3.5 Missile Protection

In support of General Design Criteria 2 and 4 of Appendix A to 10 CFR 50, safety-related structures, systems and components (SSC) on the plant site and the containment are protected from externally and internally generated missiles. Safety-related SSC are designed and constructed so as not to fail or cause a failure in the event of a postulated credible missile impact. These SSC include some, which, if they fail, could cause the failure of the integrity of the reactor coolant system (RCS), the reduction to an unacceptable level of any plant feature required for safe shutdown of the reactor, or lead to offsite radiological consequences. The recommendations of RG 1.13, RG 1.27, RG 1.76, RG 1.115, and RG 1.117, as they pertain to internally and externally generated missiles, are met. Missile protection is provided by:

- Locating the system or component in a missile-proof structure.
- Separating redundant systems or components from the missile path or range.
- Providing local shields and barriers for systems and components.
- Designing the equipment to withstand the impact of the most damaging missile.
- Providing design features to prevent the generation of missiles.
- Orienting missile sources to prevent missiles from striking safety-related equipment.

Some missiles may be determined to be non-credible by demonstrating that the event is not statistically significant if the product of the probability of missile occurrence, probability of impact on a significant target, and probability of significant damage is less than 1×10^{-7} per year. To the extent practical, equipment required for safe shutdown of the U.S. EPR is located in areas of the plant separate from potential sources of missiles. Four redundant trains of safety-related components are provided, which are housed in the four separate Safeguard Buildings, the Emergency Power Generation Buildings (EPGB), and the Essential Service Water Buildings (ESWB) which houses the Essential Service Water Cooling Tower Structures (ESWCT) and the Essential Service Water Pump Buildings (ESWPB). In the case that missile creation cannot be prevented, missile barriers are provided to preclude damage to SSC required to achieve safe shutdown or to those SSC that are required to prevent the release of radioactivity producing offsite doses greater than prescribed limits. Missile barriers are composed of walls, partitions, component housings, and other items that enclose safety-related systems or separate redundant trains of safety-related systems.

Postulated missile impacts are assumed to occur in conjunction with single active failures of the SSC used to attain safe shutdown of the plant. A single active failure is the failure of an electrical or fluid system component as a result of mechanical, hydraulic, pneumatic or electrical malfunction, without the loss of the structural integrity of the component. If a missile is generated in any of the redundant trains of a safety-related fluid system that is a Seismic Category I system and is capable of being powered from both onsite and offsite sources, a single active failure is not assumed in the remaining or associated supporting trains.

In the event that a missile is generated simultaneously with a single active failure, evaluations are performed to confirm that missile protection requirements are satisfied. Assessments are made of the missile size, energy, and potential path. Potentially impacted components associated with systems that are required to attain safe shutdown are analyzed to identify any at-risk items that may be within the postulated path and impact zone of the missile. Evaluations are performed to assess the loss of potentially impacted components, concurrent with a single active failure. These evaluations consider redundancy provided for safe shutdown equipment to determine if loss of the component due to missile impact and single active failure is acceptable. If this requirement is satisfied, no further protection from the missile is necessary.

Section 3.7.3 describes design of the non-seismic SSC which, if they fail, could potentially create seismic-generated missiles that could affect safety-related SSC. Section 9.1.5 describes evaluation of overhead lifting devices which, if they fail, could cause heavy-load drop impact events. Chapter 7 describes SSC required for safe shutdown of the U.S. EPR. Section 3.2 describes the quality classifications of SSC. Section 1.2 provides general arrangements and identification of U.S. EPR structures. U.S. EPR structures that house safe shutdown systems and components and require missile protection are identified in Section 3.5.2.

The following sections provide the bases for the selection of missiles and protection requirements for internal and external missiles.

3.5.1 Missile Selection and Description

The U.S. EPR design is based upon consideration of the following potential missile generating sources:

- Internally generated missiles (outside containment) (Section 3.5.1.1).
- Internally generated missiles (inside containment) (Section 3.5.1.2).
- Turbine missiles (Section 3.5.1.3).
- Missiles generated by tornadoes and extreme winds (Section 3.5.1.4).
- Site proximity missiles (except aircraft) (Section 3.5.1.5).
- Aircraft hazards (Section 3.5.1.6).

3.5.1.1 Internally Generated Missiles Outside Containment

The following sections describe credible and non-credible internally generated missile sources and missile prevention and protection outside containment.

3.5.1.1.1 Credible Internally Generated Missile Sources Outside Containment

Failure of rotating equipment, pressurized components such as valves, piping, fittings, tank manways and hand holes, and bolts in high energy systems, and of high pressure gas storage cylinders are among the potential internally generated missile sources outside containment that must be considered for plant protection. Internally generated missiles from sources outside containment are not postulated to occur simultaneously with other plant accidents.

Missile protection is based on the energy created from rotating components at a 120 percent overspeed condition unless other conditions exist that limit the potential for overspeed.

Any fluid system that is pressurized with a maximum operating temperature greater than 200°F or a maximum operating pressure greater than 275 psig during normal plant operation is considered a potential source for missile generation. The failure of portions of this type of system has the potential to accelerate a mass that could become a damaging missile, such as a manway cover, valve stem, or a broken pipe.

Missiles generated by onsite explosions of stored gases are also potential sources of internally generated missiles outside containment. Equipment that uses or generates hydrogen gas can generate missiles.

The methodology for considering missiles in conjunction with single active failure of other components and other types of potential internally generated missiles associated with seismic events and load handling is described in Section 3.5.

Section 3.5.1.3 describes protection against turbine missiles in accordance with the requirements of RG 1.115.

Protection against the dynamic effects associated with postulated pipe rupture events is described in Section 3.6.

3.5.1.1.2 Non-Credible Internally Generated Missile Sources Outside Containment

Internally generated missiles outside containment that are determined to be non-credible include the following types of components, along with the associated basis for this determination:

- No credible missiles can be generated from rotating parts in equipment located outside containment because safety-related and non-safety-related rotating components are designed to have insufficient energy to move the mass of potential missiles generated from rotating parts through the housings in which the components are contained.

- Missiles originating in non-high-energy fluid systems are not credible because these systems have insufficient stored energy to generate missiles.

- Pressure-seal, bonnet-type valves with bonnets designed in accordance with ASME Boiler and Pressure Vessel (BPV) Code, Section III (Reference 8), are non-credible missiles. Retaining rings prevent valve bonnets from becoming missiles. The retaining rings would have to fail in shear, and the valve yokes would capture an ejected bonnet or significantly reduce its energy. These factors combine to make the potential ejection of the bonnets non-credible.

- Valves with bolted bonnets, such as those used in gate, globe, check and large bore (larger than two inches) safety relief valves in high energy systems, are designed and fabricated in accordance with ASME Code, Section III, Reference 8, and are non-credible missiles. Bolted bonnets are prevented from becoming missiles by limiting the stresses in the bonnet-to-body bolting material. The likelihood of all bonnet-to-body bolts experiencing a simultaneous complete severance failure if a bolt failure were to occur is not credible. The low historical occurrence of complete severance failure, along with the widespread use of valves with bolted bonnets, confirms that bolted valve bonnets are not credible missiles.

- In addition to valve stem threads, at least one other feature is included in the design of valves in high-energy systems to prevent ejection of the stems. Thus, valve stems are non-credible missiles. Such features prevent valve stems with back seats from becoming missiles. Stems of valves with power actuators, such as air- or motor-operated valves, are restrained by the valve actuators. Valve systems in rotary-motion valves, ball valves (except single-seat ball valves), butterfly valves, and diaphragm-type valves are determined to be non-credible missiles. These types of valves do not have a large reservoir of pressurized fluid acting on the valve stem, and not enough stored energy is present to eject a missile.

- Nuts, bolts, nut-and-bolt combinations, and nut-and-stud combinations have such a small amount of stored energy that they are non-credible missiles.

- Thermowells and similar fittings are non-credible missiles because they are welded onto high energy piping and pressurized equipment, so that the completed joint has greater design strength than the parent metal. Threaded connections are not used for connecting instrumentation to high energy systems or components.

- Instrumentation, such as pressure, level and flow transmitters and associated piping and tubing, are non-credible missiles. The quantity of high energy fluid in these components is not sufficient to generate missiles.

- Ruptures of ASME Code, Section III, Reference 8 pressure vessels and ruptures of gas storage vessels constructed without welding using ASME BPV Code, Section VIII (Reference 9) criteria are non-credible. This determination is based on the conservative design requirements, material characteristics, inspections, quality control during fabrication and erection, and prudent operation of the components.

- Rotating components that operate less than two percent of the time are non-credible sources for missiles. Motors on valve operators and pumps in systems that rarely operate are deemed non-credible as potential missiles by this exclusion criterion. This exclusion is similar to an exclusion of lines that have limited operating time in high energy conditions.

- Components or portions of components that are not credible missile sources are also non-credible sources of missiles when struck by a falling object.

3.5.1.1.3 Missile Prevention and Protection Outside Containment

Missile generation is prevented to the extent practical throughout the U.S. EPR by implementing the design requirements described in this section. Safety-related equipment is designed to contain rotating parts in the equipment housing in the event that a component fails. High energy fluid systems and components are designed according to the requirements of the ASME BPV Code, Sections III or VIII, References 8 or 9. In high energy systems, valves with removable bonnets, for valve sizes larger than 2 inches, will be the pressure seal-type or have bolted bonnets. In high energy systems, valves sized 2 inches and smaller with removable bonnets, except for Class 2 and Class 3 relief valves, will be the pressure seal-type or have bolted bonnets. Relief valves with an inlet piping connection 2 inches and smaller may have threaded body-to-bonnet connections in accordance with ASME Code Section III, Division 1, Sections NC-3595.4 and ND-3595.4. Valves with threaded body-to-bonnet connections will be used only in non-high energy systems. Valves located in high energy systems have at least two stem retention features. Besides having threads, acceptable features for missile prevention on the valve stem include back seats or power actuators, such as air or motor operators. Thermowells and other instrument wells, vents, drains, test connections, and other fittings in high energy systems are welded to the piping or pressurized equipment. Completed joints are required to have greater design strength than the parent metal.

Permanent high-pressure gas cylinders installed in safety-related areas are designed in accordance with ASME BPV Code, Sections III or VIII, References 8 or 9. Portable and temporary gas cylinders, as well as gas cylinders that are periodically replaced in safety-related areas, are built in compliance with the regulations for seamless steel cylinders, as required by the U.S. Department of Transportation. A COL Applicant that references the U.S. EPR design certification will describe controls to confirm that unsecured compressed gas cylinders will be either removed or seismically supported when not in use to prevent them from becoming missiles.

Missiles from hydrogen gas sources that could potentially interfere with safe-shutdown equipment or release significant amounts of radioactivity are minimized by careful placement of equipment, supply line routing, and proper ventilation. The storage area for plant gases is situated a sufficient distance from the Nuclear Island (NI) so that a hydrogen explosion could not create more hazardous missiles than the tornado missile spectra that the plant is designed to resist. Battery compartments are ventilated to prevent an accumulation of hydrogen gas. Hydrogen supply lines are routed through compartments with non-safety-related systems and components. Plant heating, ventilation, and air conditioning systems provide air movement.

The effects of potential internally generated missiles are minimized by the separation and the redundancy of safety-related systems throughout the U.S. EPR. Four Safeguard Buildings provide operability of vital plant systems in the event that problems or maintenance occur simultaneously in up to three of the Safeguard Building areas. Redundancy and separation are provided by the four emergency diesel generators (EDG) and four Ultimate Heat Sink (UHS) and Essential Service Water (ESW) trains.

Missile barriers are provided between redundant trains of equipment that are housed adjacent to one another. Section 3.5.3 describes missile barrier design procedures. Components within one train of a system with redundant trains need not be protected from missiles originating from within the same train.

A COL Applicant that references the U.S. EPR design certification will describe controls to confirm that unsecured maintenance equipment, including that required for maintenance and that are undergoing maintenance, will be either removed or seismically supported when not in use to prevent it from becoming a missile.

3.5.1.2 Internally Generated Missiles Inside Containment

The following sections describe credible and non-credible internally generated missile sources and missile prevention and protection inside containment.

3.5.1.2.1 Credible Internally Generated Missile Sources Inside Containment

Credible internally generated missile sources inside containment are similar to those identified in Section 3.5.1.1.1, including the failure of rotating equipment and pressurized components in high energy systems. Internally generated missiles inside containment are not postulated to occur simultaneously with other plant accidents.

Missile protection is based on the energy created from rotating components at a 120 percent overspeed condition, unless other conditions exist that limit the potential for overspeed.

Any fluid system that is pressurized with a maximum operating temperature greater than 200°F or a maximum operating pressure greater than 275 psig during normal plant operation is considered a potential source for missile generation.

Equipment inside containment that uses or generates hydrogen gas can generate missiles.

The methodology for considering missiles with single active failure of other components and other types of potential internally generated missiles associated with seismic events and load handling is described in Section 3.5.

Protection against the dynamic effects associated with postulated pipe rupture events is described in Section 3.6.

3.5.1.2.2 Non-Credible Internally Generated Missile Sources Inside Containment

Internally generated missiles inside containment are determined to be non-credible when an inadequate amount of energy is present to produce the missile, or the likelihood of generating a missile is negligible. The following list includes the internally generated missiles inside containment that are determined to be non-credible, along with the associated basis for this determination:

- To minimize potential failures of the reactor coolant flywheels, design requirements for the reactor coolant pumps are established using the guidance of RG 1.14. Rotating parts from the reactor coolant pumps are non-credible missiles since the application of the criteria of this regulatory guide provides reasonable assurance that there will be an extremely low probability of flywheel-generated missiles that would result in negative impacts to the RCS pressure boundary, containment, or engineered safety features.

- Rotating components inside containment, such as pumps, fans, and compressors, are designed to have insufficient energy to move the mass of potential missiles generated from rotating parts through the housings in which the components are contained. Therefore, the rotating parts from this type of equipment are determined to be non-credible missiles.

- Pressure vessels inside containment, including the accumulators, residual heat exchangers, pressurizer, reactor coolant pump casings, reactor vessel, steam generators, and piping, are designed to ASME Code, Section III, Reference 8. Pressure vessels inside containment are non-credible sources of missiles because these components have closely controlled requirements for material characteristics, pre-service and in-service inspections, quality control during fabrication, erection and operation, and appropriate operation procedures.

- Valves, valve stems, nuts, bolts, and thermowells in high energy fluid systems and components in non-high energy fluid systems are non-credible missiles based on the same preventive techniques listed in Section 3.5.1.1.2 for these component types.

- A control rod drive mechanism (CRDM) housing failure, sufficient to create a missile from a piece of the housing or to allow a control rod to be ejected rapidly from the core, is non-credible. This is based on the reasons mentioned for valves, valve stems, nuts, bolts and thermowells, and on the following:

- The housings are individually hydrotested to 125 percent of system design pressure after they are installed on the reactor vessel to the head adapters. The housings are checked again during the hydrotest of the completed RCS.
- The housings are made of austenitic or martensitic stainless steel, which both exhibit excellent notch toughness.
- System thermal transients do not affect stress levels in the control rod drive mechanisms at power, and the CRDMs are not affected by thermal movements of the reactor coolant piping loops.
- Pressure boundary welds in the CRDMs meet identical design, procedure, examination, and inspection requirements as welds on other ASME Code, Section III, Class 1 components (Reference 8).

- Hydrogen is supplied to the RCS by the chemical and volume control system. However, since the hydrogen is added to the reactor coolant outside of containment, there are no sources of hydrogen gas inside containment.

3.5.1.2.3 Missile Prevention and Protection Inside Containment

The methodology for missile prevention inside containment is the same as that described in Section 3.5.1.1.3 for rotating parts, valves, pressure-retaining components and piping, and combustible and pressurized gas sources. The effects of potential internally generated missiles are minimized by separation and redundancy throughout the containment. Four trains of safety-related systems are provided for operability of vital plant systems.

To the extent possible, missile barriers are provided between redundant trains of equipment that are housed adjacent to one another. Section 3.5.3 describes missile barrier design procedures. Components within one train of a system with redundant trains need not be protected from missiles originating from the same train.

The U.S. EPR is designed so that a postulated missile from the RCS does not cause a loss of integrity of the primary containment, main steam, feedwater, or any other loop of the RCS. In addition, a postulated missile from any other system will not cause a loss of integrity of the primary containment or RCS pressure boundary.

Even though potential CRDM missiles are deemed non-credible as described in Section 3.5.1.2.2, the concrete missile shield on top of the refueling canal walls is designed to absorb the impact of a control rod ejection due to the postulated failure of a CRDM nozzle flange or pressure housing thereby providing adequate protection of other SSC inside containment.

Therefore, SSC inside containment are designed to withstand a postulated CRDM missile, even though this event is deemed non-credible.

A COL applicant that references the U.S. EPR design certification will describe controls to confirm that unsecured maintenance equipment, including that required for maintenance and that are undergoing maintenance, will be removed from containment prior to operation, moved to a location where it is not a potential hazard to safety-related SSC, or seismically restrained to prevent it from becoming a missile.

3.5.1.3 Turbine Missiles

The plant layout, as shown in Figure 1.2-1 in Section 1.2, is a longitudinal arrangement for the turbine generators. The axis of the turbine rotor shafts is positioned such that safety-related structures, except for two of the four ESWBs and two of the four EPGBs, are located outside the turbine low-trajectory hazard zone, as defined by RG 1.115. Redundancy of the UHS and ESW systems and the EDGs provides adequate protection for U.S. EPR safety-related systems. Therefore, the turbine generator is favorably positioned, as defined by NUREG-0800 (Reference 10) SRP Section 3.5.1.3, because the containment and most of the safety-related SSC are located outside the low-trajectory hazard zone defined by RG 1.115.

Section 10.2 describes the design of the turbine generator. The probability of turbine failure resulting in ejection of the turbine rotor (or internal structure) fragments through the turbine casing, P_1, will be less than 1 x 10^{-4}. In accordance with guidance provided by Reference 10, SRP Section 3.5.1.3, Table 3.5.1.3-1, an overall turbine missile safety objective for the probability of unacceptable damage resulting from turbine missiles, P_4, of less than 1 x 10^{-7} is satisfied with P_1 less than 1 x 10^{-4} for favorably oriented turbine-generators. Therefore, given the redundancy and the low probability of a turbine missile being generated, the impact of turbine-generated missiles on safety-related SSC is not safety significant. A COL applicant that references the U.S. EPR design certification will confirm the evaluation of the probability of turbine missile generation for the selected turbine generator, P_1, is less than 1 x 10^{-4} for turbine-generators favorably oriented with respect to containment.

Section 10.2 describes requirements for disk and rotor integrity, rotor material fracture toughness, overspeed protection, inspection, testing, examination, startup procedures, operation procedures, and maintenance of the turbine generator equipment. A COL applicant that references the U.S. EPR design certification will assess the effect of potential turbine missiles from turbine generators within other nearby or co-located facilities.

3.5.1.4 Missiles Generated by Tornadoes and Extreme Winds

Tornado-generated missiles are evaluated in the design of safety-related structures. Tornado-generated missiles evaluated for their impact on safety-related structures conform to the Region I missile spectrum presented in Table 2 of RG 1.76. This spectrum is based on the design basis tornado defined in Section 3.3 and represents a probability of exceedance event of 1 x 10^{-7} per year.

The selected missiles for U.S. EPR include:

- A massive high-kinetic-energy missile that deforms on impact, such as an automobile.
- A rigid missile that tests penetration resistance, such as a six-inch diameter Schedule 40 pipe.
- A small rigid missile of a size that is sufficient to pass through openings in protective barriers, such as a one-inch diameter solid steel sphere.

The missiles considered in the U.S. EPR design are listed in Table 3.5-1—Spectrum of Design Basis Tornado Missiles.

The automobile missile is considered to impact at altitudes that are less than 30 ft above plant grade.

A COL applicant that references the U.S. EPR design certification will evaluate the potential for other missiles generated by natural phenomena, such as hurricanes and extreme winds, and their potential impact on the missile protection design features of the U.S. EPR.

For sites with surrounding ground elevations that are higher than plant grade, a COL applicant that references the U.S. EPR design certification will confirm that automobile missiles cannot be generated within a 0.5 mile radius of safety-related SSC that would lead to impact higher than 30 ft above plant grade.

3.5.1.5 Site Proximity Missiles (Except Aircraft)

A COL applicant that references the U.S. EPR design certification will evaluate the potential for site proximity explosions and missiles generated by these explosions for their potential impact on missile protection design features. Evaluation of design basis threat (DBT) explosions near the U.S. EPR required by 10 CFR 73.55 is considered as a part of the plant safeguards and security measures and is not described in this document.

3.5.1.6 Aircraft Hazards

A COL applicant that references the U.S. EPR design certification will evaluate site-specific aircraft hazards and their potential impact on plant SSC.

The U.S. EPR design employs geographical separation or residence within shield buildings to provide a minimum number of SSC to achieve and maintain the plant in cold shutdown and prevent damage to fuel in the spent fuel pool following an aircraft hazard (ACH). Specifically, sufficient geographical separation between redundant or diverse SSC limits the extent of damage from an ACH. Similarly, placing SSC within shield buildings designed to prevent penetration by aircraft provides protection of redundant or diverse SSC needed to achieve and maintain the plant in cold shutdown and prevent damage to fuel in the spent fuel pool.

3.5.2 Structures, Systems, and Components to be Protected from Externally Generated Missiles

Structures, systems and components required to safely shut down the reactor and maintain it in a safe condition are protected from externally generated missiles. Structures on the U.S. EPR site that are missile protected include the following:

- Reactor Building Annulus, including containment penetrations and containment isolation components.
- Reactor Containment Building.
- Reactor Building internal structures, including the RCS components and piping.
- Safeguard Buildings 1, 2, 3, and 4, including the main control room in Safeguard Buildings 2 and 3.
- Fuel Building, including the spent fuel pool.
- The EPGBs, including underground cables and instrumentation from the EDGs to other safety-related SSC.
- ESWBs 1, 2, 3, and 4, including underground piping, cables and instrumentation between these structures and other safety-related SSC.

Missile protection is provided by the external walls and roofs of the structures. Section 3.8 provides additional information for the design of these structures. Openings and penetrations in the walls and roofs of these structures are also missile protected by enclosures, missile-resistant doors and covers, labyrinth structures, or physical protection features.

Safety-related pipes and cables routed outside of missile-protected structures are buried a sufficient depth to provide protection for these items from missile impact, or concrete or steel enclosures are provided that are designed to withstand missile impact loads.

The externally generated missiles for which the U.S. EPR is designed are addressed in Section 3.5.1.

Section 3.3.2.3 describes the evaluation of the effects that the failure of structures or components not designed for tornado loads, including missile impact, could have on nearby safety-related structures. Section 3.7.3 describes design requirements for Seismic Category II SSC, which are designed not to fail as a result of a safe shutdown earthquake and generate missiles that could affect the function of safety-related SSC.

Structures used to protect safety-related SSC meet the requirements of the following regulatory guides for externally generated missiles:

- Turbine generated missiles (RG 1.115).
- Tornado generated missiles (RG 1.117).
- Spent fuel storage facility (RG 1.13).
- Ultimate Heat Sink (RG 1.27).

3.5.3 Barrier Design Procedures

Missile barriers are designed to withstand local and overall effects of missile impact loadings. No credit is taken for non-safety-related structures providing shielding for safety-related structures from missile strikes.

Safety-related SSC are protected from missile penetration through the barrier, as well as from secondary missiles as a result of back-face scabbing. Concrete missile barriers subject to impactive loads are designed in accordance with the requirements of Appendix C to ACI 349 (Reference 1). The Modified National Defense Research Committee Formulas referenced in ASCE No. 58, “Structural Analysis and Design of Nuclear Plant Facilities” (Reference 2) are used for the evaluation of missile penetration.

Steel missile barriers subject to impactive loads are designed in accordance with the recommendations of NUREG-0800, Reference 10. The Ballistic Research Laboratory (BRL) formula and the Stanford Research Institute (SRI) equation presented in ASCE No. 58, Reference 2, are used in the design of steel missile barriers to provide reasonable assurance that postulated missiles do not penetrate the barriers.

The following sections describe the local and overall missile protection design procedures used to evaluate missile barriers for the U.S. EPR.

3.5.3.1 Local Damage Prediction

Prediction of local damage in the immediate vicinity of the missile strike depends on the material type and the nature of the missile. Local damage prediction methodologies are described in the following sections for concrete, steel, and composite missile barriers.

3.5.3.1.1 Concrete Barrier Analysis

Concrete missiles barriers are evaluated for the effects of missile impact resulting in penetration, perforation, and scabbing of the concrete using the Modified National Defense Research Committee formulas as described in following paragraphs.

The thicknesses determined by the equations will be compared to those in Table 3.5.2, with the larger thickness used in the design of the barrier.

3.5.3.1.1.1 Penetration

The depth of missile penetration, x, is calculated using the following formulas:

$$x = \sqrt{4K\,N\,W\,d\left(\frac{v_0}{1{,}000d}\right)^{1.80}}, \text{ for } \frac{\mathrm{x}}{\mathrm{d}} \le 2.0$$

$$x = \left[K\,N\,W\left(\frac{v_0}{1{,}000d}\right)^{1.80}\right] + \mathrm{d}, \text{ for } \frac{\mathrm{x}}{\mathrm{d}} > 2.0$$

Where:

x = total penetration depth (inches).

K = concrete penetrability factor = $2 < \frac{180}{\sqrt{f'_c}} < 5$, with f'_c in pounds per square inch.

N = missile shape factor:

- flat nosed bodies = 0.72.
- blunt nosed bodies = 0.84.
- average bullet nose (spherical end) = 1.00.
- very sharp nosed bodies = 1.14.

W = missile weight (pounds).

v_0 = missile impact velocity (feet per second).

d = effective missile diameter (inches); for non-solid cylindrical shaped missiles, d is the diameter of an equivalent solid cylindrically-shaped missile with the same contact surface area as the contact surface of the actual missile, for example, d = $\sqrt{4A_c / \pi}$.

A_c = missile contact area, (square inches).

3.5.3.1.1.2 Perforation

The relationship for perforation thickness, e, and penetration depth, x, is determined from the following formulas:

$$\frac{e}{d} = 1.32 + 1.24\frac{x}{d}, \quad \text{for } 1.35 \le \frac{x}{d} \le 13.5$$

$$\frac{e}{d} = 3.19\left(\frac{x}{d}\right) - 0.718\left(\frac{x}{d}\right)^2, \quad \text{for } \frac{x}{d} \le 1.35$$

3.5.3.1.1.3 Scabbing

The relationship for scabbing thickness, s, and penetration depth, x, is determined from the following formulas:

$$\frac{s}{d} = 2.12 + 1.36\frac{x}{d}, \quad \text{for } 0.65 \le \frac{x}{d} \le 11.75$$

$$\frac{s}{d} = 7.91\left(\frac{x}{d}\right) - 5.06\left(\frac{x}{d}\right)^2, \quad \text{for } \frac{x}{d} \le 0.65$$

Table 3.5-2—Minimum Concrete Barrier Thickness Requirements for Local Damage Prediction against Tornado Generated Missiles, shows minimum concrete barrier thickness requirements for local damage prediction against tornado-generated missiles, which are based on the Region I guidelines in NUREG-0800, Reference 10.

3.5.3.1.2 Steel Barrier Analysis

Steel missile barriers are evaluated for the effects of missile impact using either the BRL formula or the SRI equation as described in Bechtel Topical; Report BC-TOP-9A (Reference 3).

Steel missile barriers may be perforated by an impacting non-deformable steel missile. Sometimes protruding elements of a missile may puncture a steel target, while the entire missile does not perforate or pass through the target. The minimum contact area of a missile protrusion is used to calculate puncture thickness, and the projected area of the entire missile is used to calculate perforation thickness.

The BRL formula is given as:

$$e^{\frac{3}{2}} = \frac{0.5Mv_0^2}{17{,}400K_s^2 D^{\frac{3}{2}}}$$

Where:

e = perforation thickness (inches), which is the maximum thickness of a target that a missile with a given impact velocity will completely penetrate.

M = mass of the missile (pounds-second^2 per foot).

D = missile diameter (inches), or for irregularly shaped missiles, the equivalent diameter is used. The equivalent diameter is taken as the diameter of a circle with an area equal to the circumscribed contact area, or projected frontal area of the non-cylindrical missile.

v_0 = missile impact velocity (feet per second).

K_s = steel penetrability factor (taken as 1.0).

The BRL formula can be solved directly for the steel plate thickness just perforated by the missile using the following formula:

$$e = \frac{\left(\frac{Mv_0^2}{2}\right)^{\frac{2}{3}}}{672D}$$

The SRI equation is given as follows, with "e" substituted for steel plate thickness for comparison to the BRL formula results:

$$\frac{E_c}{d} = \frac{S}{46{,}500}\left(16{,}000e^2 + 1500\frac{W}{W_s}e\right)$$

Where:

Ec = critical kinetic energy required for perforation (foot-pounds).

d = effective missile diameter (inches).

S = ultimate tensile strength of the steel target minus the tensile stress in steel (pounds per square inch).

e = target steel plate thickness (inches).

W = length of a square side between rigid supports (inches).

Ws = span of a standard width = 4 inches.

The SRI equation is applicable within the following range of parameters:

- $0.1 < e/d < 0.8$.
- $0.002 < e/L < 0.05$.
- $10 < L/d < 50$.
- $5 < W/d < 8$.
- $8 < W/e < 100$.
- 70 feet per second < v_0 < 400 feet per second.

Where:

e, d, v_0, and W are as defined above.

L = length of the cylindrical missile (inches).

The perforation thickness, e, is obtained by comparing results of the BRL formula and the SRI equation, using the larger value for barrier design. Design values are increased by 25 percent to prevent perforation.

3.5.3.1.3 Composite Section Barrier Analysis

Missile protection barriers that use composite sections will be evaluated for local damage using the residual velocity of the missile perforating the first element as the striking velocity of the missile for the next element in the composite section. Guidance provided in Reference 10, SRP 3.5.3, Section II, SRP Acceptance Criteria 1.C, will be used to determine this residual velocity. The methodologies described in Sections 3.5.3.1.1 and 3.5.3.1.2 will be used for design of the concrete and steel portions of composite sections, respectively.

3.5.3.2 Overall Damage Prediction

Evaluations are performed on the overall response to missile impact of the barrier or portions within it. Structures or barriers subject to missile impact are analyzed to verify that they will not collapse or have excessive deformations that will impair the function of safe shutdown equipment. Non-linear, elasto-plastic response of structures may be assumed in the evaluation of the overall response of reinforced concrete and steel structures or barriers subjected to impactive or impulsive loads, provided the overall integrity of the structure is not impaired.

Evaluations of the overall damage from missile impact are performed by either considering missile impact in the elastic range of the structural element with other loadings applied and accounting for rebound effects of the impact, or by assuming that the inelastic capacity of the structural element resists missile impact loads. Section 3.8 provides additional information on loading combinations and analysis methods for reinforced concrete and structural steel. Inelastic impact analyses are performed by assuming that the full elastic capacity of the structural element is used to accommodate other loading conditions, and that the missile impact loads are accommodated inelastically based on the ductility of the structural element. Code requirements for ductility are met for missile impact evaluations.

Guidance provided in "A Review of Procedures for the Analysis and Design of Concrete Structures to Resist Missile Impact Effects," by R. P. Kennedy (Reference 5) is used for the evaluation of concrete missile barriers. Concrete missile barriers are designed in accordance with the requirements of ACI 349, including Appendix C (Reference 1).

Steel missile barriers will be evaluated utilizing the equations as defined in Section 3.5.3.1.3. Steel missile barriers are designed in accordance with the requirements of ANSI/AISC N690 (Reference 4).

The criteria recommended in Reference 10, SRP 3.5.3, and guidance provided in RG 1.142, are also used for design of concrete missile barriers. Procedures listed above are in agreement with methodology presented in "Impact Effect of Fragments Striking Structural Elements," Holmes and Narver, Inc., by R.A. Williamson and R.R. Alvy (Reference 6). Other procedures may also be used, provided the results obtained are comparable to those referenced. Ductility requirements specified in Section 3.5.3.3 are satisfied for concrete and steel structures that are subjected to impactive missile barrier loadings.

3.5.3.3 Ductility Requirements for Missile Barriers

Deformation under impactive and impulsive loads is controlled by limiting the ductility ratio, μ_d, which is defined as the ratio of maximum acceptable displacement, X_m, (or maximum strain, ε_m) to the displacement at the effective yield point, X_y, (or yield strain, ε_y) of the structural element. In addition to the specified deformation limits, the maximum deformation does not result in the loss of intended function of the structural element nor impair the safety-related function of other systems and components.

Safety-related concrete structures, other than the Reactor Containment Building, are designed for impactive and impulsive loads in accordance with ACI 349, Reference 1, with the exceptions noted in RG 1.142. The Reactor Containment Building is designed to the requirements (including those for impactive and impulsive loads) of the ASME Boiler & Pressure Vessel Code, Section III, Division 2, “Code for Concrete Containments” (Reference 7). Refer to Reference 3.8.1 for more information on design of the post-tensioned concrete Reactor Containment Building.

Safety-related steel structures are designed (including the design for impactive and impulsive loads) in accordance with ANSI/AISC N690, Reference 4.

The ductility limits for concrete and structural steel safety-related structures, other than the Reactor Containment Building, are given in Table 3.5-3—Allowable Ductility Ratios.

The effective yield displacement for reinforced concrete members is computed using a cross-sectional moment of inertia equal to $0.5(I_g + I_{cr})$.

Where:

I_{cr} = moment of inertia of cracked section transformed to concrete.

I_g = moment of gross concrete section about centroidal axis, neglecting reinforcement.

3.5.4 References

1. ACI 349-01/349R-01, Appendix C, “Code Requirements for Nuclear Safety Related Concrete Structures and Commentary,” American Concrete Institute, 2001.

2. ASCE Manual and Report on Engineering Practice No. 58, “Structural Analysis and Design of Nuclear Plant Facilities,” ASCE Committee on Nuclear Structures and Materials, 1980.

3. Bechtel Power Corporation Topical Report, BC-TOP-9A, “Design of Structures for Missile Impact,” Rev. 2, 1974.

4. ANSI/AISC N690-1994 (R2004) S2, “Specification for Design, Fabrication and Erection of Steel Safety-Related Structures for Nuclear Facilities,” American Institute of Steel Construction, 2004.

5. “A Review of Procedures for the Analysis and Design of Concrete Structures to Resist Missile Impact Effects,” Paper No. NSS 5-940.1 by R. P. Kennedy Holmes and Narver, Inc., Nuclear Engineering and Design, Vol. 37, No. 2, North Holland Publishing Co., May 1976.

6. "Impact Effect of Fragments Striking Structural Elements," R.A. Williamson and R.R. Alvy, Holmes and Narver, Inc., 1973.

7. ASME Boiler and Pressure Vessel Code, Section III, Division 2, "Code for Concrete Containments," The American Society of Mechanical Engineers, 2004 Edition.

8. ASME Boiler and Pressure Vessel Code, Section III, Division 1, "Rules for Construction of Nuclear Power Plant Components," The American Society of Mechanical Engineers, 2004 Edition.

9. ASME Boiler and Pressure Vessel Code, Section VIII, Division 1: "Rules for Construction of Pressure Vessels," The American Society of Mechanical Engineers, 2004 Edition.

10. NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Nuclear Regulatory Commission, March 2007.

Table 3.5-1—Spectrum of Design Basis Tornado Missiles

Missile Descriptions	Dimensions	Weight	Impact Area[1]	Design Impact Velocity[2]	
				Horizontal	Vertical
6 in Sch. 40 Pipe	6.625 in ϕ x 15.0 ft	287 lb	34.5 in^2	135 ft/s	90 ft/s
Automobile	16.4 ft x 6.6 ft x 4.3 ft	4000 lb	4086.7 in^2	135 ft/s	90 ft/s
Solid Steel Sphere	1 in ϕ	0.147 lb	0.79 in^2	26 ft/s	17 ft/s

Notes:

1. Barrier design evaluates impact loads assuming the missile longitudinal axis impacts normal to the barrier surface.
2. Vertical velocities are equal to 67% of the horizontal velocities.

Table 3.5-2—Minimum Concrete Barrier Thickness Requirements for Local Damage Prediction against Tornado Generated Missiles

Concrete Strength	Wall Thickness	Roof Thickness
3000 psi	18.2 in	13.2 in
4000 psi	16.9 in	12.3 in
5000 psi	16.0 in	11.7 in

Table 3.5-3—Allowable Ductility Ratios
Sheet 1 of 2

Structural Member Loading Categories:	Ductility Ratio:	Notes:
Reinforced Concrete:		
a. Flexure (beams, walls, and slabs)	$\frac{0.05}{\rho - \rho'} \leq 10$ *and* $r_\theta < 0.0065\left(\frac{d}{c}\right) \leq 0.07$ *radians*	Notation: ρ= reinforcement ratio = A_s /bd , tension zone ρ' = reinforcement ratio = A'_s /bd , compression zone r_q = rotational capacity, radians c = distance from compression face to the neutral axis at ultimate strength d = distance from compression face to the tensile reinforcement For flexure to control the design, the load capacity of a structural element in shear shall be at least 20% greater than the load capacity in flexure, otherwise, the ductility ratios given in b) shear or c) axial compression + flexure shall be used. The allowable ductility ratio in flexure shall not exceed 1.0 for loads which could affect the integrity of the structural system; localized areas of the structure under the same loading conditions shall not exceed an allowable ductility ratio of 3.0.
b. Shear (beams, walls, and slabs)		
i. Carried by concrete alone	1.0	
ii. Carried by concrete and stirrups or bent bars	1.3	
iii. Carried completely by stirrups	3.0	

Table 3.5-3—Allowable Ductility Ratios
Sheet 2 of 2

Structural Member Loading Categories:	Ductility Ratio:	Notes:
c. Axial compression + flexure (beam-columns, walls, and slabs)		
i. Compression controls	1.0	When the compression load is greater than $0.1f_c'A_g$ or one-third of that which would produce balanced conditions, whichever is greater, the maximum permissible ductility ratio shall be 1.0.
ii. Flexure Controls	See Note	When the compression load does not exceed $0.1f_c'A_g$ or one-third of that which would produce balanced conditions, whichever is smaller, the allowable ductility shall be as given in a) flexure.
iii. Combined Compression + Flexure Load Condition	Varies – See Note	For conditions between those specified in i. and ii. the allowable ductility ratio shall vary linearly from 1.0 to that given in a) flexure.
Structural Steel:		
a. Axial tension members	$\mu_d \le 0.25 \frac{\varepsilon_u}{\varepsilon_y} \le 0.1/\varepsilon_y$	ε_u =strain at ultimate strength (rupture) ε_y = strain at yield strength
b. Flexural members		
i. Tension controls	$\mu_d \le 10$	
ii. Shear controls	$\mu_d \le 5$	
c. Columns		
i. $l/r \le 20$	$\mu_d \le 1.3$	l = length; r = radius of gyration
ii. $l/r > 20$	$\mu_d \le 1.0$	

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