Enclosure 2: Functional Containment Performance Criteria
Technology-Inclusive, Risk-Informed, Performance-Based Approach

Implementation Action Plans: Prioritizing Functional Containment

As described in the SECY paper, the U.S. Nuclear Regulatory Commission (NRC) staff described efforts to prepare for possible licensing of non-light-water-reactor (non-LWR) technologies in "NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness," issued December 2016 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML16356A670). The staff developed implementation action plans (IAPs) to identify specific activities that the NRC will conduct in the near-term, mid-term, and long-term timeframes (ADAMS Accession Nos. ML17165A069 and ML17164A173). The IAPs included the following strategies to meet the objective of achieving regulatory readiness:

Strategy 3: Develop guidance for a flexible non-LWR regulatory review process within the bounds of existing regulations, including the use of conceptual design reviews and staged-review processes.

Strategy 5: Identify and resolve technology-inclusive policy issues that impact the regulatory reviews, siting, permitting, and/or licensing of non-LWR nuclear power plants.

Enclosure 1 contains background information on the policy issues related to non-LWR design features serving to limit the release of radioactive materials. The policy issue addressing the retention of radioactive materials using a "functional containment" versus a prescriptive requirement for an essentially leak-tight building was partially resolved in previous papers and Commission decisions. An important item remaining to be fully resolved is to define appropriate performance criteria for design features serving to limit the release of radioactive materials. The development of a methodology for designers to determine design-specific functional containment performance criteria would support further development of non-LWR designs.

Key Assumptions and Bases

The staff's proposed methodology to develop performance criteria for functional containment is based on NRC's objectives to use risk-informed, performance-based approaches in regulatory decisionmaking. Figure 1 illustrates the integration of risk with consideration of a basic hazard, such as radioactive materials; measures or structures, systems, and components (SSCs) to prevent a top-level event such as core damage in an LWR or a damage state involving the unplanned migration of fission products for non-LWRs; and mitigation or recovery measures such as severe accident design features, siting, and emergency planning.[1] The interrelationships among these activities and with the associated performance criteria for design features used to retain radioactive materials within a plant require an integrated approach to resolving issues and developing a regulatory framework for non-LWRs.

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1 ISO-31010, "Risk Management—Risk Assessment Techniques," describes a process known as Bow Tie Analysis as "a simple diagrammatic way of describing and analyzing the pathways of a risk from causes to consequences. It can be considered to be a combination of the thinking of a fault tree analyzing the cause of an event (represented by the knot of a bow tie) and an event tree analyzing the consequences. However the focus of the bow tie is on the barriers between the causes and the risk, and the risk and consequences."

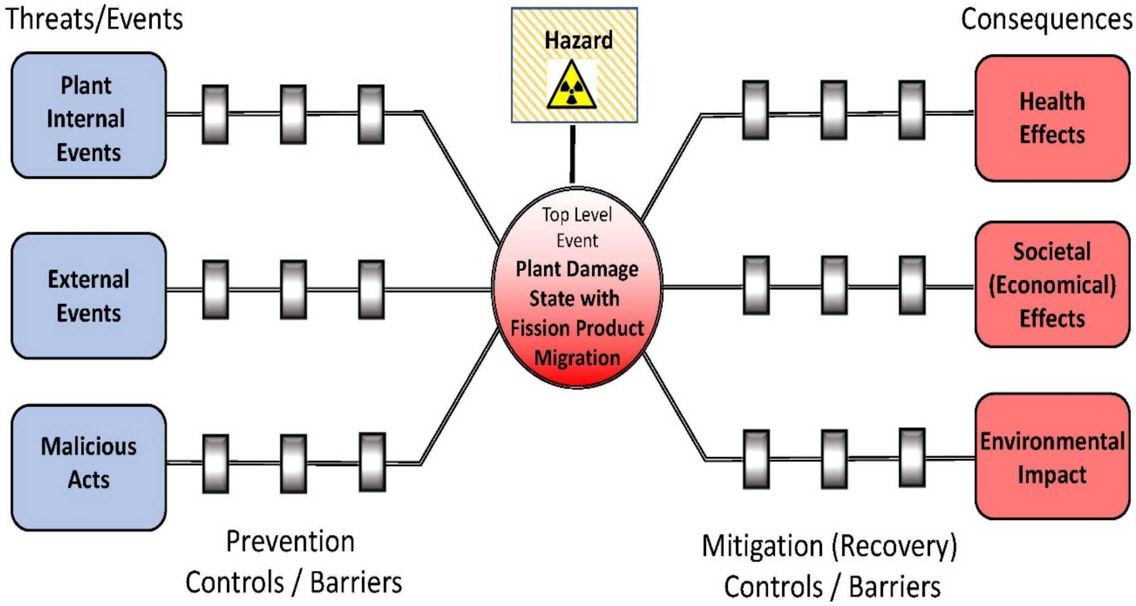

Figure 1. Risk Management—Barrier Assessment (Bow Tie) Method[2]

Reactor developers will assess various controls and SSCs in terms of their availability and capability to prevent or mitigate releases. Developers of specific reactor designs consider the potential consequences associated with a reactor technology and power level, which correspond to the hazard in Figure 1, and are able to assess the benefits and related costs of potential SSCs to prevent or mitigate a plant damage state that could involve the unplanned migration of radioactive materials across defined boundaries. The number and nature of SSCs, including physical enclosures or other barriers, are based on the identified events, the underlying hazard (i.e., the amount and form of radioactive materials), and the uncertainties associated with capabilities and the availability of other controls and SSCs.

Any evaluation of events, plant features and programs, and related uncertainties needs to address the state of knowledge related to the behavior of reactor systems, fuel, and the way in which radioactive materials may move within and be released from a facility. The established methods for addressing radiological source terms for LWRs have limited applicability to non-LWR designs, and more mechanistic approaches have been proposed. The development of mechanistic source terms and the related matter of modeling behaviors of non-LWR technologies in safety analyses and computer simulations is an important element of the NRC staff's IAPs and the activities of Department of Energy (DOE), national laboratories, and reactor developers. The analytical tools and computer codes are validated by comparing results to information available from operating experience and experiments. In its staff requirements memorandum dated July 30, 1993 (ADAMS Accession No. ML003760774) for SECY-93-092, "Issues Pertaining to the Advanced Reactor (PRISM, MHTGR, and PIUS) and CANDU 3

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2 The notion of barriers in Figure 1 can include controls, programs, or hardware serving to prevent or mitigate the top-level event. The term "barriers" in many NRC discussions of defense in depth relate to physical features such as fuel cladding, reactor coolant piping, and a containment structure. The staff will attempt to address this and other challenges related to terminology in future guidance documents.

Designs and Their Relationship to Current Regulatory Requirements," the Commission approved the staff's recommendation that source terms for non-LWRs be based upon a mechanistic analysis and will rely on the staff's assurance that the following conditions are met:

- The performance of the reactor and fuel under normal and off-normal conditions is sufficiently well understood to permit a mechanistic analysis. Sufficient data should exist on the reactor and fuel performance through the research, development, and testing programs to provide adequate confidence in the mechanistic approach.

- The transport of fission products can be adequately modeled for all barriers and pathways to the environs, including the specific consideration of containment design. The calculations should be as realistic as possible so that the values and limitations of any mechanism or barrier are not obscured.

- The events considered in the analyses to develop the set of source terms for each design are selected to bound severe accidents and design-dependent uncertainties.

The design-specific source terms for each accident category would constitute one component for evaluating the acceptability of the design.

The above criteria remain valid for the current discussions of assessing functional containment performance criteria. The development of mechanistic source terms for designs and event categories is another element of an integrated, risk-informed, performance-based approach to designing and licensing non-LWRs.

The NRC-DOE joint initiative to develop sets of advanced reactor design criteria is an example of current activities and progress in advancing the development of functional containment performance criteria. The staff's interactions with stakeholders during the development of Regulatory Guide (RG) 1.232, "Guidance for Developing Principal Design Criteria for Non-Light Water Reactors" (ADAMS Accession No. ML17325A611) resulted in the following design criterion and supporting rationale for "functional containment" for modular HTGRs:[3]

Containment design
A reactor functional containment, consisting of multiple barriers internal and/or external to the reactor and its cooling system, shall be provided to control the release of radioactivity to the environment and to ensure that the functional containment design conditions important to safety are not exceeded for as long as postulated accident conditions require.

[3] RG 1.232 acknowledges that characteristics of the coolants, fuels, and containments to be used in non-LWR designs such as molten salt reactors could share common features with modular HTGRs and propose to use similar criteria for a functional containment. A purpose of this paper is to obtain affirmation by the Commission that decisions previously made for modular HTGRs and the further development of the approach described herein may be incorporated into technology-inclusive guidance for non-LWR technologies.

Rationale

The term “functional containment” is applicable to advanced non-LWRs without a pressure retaining containment structure. A functional containment can be defined as “a barrier, or set of barriers taken together, that effectively limit the physical transport and release of radionuclides to the environment across a full range of normal operating conditions, AOOs [anticipated operational occurrences], and accident conditions.”

Proposed Methodology: Detailed Description

The proposed methodology is built around the identification and categorization of licensing-basis events. Like the system that has evolved for operating reactors, event categories consider factors such as estimated frequencies. Acceptance criteria are defined for each category considering potential consequences and ensuring sufficient defense in depth within the design and operation of any nuclear power plant. There is general consensus among the NRC staff and stakeholders on identifying events using a combination of risk assessment tools (e.g., probabilistic risk assessment) and deterministic methods, including engineering judgment. The staff has found that the inclusion of both considerations—risk assessments and deterministic methods—is necessary and sufficient to overcome occasional differences in emphasis on one element versus the other.

Figure 2 shows the logic for categorizing events developed by the Licensing Modernization Project starting from the structure used within the NGNP project. The approach is similar to what has evolved for LWRs with some adjustments to more clearly address low-frequency events and to be technology inclusive for various non-LWR designs. The figure, generally referred to as a frequency-consequence (F/C) target, illustrates the general organization of events. The staff is continuing to interact with stakeholders to reach alignment on some topics such as the demarcation of categories and ensuring consistency across the assessments of prevention and mitigation features and controls for various events and consequences. An agreed-upon general structure for event categories will support development of performance criteria for design features serving to retain radioactive materials within non-LWR facilities.

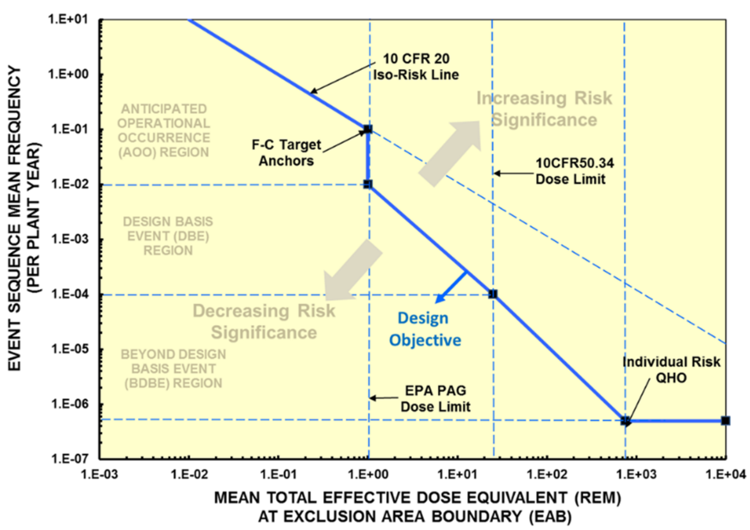


Figure 2. Licensing Modernization Project Licensing Basis Event Categories and Frequency-Consequence Target

The staff proposes that the baseline framework for non-LWRs include the set of event categories developed under the NGNP project and continued in current interactions with the Licensing Modernization Project. Although the structure and terminology differ slightly from the current system for LWRs, each category in Table 1 has accepted high-level performance criteria that generally align with current requirements and practices. Table 1 describes the event categories.[4]

Table 1. Non-LWR Event Categories

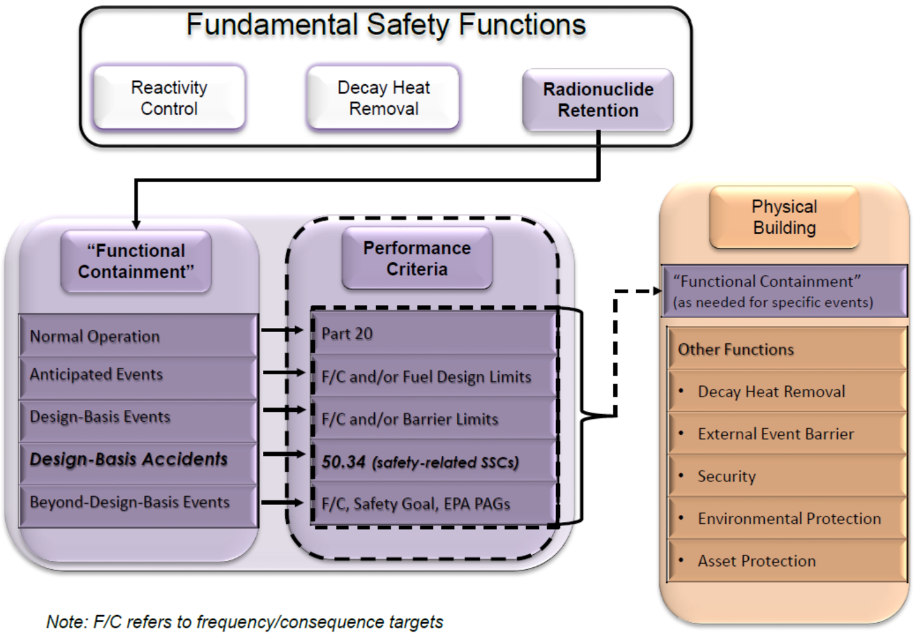
Category	Description
Normal Operations	Normal operations define initial conditions for licensing-basis events. Radiological doses resulting from normal operation are controlled by limiting routine effluent releases to below regulatory requirements (i.e., Title 10 of the *Code of Federal Regulations* (10 CFR) Part 20 limits).
Anticipated Operational Occurrences (AOOs)	AOOs encompass planned and anticipated events (e.g., frequencies exceed approximately 10^{-2} per plant-year). The radiological doses from AOOs are required to meet a fraction of the normal operation public dose requirements (i.e., 10 CFR Part 20 limits), which are established for annual dose rates due to both events and planned effluent releases. AOOs are used to set operating limits for normal operation modes and states and are historically used to establish performance criteria for reactor protection systems. Design features and programmatic controls are established to limit AOO frequencies and consequences in terms of offsite doses and success of controls and SSCs serving a prevention function (e.g., integrity of fuel cladding, coatings, or other fuel system boundary).
Design-Basis Events (DBEs)	DBEs encompass unplanned off-normal events not expected in the plant's lifetime but which might occur in the lifetimes of a fleet of plants (i.e., event sequence frequencies in the range of 10^{-4} to 10^{-2} per plant-year). The radiological doses from DBEs are required to be a fraction of accident public dose requirements (e.g., 10 CFR 50.34), as shown on the sliding illustrative F/C target in Figure 2. Design features and programmatic controls are established to limit DBE frequencies and consequences in terms of offsite doses and success of controls and SSCs serving a prevention function (e.g., integrity of fuel cladding, coatings, or other fuel system boundary). The identification and evaluation of DBEs provide input to the selection of design-basis accidents (DBAs) discussed below.

4 The categorization of events or sequences in Table 1 consider the likelihood of initiating events as well as the capability and reliability of plant features preventing the escalation of the event into a higher category. The traditional event categories for operating reactors are based more on the estimated frequency of only the initiating event. This and other aspects of the revised framework for non-LWRs will be described in a future Commission paper.

Beyond-Design-Basis Events (BDBEs)	Beyond-design-basis events (BDBEs) are rare off-normal events whose frequencies range from a very low value (e.g., approximately 10^{-7} per plant-year to 10^{-4} per plant-year. BDBEs are evaluated to ensure that they do not pose an unacceptable risk to the public. Design features and programmatic controls are established to limit BDBE frequencies and consequences in terms of offsite doses and success of preventive controls and SSCs (e.g., integrity of fuel cladding, coatings, or other fuel system boundary) or mitigation measures (e.g., severe accident design features).
Design-Basis Accidents (DBAs)	Chapter 15, "Accident Analyses," of safety analysis reports includes DBAs, which are prescriptively derived from the DBEs by assuming that only SSCs classified as safety related are available to deal with the event. The public consequences of DBAs are conservatively calculated and assessed against limits in 10 CFR 50.34, similar to DBA analyses for existing LWRs. DBAs have historically been used to define safety margins for SSCs and establish limiting conditions for operation.

The proposed methodology to define performance criteria for specific design features, such as those serving to limit the release of radioactive materials (in terms of magnitude and timing), is constructed based on the above event categories and the need to fulfill fundamental safety functions as currently incorporated into the NRC's general design criteria and similar international standards. The three fundamental safety functions are controlling reactivity, removing heat, and retaining radioactive materials.[5] Figure 3 depicts the proposed methodology, which is a top-down approach to establishing performance criteria for plant features using accepted event categories and safety functions. For each event category, performance criteria would define specific functions to be performed by an SSC of a facility and the specific values or ranges of values chosen for controlling parameters as reference bounds for design. The design of each SSC would be determined based on the aggregation of performance requirements from all event categories and fundamental safety functions, as well as other potential roles that a designer may choose for that SSC. In the case of a building surrounding a reactor system, Figure 3 lists several potential uses that are discussed later in this enclosure.

5 The phrase "fundamental safety functions" is taken from International Atomic Energy Agency (IAEA) Specific Safety Requirements SSR-2/1 (Revision 1), "Safety of Nuclear Power Plants: Design," dated February 2016 and aligns with NRC requirements, such as the general design criteria for LWRs, which are organized in terms of "protection and reactivity control," "fluid systems," and "reactor containment." Whereas this paper is focused on functional containment and radionuclide retention, similar approaches will be addressed within activities such as the Licensing Modernization Project for the other fundamental safety functions.



Note: F/C refers to frequency/consequence targets

Figure 3. Derivation of Performance Criteria

As evident from Figure 3, performance criteria for the design features associated with retaining radioactive materials within a facility will be established based on the range of event categories and the related success criteria for each category. Plant equipment and normal operational controls are needed to limit effluent releases during normal operations, and other limits on normal operations define possible initial conditions for other event categories. Success criteria for AOOs and DBEs include a graded scale for potential offsite doses based on event sequence frequencies (i.e., below an F/C target) and demonstration that prevention features such as cooling systems and fuel system boundaries limit the migration of fission products within the facility. Examples of acceptance criteria used for AOOs include fuel design limits, such as specified acceptable fuel design limits (SAFDLs) similar to LWRs, and specified acceptable radionuclide release design limits (SARRDLs) used for HTGRs. DBAs are similar to current accident analyses described in Chapter 15 of safety analysis reports, which credit only safety-related design features and show that offsite doses are below the regulatory dose criteria in 10 CFR 50.34, "Contents of Applications; Technical Information" (e.g., 25 rem total effective dose equivalent at the Exclusion Area Boundary over the worst 2-hour period). BDBEs are assessed to ensure design features and programmatic controls keep the estimated frequencies and consequences below values corresponding to the NRC's safety goals, which are reflected in the F/C targets.

In addition to evaluating specific event sequences, developers and the staff will perform assessments to ensure sufficient defense in depth has been incorporated into non-LWR designs and programmatic controls. The defense-in-depth assessments will confirm that performance criteria are met without exclusive reliance on single elements of a design or program. The staff anticipates that many non-LWR developers will incorporate design features to limit potential offsite doses to values below those that could justify alternative offsite emergency planning requirements (e.g., less than the U.S. Environmental Protection Agency protective action guides for the early phase of a radiological incident related to public evacuation or sheltering in place). Requirements are defined for specific SSCs by aggregating the design features and programmatic controls needed to meet the success criteria for each event category.

Establishing performance requirements for a set of event categories that extend from benign to severe supports the NRC philosophy of ensuring defense in depth and also generally aligns with standards and practices defined by IAEA.

The above discussions highlight the interrelationships between functional containment performance criteria, performance criteria related to other SSCs and fundamental safety functions, and the overall deployment goals being established for particular technologies or designs. An example is the relationship between performance criteria established for fuel design limits and those established for functional containments. SAFDLs are generally used as performance measures for reactor protection systems in LWRs and address specific physical phenomena, such as departure from nucleate boiling or peak fuel temperatures, which could damage fuel pellets or cladding during AOOs. Limiting the damage to fission product barriers such as fuel cladding, coatings, or other fuel system boundaries during AOOs, in turn, limits the potential release of radioactive materials to structures or systems and reliance on containment buildings to retain radioactive materials. Some non-LWR designs may not include fuel cladding or have a distinct transition from effective to ineffective heat transfer such as departure from nucleate boiling. The SARRDL concept establishes limits on the possible increase in circulating radionuclide inventory during normal operations or an AOO (e.g., from fission product releases from coated fuel particles). Defining SARRDLs for specific designs is intertwined with functional containment performance criteria and would be developed by reactor designers as part of the integrated approach described in this enclosure. Plant operators would subsequently maintain plant configurations consistent with design and analysis limits by verifying fuel performance and location of radionuclide inventories.

The proposed methodology establishes plant-level acceptance criteria and a performance-based methodology for designers to use in determining SSC-level performance criteria instead of a prescriptive set of performance criteria for "functional containment" or other design features. In addition, the staff is continuing interactions with stakeholders to reach agreement on several technical issues such as lower bounds for event sequence frequencies and some details on establishing SARRDLs for non-LWR technologies. However, the NRC staff needs to establish a logical path forward to complete the Strategy 3 activities defined in the near-term IAPs and resolve interrelated policy issues such as establishing functional containment performance criteria. An integrated and consistent approach to address both prevention and mitigation of events is especially important to developers needing to make key design decisions. The design decisions require an ability to assess tradeoffs between possible benefits and costs for various design features as well as possible operating and maintenance costs for prevention and mitigation alternatives.[6] The description of a performance-based methodology is appropriate, given the variety of technologies and designs being developed.

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6 An example could be a reactor developer assessing the value and costs of performing additional testing of fuel behavior, providing additional core heat removal systems, and including a pressure-retaining containment structure and related support systems. A prescriptive NRC requirement for a pressure-retaining containment with performance criteria related to a low leakage rate could significantly lessen the value of improving fuel performance or preventing overheating of the fuel as a means of retaining radioactive materials within the facility. The performance-based methodology being proposed allows reactor developers to assess the safety benefits and cost-effectiveness of various ways to reduce the potential for severe accidents and their consequences.

Other Requirements for Physical Enclosures

Any commercial reactor is expected to have the coolant system and other key SSCs housed within some type of physical enclosure. Even if it serves no other purpose, such an enclosure would protect a valuable asset from the elements. Many discussions of “functional containment” and “containment versus confinement” have focused on the design attributes for the physical enclosure and its possible roles in providing defense in depth as a mitigation barrier for DBEs and BDBEs. As shown in Figure 3, a physical building could serve this purpose and have associated performance criteria based on the event category for which it is serving to limit the release of radioactive materials (in terms of magnitude and timing). The physical enclosure usually referred to as a primary containment structure for LWRs is safety-related because of its role in DBAs and also has design features important for evaluating and protecting against BDBEs. The various reactor sizes and technologies being considered by non-LWR developers may or may not result in the need to credit design features of the physical enclosure for retaining radioactive materials within the facility. The performance-based methodology previously discussed would determine what requirements were imposed on the physical enclosure for the fundamental safety function of retaining radioactive materials. Examples in past interactions with non-LWR developers have included cases where attributes such as fuel form and system heat capacities reportedly limit the migration of radioactive materials and alleviate the need for the design to credit physical enclosures retaining radioactive materials for DBAs.

Beyond a physical enclosure’s role in limiting the release of radioactive materials for one or more event categories, the staff and developers have recognized that structures may serve other purposes and be used to meet specific NRC regulations. The staff included discussions of such other purposes in papers such as SECY-05-0006, “Second Status Paper on the Staff’s Proposed Regulatory Structure for New Plant Licensing and Update on Policy Issues Related to New Plant Licensing,” dated January 7, 2005 (ADAMS Accession No. ML043560093). Examples of potential roles of physical enclosures beyond the retention of radioactive materials include but are not limited to the following:

- structural support to primary cooling systems
- support for the decay heat removal fundamental safety function via structural support for and housing of backup or emergency cooling such as reactor cavity cooling systems
- prevention barrier against external events such as flooding and wind loadings
- design feature credited in aircraft impact assessments
- physical security design feature credited in preventing or delaying adversaries
- design feature credited during environmental assessments of severe accident mitigation design alternatives

In most examples, the physical enclosure is serving as or supporting a preventive barrier for the threats or events shown in Figure 1 (i.e., internal events, external events, and malicious acts). Performance criteria related to these functions (e.g., characteristics needed to address design-basis flooding or wind loadings) would be added to requirements related to fulfilling the fundamental safety function of radionuclide retention (i.e., acting as part of a functional containment). In such cases, an aggregation of performance requirements would determine the final design for a building or other physical enclosure in terms of its role as part of the functional containment and any separate purposes to meet regulations or design goals not specifically associated with radionuclide retention. The consideration of various events and roles for SSCs and using various performance criteria to reach the final design of each SSC are consistent with current practices and the definition of the design basis for specific SSCs for currently operating plants.