A METHODOLOGY FOR ASSESSING AIRCRAFT CRASH PROBABILITIES
AND SEVERITY AS RELATED TO THE SAFETY EVALUATION OF
NUCLEAR POWER STATIONS

MAIN REPORT

prepared by

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PREFACE

Persistent difficulties in safety analysis are first the qualitative and second the quantitative natures of the required assessments. In the nuclear reactor field, safety has been a subject of intensive study by technologists from the beginning, and recently it has also become a familiar topic in the popular press. Both the public and technological sectors laud the goals of reactor safety, and both reluctantly admit the impossibility of absolute safety, short of doing away with the reactors. Yet, agreement is far from perfect on what level of safety should be sought or on the optimum allocation of resources for gaining the desired level of safety. Much of this difficulty can be ascribed to a lack of a useful quantitative description.

Different probabilistic approaches to the design, siting and safety analyses of nuclear power plants have been proposed in the past by Siddall (1957, 1963), Farmer (1967), Laurence (1968, 1969), Wall (1969) and Garrick (1970). It was not until 1970 before Otway and Erdmann, Vesely, Meleis (1972) and Godbout (1972) perfected an integrated methodology for assessing probabilistically the overall safety or risk of nuclear installations. The methodology, in whole or in part, can be expected to have far-reaching ramifications.

In this report, an attempt is made to introduce those sections of the above mentioned methodology which are relevant to the probabilistic assessment of an airplane striking a nuclear power plant or striking in a delineated volume within the site. Since the above would rarely be an end in itself, an attempt is made to introduce additional methods and techniques for evaluating the possibility of structural damage from such a strike and to provide direction for design action.
This report consists of the main report and of two appendices. The main report includes the goals, the results, the conclusions and the recommendations while appendix I is entitled "The Probabilistic Approach to Assessing an Aircraft Crash on a Structure or a Site" and appendix II, entitled "Qualitative and Quantitative Evaluations" comprises the information data base and the associated calculations made for the study.

The Main Report will be sufficient for most readers.
RESUME

The probability of an aircraft striking a nuclear power plant has been evaluated. This evaluation, together with other studies, should be useful in the development of general criteria for the siting of reactors relative to airports.

Our approach for evaluation was done in a qualitative manner using the logic tree modelling technique for proper interdependence and basic events determination, and in a quantitative manner using best fit techniques for determining the accident probability density distribution when expressed in cartesian coordinates. Non-zero correlation between accident impact point coordinates was assumed. The distribution mapping technique from one coordinate system to another was used whenever it was felt that strike probability calculations could be facilitated.

In calculating probabilities we made use of the Canadian history of civilian air carriers from 1963 to 1973. All landing, take-off or on-route incidents which have resulted in fatalities or have led to damages serious enough to force the aircraft to land have been considered as accidents. Accidents involving aircraft below 18 000 pounds gross weight have been omitted. Accidents having occurred further away than 30 miles from the airport have been tabulated with the on-route accidents. All airports with or without MOT facilities have been considered in the compilation of accident data. The statistical averages used are averages of yearly averages for each year of concern since 1963. Total Canadian civilian aircraft movements for 1973 were in excess of $3.3 \times 10^6$, while the itinerant movements represented about $2.6 \times 10^6$. The totality of movements since 1963 is $31 \times 10^6$. The study results are shown in Table 1.
TABLE 1

CANADIAN AVERAGE AIRCRAFT ACCIDENT PROBABILITIES
PER MOVEMENT PER YEAR
FOR THE PERIOD BEGINNING IN 1963 AND ENDING IN 1973

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>UPPER (^1)</th>
<th>LOG-MEAN (^3)</th>
<th>LOWER (^2)</th>
</tr>
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<tbody>
<tr>
<td>Landing</td>
<td>(4.6 \times 10^{-5})</td>
<td>(2.0 \times 10^{-5})</td>
<td>(9.0 \times 10^{-6})</td>
</tr>
<tr>
<td>Takeoff</td>
<td>(1.2 \times 10^{-5})</td>
<td>(6.2 \times 10^{-6})</td>
<td>(3.2 \times 10^{-6})</td>
</tr>
<tr>
<td>On-route</td>
<td>(3.8 \times 10^{-7})</td>
<td>(2.0 \times 10^{-7})</td>
<td>(&lt;10^{-7})</td>
</tr>
</tbody>
</table>

1 - Uses all Canadian civilian movements

2 - Uses only Canadian civilian itinerant movements

3 - Arithmetic mean of the logarithm of the upper and lower calculated values and reconverted.
Together with accident distributions, these averaged results have been used to determine the probability of an aircraft strike on a hypothetical CANDU reactor, at diverse locations near a typical Canadian international airport. The airport landing or take-off movements were chosen to be $150 \times 10^3$. A typical site target area was chosen to be $0.01 \text{ mi}^2$. The results are non-symmetrically distributed with respect to the center of the runway; furthermore, aircraft yearly movement effects are twofold, a linear effect which is directly dependent on movements and a non-linear effect which is best represented by a hazard function of the WIEBULL type. The calculated results are shown graphically in Figure 1.

A few similar or related studies have been done in the past by KENNEDY (1968), EISENHUT (1973), HORNYIK (1973), WALL (1974), SOLOMON (1974) and MANNING & ATCHISON (1974). While our definition of an accident was not restricted to only those involving fatalities, while our data base was different and while our approach for analysis was different, it was found that many of our statistical behavioral tendencies evolved somewhat similarly to those found in other studies.

With proper care in analysing, it is believed that great benefit can be gained in extending the data base by the inclusion of data of other countries such as that of Great Britain, Germany, France and the United States.

The tools, techniques, methods and concepts used for evaluation allowed for minimal assumptions and formed, what may be called, a multidisciplinary and integrated approach. It made use of logic modelling, statistics, probabilities, accident and non-accident data base sensitivity analyses and of the envelope technique. Our approach was concerned with giving guidance when consistent action in the face of uncertainty is required.
FIGURE 1

AIRCRAFT STRIKING PROBABILITIES PER YEAR - AIRCRAFT ABOVE 18,000 POUNDS
LANDING AND TAKEOFF RUNWAYS SUPERPOSED - TYPICAL CANADIAN INTERNATIONAL AIRPORT WITH
150 x 10^3 LANDING OR TAKEOFF MOVEMENTS PER YEAR - PREMEDITATED ACTION PROBABILITY NOT INCLUDED

Flight path direction
The study must be done in six consecutive steps as follows:

1) The qualitative evaluation of an aircraft strike on a site using the "logic model" approach.

2) The gathering of statistical data on aircraft movements and accidents.

3) The calculation of the probability distributions and the basic event probabilities.

4) The evaluation of the probability of an aircraft strike.

5) The generation of the probability density distribution - versus energy of impact, that is, the energy envelope.

6) The probabilistic evaluation of structural failure mode events.

Canadian statistical data, as found in the open literature and in the few special reports available, were too scarce and incomplete to carry on steps five and six. Had our data base included statistics of other countries, it is felt that steps 5 and 6 could have been done also.

The Canadian data base was, nevertheless, sufficient to allow probabilistic evaluation of an aircraft strike on a nuclear power plant.
2. **MODELLING - DATA - ASSUMPTIONS AND THE EVALUATION OF A STRIKE**

The qualitative assessment of a strike was done using a logic tree model as shown in figure 2, to identify all critical activities and to provide insight into the kind of statistical data to search for and the types of distributions to calculate. As can readily be seen from the model, the quantitative assessment of a strike requires data on both aircraft movements and accidents.

Data on civil aircraft movements and accidents in Canada are available in Statistics Canada, ICAO - Special reports, MOT-Special reports, and from additional unpublished information stored on magnetic tapes at MOT's Aviation Statistics Center in Ottawa.

Military data would have certainly increased our data base and would have been useful in clarifying certain statistical behavioral tendencies but we were not able to obtain such information.

The civilian data are principally categorized into passenger or cargo operations and are further subdivided into International or domestic flights. The airports are categorized as having or not having MOT facilities but information on this aspect is somewhat incomplete.

Aircraft movements are usually tabulated in number of enplaned or deplaned passengers or in passenger-miles or in cargo weights or in landings or take-offs. Some special aviation reports give information of movements per aircraft weight categories.

The open literature on accident statistics covers only those events which have incurred fatalities. With the help of MOT we were able to get data for all types of accidents which have occurred since 1960, that is, for aircraft above 18 000 pounds and with or without fatalities. Our definition of an accident is any landing, take-off or on-route incident which has resulted in fatalities or has led to damage
For both the landing and take-off accidents it was found that the effects of yearly movements on strike probabilities were twofold; that is, a linear effect and then a non-linear effect. While the first effect had been expected the second effect appears to follow a WEIBULL type-law of distribution thus indicating a hazard function with burn-in and burn-out phenomena. Therefore, burn-in is represented by an increased hazard due to minimal airport facilities effects while burn-out is represented by an increase in hazard due to airport over-usage effects.

Most of the landing accidents occurred within 10 miles of the airport and were mostly attributed to human errors (fatigue, poor judgment, etc...) One could assume that an aircraft in landing difficulty might exhibit improper navigation up to 20 miles from the airport, however, our data were too incomplete to offer probabilistic support for this assumption.

The quantification of the top outcome of the logic tree model, as shown in Figure 2, is the answer we are looking for. The detailed quantitative evaluations are covered in Appendix II of this report and since the calculated results are non-symmetrically distributed, they are graphically summarized at the beginning of this report in Figure 1.

While a premeditative action probability has been evaluated, it has not been included in Figure 1. Premeditation has been subdivided into two main key events:

a) Premeditation - action from a loner < $10^{-4}$ per year.

b) Premeditation in general has been estimated to vary between $10^{-4}$ to $10^{-6}$ per year with a mean of $10^{-5}$ per year.

Item a) includes only those actions from a deranged person and item b) any politically or labor related actions leading to a serious accident from an aircraft strike on the site.
Figure 2. Logic model for an aircraft strike on a nuclear plant site.

Aircraft crash on a Nuclear Power Plant site

Aircraft is going to crash on the site grounds irrespective of the presence of the nuclear power plant on the site

Nuclear power plant site related aircraft crash accident

Aircraft crash accident on nuclear power plant site as a consequence of premeditation
Aircraft is going to crash on the site grounds irrespective of the presence of the nuclear power plant on the site.

Single plane crash

Preparing to land

on take-off

on-route

Mid-air
Aircraft collision near site with direct consequences to nuclear power plant site
Aircraft crash accident on a nuclear power plant site as a consequence of premeditation.

A premeditated action

Military action, Politically related action, Labor uneasiness related action
Figure 2. (cont'd)

- Aircraft is going to crash off-site
- On-route
- Preparing to land
- On take-off
Figure 2. (cont'd)

Aircraft having navigational problems

△

Preparing to land

Passer-by traffic

On take-off

Aircraft lost

Instrument problems

On route
Figure 4. HAZARD FUNCTION VERSUS AIRPORT YEARLY LANDING MOVEMENTS
FIGURE 5
Canadian Accident Histogram
(1963-1973)
3. CONCLUSIONS

The probability of an aircraft striking a nuclear plant has been evaluated. This evaluation, together with other studies, may be useful in the development of general criteria for the siting of reactors relative to airways or to airports.

The study used, on a statistical basis, the period beginning in 1963 and ending in 1973.

Our approach for evaluation is believed to have made use of minimal assumptions in evaluating the probabilities for a strike.

Because of the unavailability of accident data for aircraft below 15 000 pounds gross weight, probabilities have been calculated using an accident and non-accident data base sensitivity analysis technique which, in turn, is believed to artificially bring out, with reasonable confidence, the most probable effects to have been expected from the missing data. A similar technique was also used for the larger aircraft. Furthermore, the sensitivity technique was then used for the global evaluation of strike probabilities in order to allow upper and lower bounding of the calculated averaged results. In using this procedure it is felt that the calculated results are pessimistic.

It was found that, for a given distance from an airport, strike probabilities were non-symmetric with respect to the center of the runway thus indicating strong site position dependency as shown in Figures 1 & 5.

It was found that the effects of yearly movements on strike probabilities, for a given airport, were twofold; first, a linear dependence which increases or decreases with yearly movements; second, a non-linear dependence which decreases with an increase of yearly movements and increases with a decrease of yearly movements. The latter effect appears to follow a WEIBULL-type law of distribution thus indicating a hazard function with burn-in and burn-out phenomena.
It was found that for a site situated near an airport, on-route strike probabilities contributed very little to the overall results and may thus be omitted. On-route strike probabilities have been evaluated to be \( < 10^{-7} \) per year per CANDU site when considering an airway such as the one between Toronto and Montreal.

It was evaluated that a strike due to a premeditative action may range from \( 10^{-4} \) to \( 10^{-6} \) per year for a typical CANDU site. Other industries have been faced with such inadvertent action, in the past. For the politically or labor-related recorded cases, the intent has always been to strike only those industries which have greatest economic penalty to society and with minimal fatalities; in the case of a loner action, his reasons are often in the reverse order.

It is believed that our proposed approach may be more sophisticated in its first time application than most other approaches used in the past. Its benefits, on the other hand, are many, since it allows greater confidence in the calculated results, it becomes surprisingly expeditious in second time application, and it allows for continuous cause-to-effect guidance, to the decision makers, from proposed design or modification changes. The approach is strictly a decision enhancement approach and though it is not determinative in its results but probabilistic, it is presently the only viable way, under uncertainty, for assessing such events.
4. RECOMMENDATIONS

While the Canadian data base was sufficient to allow probabilistic evaluation of an aircraft strike on a nuclear power plant, we could not use it to calculate continuous distributions and energy envelopes.

In order to evaluate the possibility of structural damage, in order to probabilistically evaluate the protective systems in those instances, etc..., requires firstly, that a strike-energy-impact probability density function be determined. The latter could not be done with a data base of only $31 \times 10^6$ movements as we had for our study but requires that the statistical data base be widened as much as possible. This would then enable application of the proposed methodology on an integral basis from initiating event to final consequences.
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