Accident Analysis

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Probabilistic Assessment of Aircraft Risk for Nuclear Power Plants

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Abstract: *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 off-site 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.*

The basic objective in the safety assessment of nuclear power plants is to reduce the risk to the public to an acceptable level by the judicious application of the finite resources that are available. This objective requires (1) that each hazard be placed in perspective so that resources can be allocated for an overall balanced design, (2) uniform criteria for different sites, and (3) a socioeconomic judgment of acceptable risks. The problem is truly an allocation of resources and, as such, falls in the conceptual framework of applied decision analysis.[1] The tool for achieving the above-mentioned objectives is the probabilistic assessment of each event or system; probability is concerned with consistent action in the face of uncertainty.

Several people[1-3] have analyzed current societal risks to establish the magnitude of acceptable risks. Their conclusions suggest that probabilities of less than 10^{-6} to 10^{-7} per year are acceptable to an individual almost regardless of the nature of the risk, whereas, for small radioactive releases (no significant off-site dose), probabilities of less than 10^{-4} to 10^{-5} per reactor-year are acceptable. By a statistical analysis of meteorology and consideration of population densities, such probabilities can be translated into acceptable frequency of release vs. magnitude of release of fission products. Such a limit line, advocated by Farmer[4] and Wall,[5] is one convenient method for assessing the safety of nuclear power plants. To implement the method[1,4] requires that all potential accidents, including aircraft strikes, be systematically analyzed to determine their probabilities and associated fission-product-release magnitudes; the combination is compared to the limit line.

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The risk associated with an aircraft striking a nuclear power plant is particularly amenable to probabilistic assessment. The probability of an aircraft strike has been estimated for many sites.[6-8] The analysis given in the following section is for an average site within the United States; i.e., the total number of aircraft crashes is assumed uniformly distributed over all airports.[9] If an aircraft strikes a building, either the whole building or only the local component may respond. Conservation of momentum can readily show that the reactor-building response would be less than that from an operating-basis earthquake; therefore it is negligible.[10] Thus damage to specific structural components is of importance.

Three modes of structural damage to a local component can be identified if an aircraft strikes the reactor building. The first is characterized as the perforation mode, where the aircraft engine perforates the structural component upon impact.

The second type is caused by a collapse mode, where the structural member yields considerably at all restraints. In this mode of damage, the structural component loses all its integrity, and the falling debris from the aircraft or structure may enter the building. In this article, aircraft missiles are first characterized and frequency distributions generated for weight, velocity, etc., of potential missiles. Subsequent sections delineate methods of assessing the conditional probability for each of these modes of structural damage, using, as an example, an 18-in.-thick reinforced-concrete side wall of a typical boiling-water reactor (BWR).

The third type of damage is the cracking mode, which may be determined from an elastic analysis. A study[9] has shown that this mode is more probable than perforation and collapse. However, cracking will not cause extensive deformation, and any equipment inside the structure is unharmed. Thus results based upon elastic behavior would be unduly conservative with respect to estimating risks from aircraft projectiles. This mode is not discussed in this article.

Risk to the public is associated with the release of fission products to the environment because of damage to a critical safety component. From a classification of critical safety components by their structural protection and likely release magnitude in the event of their damage, three representative cases are analyzed later in this article to estimate probability vs. fission-product-release magnitude. The probability of release is the probability of a strike times the conditional probability of structural damage. Since the consequences of an aircraft crash might be amplified by fire, the article briefly analyzes this potential and concludes that it is not a significant increment of risk.

The final section of this article compares the risk to the public from the aircraft hazard to the above-mentioned socially acceptable risks and summarizes a methodology for assessing any proposed reactor site with respect to aircraft hazard. When considering risk assessments, it should be remembered that the concern is with decision making for reactor design and siting and not detailed design. Delineation between significant and trivial hazards only requires estimates of the probability and consequences within a factor of 10. Risk assessment is an aid and not the final arbiter in safety design.

PROBABILITY OF AN AIRCRAFT STRIKE

Civil-aircraft accident data within the United States are published annually,[11] and military accident data are also available.[12,13] Analysis suggests that military crash frequency is comparable with that of air carriers.[14] The later observations are equally applicable to both civil and military data. The civilian data are principally categorized into air-carrier operations and general aviation, but the more useful breakdown for risk analysis is by aircraft weight with a division at 12,500 lb. Perusal of the briefs for air-carrier accidents suggests that only accidents causing fatalities are significant with respect to an aircraft striking a building. Indeed, there is a strong correlation between accidents involving fatalities and those destroying the aircraft, and it is difficult to conceive of an aircraft striking a building without destruction and fatalities. The same conclusion seems reasonable for general aviation. For this reason, only fatal accidents are used to estimate the strike probabilities. Further statistical breakdowns[11] show that "collision with building" was the initial cause for only a small fraction of fatal accidents. Therefore the use of all fatal accidents is probably conservatively high with respect to aircraft risk. The aircraft accidents are also classified with respect to the proximity of the airport, i.e., those occurring within and beyond a 5-mile radius.[11] Accidents on the airfield were excluded from the data.

To estimate the probability of an aircraft striking a nuclear power plant requires that the shadow areas of the reactor and turbine buildings and the switchyard be estimated. It is usually conservatively assumed that the aircraft has a strike angle of 10° above the horizontal. The shadow area for a typical BWR, including turbine building and switchyard, is estimated to be 0.137

sq mile, and the estimated number of operating airports within the United States is 9200. From these estimates and an analysis of civil-aircraft accident data over several years through 1968, the probability of an aircraft striking some part of a nuclear power plant has been calculated and is summarized in Table 1.

Table 1 Probability of an Aircraft Striking a Nuclear Power Plant per Year*

Aircraft size, lb	Location of plant: Beyond 5 miles of airport†	Location of plant: Within 5 miles of airport
Small, ≤12,500	1.4×10^{-5}	3.3×10^{-5}
Large, >12,500	4.6×10^{-7}	1.1×10^{-6}

*Probability of striking specific critical safety equipment is estimated to be 1% of stated values.

†Excludes any consideration of air corridors.

Three observations should be noted about the strike probabilities shown in Table 1. First, the values are average throughout the United States, and specific sites would have different probabilities depending upon their proximity to specific airports and traffic corridors. For example, only a fraction of the airports are probably capable of handling large aircraft. If this fraction is 10%, the average probability of a large aircraft striking a plant site within 5 miles of such an airport would be increased to 1.1×10^{-5} per year. The remaining airports could be classified as beyond 5 miles and as having a strike probability of approximately 4.6×10^{-7} per year for large aircraft. Similarly a reactor site under a busy air corridor could have higher probabilities than those stated in Table 1. Each proposed reactor site should be examined on its own merits.

Second, the quoted strike probability near an airport is an average value over a 5-mile radius. A more detailed examination[6] shows that the strike probability varies approximately as $1/r^2$, where r is the distance from the airport; i.e., the strike probability for a plant located ¼ mile from an airport is about 60 times the average value, and the probability at 5 miles is about equal to the value quoted for beyond 5 miles. Further, most crashes occur within two 60° arcs about the center line at each end of the runway.[14] If we conservatively assumed that all accidents occurred within these 120°, the strike probability for a reactor site within these arcs would be tripled.

Third, the quoted strike probabilities are conservative estimates for the entire nuclear power plant, including reactor and turbine buildings and switchyard. The probability of striking a specific area containing critical equipment (e.g., control-rod-drive hydraulics) would be substantially lower, and so an approximate figure is estimated as follows. The relative target areas of the reactor building, turbine building, and switchyard are 0.68, 0.19, and 0.13, respectively. Typically, a critical piece of equipment is located on one side of a building and would only be vulnerable to aircraft coming from a specific quadrant, a factor of 0.25. Further, a typical piece of equipment occupies only about 5% of a wall. Therefore the probability of striking a wall area opposite specific equipment is about 1% of the strike probabilities of an aircraft striking the plant.

The validity of using past statistical data for aircraft crashes to estimate a future probability of an aircraft striking a nuclear power plant should be evaluated. The absolute number of air-carrier crashes in the United States, both total and fatal, has remained fairly constant over the past decade despite a huge increase in annual aircraft movements. Accordingly most analyses assume that future increases in air traffic will be offset by improved flight safety, and the above-mentioned extrapolation is justified. This assumption should be examined for each potential reactor site.

CHARACTERISTICS OF STRIKING AIRCRAFT PROJECTILES

The conditional probabilities of perforation or collapse of a structural component are functions of aircraft characteristics and speed. Frequency distributions for aircraft speed and weight, engine weight, and effective diameter may be generated from the annual census of U. S. civil aircraft.[15] A distinction should be made between site locations, within and beyond 5 miles of an airport, with respect to probable aircraft speed. Within 5 miles of an airport, an aircraft is likely to be landing or taking off. For the purpose of the following analysis, a typical speed of 140% of stall was assumed if no other data were available. Away from an airport an aircraft is most likely to be cruising at 75% power, but other possible speeds are 140% of stall (if in trouble) or maximum speed. For small aircraft, frequency distributions of 0.25, 0.5, and 0.25 were assumed for 140% of stall, 75% of power, and maximum speed, respectively. Large aircraft, predominantly air carriers, were assumed to be at cruising speed. With these additional assumptions, four frequency distributions were generated for small and large aircraft striking within and beyond 5 miles of an airport. More detail of analysis and the results are included in Ref. 9. The data are almost log normally distributed, and this fact was used in the subsequent analysis for the collapse mode of damage.

The strike probabilities in Table 1 and the preceding characteristics include both single-engine and multiengine aircraft. For the following structural analyses, it is assumed that the engine is the only part of the aircraft that offers enough impact to the structure to cause damage. Other parts of the aircraft, such as wings and fuselage, offer less resistance and are assumed to break up upon impact. This assumption is reasonable for single-engine small airplanes. For two-engine small airplanes, two points of impact have to be considered, but it is assumed that two engines are far enough apart that the solution obtained for one engine should be reasonable. However, for larger aircraft, the fuselage also offers a great resistance to crushing under impact. In this study, for the purposes of computation of perforation thickness, the engine weight only is used. It is believed that the thickness obtained using the characteristics of the engine gives more conservative results than that obtained by using the characteristics of the fuselage. For the collapse-mode calculation, the engine weight is increased by a factor to account for the portion of the body weight associated with the engine.

The potential for large aircraft to carry heavy nondeformable cargo should be considered. It is argued that air freight is not normally heavy capital equipment but rather light or perishable goods and further that the fraction of air-carrier movements associated with such shipments are small. In view of the already marginally significant strike probabilities, these considerations suggest that air freight does not pose a significant increment of risk.

PERFORATION MODE OF DAMAGE

Any discussion of the impact of projectiles on concrete makes it essential to define penetration, perforation, and scabbing. *Penetration depth* is used for the depth to which a projectile enters a massive concrete target without passing through it. No evidence of bulging or rupture of the target on the back side can be observed. Thus penetration depth is independent of the thickness of the target, and penetration per se would not damage critical equipment. The term *perforation thickness* is used specifically when the projectile just passes through the target completely; i.e., the exit velocity of the projectile after passing through the target is zero. The term *scabbing thickness* is used when the material on the back side of the target just begins to fall off. Thus, with respect to risk from external missiles, the critical thickness of target is implicitly associated with the perforation and scabbing thicknesses.

An analytical formulation of the problem of aircraft impact and perforation to determine the necessary thickness of concrete to protect the equipment inside the structure is difficult and impractical. Thus all the available formulas describing penetration phenomena are empirical and are based on experimental data. As such, these empirical formulas are valid only within the ranges of the variables for which the experimental data are available. Many of the empirical formulas are based on experiments, conducted during World War II, in which bullets and bombs struck reinforced-concrete target slabs. The range of variables encountered in the problem of aircraft impact is, in general, different from the range of variables for which the experiments were conducted. Since no further data are available, the available formulas have often been used in a number of studies without modification, thus sometimes leading to very unreasonable results. Chelapati et al.[9] studied the available empirical formulas and developed a new one for perforation which appears to have a greater range of application and to give more reasonable estimates for aircraft projectiles. Their article compares all formulas and presents a rationale for their selection. Recommended formulas for penetration depth and perforation thickness are given in the reference.

The conditional probability of the perforation of a given thickness of reinforced concrete was estimated by a simple Monte Carlo technique. Frequency distributions were assigned to each major variable in the perforation formula, and, by a random sampling for each parameter, a perforation thickness was calculated. From 10,000 trials, the complementary cumulative distribution function for perforation thickness was generated for each category of striking aircraft.

The frequency distribution for the compressive strength of concrete was derived from field measurements at a plant site. The parameters for the missile were chosen as representative of aircraft engines, using the data described in the previous section; interdependence was properly considered. Uncertainty in the empirical formulation was introduced. The selection of frequency distributions and the assignment of numerical values for each parameter are described in Ref. 9.

The probabilities of a strike, the conditional probabilities of perforation given a strike, and the absolute probabilities of perforation are summarized in Table 2 as a function of plant location and thickness of reinforced concrete. It can be seen that the absolute probability of perforation of an 18-in.-thick reinforced-concrete wall is 6×10^{-7} per year for a site within 5 miles of an airport and 10^{-6} per year for other sites. Similarly, for a 6-ft-thick wall, the absolute probability of perforation is zero for sites local to an airport and 1.5×10^{-7} per year for sites beyond 5 miles.

Three observations should be made about these estimates. First, it was conservatively assumed that the missile struck the wall perpendicularly. The penetration depth[16] is sharply reduced by oblique impact; e.g., impact at 30° from the perpendicular would reduce the penetration depth by approximately 42% for projectiles with velocities in the range 1000 to 2000 ft/sec. As the angle of impact is increased, richochet may occur.

Second, the perforation probabilities are associated with the missile just passing through the wall; i.e., exit velocity is zero. However, it should be noted that even a slight reduction of wall thickness, say 10%, results in a residual velocity of almost 40% of the striking velocity.[17,18]

Third, the strike probabilities are average values for the whole plant, and all absolute probabilities should be multiplied by approximately 0.01 to obtain the probability of perforating a wall opposite specific equipment.

One of the auxiliary benefits of a probabilistic approach to safety is the ranking of parameters with respect to their contribution to the overall uncertainty. From this information, the value of refining a specific parameter (i.e., reducing the uncertainty) by additional experiments, etc., may be assessed. The relative contribution of each parameter in the empirical equation for perforation thickness was estimated by the propagation of errors;[19] the interdependence of some parameters was properly incorporated. For the case of small aircraft and plants located within 5 miles of an airport, the uncertainty in the projectile description (i.e., size, weight, and speed) contributes about 90% of the overall uncertainty. The other variables (concrete strength, nose shape, and the empirical relation) contribute 2.3, 2.7, and 4.4%, respectively. For the other aircraft sizes and plant locations, the projectile uncertainty is even more dominant. Therefore it is evident that further experiments to refine the perforation formula would not significantly reduce the overall uncertainty in the probability of breaching a given wall thickness for a given category of aircraft; hence they are not economically justified.

COLLAPSE MODE OF DAMAGE

This section is concerned with estimating the conditional probability of collapse for the typical reinforced-concrete wall panel described below. The analysis is described in detail in Ref. 9. The original purpose of the work was twofold, consisting first of predicting the conditional probability of wall-panel collapse and second of illustrating the use of simple probabilistic techniques to account for the uncertainties associated with the prediction.

From an examination of the plans of a typical BWR building, the longitudinal side wall of the top floor was assessed to be the most vulnerable structurally. The side wall consists of a series of panels, 24.5 by 24 ft center to center. The thickness of the wall is 18 in., with reinforcement of No. 9 bars at 9 in. center to center running in both directions on both sides of the slab. Structurally the wall is continuous over the columns and the floors and is monolithic with the roof.

Table 2 Probabilities of Perforation as a Function of Plant Location and Concrete Thickness

Plant location from airport, miles	Aircraft type	Probability of strike per year	Probability of perforation (conditional; absolute)* for the indicated thickness of reinforced concrete			
			1 ft	1.5 ft	2 ft	6 ft
≤5	Small	3.3×10^{-5}	$0.003; 1 \times 10^{-7}$	0	0	0
	Large	1.1×10^{-6}	$0.96; 1 \times 10^{-6}$	$0.52; 5.7 \times 10^{-}$	$0.28; 3.1 \times 10^{-7}$	0
	Total	3.4×10^{-5}	1×10^{-6}	6×10^{-7}	3×10^{-7}	0
>5	Small	1.4×10^{-5}	$0.28; 3.9 \times 10^{-6}$	$0.06; 8.4 \times 10^{-7}$	$0.01; 1.4 \times 10^{-7}$	0
	Large	4.6×10^{-7}	$1.0; 4.6 \times 10^{-7}$	$1.0; 4.6 \times 10^{-7}$	$0.84; 3.9 \times 10^{-7}$	$0.32; 1.5 \times 10^{-7}$
	Total	1.4×10^{-5}	4×10^{-6}	1×10^{-6}	5×10^{-7}	1.5×10^{-7}

*Multiply all absolute values by 0.01 for damage probabilities for specific equipment.

As an illustrative example, one panel was analyzed. Since it was assessed to be the most vulnerable, the estimated probabilities of collapse of this panel should be greater than those for other portions of the reactor building.

An energy-balance technique is used to determine the factor of safety against a flexural failure of the single wall panel. The factor of safety is defined as the ratio of the strain-energy capacity of the individual wall panel to the kinetic energy absorbed by the wall panel as a result of aircraft impact. Probability density functions are estimated for the strain-energy capacity and the absorbed kinetic energy from which a probability-density function is determined for the factor of safety. The probability of flexural failure of a wall panel is equivalent to the probability of the factor of safety being less than unity.

The strain-energy capacity for the individual wall panel is assumed to be the nonelastic strain energy occurring along lines of yielding on the slab since the elastic strain energy occurring prior to yielding is negligible. A yield-line pattern is determined for any impact location on the slab as shown in Fig. 1. As the assumed impact location P_c is moved, the positions and lengths of individual line segments alter, but the overall pattern of yield line, denoted by m+ and m−, remains unchanged. The moment and rotational capacities are evaluated for the slab. If we assume a moment-curvature model of rigid plastic[9] for the behavior of the wall panel along the yield lines, the nonelastic strain-energy capacity per unit length of yield line is the product of the moment capacity per unit length times the rotational capacity. The total nonelastic strain-energy capacity is then equal to the product of the nonelastic strain energy per unit length times the total length of the critical yield lines. The engine striking location and thus the critical yield pattern and the moment and rotational capacities are all treated as random variables, and the median and standard-deviation values are evaluated for each.

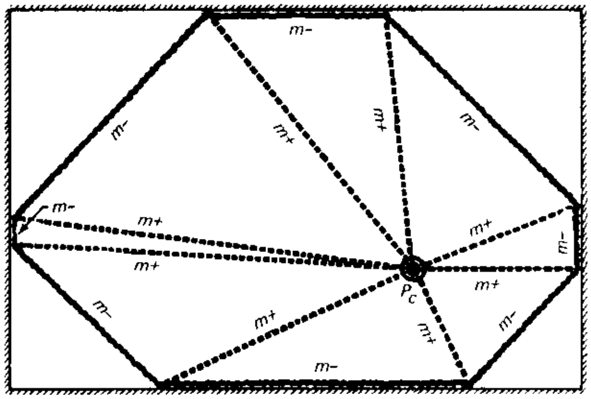

Fig. 1 Approximate yield pattern for concentrated load on rectangular slab with restrained edges.

In contrast to the Monte Carlo procedure for the perforation probability, a manual analysis was used to calculate the probability of collapse. In the calculations, several variables are in the form of products or quotients. If each variable is assumed to be distributed log normally, the distribution for a function of products or quotients of such variables may be simply derived. For small coefficients of variations, the difference between log-normal and normal distribution is not very significant except in the case of very low probabilities. By assuming a log-normal distribution and assigning a median and logarithmic standard deviation to each variable, the median, logarithmic standard deviation, and 90% confidence interval for the factor of safety may be computed. The actual assignments are stated in Ref. 9. The log-normal distribution is often used in civil-engineering applications.[20]

The results of this analysis for the categories of aircraft size and site proximity to an airport are summarized in Table 3. We can see that the conditional probability of collapse for the 18-in.-thick wall used as an example is practically zero for small aircraft and is more than 50% for larger aircraft. The probability values are comparable to those for the perforation mode of collapse. There is no simple extrapolation for thicker structures, since the probability of local collapse is a function of geometry and reinforcement as well as concrete thickness.

The probabilistic analysis gives some insight into the uncertainty of the analysis. The median factor of safety information for local flexural failure of a wall panel and also its 90% confidence interval are shown in Table 3. We should note the very large spread between the lower and upper bounds of this interval. In all cases, the upper bound on the factor of safety is at least 50 times greater than the lower bound, which suggests considerable uncertainty in the factor of safety against a local flexural mode of wall failure. Most of the uncertainty stems from the large range in the effective aircraft kinetic energy applied to the wall at impact and is not due to uncertainties concerning the structural behavior of the wall. The only way to significantly reduce the size of the 90% confidence interval for the safety factor is to specify a much larger number of classes for the impacting aircraft so that each class has a much smaller range of aircraft weight, engine weight, and aircraft velocities. Basically the

Table 3 Median Factor of Safety and Conditional Probability for Collapse Mode of Damage of Individual Wall Panel (18 in. Thick) Due to Aircraft Crash

	Small aircraft		Large aircraft	
	Within 5 miles of airport	Beyond 5 miles of airport	Within 5 miles of airport	Beyond 5 miles of airport
Median factor of safety	205	78	0.77	0.086
Log standard deviation for factor of safety	1.18	1.37	1.78	2.06
90% confidence interval for factor of safety	29 to 1440	8.1 to 750	0.04 to 14.5	0.003 to 2.6
Conditional probability of collapse mode of damage of wall panel, %	0	0	56	86

analytical techniques and material investigations used in this study are overly precise unless the applied loading is more accurately defined.

In order of influence on the uncertainty in the safety factor, the other parameters may be ranked as follows: strain-energy capacity per unit length of yield line, lack of detailed knowledge about the impact phenomena, and yield-line failure pattern as a function of impact location. Reduction in the uncertainty due to the first two parameters would require substantial experimental data on plastic behavior of reinforced concrete and on aircraft impacts. Refinements in estimating the location of engine impact or use of a more exact segmentally linear yield-line pattern to represent the actual curved pattern are not warranted, since this parameter contributes minimum uncertainty.

ASSESSMENT OF CONSEQUENCES AND RISK

The consequences of a missile striking a nuclear power plant were assessed by examination of the plan and elevation of a typical 1065-MW(e) BWR. Each significant item of equipment was tabulated with its location in the plant, its protection (number of feet of concrete) from external missiles, and a brief statement of consequences of its damage and likely fission-product-release magnitude. The probabilities of each stated consequence are the combination of the strike probabilities of Table 1 plus the conditional probability of performance or local collapse of the protecting wall as shown in Tables 2 and 3. It should be noted that the following stated probabilities include some allowance for the ratio of equipment to site area but are for average reactor sites, and so the observations in the first section of this article apply. Risk is the combination of probability and release magnitude. Three representative examples will be considered.

Most standby core-cooling equipment (e.g., HPCI turbine and core-spray pump) is located below grade with effectively 6 ft of protection. Damage to an individual item would impair shutdown capability but would not directly cause a fission-product release. Although the potential release magnitude is indeterminant, according to Table 2, the probability of damage is 10^{-8} per year or less.

Other equipment (e.g., reactor cleanup system and resin tanks) has less protection (1 to 2 ft of concrete), and the probability of damage is about 10^{-8} per year or less. A typical inventory is a few hundred curies of mostly nonvolatile solids which are relatively immobile and which, even if released, would not cause a significant dose at the site boundary.

The fuel-storage pool is protected by only a steel superstructure. A conservative assumption would be that this superstructure affords no protection, so that the probability of damage equals the strike probabilities as shown in Table 1 reduced by the ratio of reactor building to total target area, namely less than 10^{-5} per year. Usually a quarter core of irradiated-fuel bundles would be stored in the pool with an average cooling period of 60 days. It is estimated that 67,500 Ci of ^{85}Kr and 14 Ci of ^{131}I might be released if every fuel rod were broken;* such a release magnitude would

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*Release of plenum activity is assumed. For ^{85}Kr and ^{131}I the plenum activity is conservatively estimated to be 30% and 1.2%, respectively, of the total fuel inventory and a conservative partition factor of 100 was applied to the ^{131}I release.[21] The ^{131}I percentage is lower than the value recommended in Safety Guide 25 (Ref. 22) since the objective is risk assessment rather than design.

have a low probability of causing a significant dose at the site boundary. A more likely event is that a small fraction (e.g., 10% of the fuel rods) would be damaged, with a proportionally smaller release and consequence.

CONSIDERATIONS OF POSTACCIDENT FIRE

The consequences of an aircraft impact may be amplified by fire after the crash. In the event that the structural component is perforated, aircraft fuel might enter the building and cause a local fire. In the preceding section it was assumed that the critical equipment was totally destroyed, and thus a local fire would not greatly aggravate this situation. A possible exception to this conclusion would be a crash into the refueling area during a refueling outage, but the combined probability of these two independent events is significantly lower than the probabilities stated in Table 1. In the event that the building wall is not breached, most fires would dissipate themselves to the environment and only cause local cracking of the concrete unless fuel was spilled into the ventilation ducts for the control room or other critical areas. However, as shown below, the probability of such an event is less than 1% of the probabilities stated in Table 1. Thus postaccident fires do not appear to be a significant increment of risk.

Analysis of accident data[11] shows that about 30 and 50%, respectively, of the general-aviation and air-carrier fatal crashes have postaccident fires. These ratios can be applied to the probabilities stated in Table 1 to establish the absolute probabilities of fire. Such estimates are probably conservative since improvements in aircraft design, fire-prevention systems, and fuel technology should reduce the frequency of postaccident fires in the future. Examination of aircraft data suggests that small aircraft typically hold less than 100 gal of fuel with an upper bound of 400 gal, whereas the fuel capacity of large aircraft is in the range of 3000 to 50,000 gal, with a median value of about 10,000 gal or less.

The probabilities stated in Table 1 are predicated on a target area of 0.137 sq mile or 4×10^6 ft^2. The total area of the ventilation openings, which are effectively pinpoints on the overall target, is probably less than 500 ft^2. Thus a direct hit is exceedingly unlikely. A conservative estimate of the ratio of significant fire events to the probabilities in Table 1 may be obtained as follows: For a small aircraft[7] crash, 100 gal of fuel might affect an area of 500 ft^2. Thus the ratio is about $0.3 \times 500/4 \times 10^6$ or 4×10^{-5}. For a large aircraft crash, 10,000 gal of fuel might affect 25,000 ft^2, and so the ratio is about $0.5 \times 25{,}000/4 \times 10^6$, or 3×10^{-3}.

SUMMARY

The potential risk from aircraft crashes should be examined for each proposed reactor site. This review article considers some average data for a typical reactor building and suggests some methodology from which general guidelines may be stated. It is an example of the risk-assessment approach to nuclear power-plant safety.

Comparison of the risks assessed in an earlier section to the socially acceptable probabilities stated in the beginning of this article suggests that a reactor site beyond 5 miles from an airport is likely to be acceptable. Even release magnitudes that do not cause significant off-site dose have probabilities of 10^{-5} per year or less. The indeterminant release in the event of damage to the emergency core-cooling-system (ECCS) equipment has a probability of 10^{-8} per year or less. Unless there are some exceptional circumstances (e.g., location under a busy air corridor), no particular structural analyses are necessary.

For proposed sites within 5 miles of an airport, further detailed analysis is desirable on a site-by-site basis because the strike probabilities could be substantially higher than the average values reported in Table 1. Since the thickness of almost all building walls exceeds 18 in., the data of Tables 2 and 3 strongly suggest that small aircraft do not present a significant problem except possibly in the case of a steel superstructure over a fuel-storage pool. If the strike probability for small or large aircraft exceeds or is equal to 10^{-5} and 10^{-6} per year, respectively, the structure and layout of the building and the protection afforded to critical equipment should be examined.

A principal concern is that ECCS equipment be adequately protected either by location below grade or by an adequate thickness of concrete. If the strike probability for large aircraft is significantly greater than 10^{-6} per year, additional hardening of the structure should be considered. The potential of fire after an aircraft crash apparently is not a significant increment of risk.

From the information presented here, it can be concluded that the aircraft risk is acceptably low for most reactor sites. It is evident from past safety analyses[6-8] that the nuclear industry and the Atomic

Energy Commission reviews ensure adequate precautions for any proposed site where the aircraft risk might be above average.

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CONFERENCE ON RELIABILITY AND FAULT-TREE ANALYSIS

The conference will be held at the University of California, Berkeley Campus, Sept. 3–7, 1974. Its purpose is to bring forth recent developments in the fields of reliability and fault-tree analysis. Models, concepts, and methods of quantitative analysis in both fields have significant similarities. This conference, for the first time, will provide a ground for the exchange of ideas among various groups that have been following independent paths. Sessions will include:

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4. Statistical Problems in Reliability and Fault-Tree Analysis.
5. Network Reliability.
6. Computer Reliability.
7. Applications to Nuclear Power Reactors and Other Fields.

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