Methodology for Performing Aircraft Impact Assessments for New Plant Designs

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EXECUTIVE SUMMARY

This methodology has been developed to assist NSSS vendors and COL applicants in assessing the physical, shock and fire effects of the impact of a large commercial aircraft on nuclear reactor structures that contain nuclear fuel (containment building and spent fuel pool) and in other structures that contain equipment necessary for removing heat generated by nuclear fuel. The plant conditions evaluated in this guideline, while beyond design basis, are consistent with the rule for new plant designs (10 CFR 50.150).

Information considered to be sensitive or Safeguards has been removed from this public version of NEI 07-13.

The methodology is divided into three subparts:

1. Containment and Spent Fuel Pool Evaluation: Two distinct types of structural failure modes need to be evaluated for containment structures and spent fuel pools – local (scabbing and perforation) failure caused by impact of the aircraft engines and global (plastic collapse) failure caused by impact of the complete aircraft. Local failure is largely independent of the global force/deflection characteristics of the impacted structure, whereas global failure depends primarily on the dynamic characteristics of the structure. The loading characteristics for these two distinct potential failure modes are quite different, as discussed in the following sections. The methodologies and analyses described in this section are based on work performed by EPRI in response to concerns about the ability of existing US nuclear plants to survive an aircraft impact. The methodology has been previously made available to the nuclear industry and to the Nuclear Regulatory Commission in a report entitled “Resistance of Nuclear Power Plant Structures Housing Nuclear Fuel to Aircraft Crash Impact” (Safeguards Information), Final Report by ABS Consulting, Anatech, and ERIN Engineering, Electric Power Research Institute, Palo Alto, CA, February 2003.

2. Heat Removal Evaluation: Physical, shock and fire effects of an aircraft impact can cause damage to systems needed to maintain cooling of fuel in the vessel as well as the spent fuel pool. Assessing the physical, shock and fire effects of aircraft impacts on the ability to maintain fuel cooling are more complex than analyzing impacts on containment structures and spent fuel pools. Needed equipment is typically located in structures that, while strong compared to standard commercial construction, are typically less robust than containment structures and spent fuel pools. The methodology described in this section is based on work performed by ERIN Engineering and Research, Inc. for the Nuclear Energy Institute. The methodology was developed by the industry based

on insights gleaned from studies conducted at existing nuclear power plants.

3. Design Enhancements: New nuclear power plants are evaluating the physical, shock and fire effects of an aircraft impact on containment, spent fuel pool structures and structures that contain SSCs needed to maintain fuel cooling using Sections 2 and 3 of this guideline to meet 10 CFR 50.150. The objective of these design-specific assessments is to identify potential design enhancements for maintaining the containment intact, maintaining spent fuel pool integrity and maintaining core cooling and spent fuel pool cooling with reduced use of operator actions as a result of a defined beyond design basis aircraft impact. NSSS vendors and applicants should place top priority in identifying structural design changes. However, it is recognized that it may not be practicable to implement structural design changes to protect from all postulated impact locations. For these instances, it may be necessary to employ system design enhancements to maintain fuel cooling with reduced use of operator actions. Section 4 provides guidance on developing design enhancements to maintain fuel cooling.

FOREWORD

This methodology has been developed to assist NSSS vendors in assessing the physical, fire and shock effects of the impact of a large commercial aircraft on nuclear reactor structures that contain nuclear fuel (containment building and spent fuel pool) and other structures that contain equipment necessary for removing heat generated by nuclear fuel.

Information considered to be sensitive or Safeguards has been removed from this public version of NEI 07-13.

The methodology is divided into three subparts:

1. Containment and Spent Fuel Pool Evaluation
2. Heat Removal Evaluation
3. Enhanced Design Features and Functional Capabilities

The plant conditions evaluated in this guideline, while beyond design basis, are consistent with the rule for new plant designs.

1 Objectives

The Sept. 11, 2001, terrorist attacks on the United States have drawn public attention to the potential for a crash of a large modern aircraft into structures that are part of our nation's critical infrastructure, including nuclear power plants. The industry undertook a number of studies to assess and enhance the capability of current nuclear power plants to withstand an intentional aircraft impact.

The Nuclear Regulatory Commission (NRC) has determined that the impact of a large, commercial aircraft is a beyond-design-basis event. The final aircraft impact assessment rule revises 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," and Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," to require applicants for new reactor designs to perform a design-specific assessment of the effects on the facility of the impact of a large, commercial aircraft. Using realistic analyses, applicants must identify and incorporate into the design those design features and functional capabilities to show that, with reduced use of operator actions:

(A) the reactor core remains cooled, or the containment remains intact; and

(B) spent fuel cooling or spent fuel pool integrity is maintained."

(See Section 6 for a definition of the terms used in the above NRC acceptance criteria.)

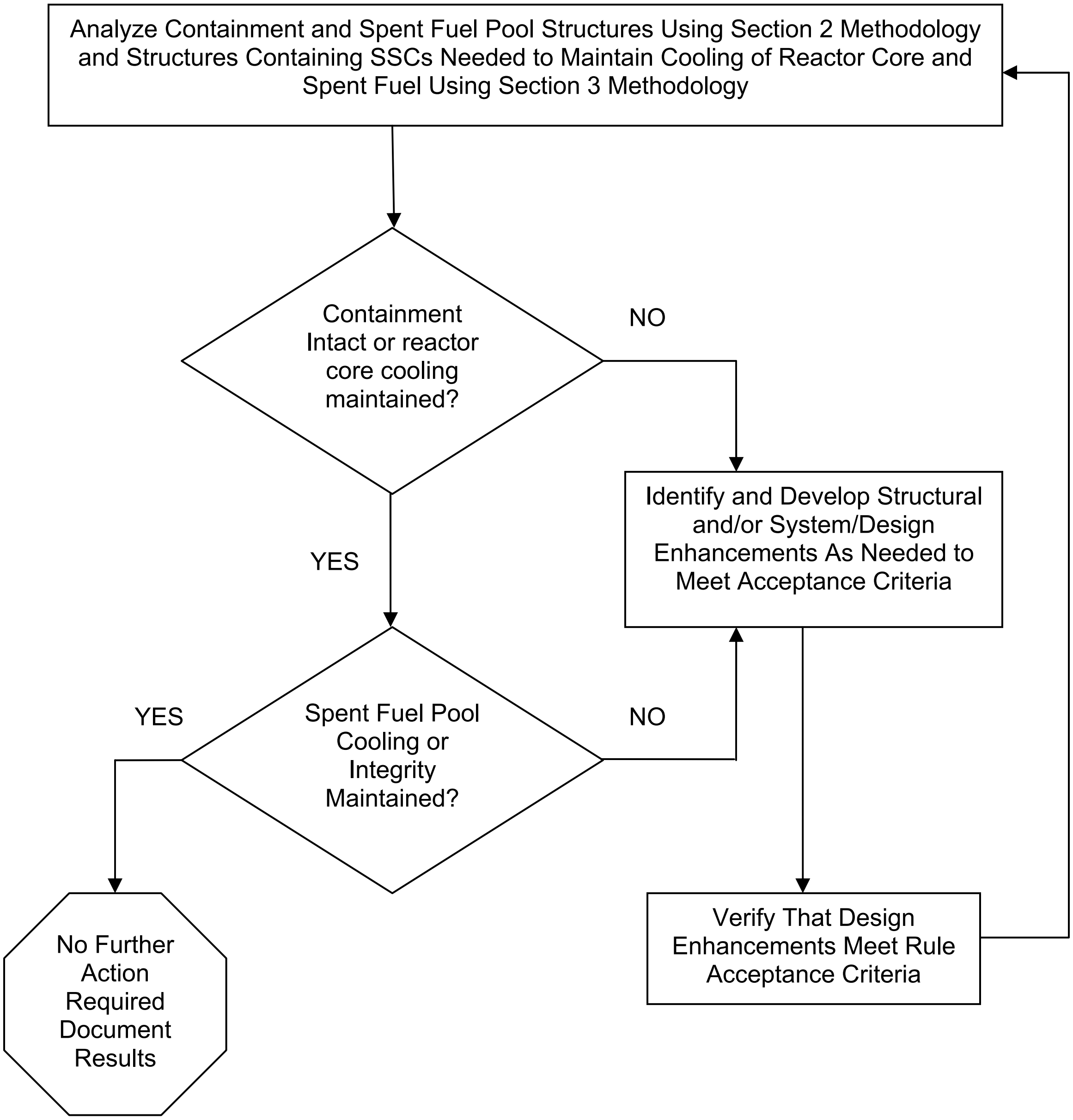
There are an almost unlimited number of potential assumptions and variables for conducting the assessments required by the NRC. The objective of this document is to provide a common methodology for performing the assessments so as to ensure a technically sound and consistent approach is used for each reactor design. To this objective, the analysis approaches defined in this document, including assumptions, criteria for material properties and overall acceptance criteria, are to be used by each applicant for a new plant design.

Given the number of variables in performing the required assessments, there is a range of uncertainty in the results obtained from the application of this guideline. There is obviously also an uncertainty associated with the characteristics of the aircraft impact itself. For these reasons, the methodologies described in this document are intended to provide "best estimate" results, consistent with the requirements of the final rule (10 CFR 50.150) to use realistic analyses. Treatment of uncertainties (hot shorts, spurious actuations, actual fire spread, shock effects, and estimated physical damage footprint) would overly complicate the assessments and are best addressed through 10 CFR 50.54 (h)(h) which requires all new plants to develop mitigation strategies to address loss of large areas of the plant due to fire or explosion from any cause.

Figure 1-1 provides an overall flow logic diagram for performing the required analyses and assessments.

Figure 1-1

Overall Guideline Logic Flow Diagram



2 Containment Structures and Spent Fuel Pools

This section of the document provides guidance for the aircraft impact structural evaluation of nuclear power plant structures that house nuclear fuel, such as containment and spent fuel pool structures. Guidance for aircraft impact evaluation of other nuclear power plant structures is provided in Sections 3 and 4. However, when the guidance in Sections 3 and 4 is found to be inapplicable, the guidance in this section can be used for the aircraft impact structural evaluation of nuclear power plant structures that do not house nuclear fuel. The guidance in this section is derived, in part, from the methodology used in the Electric Power Research Institute (EPRI) study of aircraft impact on nuclear power plant structures that house nuclear fuel [1].

Two distinct types of structural failure modes need to be evaluated for containment structures and spent fuel pools – local (scabbing and perforation) failure caused by impact of the aircraft engines and global (plastic collapse) failure caused by impact of the complete aircraft. Local failure is largely independent of the global force/deflection characteristics of the impacted structure, whereas global failure depends primarily on the dynamic characteristics of the structure. The loading characteristics for these two distinct potential failure modes are quite different, as discussed in the following sections.

2.1 Local Loading

2.1.1 Local Loading Characteristics

The sequence of localized loading effects consists of three stages - missile penetration into the target; spalling and scabbing of the target; and, potentially, missile perforation completely through the target. These terms are defined as follows:

- Penetration – the displacement of the missile into the target. It is a measure of the depth of the crater formed at the zone of impact.
- Spalling – the ejection of target material from the front face of the target (i.e., the face on which the missile impacts.)
- Scabbing – the ejection of material from the back face of the target (i.e., opposite the face of impact).
- Perforation – the missile fully penetrates and passes through the target. The term “perforation velocity” refers to the initial missile velocity, which is just sufficient to fully penetrate the target without exiting. The term “residual velocity” refers to the exit velocity of missile that has an initial velocity greater than the perforation velocity.

Such local damage modes would not, in general, result in structural collapse, but instead are considered because of their potential to damage safety-related systems or components. The induced velocity of the scabbed material or the residual velocity of the perforating missile could potentially cause equipment/system failures. Most technical references consider the engines of an aircraft as the critical missiles that can result in local structural damage. Although there are other stiff elements on an aircraft, the engines -- while absorbing energy due to crushing during impact -- are generally considered to have the greatest potential to cause local damage, since they are external appendages of the aircraft that can become independent missiles during aircraft impact. For nuclear plant structures, the aircraft will be impacting on heavy concrete walls, which will tend to crush the airframe structure. In this case, the landing gear struts are considered to have less local damage potential, since it is assumed that the aircraft is maintained in a flight configuration during the impact with the landing gear tucked away within the fuselage. As such, both the nose and main gear contribute to the global forces during the crush-up of the fuselage but they are not considered as independent missiles acting as local penetrators. Thus, the engines should be used as the “missiles” for the local damage mode assessments.

For this methodology, the primary local response effect of interest is the perforation of a compact, high density, but crushable engine through reinforced concrete walls. In addition, scabbing of concrete from the inside surface of the structure is considered briefly, but is considered to be of secondary importance unless critical equipment for plant shutdown is located at or near the back surface of the concrete wall at the location of missile impact. Testing has demonstrated that the concrete is ejected in small pieces with relatively low velocity [2], based on the observation that the ejecta tend to collect near the back surface of the reinforced concrete target. The other local effects (penetration and spalling) do not pose a threat to the safety-related systems necessary to shut down the nuclear plant and need not be considered in the evaluation, except possibly for critical equipment at that precise location.

Full-scale engine impact tests on concrete walls [3] have demonstrated that the local damage potential of turbojet engines can be predicted using modified empirical formulas developed to predict local wall damage from impact of solid cylindrical missiles. An impact test on a concrete wall using a modern turbofan engine [2] has demonstrated that the behavior of turbofan engines differs from the behavior of turbojet engines used in prior test programs. A turbofan engine is distinguished by a large diameter (approximately 6-inch) hollow shaft, which acted as a hardened penetrator in the wall test using a turbofan engine as a missile. While the shaft can punch through a wall similar to a pipe missile, it cannot exit the wall independent from the casing since the turbine discs attached to the shaft are trapped within the crushed casing. Thus, the engine cannot completely perforate and exit a wall until the casing has completed crushing and the combined crushed casing and shaft perforates a wall. Since the crushing behavior of turbofan casings is similar to turbojet casings, a modified or reduced solid missile formula developed to predict turbojet wall perforation is utilized in the methodology to predict the perforation potential of modern commercial turbofan engines impacting concrete walls.

In a similar manner, scabbing of material from the rear face of an unlined wall can be predicted with a modified or reduced solid missile formula. Tests using engine missiles have shown that the majority of scabbed pieces are small, with the largest being approximately the size of the rebar spacing and cover depth of the rebar on the rear face. Tests have also clearly demonstrated that a wall liner prevents the scabbing phenomenon.

Given that an impacting engine has an initial velocity that exceeds the perforation velocity associated with a primary structural target wall, the damage potential of the crushed engine mass impacting on secondary structural concrete walls or a steel containment shell at the residual velocity must be determined. The residual velocity of the perforating missile may be predicted by considering the residual kinetic energy (the initial kinetic energy of the missile less the energy loss during perforation) is imparted to the crushed engine mass and a volume of concrete which is also ejected. After perforation of a primary wall, the exiting casing and shaft is now a compacted semi-solid missile with the approximate diameter of the engine casing. Some of the engine mass may be lost due to scattering during the impact with the primary wall and the engine mass may be able to be further crushed (i.e., a semi-solid missile). Thus, the local damage potential of the crushed engines impacting on secondary concrete targets can be predicted using the same empirical formulas, but with a reduced mass and slightly different modification factors to account for the residual crushability of the remaining engine mass. For impact on steel containment shells, additional empirical formulas based on solid missile tests on steel plates are available for prediction of perforation potential. In this case, the residual crushability of the remaining engine mass is not considered.

The recommended empirical formulas, appropriately modified for prediction of engine impact damage to both primary concrete walls and secondary concrete walls or steel containment vessels, are provided below as a simplified approach to assessment of structural integrity for local loading on nuclear plant structures. These recommended formulas are based on comparisons in the literature with experimental results, and on expert judgment with respect to the best approximations to those data.

2.1.2 Local Loading Formulas

The NRC will provide each NSSS vendor (or their appointed representatives) with the aircraft engine parameters necessary to apply the formulas provided in

Section 2.1.2. The information provided by the NRC is considered SGI and is not contained in this document.

2.1.2.1 Missile Penetration Depth

The penetration depth (or concrete damage depth) (x_c) of the crushed mass of the engine casing is given by the Modified NDRC (National Defense Research Committee) equation for large diameter missiles:

$$x_c = \alpha_c \{4\ K\ W\ N\ D\ (V / (1000\ D))^{1.8}\}^{1/2}, \text{ for } x_c / \{\alpha_c\ D\} < 2, \qquad [2\text{-}1]$$

where x_c is the crushed casing penetration depth in inches, V is the engine velocity in ft/sec, D is the average outer diameter of the engine casing in inches, W is the total engine weight (in lbs), $K=180/(f_c')^{1/2}$, N=0.72 (flat-nose missile), f_c' is the concrete strength in psi, and $\alpha_c = 0.5$ is the penetration reduction factor to account for missile deformability as suggested in Reference 3.

2.1.2.2 Wall Thickness Required to Prevent Scabbing

The wall thickness required to prevent scabbing (t_s) is computed using the reduced Chang formula [4]:

$$t_s = \alpha_s\ 1.84\ (200 / V)^{0.13} (M\ V^2)^{0.4} / (\{D/12\}^{0.2}\ \{144\ f_c'\}^{0.4}), \qquad [2\text{-}2]$$

where M = W/g and g = 32.2 ft/sec^2. The factors of 12 and 144 used in Equation [2-2] are used to convert the units of casing diameter (inches) and concrete compressive strength (psi) to the units (ft, psf) used in the empirical Chang formula. The recommended value for α_s is 0.55.

2.1.2.3 Wall Thickness Required to Prevent Perforation

The reduced Degen formula [4] is used to calculate wall thickness to prevent perforation (t_p):

$$t_p = \alpha_p\ D\ \{2.2\ (x_c/\{\alpha_c\ D\}) - 0.3\ (x_c/\{\alpha_c\ D\})^2\}, \text{ for } x_c/\{\alpha_c\ D\} \leq 1.52. \qquad [2\text{-}3]$$

The recommended value for α_p is 0.60.

2.1.2.4 Exit Velocity of Missile

For missile velocities in excess of those required to perforate a given wall thickness, Sugano et al. [3] recommend that the exit velocity of the engine missile be estimated using the relationship cited by Kar [5] and attributed to CEA-EDF:

$$V_R^2 = \{1/(1 + W_{cp}/W)\}\ (V_I^2 - V_P^2), \text{ for } V_I > V_P, \qquad [2\text{-}4]$$

where V_R is the residual velocity of the missile after wall perforation, V_I is the initial impact velocity of the missile prior to wall impact, and V_P is the missile velocity that just initiates perforation. In Equation [2-4], W_{cp} represents the weight of the concrete plug ejected by the perforating missile with weight, W. A simple rearrangement of Equation [2-4] indicates that it represents an energy balance, $½(W/g)(V_I^2 - V_P^2) = ½[(W + W_{cp})/g]V_R^2$, where the initial kinetic energy of the missile, ½(W/g)(V_I^2), less the energy lost in perforation, ½(W/g)(V_P^2) {since V_P is the velocity that just yields $V_R = 0$}, is equal to the kinetic energy imparted to the combined missile and concrete plug mass. Sugano et al. [3] recommend that the weight of the ejected concrete be estimated using the conical plug geometry developed by Kar [5], where the volume of the ejected concrete is given by a cone with minor radius, $r_1 = D/2$, and major radius, $r_2 = r_1 + t_w(\tan\theta)$, where $\theta = 45°/(t_w/D)^{1/3} \leq 60°$, and where t_w is the wall thickness. The concrete plug weight is thus given by $W_{cp} = \pi\ \rho_c(t_w/3)(r_1^2 + r_1r_2 + r_2^2)$, where ρ_c is the weight density of concrete.

Kar [5] suggested that the perforation velocity, V_P, be estimated using the CEA-EDF formula with a wall thickness reduction factor of $\alpha_{EDF} = 0.75$. However, comparison of the Degen, CEA-EDF, Chang, and CRIEPI formulas for the wall thickness required to prevent perforation (see Reference 6) will show that each formula gives a comparable estimate for perforation velocity, V_P. Since Equation [2-4] is based on a energy balance with the assumption that the residual velocity of the missile and ejected concrete are the same, it is judged that the perforation velocity, V_P, estimated using the reduced Degen formula (Equations [2-1] and [2-3]) may also be used in Equation [2-4] to provide an estimate of residual velocity. Thus, the missile velocity required to just perforate (i.e., with no residual velocity) a given wall thickness, t_w, is found by letting $t_p = t_w$, solving Equation [2-3] for $x_c/\{\alpha_c D\}$ with a reduction factor, $\alpha_p = 0.6$, and then using Equation [2-1] with a reduction factor, $\alpha_c = 0.5$, to determine V_P.

Reference to test data measurements of residual velocity of missile perforating reinforced concrete walls (e.g., Sliter [7]) indicates that there is considerable variability in the test results, particularly when the initial impact velocity is near the perforation level. It is judged that the use of Equation [2-4], with Degen perforation velocity and the concrete cone ejection plug for the volume of ejected concrete provides a best estimate of residual velocity for the engine and concrete plug.

2.2 Global Loading

2.2.1 Global Loading Characteristics

Global structural response effects refer to the overall building behavior in response to the applied aircraft impact loading. The global response can be characterized by major structural damage, such as collapse of large portions of the building walls, floors, and load carrying members. The airplane impact will also potentially induce vibrations throughout the building, but these vibrations are judged not to challenge the structural boundaries, which are the focus of this evaluation. Thus, the analyses of global response evaluated in this methodology are limited to the assessment of overall structural integrity.

While local damage is associated with the penetration of a missile into the wall resulting in scabbing of concrete from the rear face and ultimately local fracture of rebar allowing perforation of the wall by the residual crushed engine mass and remaining portion of the shaft, global structural damage is, in the general case, associated with the excessive deformation of the entire structural system, assuming that local perforation does not occur.

In impact analysis, global structural damage of the target structure can be evaluated analytically based on 1) missile initial velocity, and 2) target inertial, structural, and dynamic characteristics. Depending on the availability of data on these characteristics and the intended level of detail of analysis, one of the following methods of evaluation can be used:

- Force Time-History Analysis Method: In this method, the impact force time-history is first determined based on the aircraft crushing strength information and impulse conservation principles, assuming that the target is rigid. The force time-history so obtained is then applied to a mathematical model of the structure in a time history analysis. Based on the internal forces and the associated stresses due to the computed response, the structure's capability to maintain integrity is then evaluated. (The time history analysis will also yield displacement/acceleration time histories throughout the structure that can be used to assess equipment functional capability during and after the impact).
- Missile-Target Interaction Analysis Method: In this method, a combined dynamic analysis model of both the missile and target is developed, and the dynamic response is determined as an initial velocity problem. The nonlinear models are typically significantly larger and more complex than those used for the force time-history analysis method. Accordingly, this method requires more detailed inertial and stiffness data of the missile than the above time-history analysis method but can potentially provide more accurate results.

2.2.2 Development of Impact Force Time Histories

The construction of a loading function for use in time history analyses is generally referred to as the Riera methodology [8] and is adopted and described in DOE-STD-3014 [8] and the associated technical support document [4] for accident analysis due to aircraft crash impact. This is an approximate method based on momentum principle and was developed for a head-on-type impact which allows the aircraft fuselage to progressively crush/buckle axially against a rigid target, resulting in the force time-history to which the target is subjected. The signature of this force time-history, as well as its peak value, depends on the spatial mass distribution of various heavy segments/components, as well as the loads/forces at which some of these components can become detached from the crushing fuselage. The basic assumptions of the Riera method are: 1) the target is rigid; 2) the length or axis of the aircraft is normal to the target; 3) the aircraft is separated into two regions, one being uncrushed and moving with velocity, V, and the other region being crushed with zero velocity; 4) all crushing takes place within a local region adjacent to the rigid target; and 5) the crushing or material behavior of the airframe is rigid-perfectly plastic.

The key formula in the computation of the force applied to the rigid target, F(t), or the impact force time-history, is given by:

$$F(t) = P_c(x) + \alpha_r \, \mu(x) \, (dx/dt)^2, \qquad [2\text{-}5]$$

where x(t) is the crushed length of the aircraft, [i.e., the distance from the nose of the plane (when uncrushed) to the point to which crushing has progressed at time t], $P_c(x)$ is the static force required to crush a lamina of the airframe axially at location x, α_r is a coefficient determined experimentally, and $\mu(x)$ is the mass per unit length at location x. At the initiation of the impact to a rigid target, V(= dx/dt), is equal to the initial velocity, V_I, of the aircraft. Equation [2-5] is a nonlinear differential equation with $P_c(x)$ and $\mu(x)$, in general, being discrete functions.

The mass per unit length may be partitioned as:

$$\mu(x) = \mu_s(x) + \mu_e(x) + \mu_f(x), \qquad [2\text{-}6]$$

where $\mu_s(x)$ is the airframe mass per unit length, $\mu_e(x)$ is the "soft" or weakly attached equipment mass per unit length, and $\mu_f(x)$ is the fuel mass per unit length.

The crushing force may be partitioned as:

$$P_c(x) = P_s(x) + P_e(x) \qquad [2\text{-}7]$$

where $P_s(x)$ is the airframe crushing resistance and $P_e(x)$ is the crushing resistance of the trapped soft equipment. In general, the crushing resistance is taken proportional to the mass per unit length or, $P_i(x) = K_i \, \mu_i(x)$, where K_i is a crushing modulus.

An additional equation

$$a = d^2x/dt^2 = -P_s(x) / \int_x^L \mu(x) \, dx \qquad [2\text{-}8]$$

provides the deceleration of the uncrushed mass caused by the structural component of the crushing force, $P_s(x)$. The force involved in crushing of the soft equipment is assumed not to have a force transfer path to the remaining uncrushed airplane.

Using the kinematic relationships between acceleration and velocity, and displacement, a numeric step-by-step scheme can readily be devised such that the force time-history can be computed.

The Riera methodology was validated against full-scale test data involving an F-4 Phantom military aircraft impacting a rigid reinforced concrete reaction block [3, 10], and the coefficient, α_r , was determined to be $\alpha_r = 0.9$.

The accuracy and applicability of the resulting impact force time-history depend on the validity of the two primary assumptions on which it is based (i.e., the target is rigid and the impact orientation is such that the fuselage crushes/buckles axially), and the accuracy with which the mass distribution, fuselage crushing strength, and the detachment forces for various segments/components can be obtained from available data.

2.2.3 Impact Force Time History To Be Applied

The NRC will provide the actual Riera function to be used in the analysis. The NRC-supplied Riera function is considered to be SGI and is not included in this document.

2.2.4 Spatial Distribution of Impact Force

For the finite element based calculations for the containment and used fuel pool structures, the input force-time history is applied as a pressure time history, and assumptions for the loading area are developed based on appropriate crushing characteristics of the airframe.

The NRC will provide the actual spatial distribution of impact force to be used for new plants. The NRC supplied spatial distribution is considered to be SGI and is not included in this document.

2.2.5 Missile-Target Interaction Analysis Method

An alternative to using the Riera function methodology is the Missile-Target Interaction Analysis Method. In this method, a combined dynamic analysis model of the missile and target is developed, and the dynamic response is determined as an initial velocity problem.

Since the NRC is providing a prescribed force-time (Riera) history for the structural vulnerability assessments, a demonstration that a missile-target interaction analysis model suitably represents that prescribed force-time history is required. Such a demonstration is based on applying the missile model representation, at a given initial velocity, to a rigid wall structure, so that all of the impact energy is absorbed in missile deformation. Typically, the missile-rigid wall force-time history that is derived from this loading application contains a considerable amount of high-frequency and potentially spurious structural response (“noise”). In order to compare the force-time history from the missile-rigid wall analysis with the prescribed force-time history, the former is passed through a low-pass numerical filter (centered in the 50 Hz to 100 Hz range) that preserves the essential characteristics of the structural response, while eliminating much of the noise. In such a way, the missile-target interaction analysis model can be shown to produce a demonstrated equivalence to the prescribed force-time history.

This method usually requires a detailed knowledge of the missile to develop a finite element model that produces equivalent force-time history characteristics.

2.3 Material Characterization And Failure Criteria Summary

The selection of realistic dynamic strength properties and strain based failure criteria for the steel and concrete materials is appropriate as the analyses are for beyond-design-basis events and are intended to represent best estimates of material behavior. Therefore, the use of industry standards based on minimum material properties is not warranted.

2.3.1 Material Properties

For analysis of impact effects on structures, an increase in strength due to the high strain rates involved in the deformation process is appropriate. In general, the static strength values should be increased by using Dynamic Increase Factors (DIFs). An exception would be the case where DIFs are explicitly included already in particular material constitutive models. In such a case, however, the analyst should ascertain that any DIF effects in the constitutive models are appropriate for the application.

Ample justification for the DIFs selected for the aircraft impact analysis is provided in the following discussion. For example, Appendix C of ACI Standard 349 [11], ASCE Manual 58 [12], ASCE Report on Blast Resistant Buildings in Petrochemical Facilities [13], and DOD Manual TM 5-1300 [14] provide recommended DIF values for strain rate effects on material strength. The DIF values given in these references are all judged to have a somewhat conservative design bias (low estimates of strength increase due to strain rate effects). These values are given in Table 2-1, and are judged to be appropriate for aircraft impact evaluation.

For concrete materials, stress-strain behavior is quantified by the compression strength of a standard test cylinder, thus the dynamic evaluation strength is given by:

$$f'_{dc} = f'_{c}\,(DIF_{c}) \qquad [2\text{-}9]$$

It must be noted that the concrete DIF factors are for use in structural analysis only and are not to be applied to the concrete strength used in empirical impact correlations with test data.

For steel materials, the evaluation stress level is quantified by the strain range expected during dynamic loading. For structural components undergoing plastic deformation, an elastic-plastic bi-linear stress-strain relationship is often assumed for evaluation of deformation and strength of structural components.

DOD Manual TM 5-1300 [14] considers two regimes of response behavior: Type 1) characterized by member ductility (ratio of maximum displacement to elastic displacement), $\mu \leq 10$ or support rotations (for assumed collapse mechanisms), $\theta < 2°$ and Type 2) characterized by member ductility $\mu > 10$ or support rotations within the range $2° < \theta < 5°$. For Type 1 behavior, the dynamic evaluation stress or the effective yield level of the bi-linear resistance function is simply given by:

$$f_{es} = f_y\,(DIF_y) \qquad [2\text{-}10]$$

For Type 2 behavior, the dynamic evaluation stress or the effective yield level of the bi-linear resistance function is given by:

$$f_{es} = f_y\,(DIF_y) + [f_u\,(DIF_u) - f_y\,(DIF_y)]/4 \qquad [2\text{-}11]$$

For steel materials, the specified minimum strength is always less than the actual strength of the material supplied for construction. For new plant construction, the typical values provided below should be used only when experience with the expected materials of construction warrant their use. In the table below, typical steel properties are compared with minimum properties from ASTM standard specifications. The typical properties are based on measurements from actual materials of construction.

An example of the comparison between minimum specified material strength values and typical (mean) test values is provided by the following tabulation:

Steel Material	Min/Typ	Yield Strength, ksi	Tensile Strength, ksi
SA 516-70 Carbon Steel	Min	38	70
	Typ[1]	48.6	77
Grade 60 Reinforcing Steel	Min	60	90
	Typ[2]	67.5	106.3

[1] Rodabaugh and Desai [15]
[2] Mirza [16]

An example determination of dynamic evaluation strength values for steel plate and reinforcing steel is given by the following:

Steel Plate:

ASTM A516 Grade 70:

$f_y = 48{,}600$ psi, $DIF_{y(steel)} = 1.29$, $f_{dy} = f_y \times DIF_y = 62{,}690$ psi

$f_u = 77{,}000$ psi, $DIF_{u(steel)} = 1.10$, $f_{du} = f_u \times DIF_u = 84{,}700$ psi

Evaluation Stress, f_{es}: (μ = displacement ductility, θ = support rotation)

Type 1 Behavior; $\mu \leq 10$, $\theta < 2°$: $f_{es} = f_{dy}$ = 62,690 psi

Type 1 Behavior; $\mu > 10$, $2° < \theta < 5°$: $f_{es} = f_{dy} + (f_{du}-f_{dy})/4$ = 68,190 psi

Reinforcing Steel:

Grade 60 rebar:
f_y = 67,500 psi, $DIF_{y(rebar)}$ = 1.1, $f_{dy} = f_y \times DIF_y$ = 74,250 psi

f_u = 106,300 psi, $DIF_{u(rebar)}$ = 1.05, $f_{du} = f_u \times DIF_u$ = 111,615 psi

Rebar Evaluation Stress, f_{es} (θ = support rotation)

Type I behavior (small displacement/no concrete crushing, $\theta < 2°$) : $f_{es} = f_{dy}$ = 74,250 psi

Type II behavior (large displacement, concrete crushing, $2° < \theta < 5°$): $f_{es} = f_{dy} + (f_{du}-f_{dy})/4$ = 83,591 psi

The actual strength of the concrete used for construction is always greater than the specified design strength. For statistical control of the batch process used to produce concrete for construction, the ACI 349 code [11] requires that the average 28-day test cylinder strength, f_c', exceed the specified design strength, $f_c'_{(design)}$, according to the relation, $f_c' \geq f_c'_{(design)} + 1.34\ s$, where s is the standard deviation of the test strength determined for the set of test cylinders. For typical batch concrete production, the variability of test cylinder strength may be estimated using a coefficient of variation of approximately 10%, or a value COV = 0.1.

It is also appropriate to consider a concrete strength increase due to the effects of concrete aging. Studies conducted on nuclear structures [17, 18] have found strength increases with age in the range of 1.2- 1.6. A 28 day test strength increase factor of 1.2 for concrete members less than 3 feet in thickness and an increase factor of 1.4 for concrete members equal to or greater than 3 feet in thickness are judged reasonable to account for the effects of concrete aging. An example determination of dynamic evaluation concrete strength is given by the following:

Concrete:

***Concrete 28 Day Test Strength*:**

$f'_c = f'_{c(design)} + 1.34s$, $s = COV \times f'_c$, $COV = 0.1$;

therefore, for $f'_{c(design)} = 4000$ psi, we have $f'_c = 4000/(1-1.34(0.1)) = 4619$ psi

***Aging Effect*:**

for t < 3 ft., $f'_{c(age)} = 1.2 \times f'_c = 5543$ psi

for t ≥ 3 ft., $f'_{c(age)} = 1.4 \times f'_c = 6467$ psi

***Dynamic Increase Factor*:**

$DIF_{(concrete)} = 1.25$, $f'_{dc} = f'_{c(age)} \times DIF_{(concrete)} = 6928$ psi

2.3.2 Ductile Failure Strain Limits

Two ductile failure criteria were developed to be used in the global structural response evaluations – a strain-based ductile failure criterion for both carbon/low-alloy and austenitic stainless steel plate material used for liners and shells, and a strain-based ductile failure criterion for reinforcing steel and pre-stressing tendons. The basis and rationale for the selection of the failure strain limits is presented in Reference 1. Table 2-2 provides a summary of the strain limits developed for the ductile materials used in nuclear power plant structures.

For the representative steel plate materials, strain limits are established to protect against 1) global membrane failure due to plastic tensile instability and 2) localized fracture due to ductile tearing of the specific material used to fabricate a given steel shell structure. The global ductile failure strain limit value includes a knockdown of the tensile instability strain to account for variability in material properties in weld regions and for material hardness. In both cases, the strain limit capacity is established by standard tensile test results, as modified by the effects of complex stress states.

For locations in the structure under more complex states of stress, ductile failure occurs by the mechanism of ductile tearing, which depends on the triaxiality of the local state of stress. Therefore, the local ductile tearing effective strain limits given in Table 2-2 include a knockdown factor to account for weld effects, and are further reduced by dividing by the triaxiality factor (TF), which is defined as.

$$TF = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_e}, \qquad [2\text{-}13]$$

where $\sigma_1, \sigma_2, \sigma_3$ = principal stresses, and σ_e = effective (or equivalent) stress, or

$$\sigma_e = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{\frac{1}{2}} \qquad [2\text{-}14]$$

In both cases, the strain limit capacity is established by median standard tensile test results, as modified by the effects of complex stress states. For application of the global membrane strain limit, it is assumed that principal tensile membrane strains are being tracked in the analysis. To apply the ductile tearing limit, effective strain must be utilized.

In lieu of computing TF, the analyst may conservatively choose TF = 2.

For reinforcing steel, the strain limit includes a knockdown of the tensile instability strain to account for local strain concentration effects caused by concrete cracking.

2.3.3 Concrete Structural Failure Criteria

In the evaluation of structures housing nuclear fuel, the definition of failure is ultimately based on the loss of structural integrity to the extent that the containment/confinement function and protection of the nuclear fuel within the structure cannot be assured. Consequently, for such a structure not to fail, it has to maintain overall structural integrity and the containment or confinement barrier must not be breached. In case of reinforced concrete and pre-stressed concrete containments and fuel storage pools, the barrier is provided by a steel plate liner anchored on the inside surface of the concrete structure. In the case of a free-standing steel containment, the entire steel vessel provides the containment boundary. For structures storing nuclear fuel, structural integrity must be maintained and there can be no perforation of the confinement barrier (typically a stainless steel liner in the used fuel storage pool.)

Reinforcing/pretensioning steel and concrete act in combination, as a system, to resist applied loading. It is acceptable for the impact loading to cause damage to the components of the lattice as long as structural integrity is maintained to the extent detailed above. Thus, it is acceptable for the impact loading to cause local inelastic deformation and damage to concrete material in the form of cracking and crushing as long as the containment/confinement barrier is not breached.

How the modern, large-scale, nonlinear finite element computer analysis programs determine if the above failure criteria are met can be thought of as consisting, essentially, of two aspects:

1. A detailed description of material response to three-dimensional stress and strain utilizing detailed material *constitutive models*. Based on the momentary state of three-dimensional (including the prior history as well as the rate of change) stress and strain, these material models provide the information for the algorithms to compute the momentary stiffness properties of each element. This modeling incorporates description of the various nonlinear material response aspects, e.g., for concrete, cracking

and crushing, and for steel, tensile or compressive yielding with associated strain hardening and hysteretic behavior. Appendix D of Reference 1 provides a complete description of the concrete constitutive equations appropriate for use in time history analyses.

2. The definition of limits on “how far” each material can deform before either failure occurs (rupture or uncontrolled deformation) or the computational limits of the constitutive model are encountered. While some of this information is incorporated into the material constitutive models, typically the analyst must either provide some of these limits as part of the modeling input data or he has to “track” the extent of nonlinear material deformation (strains) during the solution process and determine that the predefined limits are not exceeded. One consideration in setting the failure limits (in terms of strain) is the fact that finite element modeling only resolves the various response parameters on the “element level”. Because of this, the response parameters as displayed by the program are somewhat “smoothed” (or averaged) over all the values that may occur within the element. (For example, the rebar strain value reported at a particular element node is actually an “average” based on values in the neighboring elements. Localized peak strains that may occur, e.g. at locations where cracks develop in reinforced concrete, are therefore not reflected in the strain values reported by the program.)

Consequently, the accuracy of the prediction of failure depends in part on the following two key factors:

- The level of accuracy of the constitutive models implemented in a particular finite element program predicts the degree to which the true material behavior is modeled. (Many constitutive models also require “additional material characterization parameters” to be provided by the analyst, e.g., for concrete the aggregate size or the compressive strain softening curve. Obviously, the quality/accuracy of computed predictions also depends on the quality of such information)
- Proper definition of the failure strains based on (a) the specific materials in the structure, and (b) considerations such as the “averaging” discussed above.

The constitutive models are typically “built in” to the programs and as such beyond the control of the analyst (except for the “additional material characterization parameters” that the analyst may provide). The quality/accuracy of the constitutive models can be judged based on (a) review of the model formulation against the information available in the material science and finite element literature, and (b) review of the sample validation cases (against test results) available.

The prediction of failure in reinforced or post-tensioned concrete structures is a difficult task due to the composite nature of concrete combining both ductile and brittle materials. Two general types of failure can be identified 1) flexural failure, which is associated with the exhaustion of material ductility of the steel reinforcing (typically nuclear structures have both compression and tension reinforcement) and 2) shear failure, which is associated with loss of local shear transfer capacity (shear reinforcement is typically not utilized in nuclear structures). The development of appropriate strain limits to judge if an analysis of a concrete structure has reached a failure condition is much more subjective than for ductile steel shell-type structures or liners.

The selection of an appropriate strain limit that defines concrete failure depends upon the controlling type of failure -- flexural or shear failure. The controlling failure mode can usually be identified by examination of the results at different steps in the analysis. The progression toward failure that determines the governing failure mode generally follows the steps below.

1. Local tensile cracking of the concrete occurs first, governed by an interaction failure criterion for local concrete tensile behavior;
2. The tensile stress normal to the tensile crack is reduced to zero, with corresponding load shedding to reinforcement (given that reinforcement is present);
3. The local shear capacity in the cracked concrete is affected, and is a function of the "tightness" of the tensile cracks and their eventual width; as the cracks widen, the shear capacity is gradually reduced to zero;
4. The tensile cracks are permitted to close and carry compressive loads across the crack surfaces, but are never permitted to heal and carry tensile stress normal to the crack surfaces; and
5. For very high local compressive loads, the load capacity of the concrete in compression is limited to the compressive strength, as a function of biaxial or triaxial confinement conditions, with strain softening beyond the compressive yield stress.

The concrete material failure mechanisms are built into the material constitutive models. It should be noted that the ductile strain limits established for the liner plate materials, together with the residual shear strength capacity of the concrete, represent the ultimate containment/confinement barrier.

Table 2-1. Dynamic Increase Factors (DIF) for Material Dynamic Strength Increase, References 11, 13, and 14

Material	DIF	
	Yield Strength	Ultimate Strength
Carbon Steel Plate	1.29	1.10
Stainless Steel Plate	1.18	1.00
Reinforcing Steel Grade 40 Grade 60	1.20 1.10	1.05
Pre-stressing Steel	1.00	1.00
Concrete Compression Strength	-	1.25
Concrete Shear Strength	-	1.10

Table 2-2. Ductile Material Failure Strain Limits

Material	Strain Measure	Limiting Value
SA 516 Steel Plate	Membrane Principal Strain (Tensile)	0.050
	Local Ductile Tearing Effective Strain	0.140/TF
304 Stainless Steel Plate	Membrane Principal Strain (Tensile)	0.067
	Local Ductile Tearing Effective Strain	0.275/TF
Grade 60 Reinforcing Steel	Tensile Strain (Uniaxial)	0.050
Post-tensioning Steel (ungrouted tendons)	Tensile Strain (Uniaxial)	0.030
Post-tensioning Steel (grouted tendons)	Tensile Strain (Uniaxial)	0.020

2.3.4 Material Models

The behavior of concrete is highly nonlinear, with low tensile strength, high nominal compressive strength, and shear stiffness and strength that depend on crack width. In addition, the degradation of compressive capacity after the compressive strength is reached should be included. Cyclic loading induces opening and closing of cracks and can lead to further degradation of properties. Modeling of concrete material, especially under conditions where extensive damage can develop, requires advanced and detailed constitutive models. The main components of concrete constitutive models are tensile cracking, post-cracking shear performance, and compressive yielding.

An adequate concrete model should treat concrete cracking with a smeared cracking model; i.e., when cracking occurs, the normal stress across the crack is reduced and the distribution of stresses around the crack is recalculated. Cracks are assumed to form perpendicular to the directions of largest tensile strains. Multiple cracks are allowed to form, but they are constrained to be mutually orthogonal. Once a crack forms, the normal stress across the crack is reduced to zero. The shear stiffness and stress is also reduced upon cracking and further decays as the crack opens. This effect is known as "shear retention." Once a crack forms, the direction of the crack remains fixed and can never "heal." However, a crack can close, resist compression, and re-open under load reversals. The concrete model allows cracking to develop in three directions at any material point as dictated by the state of stress and strain. This allows stress redistribution and load transfer to reinforcement or other load paths in the structure.

A most important feature of concrete modeling, especially for loads causing extensive damage, is the ability to capture the shear capacity in cracked concrete. An adequate concrete model should contain a shear shedding feature to limit the buildup of shear stress across an open crack. A shear retention model reduces the incremental shear modulus across on open crack. The shear shedding model reduces the shear stresses previously built up across an open crack provided the crack continues to open

The input properties of the concrete are defined from the nominal compressive strength of the concrete. The nominal, or in this case measured, compressive strength is increased by 25% to account for rate effects due to the impact loading. The modulus is then determined from the ACI formula,

$$E_c = 57{,}000\sqrt{f'_c} \text{ in units of psi} \qquad (2\text{-}15)$$

The tensile strength is determined as

$$\sigma_t = 1.7\left(f'_c\right)^{2/3} \text{ in units of psi,} \qquad (2\text{-}16)$$

The modulus of reinforcing steel is taken to be 29.0E6 psi.

Additional information on the concrete and steel material models can be found in Reference 1.

2.3.5 Structural Integrity Failure Criteria

The recommended structural integrity failure criteria are the same as those used for the EPRI aircraft impact studies of existing nuclear power plants, and have been validated by benchmarking against test results, such as the Sandia National Laboratories rocket sled track water slug impact tests WS-1 and WS-2 [19]. The structural integrity failure criteria for use in realistic analysis are based upon strain levels without any margin.

For concrete structures, the failure criterion for the concrete itself is cracking that leads to a closed-loop shear strain mechanism forming completely through the wall, with the shear strain in the mechanism loop greater than 0.5 % through the wall.

Further detail on these structural acceptance criteria can be found in References 1 and 19.

2.4 MAJOR ASSUMPTIONS

The following major assumptions apply to the methodology for assessing the integrity of containment buildings subjected to an aircraft impact. It is noted that many of the assumptions are conservative. This approach helps to at least partially offset uncertainties in both the aircraft impact and the structural response models.

2.4.1 Containment Analyses

1. The aircraft and engine are assumed to strike perpendicular to the centerline of the structure, thereby subjecting the structure to the maximum force of the aircraft. Because the containment is curved, missing the centerline reduces impact forces.
2. For free-standing steel containment designs, special consideration of missile-target interaction may be necessary, depending upon the resistance of the shield building surrounding the containment. If perforation of the shield building is expected, missile-target interaction enables the shield building shear plug failure to be defined, the residual velocity of the combined crushed airplane/concrete plug to be determined, and the ensuing impact on the free-standing steel shell to be evaluated.
3. Past experience with aircraft impact analysis of nuclear power plant structures has not been all inclusive, and new plant designs may contain design features for which experimental and analytical experience is lacking. In such a case, it is important to recognize that these new design features may be subject to failure modes that are outside the existing

experience base, and may require experimentally-verified analytical evaluations. For example, good flexural load carrying capability of a composite steel plate encased concrete wall requires adequate capability to transfer shear across the steel-concrete interface.

4. Regions of the containment that contain potentially critical penetrations may require special consideration.

2.4.2 Spent Fuel Pool Analyses

1. Both the engine and the aircraft fuselage are assumed to strike at the mid-height and mid-span of the pool wall, which may be the location where maximum damage is expected, and where the potential for inventory loss is greater. However, the possibility that aircraft impact at other locations could result in greater consequences should be assessed.

2. Both the engine and the aircraft fuselage are assumed to strike perpendicular to the surface of the wall. Lesser impact angles would impart less force to the wall.

3. No credit has been taken in past spent fuel pool analyses for the effects of pool water inventory in reducing the consequences of aircraft impact. This effect could be substantial. If credit is taken, care should be exercised in assuring that the added mass of the water is modeled conservatively.
4. Even if aircraft impact does not cause spent fuel pool wall failure and loss of pool water inventory, potential damage from wall motion on adjacent fuel assemblies should be evaluated, in order to verify adequate clearance between the deformed pool liner and the fuel assemblies.

5. The exact location of the spent fuel pool is not visible from a plant's exterior. It would therefore be extremely difficult for an attacker to identify and strike the pool. Both the engine and the aircraft fuselage are assumed to strike at the mid-height and mid-span of the pool wall.

6. Some spent fuel pool buildings have exterior walls that are not part of the spent fuel pool. Either the Riera function approach or the missile-target interaction method may be used to evaluate such features.

2.5 SUFFICIENCY CRITERIA

2.5.1 Containment Intact

The containment structure is considered to be acceptable if the containment is maintained intact from both the local and global impact analyses. The containment remains intact if structural analyses performed with methods described in Section 2 of this guide show that perforation of a steel containment or concrete containment with steel liner does not occur on impact and that the containment ultimate pressure capability, given a core damage event, would not be exceeded before effective mitigation strategies can be implemented..

Effective mitigation strategies are those that, for an indefinite period of time, provide sufficient cooling to the damaged core or containment to limit temperature and pressure challenges below the ultimate pressure capability of the containment as defined in DCD/FSAR Chapter 19.

[NOTES: (1) For BWRs, actuation of the wetwell vent line is acceptable as this is a designed, scrubbed release. (2) The containment ultimate pressure capability described in DCD/FSAR Chapter 19 is appropriate for use provided there is no structural damage to the containment structure. If structural damage has occurred to the containment structure, a revised ultimate pressure capability considering the damaged condition must be determined.]

2.5.2 Spent Fuel Pool Integrity

Localized crushing and cracking of the concrete wall of the pool is acceptable provided the analyses conclude that the aircraft impact on the spent fuel pool wall and support structures does not result in leakage through the spent fuel pool liner below the required minimum water level of the pool.

[NOTE: Required minimum water level is the minimum operating level of the spent fuel pool as required by the plant technical specifications.]

If the fuel pool liner does not have a leakage path below the minimum water level, the fuel is protected and there would be no unacceptable release of radionuclides to the environment.

3 Heat Removal Capability

Aircraft impacts and resulting fires and shock can cause damage to important systems and support systems needed to maintain fuel cooling. Assessing the effects of aircraft impacts and subsequent fires on the ability to maintain fuel cooling is more complex than analyzing impacts on containment structures and spent fuel pools. The purpose of this part is to determine if fuel cooling can be maintained. The use of multiple trains of equipment, highly compartmentalized configurations and the spatial separation found in newer plant designs increases the likelihood of being able to maintain fuel cooling subsequent to an aircraft impact.

While it is possible to use a finite element model of the airplane and structures to evaluate all possible affected locations and their effects, this would be extremely time consuming. The industry did a limited number of these analyses for current plants from which a more simplified approach using realistically conservative assumptions can be developed.

A multi-step process can be used to limit and simplify the areas needing to be evaluated. An outline of the process follows:

Step 1: Identify the structures that contain safe shutdown equipment.

Step 2: Identify those elevations that can be impacted by an aircraft.

Step 3: Overlay a damage footprint template on accessible elevations and, using simplified sets of assumptions, determine what safe shutdown equipment is lost. Determine if surviving equipment assures adequate cooling of fuel in the reactor and spent fuel pool.

Each step is described in greater detail below.

3.1 Step 1: Structures of Concern

This step involves the identification of all buildings and structures (e.g., tanks, etc.) that contain SSCs that can be used to prevent damage of fuel in the reactor following a plant trip or maintain adequate cooling of fuel in the spent fuel pool. Buildings and structures should be retained for further analysis even if SSCs only pass through (e.g., cables, pipe runs, etc.). At a typical plant, the following buildings and structures would likely be retained for further analysis:

- Reactor/Auxiliary Building
- PWR Containments
- Turbine Building
- Diesel Generator Building
- Condensate Storage Tanks
- Refueling Water Storage Tanks
- Fuel Handling Building
- Intake Structure/Ultimate Heat Sink
- Safeguards Building
- Control Room
- Transformer Yard

Any buildings or structures that do not contain SSCs that can be used to maintain cooling of fuel in the reactor following a plant trip or maintain adequate cooling of the spent fuel pool can be screened from further consideration.

3.2 Step 2: Selection of Elevations for Evaluation

This step systematically evaluates the portions of buildings containing important SSCs that could be affected by the postulated damage footprint. The objective of this step is to identify portions of plant structures that are potentially susceptible to damage.

The process begins with the selection of a building elevation and face (i.e., external wall). First, each face on a given elevation is evaluated to determine whether adjacent buildings prevent damage. If the face at that elevation is not protected by an adjacent structure, then the potential for other intervening structures (or terrain if evaluating a specific site) to prevent direct strike is evaluated. For example, intervening terrain may apply to plants that are located near hillsides. Intervening structures such as cooling towers, or other non-adjacent buildings, may also prevent a strike. For those elevations that have faces that are not screened by adjacent or intervening objects, the potential for damage is evaluated based on the structural characteristics of the external and internal walls. Impacts on roofs do not need to be considered because the assessment of postulated strikes on the wall just below the roof will provide a reasonably equivalent damage state.

The following sections provide guidance on the screening of structures using this process.

3.2.1 Screening Based on Adjacent Buildings

Nuclear power plants are typically comprised of a variety of closely nested buildings of various dimensions. The presence of one building adjacent to another can provide protection to all or a portion of one of the buildings depending on the direction of approach by the aircraft. In some cases, the adjacent structure will only shield a portion of a face; in these cases, the face should be sub-divided into segments that identify the portion that is shielded and the portion that is susceptible to strike.

Other key assumptions to be used in evaluating the effects of adjacent structures are provided in Table 3-1.

3.2.2 Screening Based on Intervening Structures

The next step in the screening process is to evaluate intervening structures that would prevent damage by an aircraft. This evaluation must consider the influence of these objects in two dimensions: horizontal and vertical.

CAUTION: Credit for intervening structures can only be given if the location of the structures is fixed at the design certification stage. NSSS vendors should use caution in applying section 3.2.2 to make sure that the locations of intervening structures are fixed in the design and not subject to site-specific location changes. For example, structures such as service buildings, radwaste buildings and cooling towers can only be credited if their location is fixed at the design certification stage.

3.2.2.1 Assessing Intervening Structures in the Vertical Dimension

Intervening structures and terrain can prevent aircraft strike on all or a portion of a building.

In the vertical dimension, the angle of descent, or glide slope, is to be considered in this assessment. The glide slope, often expressed as a percentage, is measured in terms of the ratio of the number of feet of descent for every 100 feet of horizontal distance traveled.

The height of the portion of a building that is protected by in intervening object can be calculated based on the height of the intervening object and the distance from the building of concern:

$$h_p = H_o - (D*GS/100)$$

where,

h_p = Height of the protected portion of the structure
H_o = Height of intervening object
D = Distance from intervening object to structure
GS = Glide slope –the number of feet of drop per 100 feet of horizontal travel (SGI)

3.2.2.2 Assessing Intervening Structures in the Horizontal Dimension

Intervening objects must also be evaluated in the horizontal dimension. An object may be sufficiently tall and located in a position to prevent the worst-case strike (i.e., perpendicular) on the face of a structure. However, strikes that are not perpendicular may still be sufficient to cause damage. For the purposes of this guideline, an angle of ANGLEH (SGI) degrees from perpendicular is taken as the maximum angle of an aircraft strike that could cause damage. If the aircraft could only hit a reinforced concrete building face at an angle of more than ANGLEH degrees from perpendicular, then the face can be considered screened. If the face can be hit at an angle less than ANGLEH degrees from perpendicular, then it must be evaluated for wall failure.

Other key assumptions to be used in evaluating the effects of intervening terrain and structures are provided in Table 3-1.

Table 3-1

Key Assumptions to be Used in Determining Elevations of Concern

Assumptions in Evaluating the Effects of Adjacent Structures

1. This screening applies to buildings that are immediately adjacent to the building being evaluated. Buildings that are some distance away may also provide protection. These structures are considered in the next step as intervening structures.
2. Only reinforced concrete walls that are at least 18" thick are considered to provide screening protection. An adjacent structure can only be credited if **N** (SGI) number of walls, including the minimum 24" thick exterior wall of the structure containing the safe shutdown equipment of concern, are encountered in the projected flight path of the aircraft. Other structures may be acceptable but their acceptability needs to be verified by a structural analysis.

Assumptions in Evaluating the Intervening Structures

1. The maximum angle of decent is a glide slope of GS (SGI).
2. In accounting for the horizontal and vertical angle, no accounting is made for the fact that the pilot would likely assure significant clearance in navigating past the object (i.e., vertical and horizontal clearance of an object is assumed to be zero).
3. Strikes that could only occur at an angle of greater than ANGLEH (SGI) degrees from perpendicular are screened.
4. Within the sector in which strike must be considered, the evaluation of the structural capability of the face will be assessed assuming the standard damage footprint, even if the aircraft could not hit the face perpendicularly. This is slightly conservative, but not judged a significant factor in the assessment, given the other uncertainties involved.
5. Only reinforced concrete walls that are at least 18" thick are considered to provide screening protection. An intervening structure can only be credited if **N** (SGI) number of walls, including the minimum 24" thick exterior wall of the structure containing the safe shutdown equipment of concern, are encountered in the projected flight path of the aircraft. Other structures may be acceptable but their acceptability needs to be verified by a structural analysis.

3.3 Step 3: Damage Footprint Assessment

The purpose of the damage footprint assessment is to identify the locations that, if affected by physical, fire or shock damage caused by an aircraft strike, existing plant capability may not be sufficient to maintain cooling of fuel in the reactor and/or cooling of the spent fuel in the spent fuel pool.

The damage rule sets in this section are used to define an assumed damage footprint. The damage rule sets provided in this guidance are general in nature and principally intended to facilitate the analysis using a consistent, reasonable set of input assumptions for the purposes of investigating potential design enhancements needed to meet the rule acceptance criteria with reduced use of operator actions.. Use of these damage footprints out of the context of this analysis would be inappropriate. These rule sets have been established to allow analysts to readily identify the approximate extent of physical, shock and fire damage for each postulated strike location. For locations that can be impacted by an aircraft, apply the physical, shock and fire damage footprints to define an overall damage footprint. SSCs located within the damage footprints are assumed to be failed and not available.

Assessment begins with the locations identified in Section 3.2. For each of these locations, the appropriate damage rule sets are applied to define a damage footprint. If fuel damage could result, then the functional effects leading to the fuel damage scenario are defined and the scenario is identified for further evaluation of design enhancements.

The focus of this step of the process is identifying those areas where one of the damage footprints causes one of three different types of scenarios:

- Scenarios from 100% power involving damage that could cause loss of cooling to fuel in the reactor.
- Scenarios involving damage that could lead to damage of an operating shutdown cooling system which could lead to a containment bypass.
- Scenarios involving damage to the spent fuel pool systems required for spent fuel pool makeup and cooling that could lead to sustained loss of spent fuel pool water inventory.

This analysis can be undertaken in a graded approach involving a screening of buildings to determine whether these scenarios are possible assuming loss of all SSCs in the building. If it can be shown that none of these types of scenarios are possible, then the structure can be screened out for strike locations that only impact the one structure. If multiple structures can be impacted by a single strike, then all impacted buildings would have to be evaluated for potential screening.

The process of identifying the SSCs assumed to be affected and those that are potentially affected can be a significant effort. One tool that has been found to be beneficial in this regard is a spatial dependency matrix which identifies areas in which

SSCs are either located or have cables that are located in that area. It is recognized that for new plants at the design certification stage, specific cable information may be difficult to obtain for all SSCs. However, new plant designs have typically employed cable tray routing in train-specific compartments. In these cases, it would be reasonable to assume that the train-related control and power cables reside in the compartment with the train-related SSCs.

If a building can not be screened as a whole, then specific damage footprints are defined. The objective of this more realistic assessment is to provide a means to systematically identify success paths as well as potential enhancements when the more severe cases can not feasibly be mitigated.

Each unscreened external face of each building should be assessed.

3.3.1 Damage Rule Sets for Containment Structures

This subsection assumes that the structural analyses conducted per Section 2 conclude that perforation of the containment boundary has not occurred. Under this condition, no physical damage or fire damage inside containment needs to be considered. Shock damage does need to be considered as described below.

The general damage rules involve consideration of four different types of damage:

- Damage to the polar crane,
- The effects of a large fire outside containment,
- The effects of a fire inside any adjacent buildings below the point of impact, and
- Shock damage to fragile components directly attached to the containment wall.

[NOTE: If the structural analyses conducted per Section 2 conclude that the containment boundary is perforated, fire and physical effects inside containment must be considered in addition to the four above damage conditions. The guidance in subsection 3.3.2 should be used if containment boundary perforation occurs to assess physical, fire and shock damage effects inside containment.]

Detailed structural analyses of representative containment structures indicate that large displacements of the containment would be expected. The containment polar crane represents a large internal missile that could fall inside the containment, damaging primary system piping and SSCs important to maintaining reactor core cooling. If the polar crane is supported from the outer containment wall in a hittable region, or it is mounted on parallel tracks (as opposed to a circular rail around the containment), then it should be considered susceptible to falling. In these cases, any exposed primary system piping and exposed SSCs should be considered damaged.

Due to the size and design of containment structures, a large fire would be anticipated outside the containment. Such a fire might affect offsite power supplies, diesel generators, etc. that could be susceptible to the effects of such a fire. In evaluating containment damage scenarios, consideration should be given to the effects of a large fire outside containment.

In addition, the impact of an aircraft on the containment is likely to lead to significant debris being dispersed below the area of impact. As such, adjacent buildings without concrete roofs would be expected to be damaged by falling debris and fuel. Therefore, adjacent buildings without concrete roofs should be considered breached by this debris and subject to the effects of a jet fuel fire.

Following the assessment of general damage, the following scenario is to be evaluated for each design:

> The containment boundary is not breached, but significant structural damage has occurred. Therefore, the containment pressure capacity would be significantly reduced. As such, the focus in this scenario is on maintaining fuel cooling.

The impact of an aircraft on the containment structure has the potential to cause shock damage to any fragile SSCs attached to the outer containment wall near the assumed point of impact. SSCs considered fragile include electrical components such as containment fan coolers, switchgear, instrumentation, etc. In evaluating this scenario, any such SSCs should be considered immediately damaged and incapable of performing their intended function.

In this scenario there is no containment breach, so there is no need to consider fire-related damage or physical damage from aircraft impacts on systems inside containment.

3.3.2 Damage Rule Sets for Reinforced Concrete Buildings

All impact locations of reinforced concrete structures containing SSCs of interest are evaluated. For locations that are susceptible to aircraft impacts, physical damage, shock damage and fire damage are evaluated.

The process for defining damage footprints in these types of buildings is iterative. Locations of impact are selected and the damage rules applied. In many cases, due to the nature of the assumed damage footprint, the damage will be similar for many different impact locations within the same building and/or elevation. In other cases, moving the location of the impact can change the SSCs included in the damage footprint. For this reason, various impact points should be investigated in order to define the unique footprints.

Physical Damage Rules

The physical damage rule sets identified in this section were derived based on studies of structures with typical reinforced concrete walls representative of existing plant designs (Reference 20), as modified to reflect a wider range of aircraft characteristics. While some new plants employ structures that are similar to those of current plants, others have structures that are significantly more robust. The rule sets regarding number of walls to stop perforation described in the remainder of this section only apply to structures that are similar to current plant structures. Table 3-2 provides the parameters of concrete walls used to develop the physical damage rule sets. It is inappropriate to use the rule sets in this section for physical damage if the actual structure to be analyzed varies significantly from the parameters provided in Table 3-2.

Design specific rule sets will need to be developed for structures that vary significantly from those described in Table 3-2. If a structure is to be analyzed that varies significantly from the parameters identified in Table 3-2, Section 2.2.5 "Missile-Target Interaction Analysis Method" should be employed to determine the number of reinforced concrete walls necessary to stop further perforation into the structure on a design-specific basis. Care should be taken to select a wall span that envelopes all the strike locations requiring evaluation (i.e., select an outside wall span that is representative in terms of thickness but has the largest unsupported span in terms of length and height). The insights from this design-specific analysis are then used to develop rule sets for all postulated strike locations.

In some cases, the reinforced concrete walls may be insufficient to prevent internal physical damage of SSCs. This potential for physical impact damage to SSCs is determined by defining a damage path of width, IMPW (SGI). Physical damage is propagated into the structure until a total number of N (SGI) reinforced walls is reached. Within the damage path, the following assumptions should be applied:

- Immediate failure of all active equipment function(s)

- Immediate failure of all cables
- Rupture of pipes that can cause LOCAs. (see discussion below)
- Gross leakage of other pipes and SSCs that can cause flooding (flow area = ½ diameter)

Piping immediately adjacent to impacted walls are expected to be severed. Other piping in the impact area will sustain varying levels of damage from (1) none to (2) crushing without leakage to (3) crushing and tearing with leakage to (4) severing. Because it is impossible to predict how individual pipes will be affected, a value of ½ the diameter of pipes was selected through expert elicitation as a reasonable value for estimating the flow of fluids from the pipe(s) for evaluating flooding effects.

The potential effects on SSCs of internal flooding which may occur due to piping damage should be considered in the assessment. Flooding from limited sources is assumed to be bounded by the effect of the fire and explosion and existing pipe break flooding analyses. In the case of damage to systems that are supplied by large quantity sources (i.e., open loop systems drawing from lakes, rivers, oceans, cooling tower basins, etc.), the effect of a flood could be much more widespread. These effects should be evaluated as an overlay on the identified damage footprint (i.e., the assessment will look at the damage footprint with and without consideration of flooding from large sources).

For assessing LOCAs, a range of pipe breaks should be explored as follows:

- The lesser of an area of half the diameter of the pipe or 64 square inches.
- An area of 3 square inches

After identifying the physical damage to be assumed, the damage footprint assessment then considers the potential for shock damage.

Shock Damage Rules

Shock damage is evaluated in the damage footprint in order to determine the potential for affecting safe shutdown equipment or spent fuel pool cooling equipment. While safety-related safe shutdown equipment has been seismically qualified, the frequency spectrum associated with an aircraft impact is considerably higher than the spectrum associated with earthquakes.

All equipment within the shock damage footprint is assumed to fail at the time of impact. In most cases, the fire and/or physical damage footprint will envelope the shock damage footprint. If this is the case, only cabling and electrical equipment that is credited to operate for 5 minutes following impact needs to be evaluated to determine if it is within the shock damage footprint. If so, the fire damage rule permitting credit for 5 minutes of operation for this equipment cannot be used and this equipment is assumed to be lost at impact

For the purposes of defining the damage footprint, apply the rules in Table 3-3. Values for SD1 through SD6 are SGI. The shock damage distances are measured from the center of initial impact and then along a structural pathway to the affected equipment (i.e., shock is transmitted through walls, floors and ceilings but not across open air space). If other adjacent buildings are seismically separated from the impacted building, this distance applies only within the building that is directly impacted. Note that buildings that share a common base mat are not seismically separated. NSSS vendors have the option of using the values for SD1 through SD6 or developing their own distances based on acceleration values filtered at 200 Hz for specific strike locations.

Fire Damage Rules

Background

It is assumed that external fires caused by aircraft impacts are of relatively short duration and will not have a significant impact on systems necessary to provide cooling of fuel in the reactor vessel or spent fuel pool. This assumption is based on the following factors: (1) there is an abundance of oxygen available to support combustion of the fuel and (2) firefighter access to the fire is typically good.

If the aircraft perforates the structure, an internal fire will result, both from burning jet fuel and the ignition of secondary combustibles. The fire damage caused by an aircraft impact can extend well beyond the physically damaged area due to the overpressure effects from the initial fireball and the spread of fuel through open pathways within the structure. Much of the fuel will be consumed in the initial deflagration and most of the remaining fuel will coat internal structures and equipment. The quantity of liquid available to pool and flow to other areas is limited but can easily pass through relatively large openings such as grates and blown doors. While it is possible for fuel to pass through small openings, only openings that have a linear perimeter exceeding 12 inches needs to be considered in this analysis, unless an area does not have any significant drain paths. The assumption to be used in this guideline is that a ventilation controlled internal fire will burn for several hours, thus preventing operations personnel from being able to take manual actions in these areas for several hours. All SSCs are assumed lost immediately in the physical damaged footprint. All cabling and electrical equipment in compartments affected by fire spread beyond the physical damage footprint are considered to be available for five minutes.

Immediately upon impact, an internal fireball occurs due to the combustion of dispersed jet fuel spray, mist and droplets. This fireball can cause an overpressure on the order of a few psi. This overpressure is capable of failing doors, windows, and blow-out panels, especially in the impact zone, that are not rated for at least 5 psid. The overpressure will be transported throughout the building through larger openings (hatches, grating, etc.) and through stairwells. The expected mode of failure for typical metal fire doors is buckling of the door. Doors that fail due to overpressure are no longer capable of closing. As the fireball grows through openings and failed doors, additional doors and compartments can be threatened. Ventilation ductwork in the physical damage footprint is expected to be severely crushed and torn. As a result, ventilation ductwork that passes through the physical damage perimeter is assumed to also provide a pathway for the fireball, smoke and combustion gases to enter adjacent compartments. Ventilation systems in areas affected by fire spread are expected to be lost as temperatures quickly rise causing fusible links in dampers to actuate. Additionally, ventilation fans in the affected areas will also be lost as cables and electrical motors fail at 5 minutes due to fire exposure.

Fire Spread Rules

The extent of the interconnected regions of the structure and the resulting extent of fire damage is defined in a two step process:

Step 1: Identify Potential New Compartment Connections Due to Overpressure:

- All windows throughout the building of impact fail
- All doors, blowout panels, barriers and ventilation ducting that are at the perimeter of the physical damage fail
- The first door or barrier rated at least 5 psid beyond the physical damage perimeter stops further propagation
- Two other doors, blowout panels, and barriers (rated below 5 psid) beyond the physical damage perimeter are needed to stop further propagation
-

Step 2: Spread Fire Damage through Connected Compartments:

- Fire damage spreads up, down and laterally through:
  - Open/failed doorways, and
  - Other significant openings (e.g., hatches, gratings, penetrations, etc., with perimeter lengths of greater than 1 ft.).
- Footprint only spreads through "closed" doors or small openings (perimeters lengths less than 1 ft.) if
  - no other significant drain path exists for fluid to escape to lower elevations or outside the building, and
  - no other ventilation path exists for gases to escape to higher elevations or outside the building.

Other Fire Effects

The load bearing strength of structural steel can be significantly weakened due to the high temperatures associated with a jet fuel fire. Therefore, any structural steel not encased in concrete (such as support beams and steel columns that are only protected by fire retardant coatings) should be evaluated for high temperature effects. The integrity of the structure supported by these beams and/or columns should be evaluated to determine if the physical and/or fire damage footprint needs to be extended.

Composite Damage Footprint
The damage footprint for each hittable location is developed by identifying the total damage from all of the applicable damage rules for each location.

The damage rule sets are general in nature and principally intended to facilitate the analysis using a consistent, reasonable set of input assumptions for the purposes of investigating design enhancements. Use of these damage footprints out of the context of this analysis would be inappropriate. These rule sets have been established to allow analysts to readily identify the approximate extent of physical, shock, fire, and internal flooding damage for each postulated strike location.

Using plant information such as fire analyses conducted in conformance with Regulatory Guide 1.189, Rev. 1, fire PRAs, internal flooding studies, and plant drawings, the rule sets are translated into specific equipment that is assumed to be affected. The combined list of damaged cables and SSCs defines the threat to fuel damage for postulated damage to SSCs with the reactor scrammed from full power, to SCCs while on shutdown cooling, and to the spent fuel pool.

A number of issues will have to be addressed on a plant specific basis in defining the scenarios resulting from each damage footprint. Table 3-4 provides the approach to be taken to a number of the generic issues. Table 3-5 provides additional key assumptions applicable to the damage footprint assessment.

As each impact location is evaluated, the systemic and functional effects that are precluding protection of the fuel should be identified. Examples of functions effects that might be identified include: loss of high pressure injection, loss of all AC power, loss of ultimate heat sink, etc. It is likely that many of the damage footprints will be similar and, even if the damage footprints are slightly different, the key functional effects and system effects that lead to these functional effects are likely to be similar. Working at the functional level will facilitate grouping of damage footprints and resulting scenarios and allow the targeting of any needed design enhancements at a higher level.

3.4 Sufficiency Criteria

Reactor core and spent fuel cooling is maintained if the heat removal capability analyses performed per this section conclude that sufficient heat removal equipment is available consistent with the applicable PRA success criteria. PRA success criteria are based on nominal values (versus conservative design basis values) and credits both safety-related and non safety-related SSCs.

Each damage footprint that is found to lead to loss of cooling for fuel in the reactor or spent fuel pool for any of these conditions is identified for further evaluation in Section 4 “Enhanced Design Features and Functional Capabilities.”

Table 3-2

Representative Structure Used to Develop Physical Damage Rule Sets

Structural Configuration		
External Walls 24 inches thick # 8 reinforcing bar at 12” centers Interior Walls 18 “ thick #7 reinforcing bar at 12” centers		
Impacted Panel Dimensions 27’ Wide by 25’ High		
Concrete Slab		
Compressive Strength, Aged	5543	psi
With Rate Effects	6929	psi
Elastic Modulus	4.74E6	psi
Poisson’s Ratio	.18	
Tensile Strength	618	psi
Fracture Strain	130E-6	in/in
Weight Density	150	lb/ft^3
Reinforcing Steel, Grade 60		
Elastic Modulus	29.0E6	psi
Poisson’s Ratio	.30	
Yield Stress (dynamic)	74.25	ksi
Fracture Strain*	20.6%	in/in
Ultimate Strength (dynamic)	111.6	ksi
*The analysis assumes a fracture strain of 5% tension and 10% compression for rebars		

Table 3-3
Equipment Shock Damage Categories

Category	Linear Distance for Susceptibility	Example Equipment
A (median fragility limit 27g)	<SD1	• Sump pumps • Control panels • Monitoring and control devices (current trips, switches probes, transmitters, transducers, controllers) • Diesel generators (generator, governors, linkage) • Gas turbine generators • Relays • AC switchboard and DC power supplies • Unit substations (Transformers, voltage regulators, circuit breakers, motor controls) • Computers
B (median fragility limit 54g)	<SD2	• Air conditioning units • Air handlers • Pumps (centrifugal and positive displacement) • Air compressors, storage tanks, dryers • Indicators (pressure, temperature, flow) • Station batteries • Electrical panel boards (w/o air circuit breakers)
C (median fragility limit 80g)	< SD3	• Fans (centrifugal and axial flow) • Dampers, diffusers • Electrical motor control centers • Electrical panel boards (with air circuit breakers)
D (median fragility limit 108g)	< SD4	• Tanks • Heat exchangers • Water chillers • Instrument panels • Motor-generators • Molded case circuit breakers • Dry transformers
E (median fragility limit	< SD5	• Metal clad switchgear

160g)		
F (median fragility limit 200g)	< SD6	• Valves • Strainers & filters • Expansion joints • Flow orifices

Table 3-4
APPROACH TO KEY ISSUES IN SCENARIO DEVELOPMENT

ISSUE	APPLICABILITY	RELEVANCE	APPROACH
1. Fuel cooling success criteria with reactor initially at power	All plants	▪ For at-power conditions, the plant-specific fuel cooling success criteria define the potential success paths available	For at-power, utilize the success criteria from the plant-specific internal events PRA and/or fire PRA, as applicable.
2. Fuel cooling success criteria with reactor on shutdown cooling	All plants	▪ For damage footprints that affect shutdown cooling, timing could affect the availability of resources	For shutdown cooling scenarios, assume that the strike occurs 7 days after reactor shutdown, the primary system has a large vent, and the volume above the reactor is not flooded,
3. Reactor scram prior to strike	All Plants	▪ Some damage footprints may cause damage that could impair the ability of the reactor to scram, leading to an ATWS. ▪ In most cases, operators are expected to have some warning prior to damage so scram would be expected to occur prior to damage.	The baseline assumption will be successful reactor scram prior to damage. However, in reviewing damage footprints in areas with equipment essential to reactor scram an assessment will be made of the potential for damage to prevent a scram should it have not occurred.
4. Support system requirements (e.g., room cooling, component cooling, etc.)	All plants	▪ The realistic support system requirements may differ from design basis conditions and can be important if significant support system damage occurs (e.g., physical damage to cooling water systems can effect component and/or room cooling)	Utilize the support system success criteria from the plant-specific internal events PRA and/or fire PRA, as applicable. When crediting support systems, care should be taken to ensure that all components necessary for system function are available, including power and control cables that run though the damaged buildings.

Table 3-4 (Cont.)

APPROACH TO KEY ISSUES IN SCENARIO DEVELOPMENT

ISSUE	APPLICABILITY	RELEVANCE	APPROACH
5. Containment Isolation	All plants	▪ Cable data is not always readily available for power and control cables to containment isolation valves (CIVs). ▪ In cases where fuel cooling can not be maintained, containment isolation can be a key factor in preventing large early releases. ▪ If the containment is not isolated prior to strike, the physical, shock, and fire effects may prevent isolation.	Containment penetrations should be evaluated to assure that physical damage does not lead to containment failure. The assessment should also consider that containment isolation is not manually performed prior to damage. Isolation of the containment should be treated as an important function for scenarios involving loss of fuel cooling. If cable data s not available for CIVs, the valves will be assumed to go to the position they would take due to loss of power.

Table 3-5

Key Assumptions to be Used in Damage Footprint Assessment

1. The primary focus of this assessment is impacts that occur with the plant at-power. Thus, the base assumption is that the plant is operating at 100% power prior to the strike. However, as part of the assessment, an evaluation will be made of the potential damage that might occur if the strike were to occur when the plant is shutdown and shutdown cooling is operating. The focus here is on the potential to cause a loss of fuel cooling with containment bypass due to damage to the shutdown cooling piping.
2. The fuel in the spent fuel pool is assumed to contain a routine core off-load roughly 30 days after reactor shutdown.
3. For the evaluation of shutdown cooling scenarios, consider cases where each shutdown cooling loop is in operation. Include the following assumptions about plant configuration:
    - Equipment in the division of the non-operating loop is out of service for maintenance.
    - The reactor vessel is vented (i.e., large vent)
    - Water level is at or near the reactor vessel head flange
    - Reactor has been shutdown for 7 days
4. For the purposes of assessing plant resource availability, it should be assumed that the event occurs on a weekend during the daytime.
5. Physical damage due to the strike is assumed to cause failure at time of impact. Fire damage throughout damage footprint assumed to occur 5 minutes after impact and affects all cables and electrical equipment.
6. Off-site AC power is available unless the damage footprint specifically fails it on-site.

Table 3-5 (Cont.)

Key Assumptions to be Used in Damage Footprint Assessment

7. In identifying potential success paths, if cable information is not available for SSCs that are necessary for that success path, the cables should be assumed to be damaged unless there is evidence that they would not be within the damage footprint (e.g., if both the SSC and the power supplies are located in a different building/area and there is no reason to believe that the cables would have been run through the damage footprint).
8. In evaluating the amount of reinforced concrete available to limit a specific damage footprint, no credit should be given to internal components and structures that are not reinforced concrete walls of at least 18 inches thick (i.e., no credit is given for concrete columns, wall pilasters, bracing, crane rails, heavy pipes, large equipment, and masonry walls).
9. Multi-unit designs will need to carefully address the effects on shared systems in light of the assumed damage. Shared systems and control rooms can create damage scenarios that challenge both units simultaneously.
10. Water, either from fire water systems or other damaged pipes can lead to spread of fires. In general, these effects are included in the damage footprints, but in some cases, flooding effects should be reviewed with respect to fire propagation.

4 Enhanced Design Features and Functional Capabilities

If it was determined in applying Sections 2.0 and 3.0 that the rule acceptance criteria could be met for all postulated strike locations, no further actions are needed and the assessment is complete.

If it was determined in applying Sections 2.0 and 3.0 that the rule acceptance criteria could not be met for all postulated strike locations, 10 CFR 50.150 requires applicants to identify and incorporate design features and functional capabilities to meet the acceptance criteria.

Applicants should document the rationale for the selected approach. Examples of possible enhancements are provided in the following subsections, but they are only examples and are not intended to exclude other possibilities.

Enhancements to meet the acceptance criteria fall into three categories in order of preference:

1. Strengthen external structures to prevent damage or provide screening to prevent impact.
2. Relocate equipment outside of the damage footprints to assure fuel cooling can be achieved and maintained or strengthen internal walls.
3. Identify and incorporate design-specific system enhancements that can reduce use of operator actions.

4.1 Preventing Internal Damage

For new plants, it may be possible to strengthen external walls to the thicknesses determined by Sections 2.0 and 3.0 to limit structural damage, to relocate existing structures, or to design intervening structures that prevent impact using the guidance in Section 3.2. This is the preferred approach as it minimizes structural damage and assures little or no damage to equipment needed to maintain fuel cooling.

4.2 Minimizing Internal Damage

If the recommendations in 4.1 are not feasible or practical, the next preferred approach is to relocate damaged equipment such that it is no longer in the postulated damage footprint and would be available to maintain fuel cooling. Insights from studies at existing plants show that rerouting some key power and control cables may be sufficient to provide a successful fuel cooling pathway.

It may also be possible at early design stages to relocate equipment such that an additional wall provides protection. Alternatively, it may also be possible to add/strengthen internal walls to provide the necessary thicknesses required for protection.

If the fire footprint is preventing fuel cooling capability, it may be possible to limit the size of the fire footprint through measures such as adding additional fire doors, installing watertight fire doors or plugging holes and penetrations between elevations or adjacent compartments.

4.3 Design-Specific System Enhancements

For aircraft impact strike locations where the rule acceptance criteria could not be met and design enhancements per 4.1 and 4.2 could not be implemented, designers should identify and implement system enhancements to facilitate maintaining fuel cooling with reduced use of operator actions.

5 Documentation and Quality Requirements

5.1 Documentation

Each applicant must provide, in its application to the NRC, a description of the design features and functional capabilities credited for showing that the rule's acceptance criteria are met. In addition, each applicant must provide a description of how these design features and functional capabilities meet the rule's acceptance criteria. Each vendor should retain a file of the complete set of analyses performed consistent with the level of detail described in this methodology document. The documentation should be sufficiently complete and thorough to support an onsite review by the NRC to determine the overall adequacy of the assessments performed.

5.2 Quality Requirements

The analyses performed in accordance with this methodology are beyond design basis and, therefore, the quality assurance requirements of 10 CFR 50, Appendix B do not apply.

However, the quality assurance standards and measures applied by the vendor must establish the validity of the analyses, supporting calculations and documentation of results consistent with 10 CFR Part 50.150 requirements.

6 Key Definitions

The following key definitions for meeting the acceptance criteria in 10 CFR 50.150 are provided:

Intact Containment

The containment remains intact if structural analyses performed with methods described in Section 2 of this guide show that perforation of a steel containment or concrete containment with steel liner does not occur on impact and that the containment ultimate pressure capability, given a core damage event, would not be exceeded before effective mitigation strategies can be implemented.

Effective mitigation strategies are those that, for an indefinite period of time, provide sufficient cooling to the damaged core or containment to limit temperature and pressure challenges below the ultimate pressure capability of the containment as defined in DCD/FSAR Chapter 19.

[NOTES: (1) For BWRs, actuation of the wetwell vent line is acceptable as this is a designed, scrubbed release. (2) The containment ultimate pressure capability described in DCD/FSAR Chapter 19 is appropriate for use provided there is no structural damage to the containment structure. If structural damage has occurred to the containment structure, a revised ultimate pressure capability considering the damaged condition must be determined.]

Spent Fuel Pool Integrity

Spent fuel pool integrity is maintained if the structural analyses performed per Section 2 conclude that the aircraft impact on the spent fuel pool wall and support structures does not result in leakage through the spent fuel pool liner below the required minimum water level of the pool.

[NOTE: Required minimum water level is the minimum operating level of the spent fuel pool as required by the plant technical specifications.]

Reactor Core and Spent Fuel Cooling

Reactor core and spent fuel cooling is maintained if the heat removal capability analyses performed per Section 3 conclude that sufficient heat removal equipment is available consistent with the applicable PRA success criteria.

NOTE; The applicable PRA success criteria for fuel cooling are as defined in DCD/FSAR Chapter 19.

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A List of Acronyms

AC	Alternating Current
ACI	American Concrete Institute
ADS	Automatic Depressurization System
AFW	Auxiliary Feed Water
ANGLEH	Maximum Impact Angle
AOVs	Air Operated Valves
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATWS	Anticipated Transient Without Scram
BWRs	Boiling Water Reactors
CCW	Component Cooling Water
CIVs	Containment Isolation Valves
CRD	Control Rod Drive
CRIEPI	Central Research Institute of Electric Power Industry
CS	Core Spray
CST	Condensate Storage Tank
CVCS	Chemical and Volume Control System
DBT	Design Basis Threat
DC	Direct Current
DIF	Dynamic Increase Factor

EFW	Emergency Feed Water
FW	Feed Water
GS	Glide Slope
HPCI	High Pressure Coolant Injection
HPCS	High Pressure Core Spray
HPSI	High Pressure Safety Injection
IC	Isolation Condenser
IMPW	Impact Width
LOCAs	Loss of Coolant Accidents
LPCI	Low Pressure Coolant Injection
LPCS	Low Pressure Core Spray
MFW	Main Feed Water
MOVs	Motor Operated Valves
MSIV	Main Steam Isolation Valve
NDRC	National Defense Research Committee
NSSS	Nuclear Steam Supply System
PORVs	Power Operated Relief Valves
PRA	Probabilistic Risk Assessment
PWRs	Pressurized Water Reactors
RCIC	Reactor Core Isolation Cooling
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RHRSW	Residual Heat Removal Service Water

RPV	Reactor Pressure Vessel
RWCU	Reactor Water Cleanup
RWST	Refueling Water Storage Tank
SBO	Station Blackout
SD	Shock Distance
SG	Steam Generator
SGI	Safeguards Information
SI	Safety Injection
SITs	Safety Injection Tanks
SRVs	Safety Relief Valves
SSCs	Systems, Structures and Components
TBV	Turbine Bypass Valve
TF	Triaxiality Factor
TSC	Technical Support Center
UHS	Ultimate Heat Sink