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DRAFT REGULATORY GUIDE

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(Proposed Revision 2 of Regulatory Guide 1.115, dated July 1977)

PROTECTION AGAINST TURBINE MISSILES

A. INTRODUCTION

This guide describes methods acceptable to the U.S. Nuclear Regulatory Commission (NRC) staff for protecting safety-related structures, systems, and components against missiles resulting from turbine failure by the appropriate orientation and placement of the turbine-generator set, the management of the probability of turbine missile generation, and the use of missile barriers.

General Design Criterion 4, "Environmental and Dynamic Effects Design Bases," of Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," (Ref. 1), requires, in part, that structures, systems, and components important to safety be appropriately protected against the effects of missiles that might result from equipment failures. Failures that could occur in the large steam turbines of the main turbine-generator sets have the potential for producing large high-energy missiles.

The NRC issues regulatory guides to describe to the public methods that the staff considers acceptable for use in implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations and compliance with them is not required.

This regulatory guide contains information collection requirements covered by 10 CFR Part 50 that the Office of Management and Budget (OMB) approved under OMB control number 3150-0011. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number.

B. DISCUSSION

Failure Modes of Turbine Rotors

Although there is little information available on failures of large turbines, cumulative failure data based on the operating history for conventional plants (Ref. 2) indicate that the protection of safety-related portions of nuclear power plants from turbine missiles is an appropriate safety consideration. The two broad categories of turbine failures are usually referred to as design overspeed (up to approximately 130 percent of the rated speed) failures and destructive overspeed (up to approximately 190 percent of the rated speed) failures. Design overspeed conditions are expected to occur one or more times per year of operation, whereas destructive overspeed conditions are expected to occur rarely. Missiles resulting from design overspeed failures are the result of the brittle fracture of turbine blade wheels or portions of the turbine rotor itself. Failures of this type can occur during startup or normal operation. Missiles resulting from destructive overspeed failures would be generated if the overspeed protection system malfunctions and if the turbine speed increases to a point at which the low-pressure wheels or rotor will undergo ductile failure. Regardless of failure types, this guide addresses only large missiles that might be ejected in the event of a turbine failure that will have sufficient kinetic energy to damage even substantial reinforced concrete slabs and panels. Large turbine missiles therefore have the potential for damaging safety-related structures, systems, and components of the plant. Missiles from a turbine failure can be divided into the following two groups:

1. "high-trajectory" missiles, which are ejected upward through the turbine casing and may cause damage if the falling missile strikes an essential system, and
2. "low-trajectory" or "direct" missiles, which are ejected from the turbine casing directly toward an essential system.

This guide outlines acceptable methods of protection against both high-trajectory and low-trajectory turbine missiles.

Design Overspeed Failures

The probability of damage by turbine missiles is large enough to warrant design precautions in future plants. The historical failure data on conventional units indicate that an incidence rate of 1×10^{-4} per turbine year is appropriate for material failures at speeds up to design overspeed.

Although the turbine operating record has improved (Ref. 3) and improvements in turbine design, particularly in the selection of materials, may reduce the design overspeed failure rate, turbine blade failures have occurred during operation at or below design overspeed conditions. An operating history of the length required to permit estimates of very low failure rates, even in the absence of any failures, has not been accumulated. This factor, and the recurrence of disc or rotor degradation resulting from other causes, leads the staff to conclude that use of the failure rate of 1×10^{-4} per turbine year is still appropriate.

An inservice inspection program can enhance the assurance of low failure rates. Tradeoffs between frequency and level of testing and improvements in reliability can be assessed using the turbine missile probability analysis.

Destructive Overspeed Analysis

Runaway turbine failures that may result in turbine speeds of up to 190 percent of the rated speed before destructive failure of the turbine wheels or shaft present a more difficult protection problem. Because the control systems of a typical turbine unit limit the maximum turbine overspeed to less than 130 percent of the rated speed, any speed over 130 percent of the rated speed resulting from failure of the overspeed control systems is considered a destructive overspeed event. In practice, the probability of turbine missiles resulting from destructive overspeed events should be considered along with those resulting from turbine failures at a range of speed up to design overspeed.

Historical data indicate a destructive overspeed failure rate of about $1x10^{-4}$ per turbine year. However, the staff's view is that the application of improved overspeed protection systems, redundant turbine steam valving, improved valve design, and frequent valve testing may significantly reduce the rate of destructive overspeed failures. The reliability of turbine steam valving is apparently the primary factor that limits the degree of credit for improved systems and procedures. Many historical destructive overspeed failures that occurred in recent years were caused by the failure of turbine steam valves to close and to stop the flow of steam even though a trip signal was generated.

In 1995 (Ref. 4), the NRC evaluated the incidence of turbine overspeed protection system failure events in the nuclear industry before that year. Currently, the turbine overspeed failure (160 percent of the turbine rated speed) that occurred at the Salem Generating Station, Unit 2 (Salem 2), in 1991 remains the only destructive turbine overspeed failure among U.S. nuclear plants. Reference 4 provides a point estimate of $1x10^{-3}$ per turbine year for the turbine overspeed failure rate based on the single event that occurred at Salem 2 and on approximately 1,000 years of accumulated nuclear turbine operation as of 1995. Although the Salem 2 event did not produce the large turbine disk or rotor missiles that could have damaged safety-related systems, the study of the Salem 2 event and other overspeed events described in Reference 4 exposed deficiencies in testing, valve maintenance, control system fluid quality, and human factors. Operating experience since that time demonstrates that the industry's corrective actions addressing the findings described in Reference 4 are effective in reducing the potential of such failures. Therefore, the NRC considers the overall turbine failure rate of $1x10^{-4}$ per turbine year still valid.

Scope of Essential Systems

Consideration of turbine missile protection is relevant for essential systems, which are the structures, systems, and components necessary to ensure the following:

a. the integrity of the reactor coolant pressure boundary,
b. the plant's capability to shut down the reactor and maintain it in a cold shutdown condition, or
c. the plant's capability to prevent accidents that could result in potential offsite exposures that are a significant fraction of the guideline exposures of 10 CFR Part 100, "Reactor Site Criteria." (Ref.5)

Systems necessary only for the mitigation of design-basis accidents need not be protected because the probability of turbine failure and a limiting design-basis accident occurring simultaneously is very low. Thus, protection of only the structures, systems, and components listed in the appendix to Regulatory Guide 1.117, "Tornado Design Classification," (Ref.6), from the effects of turbine missiles is acceptable.

Protection against Turbine Missiles

The potential consequences of turbine missiles include direct effects (e.g., damage to the spent fuel storage pool) and indirect effects (e.g., impairment of vital control room functions). In either case, plants must show that the risk from turbine missiles is acceptably small either because design features are provided to prevent damage or because the probability of a strike by a turbine missile is sufficiently low. Turbine orientation and placement, shielding, quality assurance in design and fabrication, inspection and testing programs, and overspeed protection systems are the principal means of safeguarding against turbine missiles. Protection measures based on these considerations are discussed below.

Protection Provided by Turbine Orientation

Evidence indicates that low-trajectory turbine missile strikes will be concentrated within an area bounded by lines that are inclined at 25 degrees to the turbine wheel planes and that pass through the end wheels of the low-pressure stages (see Figure 1). This evidence applies to the low-pressure-stage wheels of turbines with a rotational speed of 1,800 revolutions per minute (rpm) generally used with light-water-cooled reactors. Essential systems within this area and close to the turbine axis are most vulnerable; those further removed from the turbine axis are less likely to be hit by a missile. High-energy low-trajectory missiles do not endanger systems outside of this area. Plants designed with no essential systems within the low-trajectory hazard zone are considered to have a favorable turbine orientation.

The staff has concluded that excluding essential systems from the low-trajectory hazard zone to protect them has less associated uncertainty than that of other methods and is therefore the preferred method of protection. However, plants should protect these systems from high-trajectory missiles by controlling the turbine missile generation frequency or by using barriers.

The NRC has found plants with unfavorable turbine orientation to be acceptable through control of the turbine missile generation frequency. The probability of turbine missiles is expressed as the product of the following three items:

1. the probability of turbine missile generation resulting in the ejection of turbine disk (or internal structure) fragments through the turbine casing, P_1;
2. the probability of ejected missiles perforating intervening barriers and striking essential systems, P_2; and
3. the probability of essential systems that are struck failing to perform their safety functions, P_3.

Mathematically, the probability of failure of an essential system because of turbine missiles, P_4, is $P_1 \times P_2 \times P_3$. P_4 is limited to less than 1×10^{-7} per year, which the NRC staff considers an acceptable risk rate for the loss of an essential system from a single event. Considering P_1, P_2, and P_3 in the placement of essential systems, detailed strike and damage analyses have shown that separation of redundant equipment and special attention to turbine valve reliability have accomplished the objective of ensuring a low risk of damage from turbine missiles.

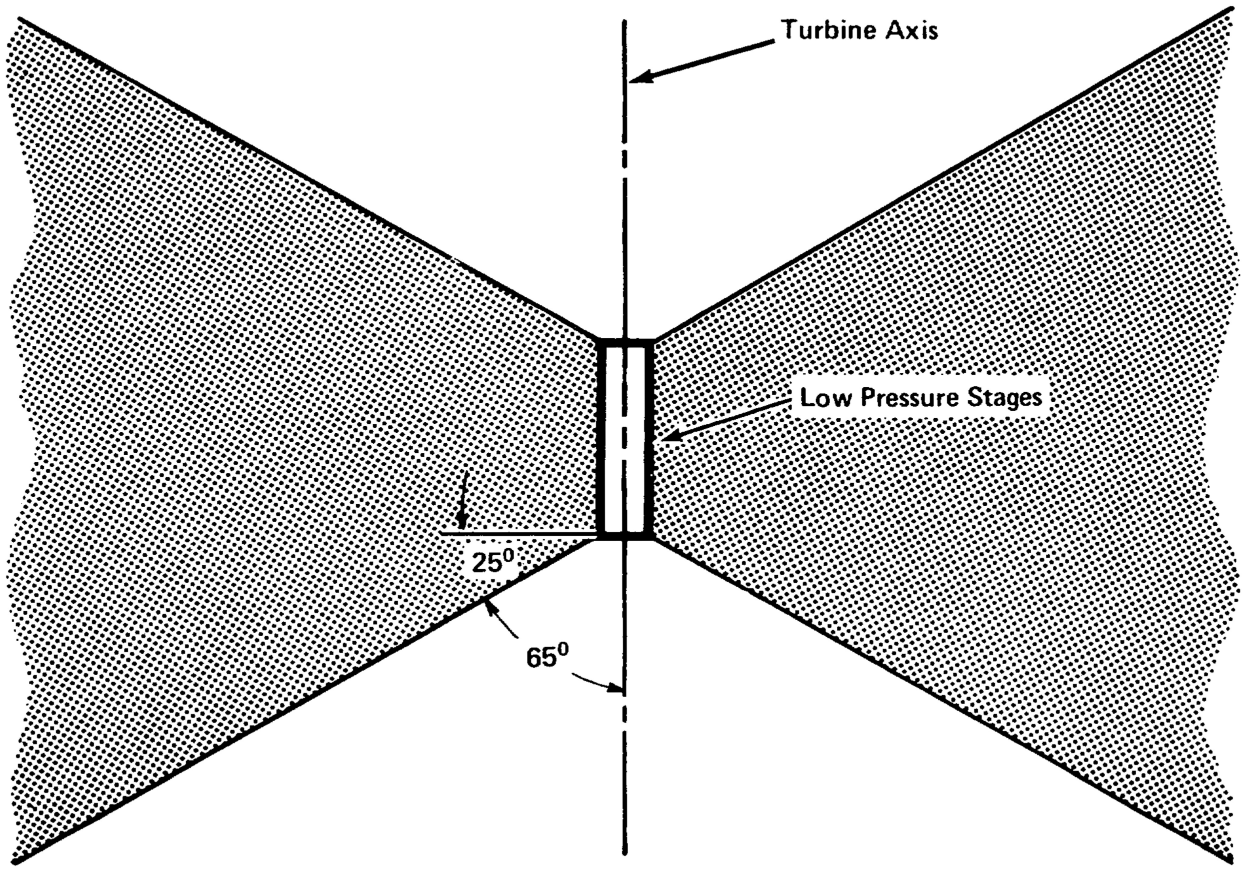

Figure 1. Low-Trajectory Turbine Missile Strike Zone

Protection Provided by Control of Turbine Missile Generation Frequency

Over the years, the NRC staff has shifted its emphasis in the review of turbine missile issues from the strike and damage probability, P_2 x P_3, to the missile generation probability, P_1. The minimum reliability requirement for loading the turbine and bringing the system online was established in 1986 and was first used in an application documented in Appendix U to NUREG-1048, "Safety Evaluation Report Related to the Operation of Hope Creek Generating Station," Supplement 6, issued July 1986, (Ref. 7), as $P_1 < 1x10^{-4}$ for favorably oriented turbines, and $P_1 < 1x10^{-5}$ for unfavorably oriented turbines.

Table 1 summarizes the NRC's criteria for low-trajectory and high-trajectory turbine missiles. The frequency of turbine missile generation resulting in the ejection of turbine disk or rotor fragments through the turbine casing may be divided into separate frequencies for high-trajectory missiles and low-trajectory missiles based on a Monte Carlo analysis that considers turbine casing resistance.

Because protection of an essential system from low-trajectory turbine missiles is considered acceptable if the turbine is favorably oriented, industry has used the Table 1 criteria primarily for the low-trajectory turbine missile issues for unfavorably oriented turbines and for the high-trajectory turbine missile issues. The NRC has also used the Table 1 criteria in evaluating the submittals related to these turbine missile issues since 1986. Currently, the maintenance and inspection of turbine rotors and valves are based on the P_1 calculation, the operating experience of similar equipment, and inspection results.

A recent industry report (Ref. 8) proposed the management of turbine missiles by focusing on their contribution to core damage frequency in lieu of their probability of damaging essential systems. Adoption of this approach would require a revision of both General Design Criterion 4 and the NRC's underlying regulatory philosophy on missile protection. Without a significantly improved turbine missile operating record and a comprehensive study of the approach based on core damage frequency versus the conventional approach, the staff is not prepared to endorse an approach that would permit licensees to rely solely on the final defense (i.e., prevention of core damage).

Protection Provided by Missile Barriers

Barriers may provide some degree of protection against low-trajectory turbine missiles. However, considerable uncertainty attends the current practice of using damage predictions based on ordnance data, particularly in the choice of an "effective impact area." Some data (Ref. 9) were motivated by protection against tornado missiles. For cases in which the impact was normal and the impact area was known, actual penetration distances into reinforced concrete correlated well with those predicted by the modified National Defense Research Council formula (Ref. 10). For metal structures, application of the U.S. Army Ballistic Research Laboratory formula (Ref. 11) should give conservative results for large missiles.

If plants count on multiple barriers to protect essential systems, the protection is deemed adequate if the last barrier will stop the missile without generating secondary missiles that could damage any essential system. For calculating residual velocities after the missile has perforated a barrier, the following relationship is conservative:

$$V_r = (V_i^2 - V_p^2)^{1/2}$$, where

V_r = residual missile velocity after perforation;
V_i = incident missile velocity; and
V_p = incident missile velocity required to just perforate the barrier, which is calculated by the conservative use of penetration data.

A paper published in 1997 (Ref. 12) reconfirmed the appropriateness of using this equation. The study described in the paper applied available damage assessment models for composite and multiple barriers to test data from 1977 to 1997, and the paper recommended the best assessment model for analyzing each of these two types of barriers.

This guide addresses only large missiles that might be ejected in the event of a turbine failure. The inherent protection provided in most plants (generally 1.5 to 2 feet of reinforced concrete) ensures that minor missiles, which could be ejected in significant numbers and in widely scattered directions once the casing is breached, would not result in damage to essential systems.

Because turbine missile hazards may arise from nonnuclear and other nuclear units on the site, consideration should be given to the placement of present and, to the extent possible, future units on the site. In addition, the placement of currently proposed plants may affect the future placement of additional units. Current plants should reevaluate their missile protection for effects of any additional units built on the site. Future units should also evaluate their missile protection by considering the effects of turbine missiles from existing units.

C. REGULATORY POSITION

1. Nuclear power plants should protect their essential systems against both high-trajectory and low-trajectory turbine missiles resulting from the failure of main turbine-generator sets. Consideration may be limited to the structures, systems, and components listed in the appendix to Regulatory Guide 1.117. The effect of physical separation of redundant or alternative systems may also be considered. Dimensioned plan and elevation layout drawings should identify each essential system and its location.

2. Plants can protect essential systems or structures against turbine missiles by appropriately placing and orienting the turbine units and by limiting the calculated turbine missile generation frequency or the essential system failure frequency. For favorably oriented turbines, the NRC considers the protection of an essential system acceptable if the system and any protecting structures thereof are located outside the low-trajectory missile strike zones. These zones are defined by ±25-degree lines emanating from the centers of the first and last low-pressure turbine wheels as measured from the plane of the wheels (see Figure 1). In addition, the NRC considers the protection of essential structures, systems, and components against high-trajectory missiles acceptable if either the frequency of high-trajectory missiles is less than $1x10^{-4}$ per year or appropriate barriers provide protection against high-trajectory missiles, consistent with Regulatory Position 5 below.

3. For unfavorably oriented turbines, the NRC considers the protection of essential structures, systems, and components against direct strikes by low-trajectory turbine missiles acceptable if the turbine missile generation frequency P_1 is less than $1x10^{-5}$ per year or appropriate barriers provide protection against the missiles, consistent with Regulatory Position 5. The evaluation for high-trajectory turbine missiles is not needed because the turbine missile generation frequency for low-trajectory missiles is bounding.

4. In addition to material and fracture toughness properties, the P_1 calculation should consider initial crack depth, crack branching effects, and crack growth caused by degradation mechanisms of comparable significance such as high-cycle fatigue, low-cycle fatigue, and stress-corrosion cracking. Furthermore, the calculated P_1 values for normal (or rated) speed, design overspeed, and destructive overspeed failures should be considered. Selection of these parameters for the turbine missile analysis depends on the turbine rotor construction and should be justified and documented properly.

5. When barriers are used to protect essential systems, dimensioned plan and elevation layout drawings should include information on wall or slab thicknesses and materials of pertinent structures. The protection is considered acceptable if no missile can compromise the final barrier protecting an essential system. Steel barriers should be thick enough to prevent perforation. Concrete barriers should be thick enough to prevent backface scabbing.

6. The strike zones associated with the turbines of all present and future nuclear and nonnuclear units at the site should be considered. The NRC will review turbine designs that are significantly different from the current 1,800-rpm machines on a case-by-case basis to determine the applicability of the strike zone.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this draft regulatory guide. The NRC does not intend or approve any imposition or backfit in connection with its issuance.

The NRC has issued this draft guide to encourage public participation in its development. The NRC will consider all public comments received in development of the final guidance document. In some cases, applicants or licensees may propose an alternative or use a previously established acceptable alternative method for complying with specified portions of the NRC's regulations. Otherwise, the methods described in this guide will be used in evaluating compliance with the applicable regulations for license applications, license amendment applications, and amendment requests.

Table 1 Summary of the NRC criteria on turbine missiles

			P_1 (probability of turbine missile generation) Yr^{-1}	P_2 (probability of an ejected turbine missile striking an essential system)	P_3 (probability of a struck essential system not performing its safety function)	P_4 (hazard rate due to turbine missiles) = $P_1 \times P_2 \times P_3$ Yr^{-1}
Favorably oriented*	Preferred option	Low-trajectory	No turbine missile probability analysis is required.			
		High-trajectory	10^{-4}	N/A	N/A	10^{-7} ($P_2 \times P_3$ is credited by the NRC to be 10^{-3})
Unfavorably oriented*	Preferred option	Low-trajectory	10^{-5}	N/A	N/A	10^{-7} ($P_2 \times P_3$ is credited by the NRC to be 10^{-2})
		High-trajectory	Evaluation is not required			
	Acceptable option	Both trajectories	P_1 (Not greater than 10^{-4})	P_2	P_3	10^{-7}

* See Figure 1 for the definition of turbine missile strike zone: the turbine is favorably oriented if essential systems are outside the strike zone; the turbine is unfavorably oriented if an essential system is inside the strike zone

E. REGULATORY ANALYSIS

Statement of the Problem

The NRC issued Regulatory Guide 1.115, "Protection against Low-Trajectory Turbine Missiles," Revision 1, in July 1977. In July 1986, the NRC revised its guidance on turbine missiles again in Appendix U to NUREG-1048, which has been used to date by the industry in its owners group and plant-specific applications related to turbine missiles and by the NRC in its safety evaluation of these applications. However, the revised guidance did not appear in another revision of Regulatory Guide 1.115, which makes identification of the current NRC guidance on this issue difficult, if not impossible.

Therefore, revision of this regulatory guidance is necessary to accomplish the following four objectives:

1. incorporate NRC guidance on the turbine missile issue, which is currently documented in several documents, into one document—the proposed Regulatory Guide 1.115, Revision 1;
2. expand the scope of guidance to include concerns about high-trajectory missiles;
3. assess the failure data from the past 15 years to determine whether a risk-informed approach is ready for implementation; and
4. present a better organization of the regulatory guide by removing contradictory statements and adding new information and technical discussions throughout the guide.

Objective

The objective of this revision is to provide clear and up-to-date guidance for protecting safety-related structures, systems, and components against turbine missiles.

Alternative Approaches

The NRC staff considered the following alternative approaches:

Do not revise Regulatory Guide 1.115.
Revise Regulatory Guide 1.115.

Alternative 1: Do Not Revise Regulatory Guide 1.115

Under this alternative, the staff would not revise this guidance, and the current guidance would be retained. If the NRC does not take action, there would not be any changes in costs or benefit to the public, licensees, or the NRC. However, the "no-action" alternative would not address identified concerns with the current version of the regulatory guide. The NRC would continue to review each application on a case-by-case basis. This alternative provides a baseline condition from which any other alternatives will be assessed.

Alternative 2: Revise Regulatory Guide 1.115

Under this alternative, the NRC would revise Regulatory Guide 1.115, taking into consideration the operating experience and failure data from the last 15 years and combining guidance for low-trajectory and high-trajectory turbine missiles.

The impact to the NRC would be the costs associated with preparing and issuing the revised regulatory guide. The impact to the public would be the voluntary costs associated with reviewing and providing comments to the NRC during the public comment period. The value to the NRC staff and its applicants would be the benefits associated with enhanced efficiency and effectiveness in using a common guidance document as the technical basis for license applications and other interactions between the NRC and its regulated entities.

Conclusion

Based on this regulatory analysis, the NRC staff recommends revision of Regulatory Guide 1.115.

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4. NUREG-1275, "Operating Experience Feedback Report—Turbine-Generator Overspeed Protection Systems," Volume 11, April 1995.

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[1] Publicly available NRC published documents such as Regulations, Regulatory Guides, NUREGs, and Generic Letters listed herein are available electronically through the Electronic Reading room on the NRC's public Web site at: http://www.nrc.gov/reading-rm/doc-collections/. Copies are also available for inspection or copying for a fee from the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail PDR.Resource@nrc.gov.

[2] Copies of the non-NRC documents included in these references may be obtained directly from the publishing organization.