Probabilistic Analysis of Turbine Missile Damage to Nuclear Power Plant Structures

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Current design criteria for nuclear power plants require that safety-related plant structures, systems, and components be adequately protected against the effects of potential missiles that could result from equipment failures. One such class of failures include those from the low pressure stages of a large steam turbine, which has the potential for producing high energy fragments. The acceptance criterion for damage to safety-related structures, as specified by the Nuclear Regulatory Commission (NRC), for this potential accident is approximately 10^{-7} per reactor-year. These regulations have introduced several important nuclear plant design and turbine operation issues and have resulted in detailed turbine missle risk analysis requirements. As a result of the influence of the turbine missile regulations on plant design and in view of the need for new experimental and analytical research to provide improved data bases and mathematical models for prediction of turbine missile risks, a research program was initiated by the Electric Power Research Institute (EPRI) in 1976. This program has included experimental and analytical casing impact analyses, full and sub-scale concrete impact tests, turbine failure and missile generation analysis, and the development of a probabilistic analysis methodology.

This paper summarizes the results of the EPRI project [1] that focused on the development of the overall probabilistic methodology to assess the risks of turbine missile induced damage to nuclear power plant structures and components. The project was structured to use the results of other EPRI projects that provided information on turbine failure and missile generation frequencies, models to predict the characteristics and exit conditions of the missiles, and experimental data for use in updating empirical impact formulas for reinforced concrete barriers. The research effort included: (1) adaptation and implementation of the missile generation probability and turbine casing impact models developed in Ref. [2]; (2) development of a methodology for the prediction of the motion of the postulated missile fragments that perforate the turbine casing; (3) development of a model using the experimental impact data to predict the effects of fragment impact on nuclear power plant barriers and components; (4) construction of a probabilistic damage assessment methodology using Monte Carlo simulation methodology; and (5) implementation of the methodology into an independent computer program (TURMIS), demonstration of its application to an example case study problem, and assessment of prediction sensitivity.

1. Introduction

Missiles that could result from the failure of a large steam turbine have been recognized as a potential hazard to the safe operation of nuclear power plants since the late 1960s. The initial paper by Bush [3] and regulations [4,5] that followed made turbine missiles an important issue for many nuclear plants in the United States. Probabilistic methods have been used to quantify the likelihoods of such events and to establish acceptable criteria for plant design and decision making. In view of the many uncertainties regarding turbine failure rates, missile exit characteristics, and the effects of impact on reinforced concrete barriers, widely varying results were obtained for specific studies and the need for relevant experimental data and improved prediction methods became apparent. The Electric Power Research Institute (EPRI) initiated a program in 1976 [6] to develop needed data that would culminate in an improved methodology for turbine missile plant risk assessment. This paper is based on an EPRI project that focused on the integration of the experimental and analytical results into a probabilistic simulation methodology. Figure 1 summarizes the five project tasks, inputs from other projects, and outputs of the research. The first three tasks involved development of missile generation, transport, and structure impact event models, which were integrated into a probabilistic simulation methodology and applied to a hypothetical plant using the developed TURMIS computer code. In this brief paper, a summary of the main aspects of the model development and case study results are presented.

2. Methodology Summary

2.1 Turbine Casing Perforation

The results of full-scale and scale-model casing impact tests were used by Patton et al. [2] to benchmark a model for turbine casing perforation analysis. The developed GETOUT model is based on a concentric ring and shell plate geometry in which the plates may shear on 2, 3, or 4 sides, depending on the boundary conditions. It is based upon an abstraction of the Westinghouse 88281 turbine and is appropriate for segmented casing designs. A variation of the Hagg-Sankey perforation equations is used to predict the exit speeds of the disc and secondary fragments. A version of the GETOUT model has been generalized and incorporated into the TURMIS computer code. The TURMIS methodology also enables the user to bypass the GETOUT model and directly input the disc and casing exit parameters for plant simulations.

2.2 Missile Transport Model

A transport model that considers aerodynamic drag, lift, and side forces has been developed as an alternative to the conventionally used 2-D analytic model for turbine missile analysis. Trajectory comparisons indicate that when the distance to the targets is less than about 1000 ft, the 2-D analytic model is sufficiently accurate for plant analyses. Therefore, 2-D analytic trajectory analysis is valid for low trajectory missiles impacting single unit plants. For high trajectory missiles, the 2-D model overpredicts impact velocity but underestimates impact probability. The TURMIS methodology includes options for both transport models, the analytic 2-D model being the default option.

2.3 Structure Impact Models

The 42 new data points that resulted from the turbine missile impact tests have been used to update empirical formulas for turbine disc fragments impacting reinforced concrete barriers. The coefficients of these empirical formulas were updated to provide consistent agreement with the scabbing, perforation, and residual velocity measurements. The updated SAF model is used for scabbing calculations and the updated CEA formula is used for perforation of reinforced concrete barriers. Impulse analysis is used to develop a scaling factor to account for the effects of fragment angular velocity, obliquity, and noncollinearity in the estimation of an equivalent impact speed for use in the empirical models.

2.4 Probabilistic Model

A sequential event probability model of the turbine missile hazard has been developed that permits the analysis of multiple fragment rotating component failure events. The basic sampling experiment is formulated to account for correlation among missile exit conditions but treats missile transport and target impact events independently. Complete probability distributions are used to model the uncertainties in the process, and a conditional probability formulation is used to treat the time-sequenced events. The outcomes for target impact form a discrete event space in which the potential missiles are treated as indistinguishable and mutually independent in the mathematical formulation. The simulation scoring of target combination cut-sets is not based on *a priori* assumptions of independence.

2.5 TURMIS Computer Code

An independent FORTRAN computer code has been developed to analyze turbine missile impact and damage probabilities at specific plants. Up to 23 explicitly defined random variables can be used to model the uncertainties that characterize the turbine missile event sequence. A simulation output stream is generated that includes individual missile results, statistical estimation summaries of missile exit and target impact velocities, and the estimated damage event probabilities with statistical confidence intervals. The event probabilities estimated by TURMIS include: (1) the probability of one or more missiles striking each barrier or component; (2) the probability of damaging each component for the specified damage criterion for that component; and (3) the probability of damaging specified sets of components simultaneously in the same rotating component failure event.

3. Plant Case Study

A single-unit plant with the non-peninsular turbine orientation shown in Fig. 2 is evaluated. The turbine is modeled as a Westinghouse BB281 design with 5 discs per side of a low-pressure stage. There are a total of 8 major external structures and 7 additional internal targets that are modeled for this analysis. The turbine building is modeled as a non-safety control volume target below the elevation of the operating floor. Missiles emitted into the lower half of the turbine are not followed since it is assumed that they would be contained by the turbine pedestal and condenser equipment. The turbine building walls and roof above the operating floor and all equipment within the turbine building are assumed to offer negligible perforation resistance. Targets 2, 3, 6, 7, and 8 are assumed to have external walls of 18-inch reinforced concrete with nominal 4,000 psi compressive strength and less than 2 percent reinforcement. The containment structure (Target 3) is thick-walled (24-inch dome, 48-inch cylinder) with heavy reinforcement and a 3/8 inch liner. Internal Targets 9 and 10 define rooms in the auxiliary building; Targets 11 and 12 are one floor below and hence are protected by two 18-inch barriers. Targets 13 and 14 represent spaces of electrical panels and hence are specified as control volumes. Target 5 is the Fuel

Handling Building, which is assumed to have thin metal cladding exterior above the top of the Spent Fuel Pool (Target 15).

All of the exterior buildings have a perforation damage criterion except the Control Building, which has a scabbing criterion. All of the internal targets (except Targets 13 and 14, which are in the Control Building) have a perforation damage criterion. Thus, if a fragment perforates the barrier and enters the internal target space, the event outcome is scored as a damage. The Spent Fuel Pool Target has no barrier at the top of the pool; thus the perforation criterion translates into a pool entrance criterion, either through the top of the pool or through one of the concrete walls.

3.1 Results of Base Case Simulation

The base case simulation was performed assuming turbine failure rates of 1.64×10^{-4}/yr for operating speed failures and 0.53×10^{-4}/yr for overspeed failures, as taken from Ref. 2. Table 1 summarizes the target hit and damage probabilities combined from the operating speed and overspeed of 6088 and 1956 rotating component failures (rcf) simulations. The confidence bounds in Table 1 do not include any uncertainty on the turbine failure rate. The probabilities are summarized by individual targets and 6 combinations of targets. The target combination sets include: a union combination for targets 9 and 10; intersection combinations for target sets 9 and 10, 11 and 12, 13 and 14, and 7 and 8; and union combination of the external safety-related targets (2 through 8). The union combination sets are scored if any of the targets are damaged during a rcf and the intersection combination sets are scored only if all targets in the set are damaged during the same rcf.

The results in Table 1 indicate that for this hypothetical plant with a nonpeninsular turbine orientation, the conditional hit probability on all the external targets is 0.31/turbine failure, which translates into a hit probability of 6.75×10^{-5}/tur yr. Seventy-two percent of this probability is contributed by operating speed failures. The damage probability for the external target category is 5.31×10^{-6}/tur yr, of which 71 percent is contributed by operating speed failures. This damage probability is dominated by Target 5 with its thin metal cladding exterior. The damage probability of all external targets except Target 5 is less than 9.49×10^{-7}/tur year. Hence, these results for this hypothetical case study indicate that more detailed modeling of the targets within the Fuel Building might be appropriate. For example, if the Spent Fuel Pool (Target 15) is the main safety-related target within the Fuel Building, from Table 1 the pool entrance probability is less than 1.00×10^{-7} at the 97.5 percent confidence level. Then, the all external target perforation category with Target 5 replaced by Target 15 is 1.949×10^{-6}/tur year. These results indicate that the different target modeling hierarchies and damage criterion options available in TURMIS may be useful in evaluating plants for specified safety goals.

3.2 Safety Implications for Hypothetical Plant Case Study

Since the calculated damage probability in this case study exceeds the value of 10^{-7}/reactor-yr currently specified by the NRC [4], several avenues of approach are available to demonstrate an acceptable level of safety with respect to turbine missile effects for this hypothetical plant. One approach, mentioned above, is to construct a more detailed model of targets, paying particular attention to the separation between redundant safety systems. Another is to take advantage of turbine inspection to reduce the *a priori* turbine failure rate [1,6]. Another is to demonstrate, on the basis of a plant-wide probabilistic risk assessment, that a turbine missile damage probability substantially greater than 10^{-7}/reactor-yr is acceptable in terms of contribution to risk; as discussed in [6], a criterion more consistent with the safety goals for other dominant accident contributors to risk would be 10^{-5}/reactor-yr. Finally, a last-resort approach might be to construct plant barriers or turbine missile shields.

4. Sensivitity Analysis

The results summarized in Table 1 represent estimates of the target impact and damage probabilities using the best estimate parameters for this case study. Changes in the input parameters, such as plant geometry, barrier properties, turbine orientation and position, and turbine casing parameters would affect these results. In addition, for a particular plant, variations in the parameters and distributions that specify the perforation model, the transport methodology, and the impact models would also influence the results. In the following subsections, results are summarized from the sensitivity analysis in Ref. 1.

4.1 Missile Transport Methodology

As discussed in Ref. [1], several models are available for turbine missile trajectory analysis. For high trajectory missiles (HTM), the 2-D analytic model tends to overpredict impact velocities but underpredict impact probabilities. To test the sensitivity of the HTM impact and damage probabilities to the transport model, separate simulations of 1,000 overspeed rcf were performed. The results indicate that the target hit probabilities are approximately proportional to the plan area of each, with the auxiliary building having the highest hit probability of the safety related targets. For the all external targets category, the time history transport simulations predict an impact probability that is 18 percent greater and a perforation probability that is 9 percent greater than the 2-D analytic simulations. The impact speeds are reduced by about 10 percent impact from the 2-D analytic transport calculations. Thus, the inherent negative correlation of hit probability and impact speed tends to keep the error introduced by the simpler analytic model acceptable for most plant analyses.

4.2 Equivalent Impact Conditions

In the TURMIS simulation methodology, the effects of noncollinear, oblique, and spinning fragment impacts are scaled using impulse analysis to yield an equivalent normal velocity for use in empirical impact formulas. The average effect of obliquity and noncollinearity for this particular plant geometry is to reduce the mean disc fragment impact speed in the overspeed simulation from 191 ft/sec to a mean effective impact speed of 114 ft/sec. To evaluate the sensitivity of the damage calculation to the impulse model, two simulations were performed. A Case I simulation used the TURMIS impulse methodology that accounts for obliquity, noncollinearity, and spin rates characteristic of ejected turbine fragments. A Case II simulation was also performed in which: (1) each normal and oblique impact was assumed to be collinear, (2) angular velocity was ignored, and (3) the fragment was oriented in a piercing orientation such that its projected area was minimum.

The results of these simulations indicate that the effective impact velocities for Case I are significantly less than Case II. For example, at operating speed the ratio of the mean effective impact velocity to the mean impact velocity was 0.54 for Case I and 0.77 for Case

II disc fragments. For secondary fragments, the difference is even more dramatic (0.45 and 0.81) since the influence of noncollinearity is more important for these more slender fragments. The combined effects of increased effective impact speeds and the use of a piercing impact orientation increased the damage probability by a factor of 3.37. Hence, deterministic type analyses that assume piercing collinear impacts introduce considerable conservatism in the turbine missile damage probability calculation.

4.3 External Target Damage Criterion

In the base case simulation, the damage criterion was taken as perforation for all targets except the Control Building (Target 3). Hence, those reinforced concrete structures that scabbed but were not perforated were not considered to be damaged. The effects of specifying a scabbing damage criterion on all reinforced concrete structures except the Control Building was evaluated in an overspeed simulation of 576 histories. The results for all the external targets category indicate a conditional $P(D|F)$ damage probability of 1.80×10^{-2} for perforation compared with 4.35×10^{-2} for scabbing damage, a factor of 2.42 increase.

4.4 Turbine Orientation

The impact and damage probabilities for nonpeninsular plants, such as the hypothetical layout considered herein, have been generally assumed to be much higher than those for peninsular plants. In peninsular designs, the risk stems largely from high trajectory lob-type hits. To assess the influence of turbine orientation for this single unit plant layout, a set of operating and overspeed simulations were made with the turbine axis rotated 90 degrees. The results indicate that the hit probabilities for the peninsular turbine orientation case are significantly reduced (by about an order of magnitude) for all targets at both speeds. However, the influence on damage probability is less, indicating that the conditional damage given hit frequency is higher for the peninsular orientation for this plant layout. For example, the conditional $P(D|F)$ plant perforation probability is reduced by a factor of 4.4, from 1.60×10^{-2} to 3.62×10^{-3} for operating speed failures.

5. References

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[2] Patton, E. M., P. G. Heasler, S. H. Bush, F. A. Simoneu, and D. L. Hall. "Probabilistic Analysis of Low Pressure steam Turbine Missile Generation Events." Final Report RP 1549-1, Electric Power Research Institute, Palo Alto, California, November 1981.

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[4] U.S. Nuclear Regulatory Commission. Regulatory Guide 1.115. "Protection Against Low-Trajectory Turbine Missiles." Revision 1, July 1977.

[5] U.S. Nuclear Regulatory Commission. Standard Review Plan, Section 3.5.1.3. "Turbine Missiles." NUREG 75/007, Rev. 1.

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Table 1

IMPACT AND DAMAGE PROBABILITY - BASE CASE COMBINED SPEEDS

Target Number	Event H, D	$P_T(H)$ and $P_T(D)$ Probabilities and Confidence Bounds (per turbine yr): 2.5% Lower	Mean	97.5% Upper
1	Hit	2.99×10^{-5}	3.16×10^{-5}	3.33×10^{-5}
2	Hit	4.19×10^{-5}	4.38×10^{-5}	4.57×10^{-5}
	Perf	D	5.42×10^{-8}	1.29×10^{-7}
3	Hit	3.18×10^{-5}	3.35×10^{-5}	3.52×10^{-5}
	Scab	1.04×10^{-7}	2.71×10^{-7}	4.38×10^{-7}
4	Hit	4.81×10^{-5}	5.01×10^{-5}	5.21×10^{-5}
	Perf	0	5.42×10^{-7}	1.29×10^{-7}
5	Hit	1.00×10^{-5}	1.32×10^{-5}	1.63×10^{-5}
	Perf	4.17×10^{-6}	4.87×10^{-6}	5.57×10^{-6}
6	Hit	3.50×10^{-6}	4.15×10^{-6}	4.80×10^{-6}
	Perf	0	8.13×10^{-8}	1.73×10^{-7}
7	Hit	1.73×10^{-6}	1.98×10^{-6}	2.22×10^{-6}
	Perf	0	*	1.00×10^{-7}
8	Hit	3.62×10^{-6}	4.28×10^{-6}	4.94×10^{-6}
	Perf	0	*	1.00×10^{-7}
9	Hit	9.58×10^{-6}	1.06×10^{-5}	1.16×10^{-5}
	Perf	0	*	1.00×10^{-7}
10	Hit	5.56×10^{-6}	6.36×10^{-6}	7.16×10^{-6}
	Perf	0	*	1.00×10^{-7}
11	Hit	0	*	1.00×10^{-7}
12	Hit	0	*	1.00×10^{-7}
13	Hit	2.28×10^{-6}	2.82×10^{-6}	3.36×10^{-6}
14	Hit	2.48×10^{-7}	3.04×10^{-6}	3.60×10^{-6}
15	Hit	8.89×10^{-7}	1.25×10^{-6}	1.60×10^{-6}
	Perf	0	*	1.00×10^{-7}
$9 \cap 10$	Hit	1.31×10^{-5}	1.42×10^{-5}	1.54×10^{-5}
	Perf	0	*	1.00×10^{-7}
$9 \cup 10$	Hit	2.21×10^{-6}	2.73×10^{-6}	3.26×10^{-6}
	Perf	0	*	1.00×10^{-7}
$11 \cup 12$	Hit	0	*	1.00×10^{-7}
$13 \cup 14$	Hit	3.27×10^{-7}	5.69×10^{-7}	8.11×10^{-7}
$7 \cup 8$	Hit	3.06×10^{-7}	5.42×10^{-8}	7.78×10^{-7}
	Perf	0	*	1.00×10^{-7}
All External $(2 \cup 3 \cup .. \cup 8)$	Hit	$6.53\times1D^{-5}$	6.75×10^{-5}	6.97×10^{-5}
	Perf	4.58×10^{-6}	5.31×10^{-6}	6.04×10^{-6}

* Denotes no hits or damages were scored.

Task Sequence and Project Interface

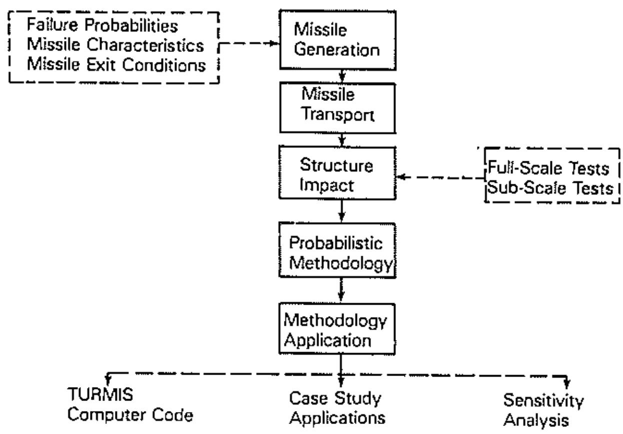

Figure 1. Project Tasks and Data Inputs

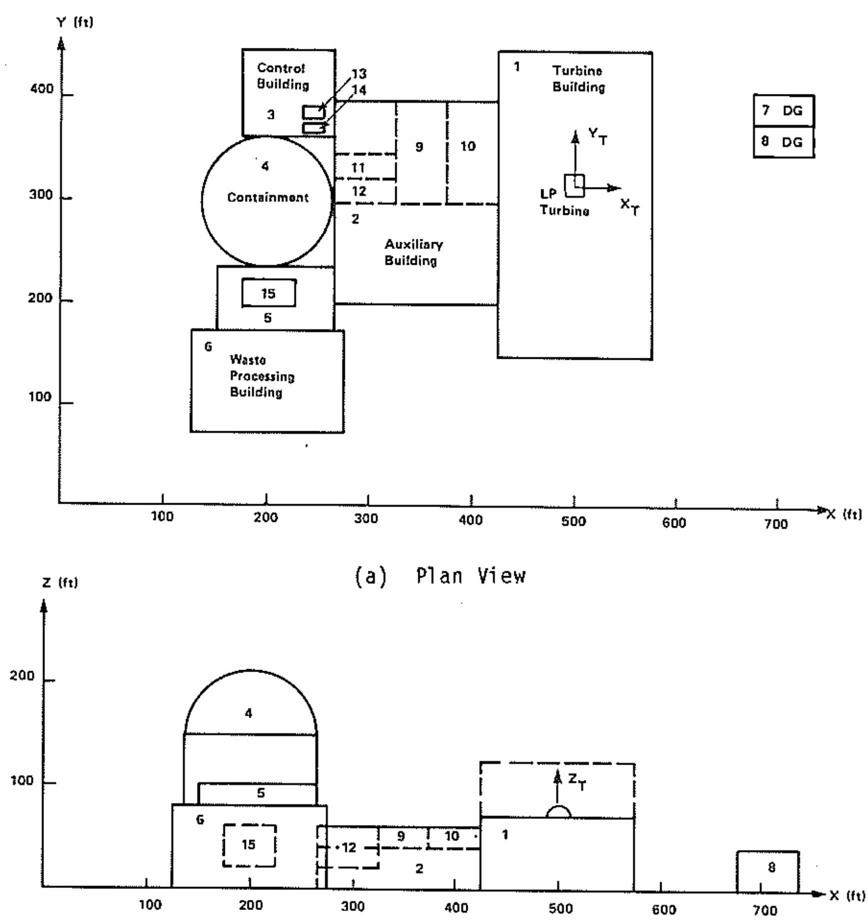

Figure 2. Plant Layout For Case Study Analysis