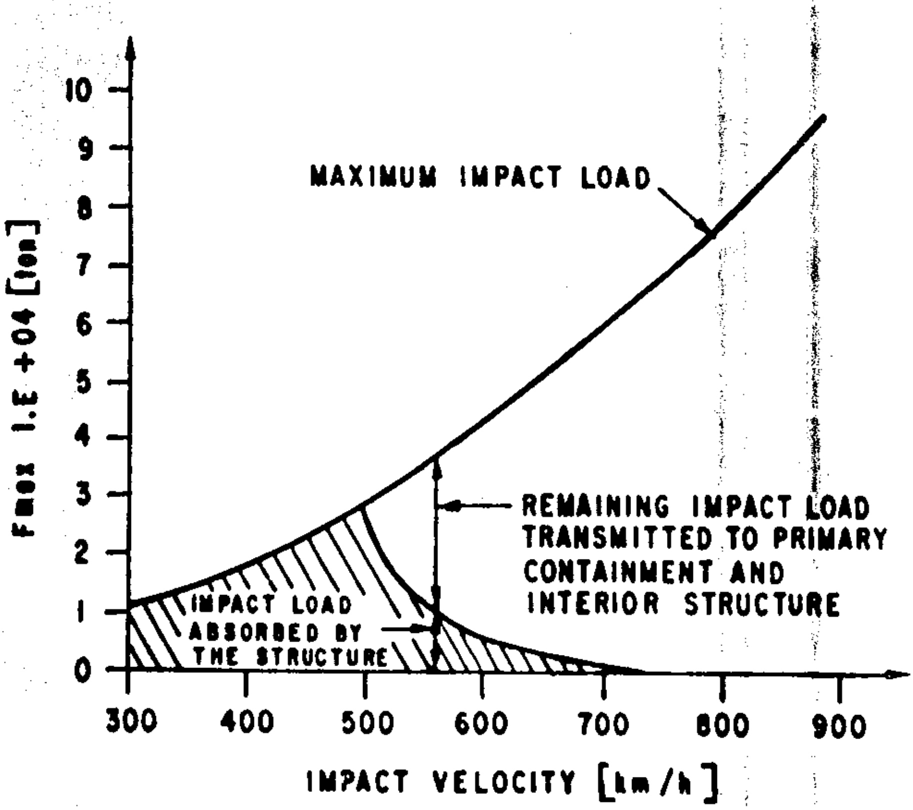

Fig. 15 Maximum Remaining Impact Load as a Function of Impact Velocity [14]

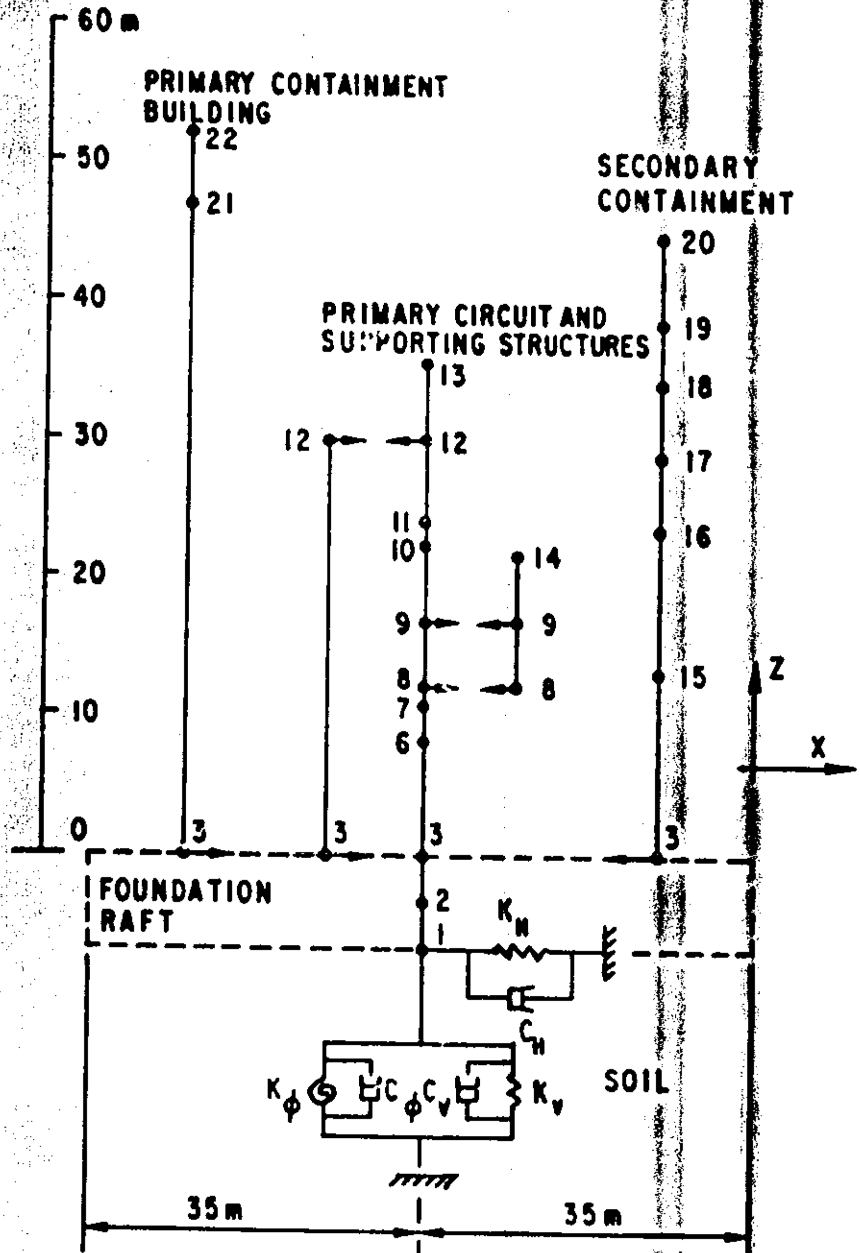

Fig. 16 Structural Idealization of the Nuclear Power Plant [51]

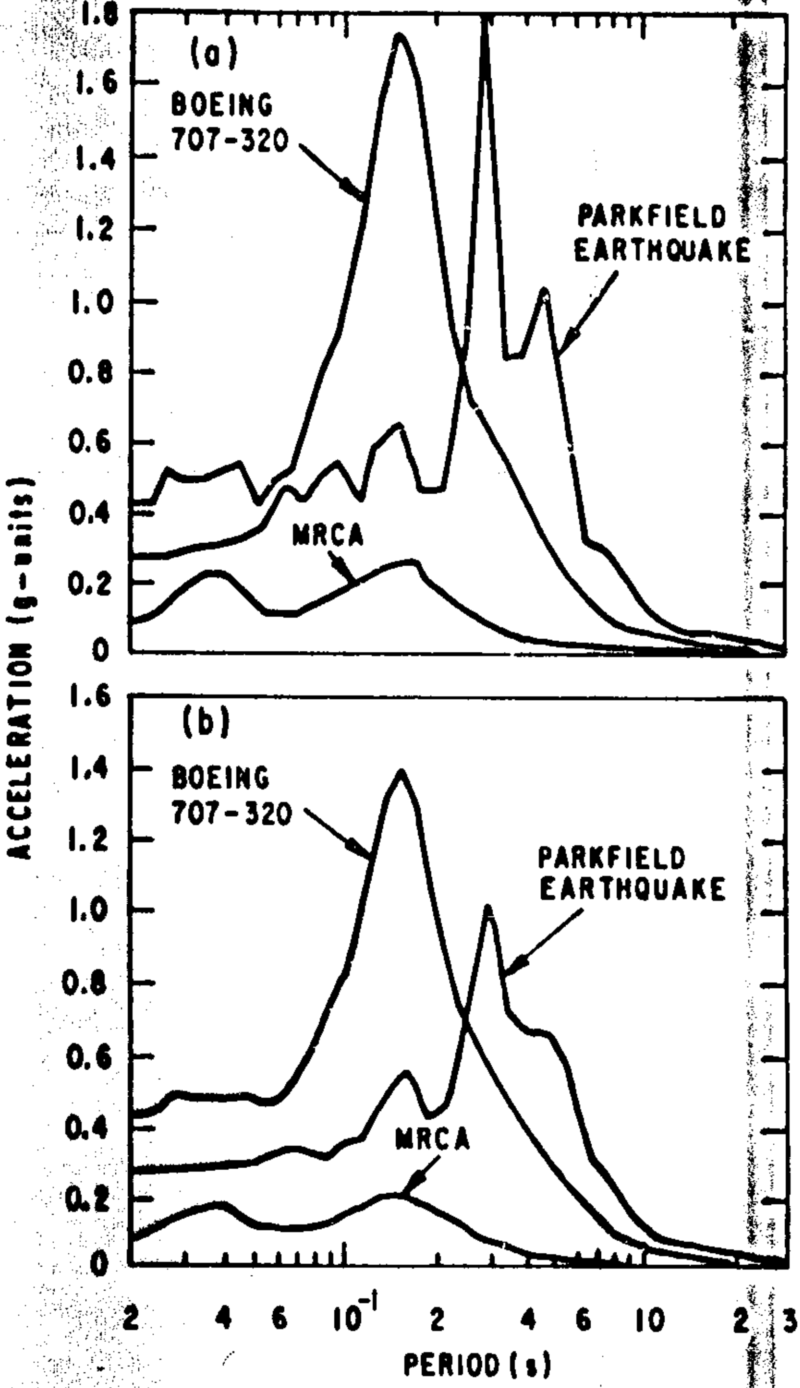

Fig. 17 Floor Response Spectra at the Top of the Foundation Raft, Node 3. (a) 1% Damping (b) 5% Damping [51]

floor response spectra at the top of the foundation raft for some selected damping. These spectra show clearly that the effect of impact by a Multi-Role Combat Aircraft (MRCA) at 215 m/s is considerably less severe than a modest Safe Shutdown Earthquake (SSE) as represented by the Parkfield earthquake. On the other hand, the effect due to the impact of the Boeing 707-320 at 103 m/s is clearly more severe than that due to an earthquake.

As indicated in [51], if the local inelastic impact effects were considered, the effects of the impact of the Boeing 707-320 on the reactor plant could be less onerous than the SSE. Krutzik [56] made comparisons of aircraft crash effects with both an earthquake and an explosion shock wave on reactor buildings. Although the excitation functions of these loads are of a transient and stochastic nature, their effects are quite different due to their different durations and frequency contents. Figures 18 and 19 show the comparisons of frequency-dependent responses of the structure in terms of accelerations. All results in the figures are based on the same analytical shell model. From these figures it can be seen that in the low frequency range (up to 5 Hz) the load for the earthquake case is governing, whereas in the high frequency range above 10 Hz the load for the aircraft case crash governs. The external explosion shock wave effect is small compared to both SSE and aircraft crash in all frequency ranges presented here.

6.5 Comparison of Modeling Techniques

Investigations of the influence of the type of model representation on the results of dynamic calculations for the aircraft crash by Krutzik [56] are shown in Figs. 20 and 21 in terms of response spectra. As indicated in [56] the local behavior and the dynamic response can be determined more accurately using shell models than using stick models as expected. Figures 20 and 21 show comparisons of the results for a representative region of an axisymmetric building obtained using stick and shell models. Figures 22 and 23 show the similar comparisons for a boxed-shaped building idealized by a beam model and a three-dimensional model. It can be seen that not only the outside structures but also the inside structures show quite different dynamic response patterns in the high frequency range. The results relating to the directly loaded regions of the outside structures differ radically (Fig. 24). In general, a more sophisticated model (such as a shell model) gives better results than simpler (such as beam or stick) models, provided both have the same model representation. Of course, simpler models involve shorter computer running time than more complicated models. Whenever possible a more accurate model should be applied in order to obtain a better understanding of the structural response.

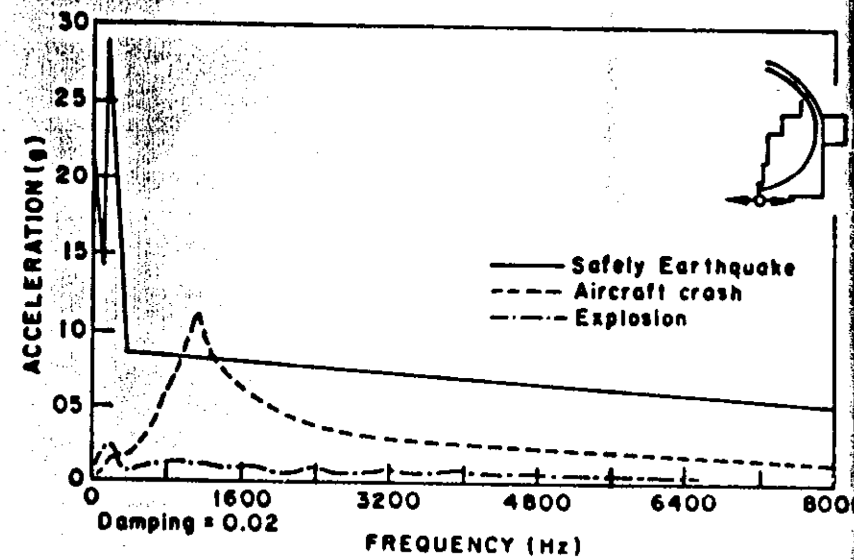

Fig. 18 Comparinon of Response spectra due to External Dynamic Loads. PWR Reactor Building/Foundation Plate, Radial [56]

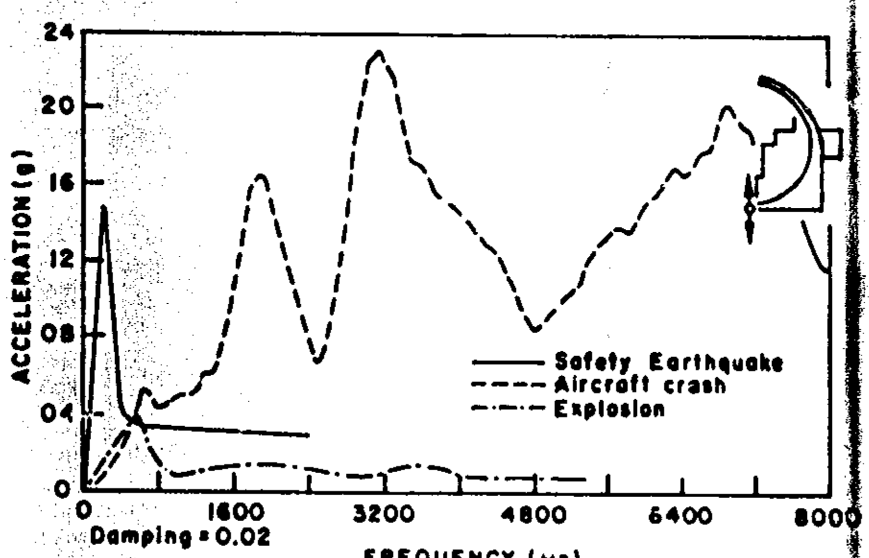

Fig. 19 Comparison of Response Spectra due to External Dynamic Loads, PWR Reactor Building/Foundation Plate, Vertical [56]

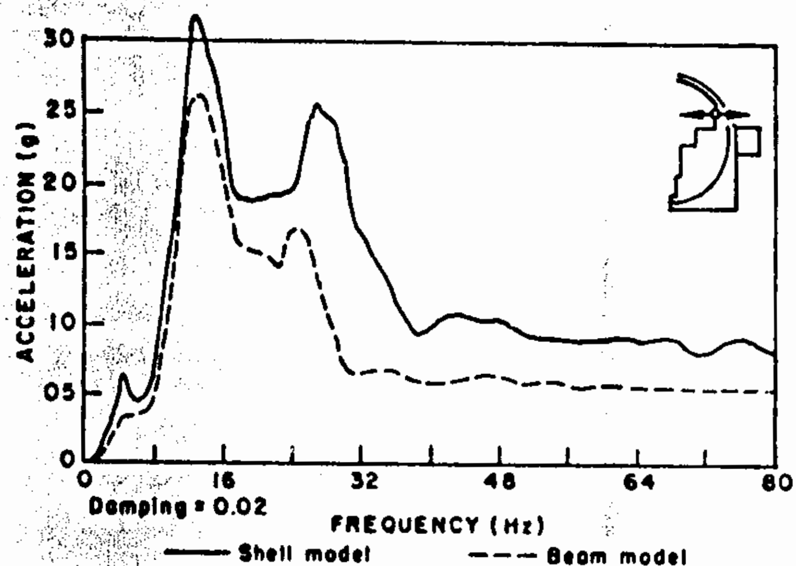

Fig. 20 Response Spectra, Comparison [56]

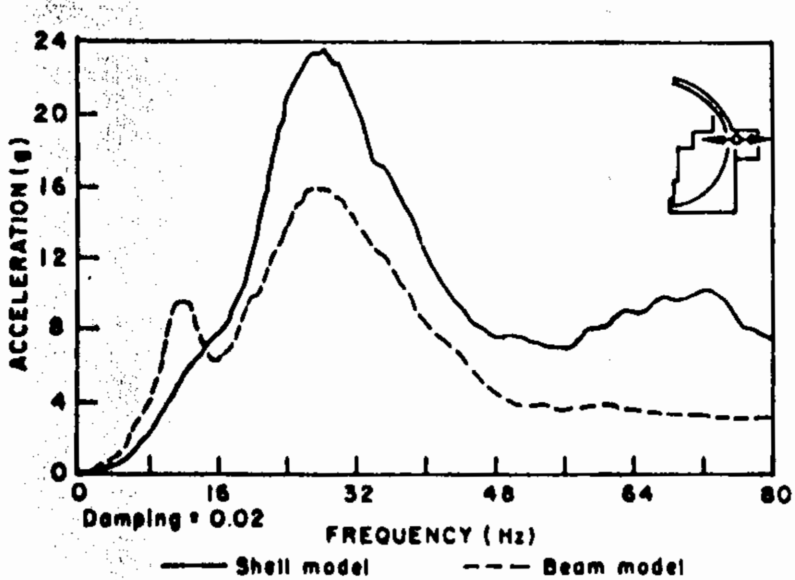

Fig. 21 Response Spectra, Comparison [56]

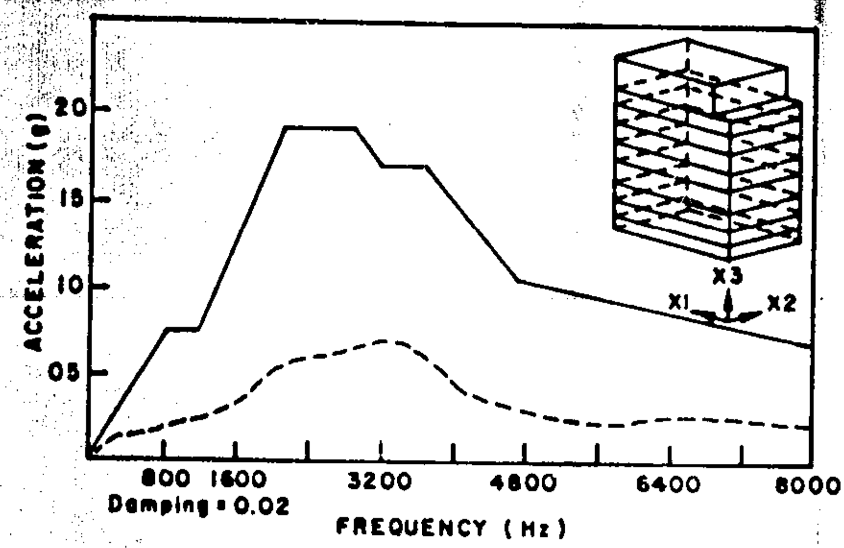

Fig. 22 Response Spectra, Comparison, X1 [56]

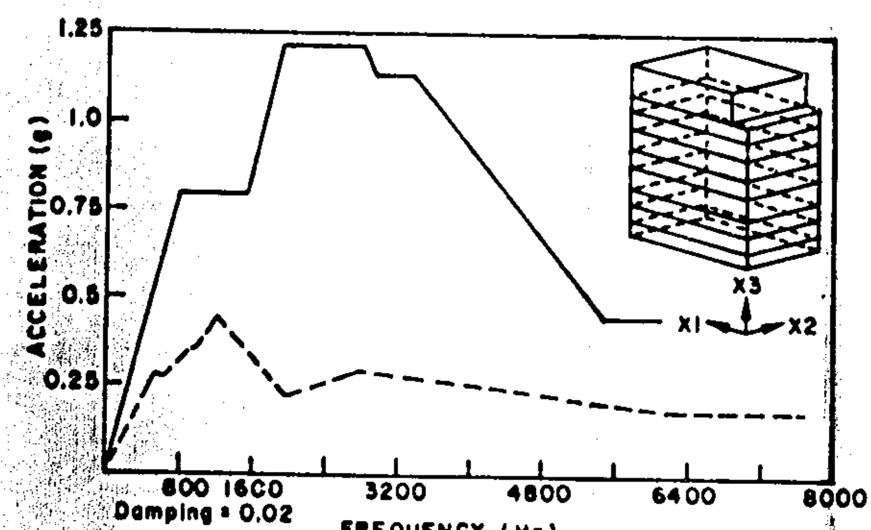

Fig. 23 Response Spectra, Comparison, X3 [56]

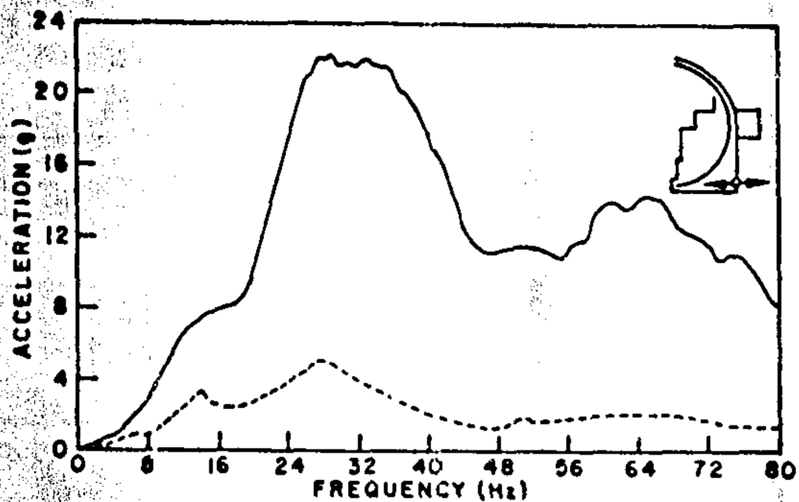

Fig. 24 Response Spectra at Impact Area, Outer Containment (Damping 2%) [56]

6.6 Evaluation Summary

The structural response of a substantial nuclear power plant structure to the impact of an aircraft has been discussed in the previous subsections with respect to (i) the establishment of the impulsive load that the aircraft imposes upon the structure under a normal flight impact condition, (ii) the available structural response models or methodologies for examining the local (i.e., puncture) and the gross response of the structure, (iii) the current state-of-the-art of the constitutive models for concrete/reinforced steel systems experiencing plastic deformation, and (iv) the vibrational response of the structure and its attendant equipment. These deterministic aspects of the response need to be augmented by a series of stochastic variables relating to the aircraft type (e.g., weight), aircraft speed, flight impact direction, aircraft orientation (pitch and yaw), and impact location on any given structure or structural system. The level of deterministic analyses currently available and being applied to this problem appears to be adequate in most cases, except perhaps for those dealing with the system vibration. These analyses are also adequate to establish the level of the hazard imposed upon the plant or the degree of engineering safety systems required to mitigate this hazard to an acceptable level. However, it is clear that these methodologies should include the stochastic nature of the problem to better define the hazard.

7. FIRE AND EXPLOSION HAZARD ASSOCIATED WITH AN AIRCRAFT CRASH

The crash of an aircraft, at least those events in which the aircraft structure is significantly damaged, will release large quantities of fuel in the general vicinity of the crash site. A significant fraction of the maximum aircraft takeoff weight is fuel; thus, quantities of the order of 50,000 lb of fuel can be expected to be released by large military aircraft such as an FB-111 fighter. Even larger quantities of fuel are used in large commercial aircraft. The fuels are, typically, JP-1, JP-4, or kerosene. These fuels are not highly volatile, but they burn readily and when properly mixed with air can explode.

Crash events which consist of relatively long ground traverses frequently sever or puncture fuel tanks (i.e., wing structures), and the leaking fuel is sprayed and spilled out over rather long distances forming vapor clouds and liquid pools. Crash events which consist of the abrupt arresting of the entire aircraft, and, therefore, providing essentially total structural collapse of the aircraft in a few tenths of a second, release their fuel very rapidly, spilling the fuel on the impact point (structure) and the immediate area. Again a portion of the fuel will tend to mix with the surrounding air forming a potentially explosive cloud. A major portion of the fuel will form pools or wet down the adjacent surfaces.

The crash event, being rather catostrophic, will be associated with the release of significant amounts of energy, heat, and sparks such that ignition sources will generally be present; it is therefore most likely that a fuel fire will occur. These fires will be local events and last for periods of time of the order of many minutes, perhaps a few tens of minutes. They will generate a significant amount of heat (thermal radiation and hot gases) and combustion products (smoke and toxic fumes). The hot combustion products, largely gases, will be transported upward due to buoyancy forces and will move downwind. Thus, these gases have the potential of reaching nearby intake vents of the surrounding facilities.

In addition to the above potential combination and toxic hazards, which appear to be tolerable in many instances, at least for adequately designed facilities, it is important to examine the crash event and the local impact area for unique situations which may cause an unacceptable hazard. For example, in the case of an impact on a double enveloped containment structure it may be possible to deposit a significant adequate quantity of fuel between the two envelopes. The subsequent vaporization and ignition of the resulting vapor-air mixture could lead to a rather violent explosion environment and impose upon the primary containment relatively severe loads. These loads are different in character than those imposed by the impact process, but may be just as severe. Furthermore, these loads will occur shortly after the impact load, and, therefore, the response of the structure to the combined load event should be examined.

A relatively large body of data and analysis methodologies exists relating to fires resulting from the crashes of aircraft. This data base resides primarily in the FAA domain and is supported by a yet larger data base dealing with fire and fire effects in general. The quantification of fires and their effects, expecially pool fires, has been developed to a stage where the general characteristics (i.e., flame height, duration, radiative flux, etc.) are known. While it is still difficult to predict with precision the outcome of various aircraft fuel-spill fires, the influence of many major parameters such as fuel properties and wind effects is understood. The major difficulties generally lie in the complex nature of the fuel distribution, the influence of random effects, and the somewhat extreme geometries which may be encountered in any realistic aircraft crash at a plant site (i.e., cluster of buildings).

The explosion hazard resulting from the crash of an aircraft is difficult to define for several reasons. One is that the basic phenomenon is very complex, and many or varied degrees of energy release or combustion can occur. The other is that the dissemination of the fuel and its partial mixing with the surrounding air to form an explosive cloud are virtually impossible to predict with any acceptable degree of accuracy. The approach used by Eichler and Napendensky [59] and others in dealing with a broad class of accidental vapor cloud explosions was to define, from accident and experimental data, reasonably conservative TNT equivalence factors for these events. Because of the very dynamic fuel dispersion and the low vapor pressure of aviation fuels, the applicability of the TNT equivalency approaches to the explosion hazards from catastrophic aircraft crashes must be carefully evaluated. This is particularly true for the effects close-in to the explosion. Napadensky and Takata [60], while examining train accidents involving the release of combustible materials for a 10-year period in which a fire and/or an explosion occurred, observed that approximately 36 percent of the events involved both fire and explosion, while approximately 56 percent of the events involved only fire. The remaining 8 percent of the events involved only an explosion.

It is clear that a broad spectrum or mix of fire and explosion events can occur, and while the amount of fuel involved in any explosion event may be quite small, the occurence of such events must be considered. If only one percent of the fuel, say 500 lb for the FB-111 fighter plane, is involved in such an event, the blast environment will be equivalent to the detonation of approximately 1000 lb of TNT. The local blast characteristics of a vapor cloud are substantially different from those of a TNT explosion; however, at longer ranges the equivalency concept is appropriate. For the above explosion the "safe" overpressure of 1 psi will exist at a range of approximately 120 m.

It is difficult to obtain a complete and perhaps correct picture of the design review and acceptance process as it applies to any given offsite hazard feature, since the details are frequently divided between many diverse documents in the dockets and in the iterative question and answer format which is employed. Using the fire hazard analysis of the Seabrook Station [37], the following level of treatment appears to be typical. The production of a combustible vapor is dismissed as being insignificant (in quantity) on the basis that the atomization process takes place over the 0.3-sec. impact (load) duration. This duration is not representative of the vapor production period. Clearly a number of vapor production mechanisms will exist. For example, some fuel will be sprayed into the atmosphere and then fall as "rain" settling at a rate much less than 0.1 m/s, depending upon droplet size. Furthermore, fuel can be expected to be thrown over large elevated surfaces with subsequent flow downward over these surfaces due to the action of gravity.

Depending upon the surface temperature of these exposed surfaces (exposed perhaps to the sun) and the possible presence of fire, the vaporization rate can be amplified significantly and the vaporization period may last for many minutes. Fires are usually treated in a more comprehensive manner than explosions since a variety of pool conditions can be postulated, and using a vaporization rate (for a burning pool) of approximately 0.004 cm/s, the durations of the fires can be estimated. Flame temperatures, radiative flux levels, and fire durations can then be used (but usually not explicitly used) to claim that fires do not constitute a threat to the facility. The probability of fuel entering the relatively few openings (vent stack, air intake vents, steam line tunnels, etc.) to these collective structures will generally be quite low simply on an area basis, although specific values are frequently not cited. Account has been taken [61] of the internal concrete wall which acts as a missile barrier when present to prevent flames and fuel from directly entering the air intake. It would appear, however, that this is too optimistic since vaporized fuel, hot gaseous reaction products, and to a certain extent portions of liquid (fuel) streams will flow around such obstructions.

Based on the review of past licensing experience, it appears that fire and explosion hazards have been treated with much less care than the direct aircraft impact and the resulting structural response. Therefore, the claim that these fire/explosion effects do not represent a threat to nuclear power plant facilities has not been clearly demonstrated.

8. EVALUATION OF METHODS AND APPROACHES

In this section we will provide an overall evaluation of the methods and approaches employed in aircraft hazards studies and present conclusions that can be drawn therefrom. Siting of nuclear power plants relative to aircraft hazards is generally treated as a risk-based procedure that considers both the probabilities of occurrence and consequences of a radioactive material release given the probability of occurrence of an aircraft crash. In actual practice 10 CFR 100 and SRP guidelines have been (exclusively) employed on a case-by-case basis. This methodology provides for the implicit inclusion of risk by requiring that the exposure probability of aircraft crash events is acceptably small; deterministic analyses and engineered safety features are used in cases of design basis events, those having otherwise unacceptable exposure probabilities, until the exposure (risk) guidelines are satisfied.

The aircraft crash hazard for nuclear power plants is primarily a stochastic problem, which depends on many conditional probabilities including the probability of a radioactive material release given a particular crash event. Conservatism is usually applied in estimating the conditional probability of occurrence of any given level of radiological consequences - in the extreme a value of unity is assigned to the conditional probability of having an unacceptable release. However, it is observed that there is a direct coupling between the calculation of crash probabilities and these conditional probabilities, and, therefore, the problem is not simply defined.

In general, account is taken of the stochastic features, response, and relative vulnerability of structures, systems, and components. Major criticisms that may be made of typical aircraft hazards analyses are the lack of clear and supported statements on many key underlying assumptions and comprehensive treatments of the overall hazard. Thus both the open literature and documentation concerning specific power plants abound with studies of the impact phenomena of aircraft or aircraft missiles on substantial concrete structures. These analyses are pursued to the virtual exclusion of other aircraft crash scenarios. While it is recognized that the breaching of some of the plant's concrete barriers may often be tantamount to a release of radioactivity, it is not readily evident why other crash scenarios should not be considered in similar detail.

As discussed in Section 5, it is possible to envision a chain of events that involves nonhardened plant systems, e.g., switchyard-turbine hall, which could lead to severe consequences. It is realized that to obtain a substantial radioactive release through the failure of those nonhardened plant systems it is necessary to have multiple initiating events or a propagating failure where the malfunction of a nonsafety system ultimately affects a plant safety system. There is some indication that the latter, a propagating failure, can sometimes occur. The crash of a large aircraft with the resulting projectile impacts, fuel spillage, and fire/explosion scenarios suggests that multiple initiating events may also be possible. In none of the reviewed literature have these problems been addressed; the combination of fire/explosion and impact damage has received a little but highly superficial attention.

Since plant features directly influence the estimation of radioactive exposure probability and the crash probability itself, through site location, susceptible target areas, etc., it is necessary to represent them consistent with the range of possible accident scenarios. As indicated above this process is usually performed either inadequately or without pertinent supporting data or calculations. In particular, potentially vulnerable plant features are not identified through a uniform code of practices, as, for example, the inclusion or not of switchyard, turbine hall, and other structures. On the other hand, calculations of the effective plant area for the included susceptible targets are made conservatively through the choice of the aircraft crash angle, although the skid problem and its contribution to plant area have not been adequately resolved. Another shortcoming of many aircraft crash analyses is the employment of simplified and/or outdated methodologies or data when much more advanced methods and better data are available. An example of this is the treatment of local structural damage to concrete walls where both better material representations and computational procedures are available than those which are usually employed.

Although considerable conservatism is apparently included in the conditional probabilities of radioactive release that are typically used for the plant features included in the analyses performed, crash probability calculations for a number of nuclear power plant sites have yielded values that are often (i) marginal with respect to 10 CFR 100 and SRP guidelines, i.e., in the general range of 10^{-6} to 10^{-7} per year, and/or (ii) unacceptably high without taking into account either the inherent hardness of plant structures or engineered safety features. Generally these sites are close to one or more airports (civilian and military) and in some instances within 5 miles. Also, the presence of General Aviation light aircraft flights in uncontrolled airspace and major air corridor traffic in the immediate vicinity of a site usually result in unacceptable crash probabilities without taking account of hardness factors through a significant reduction in effective target area. In addition, the following specific observations and conclusions can be made:

- For light General Aviation aircraft it is found that at about 5 miles from most airports, the effect of the airport becomes unimportant; i.e., the background level dominates. Using national averages for crashes of light aircraft results in a relatively high frequency of approximately 10^{-4} events per year per square mile. This in general gives marginal crash probabilities (on the order of 10^{-6} per year) for nuclear power plants of any significant size, and, therefore, a major portion of the plant area must be nonsusceptible or hardened against such crashes. It should also be noted that in areas of high traffic density the employment of national average crash rates may be nonconservative.

- In the immediate vicinity of heavily traveled airways, more than 10^5 flights per year, the crash frequencies again appear to be high, i.e., $> 10^{-4}$ events per year per square mile, resulting in marginal situations for power plants with vulnerable areas of the order of 10^{-2} square miles. Since airways are predominantly used by large aircraft, power plant hardening is not an easy task. Again, the effects on national average crash rates due to local air-corridor conditions and traffic patterns is not established.

- There exist about 330 major FAA-controlled airports in the U.S., and the number of critical Air Carrier crashes, i.e., crashes that could damage a nuclear power plant, is of the order of about ten per year. Assuming that one-third of such crashes occur within 5 miles of these major airports and using the national accident statistics, one finds that the probability of such a crash within the 5-mile radius from the airport is on the average 10^{-4} events per year per square mile - again a rather excessive value. Sensitivity studies performed during the current work, however, indicate that this airport effect may extend to significantly greater distances, e.g., say to 10 miles or more.

- Data for military airports are much less defined; however, they appear in general to be comparable to commercial airports. However, special flight patterns, e.g., training flights, high-speed flights, low-flying aircraft, bomb runs, etc., must be considered carefully. Indications are that past practice has taken these aspects into account.

Additional comments concerning the actual analysis methodologies can also be made:

- It is customary to employ the virtual areas of power plants, which are based on the shadow areas of vulnerable structures, when making aircraft hazards analyses. Indications are that aircraft skid areas may in some cases be considerably larger than those virtual areas, but skid analyses are generally not performed.

- When defining plant vulnerable areas, the nonhardened features are normally not included. As indicated earlier, consideration should be given to multiple failures and the potential for failure propagation associated with the nonhardened areas, in particular, the switchyard and turbine hall.

- The best available methods, approaches, and data should as a matter of practice be employed in any detailed analysis of aircraft crash hazards. Past practice is often found deficient with respect to the state-of-the-art, relying instead on expedient and simplified procedures.

- SRP guidelines are presently oriented to defining the aircraft threat and the nature of the probability assessment. More explicit guidelines concerning what are acceptable methodologies and models in a much broader context are lacking which partially accounts for a degree of confusion and inconsistency among similar based studies. Another difficulty is that it would appear to be difficult to assess or quantitatively measure the level of realism or conservatism in the results obtained in most cases.

In summary, it appears subject to the above comments that the methods and data required to make an adequate analysis of the aircraft crash hazards are reasonably well in hand. Excellent information sources exist and are readily available for establishing aircraft-related data bases and statistics. The absence of or difficulties involved in generating certain types of accident parameters can usually be compensated for by analytical procedures, conservative assumptions, or probability distribution functions. Major aircraft crashes at any given site do represent very low probability events. Aircraft crash rates that scale with the number of operations can be estimated as functions of basic aviation parameters with reasonably high degrees of confidence, but certain higher order scaling possibilities have not been adequately studied. The crash probability is itself a conditional probability, conditioned by the accident scenario characteristics and the effective target features. Since the nature of the target depends itself upon the assumed accident scenario, the calculation process can be rather involved; further, potential nuclear power plant targets are complex and varied.

Crash probability calculations for the specific sites previously studied involved considerable data gathering and modeling of site features and accident parameters. Results are strongly dependent upon those factors and invariably reflect derived and in most cases assumed conditional probability estimations of certain event occurrences. The procedure requires identification and quantification of likely accident scenarios and evaluation of corresponding target features on the basis of deterministic and judgmental methodologies and consequences criteria. However, necessary detail supporting both scenario and plant feature assumptions and sensitivity calculations are difficult to find and evaluate. The state-of-the-art of this complex problem is relatively advanced at the present time; however, the available knowledge has not been employed to its full advantage in past applications, and a lack of detailed procedures or codifications appears to persist. It appears, therefore, that room for improvement exists in carrying out the stochastic analyses and, in particular, in the more deterministic areas of scenarios and damage mechanisms, and where a complex aviation environment exists.

9. REGULATORY APPROACH RECOMMENDATIONS

The present regulatory approach re aircraft hazards to nuclear power plants is to allow for a compensatory combination of site location and engineered safety features to meet federal regulations and licensing standards. Neither this study nor to our knowledge any other study has shown that this approach is fundamentally unsound or deficient in achieving the desired safety standards although these standards and the topic of risks were not themselves included in the current scope. A reasonable argument can be made that this approach results in better plant design compatible with its (aircraft) environment although again this point has not been proven and is beyond the current scope. Equally credible arguments have been made that the present approach results in some cases in an over-reliance on engineering solutions, unnecessary exposure to aircraft hazards with possible increased risk, and does not effectively utilize or emphasize siting as an inherent defense-in-depth factor.

The three areas where changes have been suggested and can be made to establish alternate regulatory approaches are in the Code of Federal Regulations, NRC Standard Review Plan, and Regulatory Guides. Several alternate approaches are discussed in Section 2 and are summarized here as follows:

- establishment of minimum standoff distances from geographically located offsite hazards;
- exclusion distances from the same;
- site acceptance limits where sites not meeting these thresholds are excluded;
- site acceptance floors where sites not exceeding these thresholds are approved;
- containment design to withstand certain aircraft crash scenarios;
- design against most severe aircraft-induced consequences;
- establishment of screening distance values and screening probability levels to identify situations requiring substantive treatments.

In particular, the question is raised as to whether a siting approach relative to aircraft (and other) offsite hazards is feasible and practicable whereby site approval requirements can be established independently of specific plant design. As an example, it has been recommended that nuclear power plants be located no closer than 5 miles from major airports. At the present time there are no requirements on the frequency of occurrence of aircraft crashes per se on nuclear power plants provided that the risk is acceptably small, and the risk evaluation process is strongly dependent upon plant features. Another question that arises concerns whether more uniform siting standards can be developed as, for example, procedures for screening potential site locations or evaluating safe standoff distances.

Presently, federal regulations are written to ensure that no credible risk is posed by aircraft (and other offsite) hazards to nuclear power plants on the basis of radiation exposure criteria. Thus, in terms of both probability (credibility) and consequence (exposure) analyses, plant features are at present central to the determination of compliance to regulations through effective target area and vulnerability characteristics; these characteristics are themselves coupled to the aircraft crash scenarios. The current SRP review procedure (Rev. 2 - July 1981) does establish site screening proximity criteria relative to airspace usage and otherwise ensures that all potential design basis accidents are eliminated as credible events through proper identification, characterization, and treatment. The net effect of the present approach is that the annual frequency of unacceptable radiation exposure resulting from offsite hazards (integrated over all aviation and other situations) must be less than 10^{-6} to 10^{-7} per year depending upon the nature of the modeling.

On the basis of these risk criteria, our findings indicate that certain alternate regulatory approaches to siting standards and more uniform procedures are feasible but not completely independent of plant design considerations. Siting penalities (and possibly plant hardening) would need to be imposed in those cases where the effective areas of susceptible targets exceed nominal values that could, in principal, be associated with the various classes of aircraft hazard scenarios. As an example, the nationally averaged background crash rate of light General Aviation aircraft is on the order of 10^{-4} crashes per square mile per year and could be substantially higher in regions having above average traffic rates. Therefore, a nominal effective area calculation relative to background aviation and based upon susceptible targets together with conditional probabilities of radioactive material releases would in the first place have to be small enough so as to present no credible risk, and in the second place have to vary to the extent that local aviation statistics vary.

Having made this point, however, the presence of background aviation hazards is common to all facilities and should be viewed as a basic design consideration that is a siting problem only insofar as there are geographical variations in the hazard levels. Accordingly, it is recommended that the present approach be applied in the treatment of background aviation hazards since this, for all practical purposes, is synonymous with containment (and other) design to withstand certain aircraft crash scenarios - primarily from light single-engine pleasure aircraft; other suggested siting alternatives do not appear applicable to background aviation. Our findings indicate that specialization of the SRP to background aviation is feasible and that the following steps are important to this task:

- provide a clearer definition of the background aviation which a plant is exposed to irregardless of siting details;
- generate appropriate crash rate statistics relative to geographical variations, fleet mix, and aviation parameters;
- establish procedures for estimating local background aviation activity;
- perform more detailed crash scenario and susceptibility analyses primarily for the switchyard and other noncontainment features.

With respect to fixed air traffic concentrations, such as airports, air corridors, and other restricted air spaces, our findings indicate that other siting approaches appear to be feasible and practicable, and that the basic information required in any alternate formulation exists. This conclusion is based upon the observation that nominal crash probabilities, i.e., independent of plant design, can be evaluated for any assumed site location relative to fixed aviation air-spaces. Thus, minimum distances between the suggested plant site and airports, air corridors, etc. or acceptability criteria could be applied on a site-specific basis and based upon, say, the background crash probabilities of light (and heavy) aircraft in the region. Although the data bases and methodologies are generally available, such calculations have not been made in a systematic manner.

It appears that the following alternate regulatory approaches are worthy of pursuit and potentially capable of yielding additional practical guidelines with respect to aircraft hazards in the vicinity of fixed aviation air-spaces:

1. Continued development of the site screening methodology that depends only upon local aviation statistics and locations and is independent of plant design; suitable probability criteria would need to be estabilished relative to acceptability.

2. Development of minimum standoff or exclusion distances from airports, airways, and other controlled or restricted air spaces based only upon levels of potential hazards and independent of plant design; this approach is based upon the observation that

these aviation zones concentrate traffic levels, increase crash rates, and increase phases of operation in their vicinity.

Due to the background and possible residual effects of fixed air-spaces, it does not appear feasible to develop safe standoff distance methodologies for aircraft hazards independently of nuclear power plant design considerations as discussed above.

The alternate approaches would clearly emphasize site selection over engineering solutions to aircraft hazards presented by airports, air corridors, etc.; however, to be effective procedures should cover situations that are complex in the sense that multiple airports (of varying size), overlapping air corridors and other air-usage spaces, and a wide range of aviation parameters will generally be involved in any actual situation. It is anticipated that a principal advantage of the indicated alternate treatments will be in the handling of large (Air Carrier) aircraft hazards for which engineered safety features are costly and defense-in-depth through site selection is most desirable.

Our findings indicate, for example, that airports handling General Aviation traffic only become unimportant relative to the background at distances on the order of 5 miles (say from 2 to 6 miles depending on the airport size); this type of data analysis could be readily employed in siting guidelines. Similar results apply to air corridors handling large commercial aircraft although the actual decay of crash frequency with distance from an airway is ill defined at present. Major airport air-spaces can be viewed as consisting of an immediate zone of influence extending to 5 miles and within which takeoff, landing, and other phases of operation occur and where one-third of all large aircraft crashes takes place, and of an airport-related zone extending to greater distances and within which phases of operation such as climb and descent, holding patterns, and the confluence of air corridors exist. The extent of the latter region is not at present clear, but if one-half of all Air Carrier accidents is assumed to be airport-related, then it must extend for some possibly considerable distance beyond 5 miles. The formulation or continuing development of additional regulatory procedures will require more detailed analyses of these and other aviation characteristics but the data bases appear to be adequate to the task.

Finally, it should be noted that the present screening criteria contained in the SRP establish site proximity distances to airports, military training routes, and commercial aviation designated air spaces as a function of the annual number of airport operations, at five miles, and at two miles, respectively. In each of these situations, the screening distance value appears to be very reasonably and/or conservatively defined on the basis of the review performed here; for example, the screening distance to an airport having 625,000 annual operations is 25 miles. However, the present approach must be viewed as only directly applicable in relatively clear-cut aviation environments and for plants not susceptible to background light aircraft crashes on a target area or hardening basis.

10. PROBLEM AREAS

A number of areas concerning aircraft hazards to nuclear power plants are presently unresolved and/or treated in an inadequate manner. It is fair to say that although some of the problem areas relate to advances in the state-of-the-art (e.g., aircraft skid and fires), most only involve the generation of additional specialized information and procedures, and the orientation of these more to the point of view of the regulatory and review processes. Thus, resolution of these problem areas is significant to the existing regulatory approach as well as possible alternate approaches. Important benefits that can be expected to result include overall simplification of the siting procedures relative to aircraft hazards and streamlining of the regulatory process. The more important areas that appeared during this study will be briefly noted below under the headings of aviation, scenarios, and plant; it should be noted that these are nonsite-specific, i.e., generic with respect to nuclear power plants:

Aviation

- detailed review of aircraft accident reports and data to establish criteria to better define those aircraft accident scenarios that are potentially threatening to nuclear power plants and appropriate normalizing statistics;

- definition of aviation categories from hazard and siting points of view, e.g., background crash exposure, airport-related crash zones, situations threatening to nuclear power plants, etc.;

- scaling characteristics of crash rates relative to aviation parameters such as airport size, traffic density, air corridor characteristics, geographical variations, etc.;

- more detailed statistics on aircraft in-between the light single-engine and heavy commercial aircraft, e.g., twin-engine and military aircraft;

- procedural guidelines for gathering and statistically treating local aviation data bases and the scaling of crash rates;

- methodologies for treating complex aviation environments such as the presence of multiple nearby airports, overlapping airways, etc;

- methodologies for treating fleet mixes with respect to aircraft parameters and aviation activities.

Scenarios

- modeling and verification of crash characteristics including flight path parameters such as speed and altitude, crash path characteristics such as orthonormal deviations to the flight path and crash inclination angle, and skid momentum-distance relationships, among others;
- establishment of probability distribution functions relative to aircraft impact parameters, e.g., speed and orientation at impact, fleet mix effects, etc.;
- analysis of aircraft fire/explosion characteristics.

Plant

- further identification of plant features susceptible to aircraft crashes, multiple failure possibilities, and plant failure-mode response characteristics;
- procedural guidelines for target area calculations particularly relative to fleet and accident scenario mixes.

All of the above areas are, of course, necessarily addressed in past studies if only through implicit assumptions (such as ignoring the possibility of fire), highly simplified or unsupported models, and the application of subjective judgement. In some areas, such as identification of threatening crashes, the data base appears adequate and is readily available and only criteria development and standardization is needed, while other areas need considerable statistical or modeling efforts, e.g., airport-related crash zones, the aircraft skid problem, and crashes into the switchyard, to name a few. More emphasis should be placed on the sensitivity of results to variations in the many probabilistic and phenomenological aspects of the aircraft hazard to nuclear power plant problem.

To conclude, it should be emphasized that it has been found that the aircraft hazards to nuclear power plants are generally very low risk events with respect to 10 CFR 100 radiological exposure guidelines, and most of the phenomenological and incidental factors can usually be estimated or bounded to some degree. Therefore, the conclusions and problem areas spelled out in this study need not be cause for alarm although many details cannot be expected to be adequately resolved for at least many years.

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57. Kamil, H., Krutzik, N., Kost, G., and Sharpe, R., "Overview of Major Aspects of the Aircraft Impact Problem," Nucl. Eng. Des. 46 (1978) 109-121.

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59. Eichler, T. V. and Napadensky, H. S., "Accidental Vapor Phase Explosions on Transportation Routes Near Nuclear Power Plants," NUREG/CR-0075, April 1977.

60. Napadensky, H. S. and Takata, A. N., "Potential Danger of Fixed Propane-Isobutane Storage Tanks in a Residential Area," IIT Research Institute Report V6141-J19, March 1976.

61. Docket - 50295-49, "Potential Effects of Aircraft Impact and Post-Crash Fires on the Zion Station," 1972.

APPENDIX

LITERATURE SUMMARIES

Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Ahmed, K. M. and Ranshi, A. S.
Title: Dynamic Response of Nuclear Power Plant due to Earthquake and Aircraft Impact Including Effect of Soil-Structure Interaction
Reference: Journal of Sound and Vibration (1978) 59(3), 423-440
Brief Description:

This paper compares the dynamic response of a typical nuclear power plant to a modest earthquake (Parkfield) and to the impact of MRCA and Boeing 707-320. Finite element and modal superposition techniques are used to obtain the time-history response and the corresponding floor response spectra. It is shown that the response of reactor plants due to impact of MRCA on the primary containment structure is small compared to the response due to a modest earthquake. In the event of Boeing 707 crashing onto the facility, the design of reactor plants could be damaged depending upon the amount of energy absorbed locally.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Attalla, I. and Nowotny, B.
Title: Missle Impact on a Reinforced Concret Structure
Reference: Nuclear Engineering and Design 37 (1976) 321-332
Brief Description:

This paper studies the behavior of reinforced concrete structures under missile impact loading using PISCES 2 DL code. The local deformations in all directions including wall thickness, plasticity, and stress waves near the loading area were considered. Many discussions are on defining the material and yield models for reinforced concrete.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Bahar, L. Y. and Rice, J. S.
Title: Simplified Derivation of the Reaction-Time History in Aircraft Impact on a Nuclear Power Plant
Reference: Nuclear Engineering and Design 49 (1978) 263-268
Brief Description:

This paper presents a simplified derivation of the reaction-time history of an aircraft impact on a nuclear power plant. The equation of motion for the rigid part of the aircraft is assumed to be a variable system of particles loosing mass. The equation of motion for the crushing region is obtained using containuum mechanics approach. The results indicated that the reaction is not affected by the assumed velocity distribution in the crushing region of the aircraft.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Author: Bonnin, D. M.
Title: An Aircraft Accident Probability Distribution Function
Reference: Transactions American Nuclear Society 18: 225-226, June 1974

Brief Description:

Proximity to an airport has been considered a disadvantage to a nuclear reactor; hence, the likelihood of aircraft crashes must be carefully considered during site selection and licensing activities. While preparing an amendment to the application for construction permit of a nuclear reactor a study was made to establish a detailed aircraft accident probability distribution function which would reflect the likelihood of aircraft accidents.

The study covered civil aircraft accidents within 5 miles of an airport in the United States for the years 1966-1970. The aircraft and thereby the probability function were subdivided by usage (general aviation, air taxi, and air carrier) and aircraft size (large and small) categories.

Several basic conclusions were noted from the results of the probability distribution function:

1. The probability distribution function was always quite low varying from 1.100×10^{-6} to 2.076×10^{-9} accidents per operation per square mile depending on the fleet mix and the radial distance from the center of the runway.
2. The probability decreased as the radial distance from the airport increased.
3. Use of the function requires only the air traffic figures compiled at any specific civil airport of interest and the critical area, in square miles, of the site.

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Offsite Hazards: Aircraft Crash
Type of Model: Survey
Author: Buchhardt, F.
Title: Some Comments on the Concept of "Underground Siting of Nuclear Power Plants" - A Critical Review of the Recently Elaborated Numersous Studies
Reference: Nuclear Engineering and Design 59 (1980)

Brief Description:

This paper reviews various aspects of underground nuclear power plants. It discusses some critical analyses concerning different basic design criteria, constructional concepts, and impacts as well as problems of licensibility and operation.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Carlton, D. and Bedi, A.
Title: Theoretical Study of Aircraft Impact on Reactor Containment Structures
Reference: Nuclear Engineering and Design 45 (1978) 197-206
Brief Description:

This paper presents results using a finite difference dynamic code (PISCES) based upon dynamic relaxation initially developed for static problems. The code models concrete, reinforcement and prestressing throughout the short term nonlinear range. Concrete is assumed to have a limited tensile stress capacity, coupled with a shear carrying capacity which is dependent upon the aggregate and crack size. And a yield condition is also specified to allow for triaxial stress states. The results of a particular reinforced concrete slab subject to MRCA loading indicated that 80 mm thick model slabs can resist the load. In real structures this corresponds to a wall thickness 1.4-2.0m.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic and Deterministic
Authors: Chelapati, C. V., Kennedy, R. P., and Wall, I. P.
Title: Probabilistic Assessment of Aircraft Hazard for Nuclear Power Plants
Reference: Nuclear Engineering and Design 19 (1972) 333-364
Brief Description:

As part of a general probabilistic safety analysis, the risk of structural damage to a nuclear power plant from aircraft crashes has been evaluated in a quantified manner. Frequency distributions of aircraft speed and weight and engine weight were constructed for small and large aircraft and for site locations adjacent to and remote from an airport. Based upon United States data an analysis of aircraft incidents is presented to establish the probability of an aircraft hitting a nuclear power plant.

This paper presented a quantified risk analysis of structural damage to a nuclear power plant from aircraft crashes. Three modes of damage are discussed here: perforation, collapse, and cracking. The probability of damage to an 18-inch thick reinforced concrete sidewall of a typical BWR in the perforation and collapse modes is investigated. The results are also compared to the damage of cracking mode. A new formula is proposed to cover the range of parameters encountered in aircraft engine impact. The conditional probability of local collapse of the wall panel is evaluated by using probabilistic approaches and yield line theory. An elastic finite element method was used to estimate the cracking mode.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Cravero, M., Lucenet, G.
Title: Evaluation of the Probability of an Aircraft Crash on a Nuclear Power Plant
Reference: Proceedings of the Fast Reactor Safety Meeting, Beverly Hills, California, April 1974
Brief Description:

The liquid Metal Fast Breeder Reactor SUPER-PHENIX, (electrical power 1200 MW) which will be built at CREYS-MALVILLE in the Rhone valley must follow the guidelines given in France for the safety of this reactor. One of these guidelines is to evaluate the risks in relation with air traffic. Consequently, a study of this problem was begun to estimate the probability of an aircraft crash on the power plant SUPER-PHENIX, particularly on reactor building.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Degen, P., Furrer, H., and Jemielewski, J.
Title: Structural Analysis and Design of a Nuclear Power Plant Building for Aircraft Crash Effects
Reference: Nuclear Engineering and Design 37 (1976) 249-268
Brief Description of Modeling Effort:

This paper discusses the effect of a large commercial airplane crashing perpendicularly on the surface of a spherical reactor building dome. The carrying capacity of the structure under an equivalent statical load is considered. The presentations include:

(i) calculation of the failure load following the yield line theory.
(ii) calculation of the sectional forces using the linear elastic shell theory and subsequent design by the ultimate strength method.
(iii) calculation of the failure load, establishing of the failure mechanism and distribution of sectional forces using plastic shell theory.
(iv) calculation using a 3-D FEM with plastic capability (TRIDI).

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Author: Dietrich, R.
Title: Structural Analysis of Aircraft Impact on a Nuclear Powered Ship
Reference: Nuclear Engineering and Design 37 (1976) 333-346
Brief Description:

This paper evaluated the reliability against structural damage due to an aircraft crash on a nuclear powered ship. The following two effects are considered in the paper: local penetration and dynamic response of the structure. The empirical formula derived from military applications were used for calculating the penetration distance. The solution of the dynamic analysis is obtained using finite element method. Both results indicated the safe design of a specific ship subject to an aircraft impact.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Drittler, K. and Gruner, P.
Title: Calculation of the Total Force Acting Upon a Rigid Wall by Projectiles
Reference: Nuclear Engineering and Design 37 (1976) 231-244
Brief Description of Modeling Effort:

A numerical (finite difference) method is presented for the calculation of total force acting upon a building during impact of a projectile. Variations of geometric and material properties across the projectile axis are replaced by proper average values.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Drittler, K. and Gruner, P.
Title: The Force Resulting From Impact of Fast-Flying Military Aircraft Upon a Rigid Wall
Reference: Nuclear Engineering and Design 37 (1976) 245-248
Brief Description of Modeling Effort:

The authors using the previous proposed method to calculate the impact force of phantom aircraft on a rigid wall. The results indicated that the impact force is almost insensitive to various relevent parameters. Therefore only one force vs. time F(t) curve may be used for safety consideration.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Author: Eisenhut, D. G.
Title: Reactor Sitings in the Vicinity of Airfields
Reference: American Nuclear Society Transactions, 16:210-211, Chicago, June, 1973
Brief Description:

An evaluation of the probability of an aircraft crash at a nuclear facility in the vicinity of an airport has been performed. This evaluation, together with other studies, may assist in the development of general criteria for the siting of reactors near airports. The analysis considered those accidents that occurred within a few miles of the runway and also occurred within a 60-degree reference flight path symmetric about the extended centerline of the runway.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Author: FSAR
Title: Potential Effects of Aircraft Impact and Post-Crash Fires on the Zion Station
Reference: Docket 50295-45, 1972
Brief Description:

Presents a study of the Probability of an aircraft using a nearly airport hitting the station. Includes a second report on the potential effects of aircraft impact and post-crash fires on the station.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic - Deterministic
Author: Godbout, P. and Brais, A.
Title: A Methodology for Assessing Aircraft Crash Probabilities and Severity as Related to the Safety Evaluation of Nuclear Power Stations - Phase III, Final Report
Reference: Centre de Developpement Technologique, L'Ecole Polytechnologique de Montreal Atomic Energy Control Board (Canada), March 1980.
Brief Description:

Reports (1) the accumulation of a special and exhaustive experimental data bank results from related experiments done in the U.S., U.K., France, Germany and Australia, (2) an involved detailed theoretical modelling and its proper coupling of each phenomenologically significant phenomenon present during the impact process of an aircraft and per missile type, (3) use of existing (or development of new) computer codes to identify important processes and (4) benchmarking of results against experimental data.

Specific results for CANDU Reactor Types, principally and to hard projectiles having low velocities, large diameters and large masses. Techniques can be applied to other types of projectiles.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Godbout, P. and Brais, A.
Title: A Methodology for Assessing Aircraft Crash Probabilities and Severity as Related to the Safety Evaluation of Nuclear Power Stations - Final Report.
Reference: Centre de Developpment Technologique, Ecole Polytechnique de Montreal, Fot Atomic Energy Control Board (Canada), 1204-3, September, 1976.
Brief Description:

This Phase II effort compiled more extensive statistical data on aircraft including international experience. The categories of light and heavy aircraft were investigated and crash rate models developed. Probability distributions for aircraft strikes on nuclear power plant structures were generated, with particular emphasis on sites near to an airport. Impact forcing functions for the crash of an aircraft on the plant containment structure were evaluated using the characteristics of each aircraft type. Standarized forcing functions were developed of the global energy envelope for the striking phenomena as a whole was generated.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Author: Godbout, P.
Title: A Methodology for Assessing Aircraft Crash Probabilities and Severity as Related to the Safety Evaluation of Nuclear Power Stations - Main Report and Appendices I and II.
Reference: Centre de Developpment Technologique, Ecole Polytechnique de Montreal for Atomic Energy Control Board (Canada), AECB-1204-1 and 2, May 1975.
Brief Description:

The probability of an aircraft striking a nuclear power plant has been evaluated. The method of approach as used in this study consists of a series of orderly steps or procedures which make use of logic modelling, of probability theory, of the energy envelope technique, of the sensitivity technique and of the limit line concept, in that order. Accident data was obtained for all types of aircraft accidents since 1960. The criterion was chosen that any aircraft which has navigational difficulties forcing it to land improperly or unwillingly is an accident and a possible danger to the surroundings.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Author: Gottlieb, P.
Title: Estimation of Nuclear Power Plant Aircraft Hazards
Reference: Probabilistic Analysis of Nuclear Reactor Safety Topical Meeting, Los Angeles, CA, May 8-10, 1978
Brief Description:

The standard procedures for estimating aircraft risk to nuclear power plants provide a conservative estimate, which is adequate for most sites, which are not close to airports or heavily traveled air corridors. For those sites which are close to facilities handling large numbers of aircraft movements (airports or corridors), a more precise estimate of aircraft impact frequency can be obtained as a function of aircraft size. In many instances the very large commercial aircraft can be shown to have an acceptably small impact frequency, while the very small general aviation aircraft will not produce sufficiently serious impact to impair the safety-related functions. This paper examines the in between aircraft: primarily twin-engine, used for business, pleasure, and air taxi operations. For this group of aircraft the total impact frequency was found to be approximately once in one million years, the threshold above with further consideration of specific safety-related consequences would be required.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Gupta, Y. M. and Seaman, L.
Title: Local Response of Reinforced Concrete to Missile Impacts
Reference: Nuclear Engineering and Design 45 (1978) 507-514
Brief Description:

This paper presents an experimental and computational (finite difference) study of reinforced concrete walls response to impacts from postulated tornado and missiles. This paper also presents the results of a study to determine the dynamic constitutive relations of reinforced concrete for use in two-dimensional calculations of local impact response.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Author: Hammel, J.
Title: Aircraft Impact on a Spherical Shell
Reference: Nuclear Engineering and Design 37 (1976) 205-223
Brief Description of Modeling Effort:

This paper discussed the influence of the elastic displacements of a structure on the impact load F(t). The aircraft is idealized by a linear mass-spring-dashpot combination. The time-dependent reactions of the shell as a function of F(t) are expanded in terms of normal modes.

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Offsite Hazard: Aircraft Crash
Type of Model: Analytical (Structural response and impact load)
Author: Haseltine, J. D. (Project Manager)
Title: Seabrook Station Containment Aircraft Impact Analysis
Reference: License Application (March 30, 1973)
Docket Nos. 50-443 and 50-444
Brief Description of Modeling Efforts:

1. Conventional elastic-static analysis
2. Conventional elastic-dynamic analysis
3. "Biggs Type" elastic-plastic analysis
4. "Wave Type" impact analysis for aircraft

Result of Analysis:

The elastic-static and elastic dynamic calculations indicated that plastic behavior would occur. The elastic-plastic calculations indicated that the concrete containment structure design was adequate. A methodology for determining the impact loads on a rigid structure is presented in an Appendix and a sensitivity analysis indicates that the crushing strength of the aircraft is not an important parameter. A brief fire analysis claims that fire and explosion effects are not important.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Hornyik, K. and Grund, J. E.
Title: The Evaluation of the Air Traffic Hazards at Nuclear Plants
Reference: Nuclear Technology: Volume 23, July 1974
Brief Description:

Analytic models have been developed and applied to the investigation of the hazards to a nuclear power plant from air traffic. Separate models applying to collisions with and crashes into the plant, respectively, employ concepts traffic density and crash site distributions. These, along with the more conventional concepts of accident rates and effective plant area, are used to determine the annual strike probability of aircraft into safety-related plant structures. Although the models are quite general, they are applied to two specific flight patterns of common interest. The probability maps which are obtained may be used to resolve siting problems in a quantitative manner.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Hornyik, K.
Title: Airplane Crash Probability Near a Flight Target
Reference: Transactions American Nuclear Society, 16:209-210, 1973
Brief Description:

A summary of the crash and collision probability models developed in previous work for a proposed nuclear plant site near a military aviation training area is presented.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Hornyik, K., Robinson, A. H., and Grund, J. E.
Title: Evaluation of Aircraft Hazards at the Boardman Nuclear Plant Site
Reference: Portland General Electric Company, Report No. PGE-2001, May 1973
Brief Description:

The document presents an assessment of the probability of aircraft crashing into a proposed nuclear power generating plant located near Boardman in Morrow Count, Oregon. Quantitative estimates of crash probabilities into the proposed plants are based on analyses of operations of commercial aircraft use of federal airways and the U.S. Navy aircraft use of a nearby Navy weapons Systems Training Facility. The WSTF, its procedures, its utilization, the aircraft used and operating experience at this and other related facilities are described in some detail. Both low altitude collision and high altitude crash probability models are constructed.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Author: Joerissen, G. and Zuend, M.
Reference: International Nuclear Industries Fiar, Basel/Switzerland, October 1973

Brief Description:

The probability and the consequences of an aircraft crash on a nuclear power plant incorporating a light water reactor are estimated considering the probabilities of an aircraft strike, missile penetration through walls and damage of structures and systems important for safety. The estimated risks are presented in a Farmer diagram and compared with tolerable risk limits.

The probability that an aircraft crash would initiate an accident in a nuclear power plant with subsequent release of radioactive material is lower by several orders of magnitude than those of the design basis accidents. Although the consequences in terms of activity release to the environment would be rather severe in the worst conceivable case, the risk would still be about two orders of magnitude below the risk limit stated by Farmer. Dose calculations show that even under unfavourable meteorological conditions the maximum radiation doses to the population would be far below the lethal dose. The consequences for the population would therefore be less severe than for the much more probable aircraft crash in a densely populated area.

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Offsite Hazards: Aircraft Crash
Type of Model: Survey
Authors: Kamil, H., Krutzik, N., Kost, G., and Sharpe, R.
Title: Overview of Major Aspects of the Aircraft Impact Problem
Reference: Nuclear Engineering and Design 46 (1978) 109-121

Brief Description:

This paper identifies the major aspects of the aircraft impact problem and spotlights the most relevent topics for future investigation. Three main topics are presented: modeling techniques, influence of nonlinear behavior, and damping effect in the dynamic structural response for aircraft impact loading.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Author: Kennedy, R.P.
Title: A Review of Procedures for the Analysis and Design of Concrete Structures to Resist Missile Impact Effects
Reference: Nuclear Engineering and Design 37 (1976) 183-203

Brief Description of Modeling Effort:

This paper deals with the effects of "hard" missle impact. Missile velocities between 100 and 1500 ft/sec are considered. The paper reviews the various empirical procedures for determining penetration, depth perforation thickness, and scabbing thickness for concrete targets subjected to missile impact. Simplified procedures are defined for determining the dynamic response of the target wall and for eventing overall failure of the wall.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Author: Krutzik, N. J.
Title: Analysis of Aircraft Impact Problems
Reference: Advanced Structural Dynamics, Ed. by Donea, J. Applied Science Publishers, Ltd., London, 1978, pp 337-386
Brief Description:

This paper presented the characterization of the load case induced by various aircraft impacting on the nuclear power plants. Also the influence of elastoplastic deformation in the area of impact on load function is discussed. The dynamic structural investigations for reactor building are presented using beam and shell models. The modal damping, damping parameters, soil parameters are discussed. Investigation of two neighboring buildings of unequal sizes show that the presence of the smaller building has a damping effect on the dynamic response of the larger building, and the impact on the larger building excites oscillations in the smaller buildings. As far as the comparisons with an earthquake and an explosive shock wave, in the low frequency range (up to 5 Hz) the load case of an earthquake is governing whereas in the high frequency range (above 10 Hz) the load case of an aircraft crash dominated.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Niyogi, P. K., Boritz, R. C., and Bhattacharyya, A. K.
Title: Safety Design of Nuclear Power Plants Against Aircraft Impacts
Reference: United Engineers & Constructors, Inc., Philadelphia, PA.
Brief Description:

A nuclear power plant is considered adequately designed against aircraft hazards if the probability of aircraft accidents resulting in radiological consequences greater than 10 CFR part 100 guidelines is less than about 10^{-7} per year Otherwise an aircraft accident is considered a design basis event and the plant must be hardened up to the point at which the above criterion is met. In many cases it has been sufficient to demonstrate that the probability of an impact on a safety-related building is less than 10^{-7} per year. In other cases, it is necessary to take into account the intrinsic hardness of buildings and structures designed to withstand tornado, seismic, and manmade hazards in order to demonstrate that an aircraft impact presents an acceptable risk In some cases, however, it is necessary to consider aircraft impacts as design basis events and to specify the level of hardening required to satisfy the design criterion.

This paper presents a number of techniques which may be utilized to accomplish the above objectives. Firstly, a re-evaluation is made of aircraft crash probabilities. Secondly, methods are described for calculating aircraft impact forcing functions, for obtaining probability distributions for the impact parameters. Thirdly, evaluations are made for assessing the probability that an impact on a given structure will result in consequences exceeding those listed in 10 CFR 100 and recommendations are made for treating lower consequence events. Finally, other effects such as fires, explosions, and secondary missiles are examined briefly.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: NRC
Title: Aircraft Crash Probabilities
Reference: Nuclear Safety, Vol. 17. No. 3, May-June 1975
Brief Description:

The present article is taken from the NRC Reactor Safety Study and summarizes the procedure followed by the Regulatory Staff in assessing aircraft risk and also tabulates crash probabilities. Such information is necessary for an aircraft hazards analysis as described in the NRC Regulatory Guide.

The AEC Regulatory Staff has compiled data on aircraft movements and calculated crash probabilities as a function of distance from an airport and orientation with respect to runway flight paths. The probabilities are computed per square miles per aircraft movement so that the individual plant sites can be evaluated by determining the plant vulnerable area, distance from the airport, and the number of aircraft movements involved.

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Offsite Hazards: Aircraft Crash
Type of Model: Risk
Authors: Otway, H. J. and Erdmann, R. C.
Title: Reactor Siting and Design from a Risk Viewpoint
Reference: Nuclear Engineering Design 13: 365-376, August 1970
Brief Description:

This paper proposes a method for the assessment of reactor safety, based upon the individual mortality risk, which allows (i) the determination of necessary site exclusion radii and (ii) the evaluation of safeguards in terms of the risk reduction provided. An application to a 1000 MWe PWR indicates that for a maximum individual mortality risk of 10^{-7} per year (at the site boundary) an exclusion radius of 350 m is required. For a densely populated urban site the total risk was found to be 0.003 deaths over a 30-year reactor lifetime. Risk was found to be not particularly sensitive to accident probabilities.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Parker, J. V., Ahmed, K. M., and Ranshi, A.S.
Title: Dynamic Response of Nuclear Power Plant due to Earthquake Ground Motion and Aircraft Impact
Reference: 4th SMiRT, paper No. K9/5, San Francisco, CA, August 1977
Brief Description:

This paper presents a comparison between earthquake induced vibrations and aircraft impact induced vibrations. The nuclear power plant has been simulated as beam in finite element method. The aircraft assumes to impact the primary containment directly and horizontally near the top of the structure. The results of structural response is overestimated since the local impact effect which will absorb much of the energy has been ignored. Nevertheless, it is shown that the response of the reactor plant due to the impact of the multi role combat aircraft (MRCA) at 215 m/s on the primary containment structure is small compared to the response due to a modest earthquake. By contrast the maximum response to impact by the Boeing 707-320 at 103 m/s is considerably more onerous than the earthquake.

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Offsite Hazards: Combination
Type of Model: Probabilistic
Author: Ravindra, M. K.
Title: Load Combinations for Natural and Man-made Hazarde in Nuclear Structural Design
Reference:
Brief Description:

This paper outlines a methodology for deriving combinations of statistically independent and dependent hazard events that may affect a nuclear power plant by considering the uncertainties in hazard, occurrence, intensity, and duration.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Rice, J. S., and Bahar, L. Y.
Title: Reaction-Time Relationship and Structural Design of Reinforced Concrete Slabs and Shells for Aircraft Impact
Reference: 3rd SMiRT Conference, Paper No J5/3, London, England, 1975
Brief Description:

This paper outlines a procedure by which reinforced concrete structures (slabs and shells) may be designed to retain the required structural integrity after an aircraft impact. The reaction-time relationship for a deformable aircraft impacting on a rigid wall is developed. The results indicated that the reaction load is significantly less (40 percent) than that predicted by other models. The sensitivity of the reaction load to the uncertainty in the crushing strength of the aircraft frame is examined and it was found that this parameter is not important. The dynamic effects of the structural systems were examined using the method of Biggs.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Schalk, M. and Wölful, H.
Title: Response of Equipment in Nuclear Power Plants to Airplane Crash
Reference: Nuclear Engineering and Design 38 (1976) 567-582
Brief Description of Modeling Effort:

This paper deals with airplane induced vibrations of the whole building which cause loadings for secondary system (equipment). Floor response spectra due to airplane crash are studied for two different power plant buildings. The influence of various parameters such as time history of excitation, direction and location of impact mathematical model, soil, damping, etc. are discussed. A comparison with the results of earthquake loading is also given.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Schmidt, R., Heckhausen, H., Chen, C., Rieck, P. J., and Lemons, G. L.
Title: Structural Design for Aircraft Impact Loading
Reference: International Seminar on Extreme Load Conditions and Limit Analysis Procedures for Structural Reactor Safeguards and Containment Structures, Berlin, September 1975. 3 494-514
Brief Description:

This paper uses Phantom RF-4E fighter (weight-20 tons metric) impacting perpendicularly midway along a soft shell-hardcore structure at 215 m/s. This paper defines the important structural features that would allow soft-shell to sustain the aircraft impact without damaging hardcore. The analytical model used here is a simple spring-mass system. The results indicated that the kinetic energy of the aircraft has been effectively attenuated using 1/2 meter thick walls.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Author: Selvidge, J. E.
Title: Probabilities of Aircraft Crashes at Rocky Flats and Subsequent Radioactive Release
Reference: Rockwell International, TID-4500-R65, April 1977
Brief Description:

The probability of a small airplane from Jefferson County Airport (Jeffco) or Stapleton International Airport crashing into a plutonium area at the Rocky Flats Plant has been calculated at 1.4×10^{-4} and 4.2×10^{-6} per year, respectively. The probability of such a crash involving a large airplane from Jeffco or Stapleton is 3.5×10^{-6} and 1.1×10^{-6} per year, respectively. Overall, the chance of an aircraft of any size, or any type, and from any source crashing into a plutonium area at Rocky Flats is 2.88×10^{-4} per year. An event tree was developed to cover every plausible series of events leading to a release of plutonium in the range of 0 to 1000 grams. Selected results show an annual release probability of 3.9×10^{-5} for less than 0.5 grams, 5.8×10^{-6} for 50 to 70 grams, 5.6×10^{-8} for 200 grams, and 6.4 $\times 10^{-8}$ for 200 grams, and 6.4×10^{-10} for 1000 grams. Calculations led to a seighted average release amount of 3.7×10^{-4} grams of plutonium per year. Because of conservative assumptions, it is estimated that these probabilities are high by a factor of about two for small aircraft and 10 for large aircraft.

This study consists of three parts. First, the probability of an aircraft crashing into a building containing plutonium is computed. Secondly, the damage that such a crash might cause is estimated. The third part is an assessment of the amount of plutonium that could escape assuming the damage described were to occur
Several categories of aircraft, all having different probabilitios of crashing, are considered. Construction of the various buildings containing plutonium is taken into consideration as is the amount and form of plutonium that might be subject to release. Results of the study are summarized in probability tables and graphs that show different amounts of plutonium versus the probabilities of those amounts being released. Incorporated in these probabilities are the three principal types of uncertainties previously mentioned; namely, the probability of a crash, the probability of certain damage if a crash occurs, and the probability of a certain size of release if the damage occurs.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Solomon, K. A.
Title: <u>Analysis of Ground Hazards Due to Aircrafts and Missiles</u>
Reference: Hazard Prevention Journal, Vol 12, No 4, March/April 1976
Brief Description:

The purpose of this generic study is to develop and to apply a generalized methodology which approximates both the best estimate and pessimistic probabilities that an aircraft or a missile will impact the defined target area of an industrial, commercial or residential facility. To best demonstrate the application of this methodology, the probability impact for a hypothetical facility and assumed air activity are estimated.

Coordinates of a proposed facility are parametrically selected relative to fixed, assumed locations of (a) Victor airways, (b) general aviation airports, (c) air carrier airports, (d) military installations, and (e) other areas of air activity such as crop dusting fields. The probability that an aircraft or missile will impact the target area is the sum of the individual probabilities that an aircraft or a missile originating from a particular source will impact the subject area. The probability of target area impact and the magnitude of damage after impact are functions of (a) purpose or category of flight, (b) mode of flight, (c) effective target area, (d) relative location of facility target area and air activity, (e) number of operations, (f) mode of impact, (g) pilot experience, (h) weather conditions, (i) time of day, (j) air traffic density and so on. This study discusses how to estimate the influence that each of these parameters has on the value of the impact probability. For the purpose of this study, site data and target area have been assumed as discussed. However, actual crash rates per mile are used.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Solomon, K. A.
Title: Estimate of the Probability that an Aircraft will Impact the PVNGS
Reference: NUS Corporation, NUS-1416, June 1975
Brief Description:

The probability that an aircraft (if any size) will impact the PVNGS is estimated to be less than 6.0×10^{-8} per year. This estimate is based on conservative input assumptions and can be considered an upper bound. This estimate does not represent the probability of having a major accident at PVNGS, but, rather, can be considered to represent the probability of all types of postulated aircraft accidents into the PVNGS (including a postulated strike from a small aircraft and a postulated glancing angle strike of a large aircraft). The probability that a DC-10 (largest aircraft expected in the vicinity) will directly impact the PVNGS is estimated at less than 10^{-8} per year. Previous site experience has required containment construction to withstand direct aircraft impact when the yearly probability of direct impact by an aircraft sufficient in size to cause damage has been estimated to range between 10^{-6} and 10^{-7} or greater.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Solomon, K. A., Okrent, D.
Title: Airplane Crash Risk to Ground Population
Reference: Hazard Prevention Journal, Vol 11, No 3, January-February 1975
Brief Description:

This paper is a summary of the methods, models, and results contained in the report UCLA-Eng-7424 of the same name, dated March, 1974.

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Offsite Hazards: Aircraft Crash
Type of Models: Probabilistic
Authors: Solomon, K. A., Erdmann, R. C., Hicks, T. E., Okrent, D.
Title: Airplane Crash Risks to Ground Population
Reference: UCLA-Eng-7424, March 1974
Brief Description:

Analysis of national aircraft accident statistics yielded an average value of 4×10^{-9} as the probability, per square mile, per operation, of a crash within a five mile radius of Los Angeles International Airport (LAX) and Hollywood-Burbank Airport. Taking into account the annual air traffic at each results in average values of 1.6×10^{-3} and 4×10^{-4} for the probabilities, per square mile, per year, of a crash averaged over the five mile radial region for LAX and Hollywood-Burbank, respectively.

Using these crash probabilities and considering both resident and transient populations, estimates of expected annual mortalities were 0.8 fatalities per year, per 80 square miles around LAX and 0.5 fatalities per year, per 80 square miles around Hollywood-Burbank Airport, (this 80 square mile region corresponds to about a 5 mile radius around the airport).

The study identified nine sites in the vicinity of LAX at which large numbers of people are frequently brought together. Maximum occupancies varied from several hundred to many thousands of persons. Probabilities of accidental aircraft impact while occupied, per year, per target site, varied from 1.6×10^{-6} to 3.5×10^{-4}. Three of these sites were large sports facilities. Analysis for one of them, Hollywood Park Race Track, is presented later in detail since its period of greatest occupancy corresponds with the time of maximum crash probabilities (80% of air crashes occur during daylight hours). The probability of an aircraft impact on the facility is estimated as 6.6×10^{-5} per year. The probability that such an accident will occur while the facility is occupied is estimated as 1.3×10^{-5} per year. The probability that such an accident will occur while the facility is occupied is estimated as 1.3×10^{-5}. Maximum mortalities, based on capacity occupancy of 50,000 people and a hypothetical impact by one of the largest aircraft in service, is estimated as 32,000 people; this is a much lower probability event than the "average crash". It is estimated that the average crash during occupancy would result in 5,000-6,000 mortalities.

Twenty-five sites of frequent high occupancy in the vicinity of Hollywood-Burbank Airport were identified and investigated. Maximum occupancies vary from 450 to 5000 persons. Probabilities of impact while site is occupied vary from 2.8×10^{-7} to 4.0×10^{-5} per year, per target site.

The values derived are, of course, subject to an element of uncertainty. Assuming a Gaussian Distribution of aircraft crash probabilities, the 90% confidence bounds are crudely estimates as ±20% of the stated values.

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Offsite Hazards: Aircraft Crash, Flood, Explosions
Type of Model: Survey
Author: Stevenson, J. D.
Title: Current Summary of International Extreme Load Design Requirements for Nuclear Power Plant Facilities
Reference: Nuclear Engineering and Design 60 (1980) 197-209
Brief Description:

This paper gives a summary of extreme load design criteria within any national jurisdiction as applied to nuclear power plant design. Extreme loads are defined as those loads having probability of occurence less than 10^{-1}/yr and where occurence could result in radiological consequences in excess of those permitted by national health standards. The specific loads considered include earthquake, tornado, airplane crash, explosion.

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Offsite Hazards: Combination
Type of Model: Survey
Author: Stevenson, J. D.
Title: Survey of Extreme Load Design Regulatory Agency Licensing Requirements for Nuclear Power Plants
Reference: Nuclear Engineering and Design 37 (1976) 3-22
Brief Description:

This paper presents the results of a survey made of national atomic energy regulatory agencies and major nuclear steam supply design agencies, which requested a summary of current licensing criteria associated with earthquake, tornado, flood, aircraft crash, and accident (pipe break) loads applicable within the various national jurisdictions. Also presented are a number of comparisons of differences in national regulatory criteria. No evaluations are made.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Viti, G., Olivieri, M., and Travi, S.
Title: Development of Non-linear Floor Response Spectra
Reference: Nuclear Engineering and Design 64 (1981) 33-38
Brief Description:

The paper presented a computational scheme for nonlinear floor response spectra using an ideal elastoplastic single degree of freedom model. The developed numerical procedure applied to the case of an assumed impact of a missile on the integrated Reactor-Auxiliary-Fuel-Building of a BWR Mark III nuclear power plant. The results indicated that in general the peak reduction factors are higher than those predicted for seismic conditions.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Authors: Wall, I. B.
Title: Probabilistic Assessment of Risk for Reactor Design and Siting
Reference: Transactions American Nuclear Society 12: 169, 1969
Brief Description:

This paper outlines a method of formal assessment of risk, thereby permitting a rational approach to safety design and siting of power reactors. The amount and allocation of investment among engineered safeguards is properly estimated by (1) a probabilistic assessment of initiating events, e.g., earthquakes, mechanical failure, operator error, combined with (2) a reliability analysis of the whole reactor system leading to a complementary cumulative probability density function of fission product release, and (3) an assessment of the probability density function of damage given any radioactive release. The latter aspect depends upon the site meteorology and local demography.

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Offsite Hazards: Aircraft Crash
Type of Model: Probabilistic
Author: Wall, I. B.
Title: Probabilistic Assessment of Aircraft Risk for Nuclear Power Plants
Reference: Nuclear Safety, 15(3): 276-284, May-June, 1974
Brief Description:

The risk to the public from an aircraft striking a nuclear power plant has been evaluated in a quantified manner. Aircraft accident data have been analyzed to estimate the probability of an aircraft striking a typical nuclear power plant at sites adjacent to and remote from an airport. In the event that an aircraft strikes a building, the region of impact is generally restricted to a local component. Two modes of significant damage are delineated: (1) perforation and (2) local collapse. Methods have been developed to estimate the conditional probabilities of such structural damage given an aircraft strike and probability values calculated for a representative structure. Actual risk to the public (probability vs. radioactive-release magnitude) may be estimated from a classification of critical safety components by their structural protection and the likely release magnitude in the event of their damage. All foreseeable releases either cause insignificant offsite dose or, for most sites, are associated with very low probabilities. A brief evaluation shows that fire upon impact is not a significant increment of risk. Comparison of these risks to socially acceptable risk levels shows that reactor sites beyond 5 miles from an airport or away from a busy air corridor should be acceptable. Other potential sites need individual examination and, in some cases, hardening of the structure may be necessary.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Wolf, J. P., Bucher, K. M., and Skrikerud, P.E.
Title: Response of Equipment to Aircraft Impact
Reference: Nuclear Engineering and Design 47 (1978) 169-193
Brief Description:

This paper discusses the state-of-the-art of the development of equivalent force-time relationships for aircraft impact, the results of the so-called Riera model and of a lumped-mass model are compared for rigid and deformable targets. A typical response spectrum shows that the airplane crash is dominant in the high-frequency range when compared to the effect of an SSE. It also examined the effect of the aircraft-structure interaction, of the material nonlinearity, of the damping and of the mass distribution on the response of equipment.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Wolf, J. P. and Skrikerud, P. E.
Title: Collapse of Chimney Caused by Earthquake or by Aircraft Impingement with Subsequent Impact on Reactor Building
Reference: Nuclear Engineering and Design 51 (1979) 453-472
Brief Description:

The paper presented a numerical analysis of typical chimney stack of a nuclear power plant subjected to earthquake and impact loads. Convected coordinate finite element methods were used. Force-time curves of the aircraft impinging on the chimney were derived. The subsequent impact of the chimney on the reactor building is also studied.

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Offsite Hazards: Aircraft Crash
Type of Models: Deterministic
Authors: Zerna, W., Schnellenbach, G., and Stangenberg, F.
Title: Optimized Reinforcement of Nuclear Power Plant Structures for Aircraft Impact Forces
Reference: Nuclear Engineering and Design 37 (1976) 313-320
Brief Description:

This paper deals with the development concerning the reinforcement of nuclear power plant structures for protection against aircraft impact. Reinforcements with high-tensile bars, with tensile cables, and with steel fibers in connection with cables are considered. Steel fibers and cables seem to enable new design for aircraft-impact resistent structures.

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Offsite Hazards: Aircraft Crash
Type of Model: Deterministic
Authors: Zimmermann, TH., Rebora, B., and Rodriguez, C.
Title: Aircraft Impact on Reinforced Concrete Shells: Influence of Material Nonlinearities on Equipment Response Spectra
Reference: Computers and Structures 13, pp 263-274, 1981
Brief Description:

The paper investigates the effects of material non-lineartles on equipment response spectra for the impact of a Boeing 707-320 on the secondary containment of a BWR reactor. A finite element model taking into account concrete cracking and crushing and steel yielding is used for the analysis. The results indicated that no reduction of the response spectra due to material non-linearity in the impact zone. However, comparison of the non-linear versus linear displacement time-historeies show a significant increase in the vertical displacement in the impact zone, which fades out rapidly away from the impact point.

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