# *Planning for Preapplication Focus Topic: SSC Safety Classification & Defense-in-Depth*

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# Discussion Outline

- Issue Definition & Objective Outcomes
- Issue Details for Planning
- Communication Information
- Exelon RAIs
- Suggested Sequence of Activities
- References


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# Issue Definition

- **Background**
  - Implementation of SSC safety classification has evolved for LWRs over several decades.
  - The development of SSC safety classification for non-LWRs with a unique set of DBE challenges has not been established.
  - Advanced reactors contain inherent features and passive safety-related SSC that have no reliance on AC power or other conventional means of assuring public safety.

- **Issue**
  - Establish the approach for determining the safety classification and special treatment for the PBMR SSCs relied on or providing added safety margins during LBEs.


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# Outcome Objectives

- Agreement on what is meant by safety classification
- Agreement on the process by which SSCs are classified as safety-related and their regulatory special treatment
- Agreement on the role of defense-in-depth in safety classification for the PBMR
- Agreement on the kinds of regulatory review and treatment to be applied to SSCs that are not classified as safety-related
- Agreement that the PBMR process is consistent with the Staff's technology-neutral licensing framework


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# Summary of Licensing Approach Elements

- **What must be met?**
  - TLRC
- **When must TLRC be met?**
  - LBEs
- **How must TLRC be met?**
  - Safety Functions
  - SSC Safety Classification
  - Regulatory Design Criteria
  - DBA Design Conditions
- **How well must TLRC be met?**
  - Regulatory Special Treatment


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# Discussion Outline

- **Issue Definition & Objective Outcomes**
- ➔**Issue Details for Planning**
  - Safety Functions
  - SSC Safety Classification
  - Regulatory Design Criteria
  - DBA Design Conditions
  - Defense-in-Depth
  - Special Treatment
- **Communication Information**
- **Suggested Sequence of Activities**
- **References**


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# Required Safety Functions

- **Safety functions are developed from review of LBEs in relation to TLRC.**
- ***Required* safety functions are those needed for compliance with DBE region dose criteria and include:**
  - Retain radionuclides within fuel
    - *Control heat generation*
    - *Remove core heat*
    - *Control chemical attack*
    - *Maintain core geometry*
- ***Required* safety functions establish *how* it will be assured that the TLRC are met.**


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# Selection of Safety-Related SSCs

- **Select SSCs that are available and sufficient to perform the required safety functions for**
  - mitigation of consequences of spectrum of DBEs to meet DBE region dose criteria
  - prevention of high consequence BDBEs to assure that the frequency is below the DBE region frequency boundary
- **Safety-related SSCs provide assurance as to *how* TLRC are met.**


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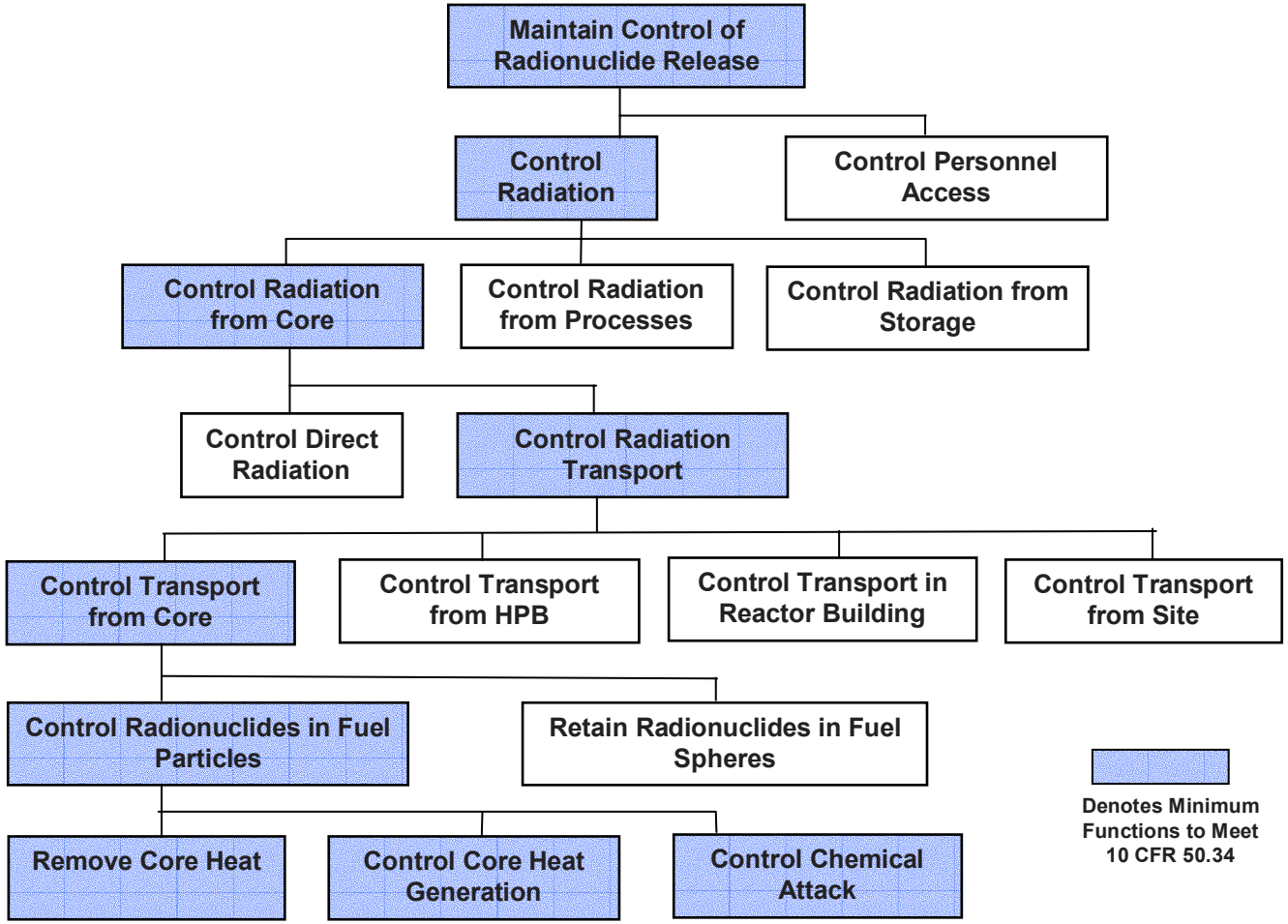
# PBMR Required Safety Functions




Ref: Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5.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# Example of Safety-Related SSC Selection for Core Heat Removal

| SSC Available and Sufficient to Remove Core Heat in the DBE? | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Sets of Alternative SSC** | **DBE 1c** | **DBE 2b** | **DBE 6c** | **DBE 7a** | **DBE 7b** | **DBE 11b** | **Safety Related?** |
| **Reactor<br>PCU<br>ACS** | **No** | **No** | **No** | **No** | **No** | **No** | |
| **Reactor<br>SBS<br>ACS** | **No** | **No** | **No** | **Yes** | **No** | **No** | |
| **Reactor<br>CCS<br>ACS** | **No** | **Yes** | **No** | Yes | **Yes** | **Yes** | |
| **Reactor<br>Reactor vessel<br>Active RCCS<br>ACS** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** | |
| **Reactor<br>Reactor vessel<br>Passive RCCS** | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Reactor<br>Reactor vessel<br>Building & ground** | Yes | Yes | Yes | Yes | Yes | Yes | |

Note: **Bold** indicates actual response during DBE


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**Ref: Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5.**

# Insights from Selection of Safety-Related SSCs for Core Heat Removal

- **Passive RCCS (with reactor and reactor vessel) selected as safety-related**
  - Available and sufficient for spectrum of DBEs
  - Amenable to providing requisite assurance
- **Other sets of SSCs provide defense-in-depth for certain DBE and limit the challenge to the passive RCCS**
  - PCU set (primary function is power generation)
  - SBS set (primary function is power generation)
  - CCS set (primary function is availability)
  - Active RCCS (primary function is investment protection)
- **Reactor, reactor vessel, buildings/ground provide ultimate defense-in-depth**


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# Preliminary PBMR Safety-Related SSCs

| Specific SSC Selected as Safety-Related | Required Safety Function Performed by SSC |
|---|---|
| Fuel Particles | Retain radionuclides<br>Control heat generation |
| Fuel and Graphite Spheres | Remove core heat<br>Control heat generation |
| Reactivity Control System (RCS) | Control heat generation |
| Reactor Core Structure | Remove core heat<br>Maintain core geometry |
| Core Barrel | Remove core heat<br>Maintain core geometry |
| Core Reflector | Remove core heat<br>Control heat generation<br>Maintain core geometry |
| Reactor Vessel | Remove core heat<br>Maintain core geometry<br>Control chemical attack |
| Passive Reactor Cavity Cooling System (RCCS) | Remove core heat |
| Reactor Building | Maintain core geometry<br>Control chemical attack |


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Ref: Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5.

# SSC Safety Classification

- **Safety-Related**
  - Subset of SSCs relied on to perform **required** safety functions for mitigation of DBE consequences and prevention of BDBE with high consequences to meet TLRC
  - Receive regulatory special treatment
- **Supportive Safety**
  - SSCs with primary functions for power generation, availability, and investment protection that may in certain LBEs also be capable of performing
    - **required** safety functions for DiD

    and/or
    - supportive safety functions
  - Receive treatment commensurate with requirements needed to accomplish primary functions
  - Treatment receives limited review by regulator
- **Not Safety**
  - SSCs that do not perform any safety function
  - Receive treatment commensurate with requirements needed to accomplish primary functions
  - Treatment not reviewed by regulator


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# PBMR Regulatory Design Criteria (RDC)

- Qualitative, functional statements for SSC classified as Safety-Related
- RDC are developed with risk insights for each required safety function.
- PBMR-specific RDC supplement LWR General Design Criteria (GDC) i.e., 10 CFR 50, Appendix A
- RDC establish *how* it is assured that the TLRC are met.


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# Example of Regulatory Design Criteria

**Conduct Heat from Core to Vessel Wall:**

*The reactor core design and configuration shall ensure sufficient heat transfer by conduction, radiation, and convection to the reactor vessel wall to maintain fuel temperatures within acceptable limits following a loss of forced cooling.*

*The materials which transfer the heat shall be chosen to withstand the elevated temperatures experienced during this passive mode of heat removal.*

*This criterion shall be met with the primary coolant system both pressurized and depressurized.*


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# Design Basis Accidents

- Design Basis Accidents (DBA) provide deterministic confirmation that the safety-related SSC can alone mitigate the consequences of the selected DBEs.

- The DBA are used to develop the limiting parameter values i.e., temperatures, stresses, heat loads, etc., that SSC must be able to meet in order to fulfill its mission for each DBE.

- DBAs are used to establish conservative operating conditions.


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# Relation of Deterministic DBAs to DBEs

| SSC Available and Sufficient *and Relied on* to Remove Core Heat in the DBA | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Sets of Alternative SSC** | **DBA 1c** | **DBA 2b** | **DBA 6c** | **DBA 7a** | **DBA 7b** | **DBA 11b** | **Safety Related?** |
| **Reactor<br>PCU<br>ACS** | No | No | No | No | No | No | |
| **Reactor<br>SBS<br>ACS** | No | No | No | No | No | No | |
| **Reactor<br>CCS<br>ACS** | No | No | No | No | No | No | |
| **Reactor<br>Reactor vessel<br>Active RCCS<br>ACS** | No | No | No | No | No | No | |
| **Reactor<br>Reactor vessel<br>Passive RCCS** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |
| **Reactor<br>Reactor vessel<br>Building & ground** | No | No | No | No | No | No | |


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# Example of Process for DBA Design Criteria

- **Reactor pressure vessel selected as safety-related for the following required safety functions**
  - *radiate core heat from vessel wall*
  - *limit chemical attack of core*
  - *maintain core geometry*

- **To maintain core geometry, examination of following DBA led to quantitative requirements, e.g.,**
  - *pressurized loss of forced cooling (DBE-reactivity events, loss of offsite power, etc.)*
  - *depressurized loss of forced cooling (DBE-HPB leaks, etc.)*

- **Selected ASME Code as one element of special treatment for maintaining HPB integrity function**


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  - Special Treatment
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- **Suggested Sequence of Activities**
- **Exelon RAIs**
- **References**


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# Generic Aspects of Defense-in-Depth

- **Three Defense-in-Depth Aspects***
  - Design DiD
  - Process DiD
  - Scenario DiD
- **All three aspects of DiD are needed**

**Ref: Karl Fleming and Fred Silady, Technology Insights, "A Risk Informed Defense-in-Depth Framework For Existing and Advanced Reactors," Reliability Journal, 2002.**


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# Design Defense-in-Depth

- **Reflects all decisions made by the designer to incorporate defense-in-depth into the physical plant**
- **Includes**
  - selection of plant site and boundary in relation to surrounding population
  - selection of the inherent features of the reactor that dictate its fundamental behavior during normal, abnormal and accident conditions
  - design of barriers between radionuclide sources and environment
  - design of engineered safety features to support an appropriate set of safety functions that support integrity of these barriers
    - *Passive features*
    - *Active features*


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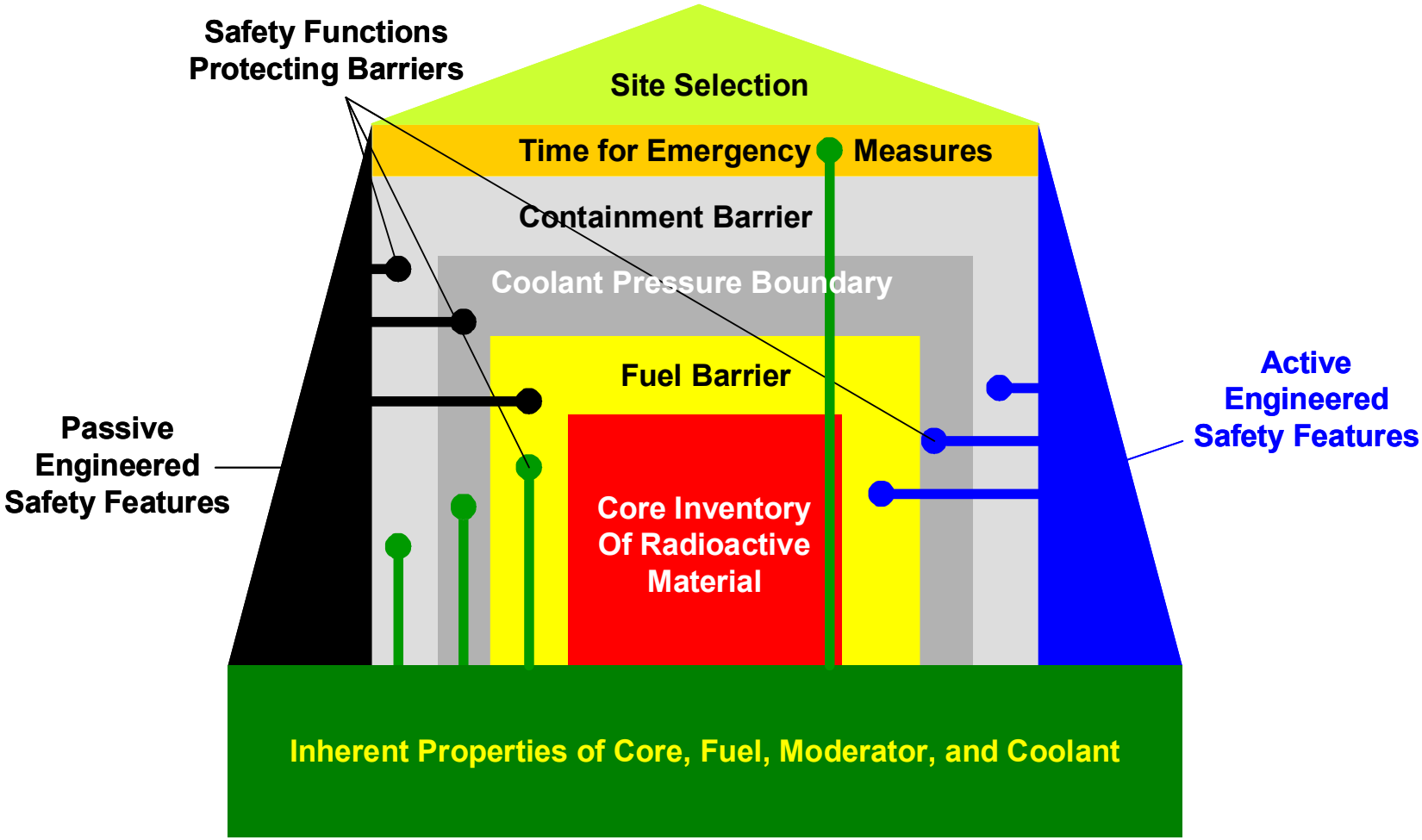
# Generic Schematic of Design Defense-in-Depth





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# Elements of Design Defense-in-Depth

- **Inherent features of reactor important to safety**
  - Fundamental properties of core/fuel elements/reactor
  - Fundamental properties of reactor coolant
  - Fundamental properties of moderator (thermal reactors only)
- **Use of multiple barriers**
  - Fuel barrier design features
  - Coolant pressure boundary design features
  - Containment design features
  - Independence and concentricity of barriers
- **Engineered safety features to protect barrier integrity**
  - Reactor specific safety functions to protect barriers
  - Passive engineered safety systems
  - Active engineered safety systems
  - Operator actions needed to implement or inhibit safety functions
- **Detailed design decisions to ensure adequate reliability of barriers and engineered safety features meeting requirements set in *Process Defense-In-Depth***
- **Time available to implement emergency measures**
- **Selection of appropriate reactor sites**


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# Preliminary PBMR Design Features Providing DiD of Fuel Barrier

| Barrier to Radio-nuclide Release | Safety Functions Supporting Barrier Integrity | Elements of Defense-in-Depth in Supporting Safety Functions | |
|---|---|---|---|
| | | Inherent Features and Attributes | Engineered Active and Passive Features |
| Retain Radionuclides in Fuel | • Maintain fuel integrity | • Multiple layer ceramic TRISO fuel particles encapsulated by graphite sphere<br>• Low levels of circulating and plateout activity within pressure boundary via fuel reliability and performance | • Robust fuel quality assurance program to assure high fuel particle reliability<br>• On-line fuel measurements to monitor burn-up<br>• On-line monitoring of circulating activity<br>• On-line sphere physical defect monitoring |
| | • Control heat generation | • Negative temperature coefficient<br>• Small excess reactivity<br>• Slow reactivity response | • Gravity-driven control rods via EPS and RPS<br>• Diverse, gravity-driven boron pellets via RSS<br>• High shutdown margins achieved by either system |
| | • Control heat removal | • Low power density<br>• High thermal heat capacity<br>• Core geometry and power level allows passive cool-down capability independent of coolant convection | • Forced cooling via MPS (Brayton cycle) operation<br>• Forced cooling via SBS and normal MPS heat sinks<br>• Forced cooling via Reactor Unit Conditioning System<br>• Passive conduction/radiation cool-down via the active/passive RCCS<br>• Redundant and diverse heat removal paths<br>• Several day passive capability independent of active components or operator actions |


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Ref: Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5. The design at that time was 268MWt.

# Preliminary PBMR Design Features Providing DiD of Fuel Barrier (Cont'd)

| Barrier to Radio-nuclide Release | Safety Functions Supporting Barrier Integrity | Elements of Defense-in-Depth in Supporting Safety Functions | |
|---|---|---|---|
| | | Inherent Features and Attributes | Engineered Active and Passive Features |
| Retain Radionuclides in Fuel | • Control chemical attack | • Ceramic fuel particles and graphite matrix<br>• Reactor Design limits extent of air or water ingress<br>• Self limiting aspect of reactions<br>• Inert gas coolant | • Low pressure cooling water sources limits potential for water ingress<br>• Design interfaces with high pressure primary system<br>• High quality primary vessels & piping with robust seismic capability |
| | • Maintain core geometry | • Use of refractory ceramics for structural materials exposed to high temperatures<br>• Use of high temperature alloys for reactor vessel and core barrel components | • High quality reactor vessel and PPB designed to large seismic margins<br>• Robust citadel structure provides strength and protection from external missiles<br>• Forced convection of Helium maintains vessel and core barrel metal components at relatively low temperatures |


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Ref: Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5. The design at that time was 268MWt.

# Preliminary PBMR Design Features Providing DiD of HPB Barrier

| Barrier to Radio-nuclide Release | Safety Functions Supporting Barrier Integrity | Elements of Defense-in-Depth in Supporting Safety Functions | |
|---|---|---|---|
| | | Inherent Features and Attributes | Engineered Active and Passive Features |
| Retain Radionuclides in Helium Pressure Boundary | Maintain HPB integrity | • Use of chemically inert single phase gas coolant<br>• Inherently low over-pressurization potential due to low stored energy, large pressure gradients during normal operation, and limited pressurization capacity of HICS<br>• Immediate reduction in HPB pressure on cessation of Brayton Cycle | • Maintenance of high chemical purity by operation of helium purification system<br>• Use of high quality reactor vessel and HPB components<br>• HPB capability to retain PTG missiles<br>• Use of a Citadel structure to protect the HPB<br>• Forced convection flow paths maintain HPB components at relatively low temperatures.<br>• Capability of HICS to pump down inventory to reduce driving head for releases from HPB. |

Ref: Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5. The design at that time was 268MWt.


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# Preliminary PBMR Design Features Providing DiD of Reactor Building Barrier

| Barrier to Radio-nuclide Release | Safety Functions Supporting Barrier Integrity | Elements of Defense-in-Depth in Supporting Safety Functions | |
|---|---|---|---|
| | | Inherent Features and Attributes | Engineered Active and Passive Features |
| Retain Radionuclides In Reactor Building | Maintain integrity of Reactor Building | • Low stored energy and inert primary coolant<br>• Completely envelopes HPB boundary<br>• Events evolve slowly allowing for manual compensating measures | • HVAC filtration system to reduce exposures<br>• Blowout panels for large depressurization events prevent pressure loads<br>• Re-closable vent for an elevated release<br>• Robust construction to protect equipment from external hazards<br>• Partially below grade |

Ref: Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5. The design at that time was 268MWt.


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# Preliminary PBMR Design Features Providing DiD of Emergency Planning

| "Barrier" to Radio-nuclide Release | Safety Functions Supporting "Barrier" Integrity | Elements of Defense-in-Depth in Supporting Safety Functions | |
|---|---|---|---|
| | | Inherent Features and Attributes | Engineered Active and Passive Features |
| Provide Emergency Planning | Provide ample warning time for effective protective actions | • Large thermal capacity provides ample time for implementing emergency plans<br>• Low source terms reduce EP contingencies | • Features relied upon in EP strategy limit radiological doses at the site boundary below Protective Action Guidelines levels for all LBEs. |

Ref: Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5. The design at that time was 268MWt.


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# Process Defense-in-Depth

- **Reflects all decisions made in formulation of regulatory requirements associated with licensing, operating, maintaining, and inspecting the plant and in all processes that contribute to safety**

- **These processes ensure safe operation of the plant and cover**
  - design
  - procurement
  - fabrication
  - construction
  - operation
  - maintenance
  - testing
  - Inspections
  - Independent assessments


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# Elements of Process Defense-in-Depth

- **Design Requirements**
  - Top Level Regulatory Criteria (TLRC, e.g. safety goals)
  - Selection of Licensing Basis Events
  - Selection of safety-related SSCs
  - Definition of safety margins for deterministic safety evaluations
  - Special treatment requirements
  - Independent design reviews
- **Organizational and Human Factors**
  - Management safety culture
  - Operator training requirements
  - Emergency operating procedures
  - Accident management guidelines
- **Technical Specifications**
  - Limited Conditions for Operation
  - Surveillance testing requirements
  - Allowable outage (completion) times
- **Maintenance and Monitoring of SSC Performance**
  - Factory testing and qualification
  - Startup testing
  - Fuel manufacturing tests and inspections
  - In-service testing
  - In-service inspection
  - Maintenance of SSCs
  - Selection of appropriate performance indicators
  - Regulatory inspections and oversight
- **Quality Assurance Program**
- **Corrective Action Programs**
  - Root cause analysis
  - Event trending
  - Closure effectiveness


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# Scenario Defense-in-Depth

- Reflects development and evaluation of strategies to manage risks of accidents, including strategies for accident prevention and mitigation

- Provides the framework for performing deterministic and probabilistic safety evaluations which help determine how well various prevention and mitigation strategies have been implemented


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# Elements of Scenario Defense-in-Depth

- **Comprehensive set of challenges to Barrier Integrity (from a PRA)**
  - Internal event scenarios
  - Internal plant hazard scenarios
  - External events scenarios
- **Evaluation of accident prevention strategies**
  - Strategies to prevent initiating events
  - Strategies to prevent initiating events from progressing to accidents
  - Strategies to prevent accidents from exceeding the design basis
- **Evaluation of accident mitigation strategies**
  - Strategies to reduce frequency of challenges to safety systems
  - Strategies to limit impact of challenges to barriers
  - Strategies to retain and delay transport of radionuclides from barriers during accidents
    - *Retention and delay within fuel elements*
    - *Retention and delay within coolant pressure boundary*
    - *Retention and delay within containment*
    - *Strategies to provide offsite protective actions*
- **Risk management strategies**
  - Configuration risk management strategies
  - Change risk management strategies
- **Optimization of safety resources with respect to risk and cost**


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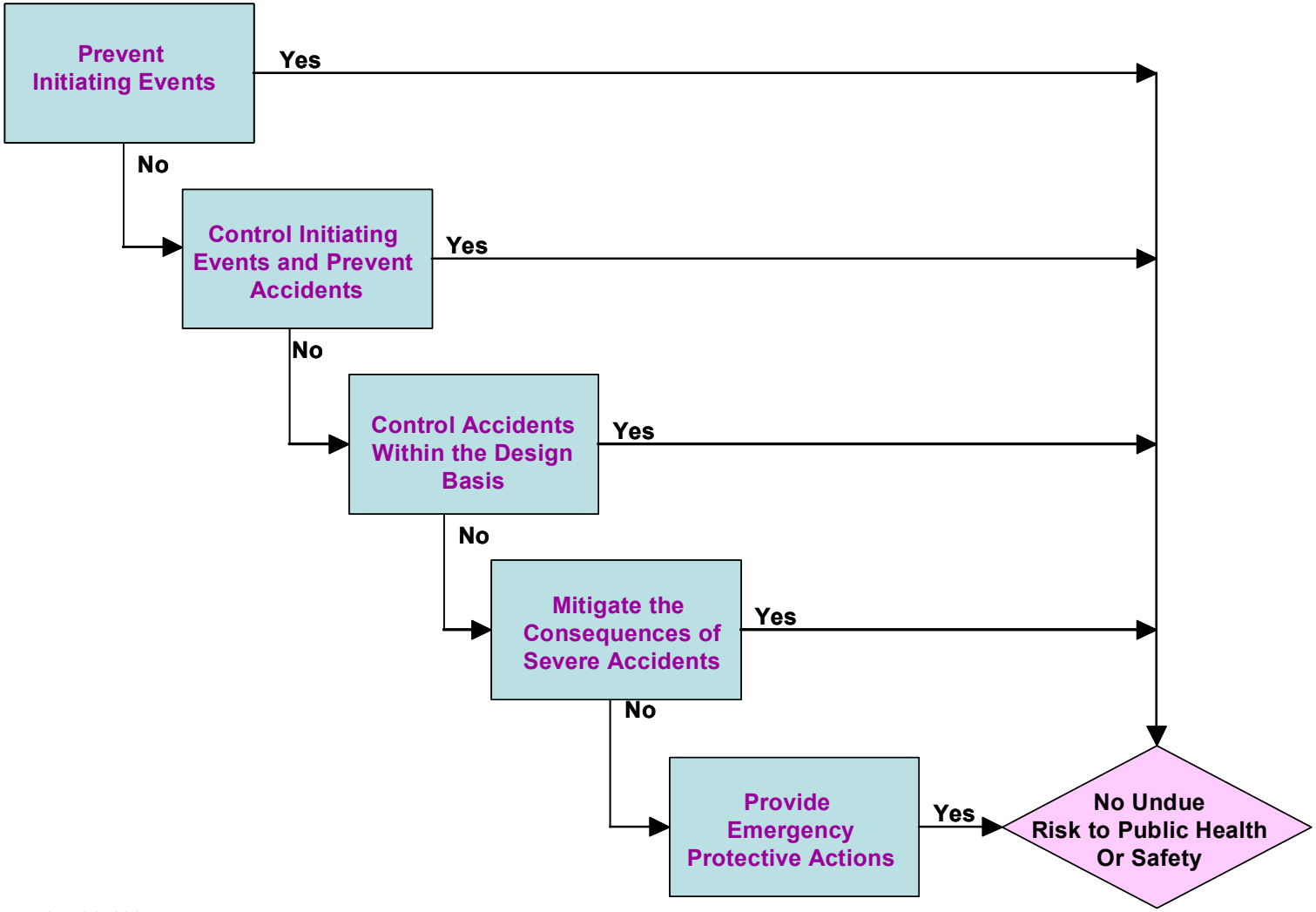
# Scenario Defense-in-Depth from IAEA





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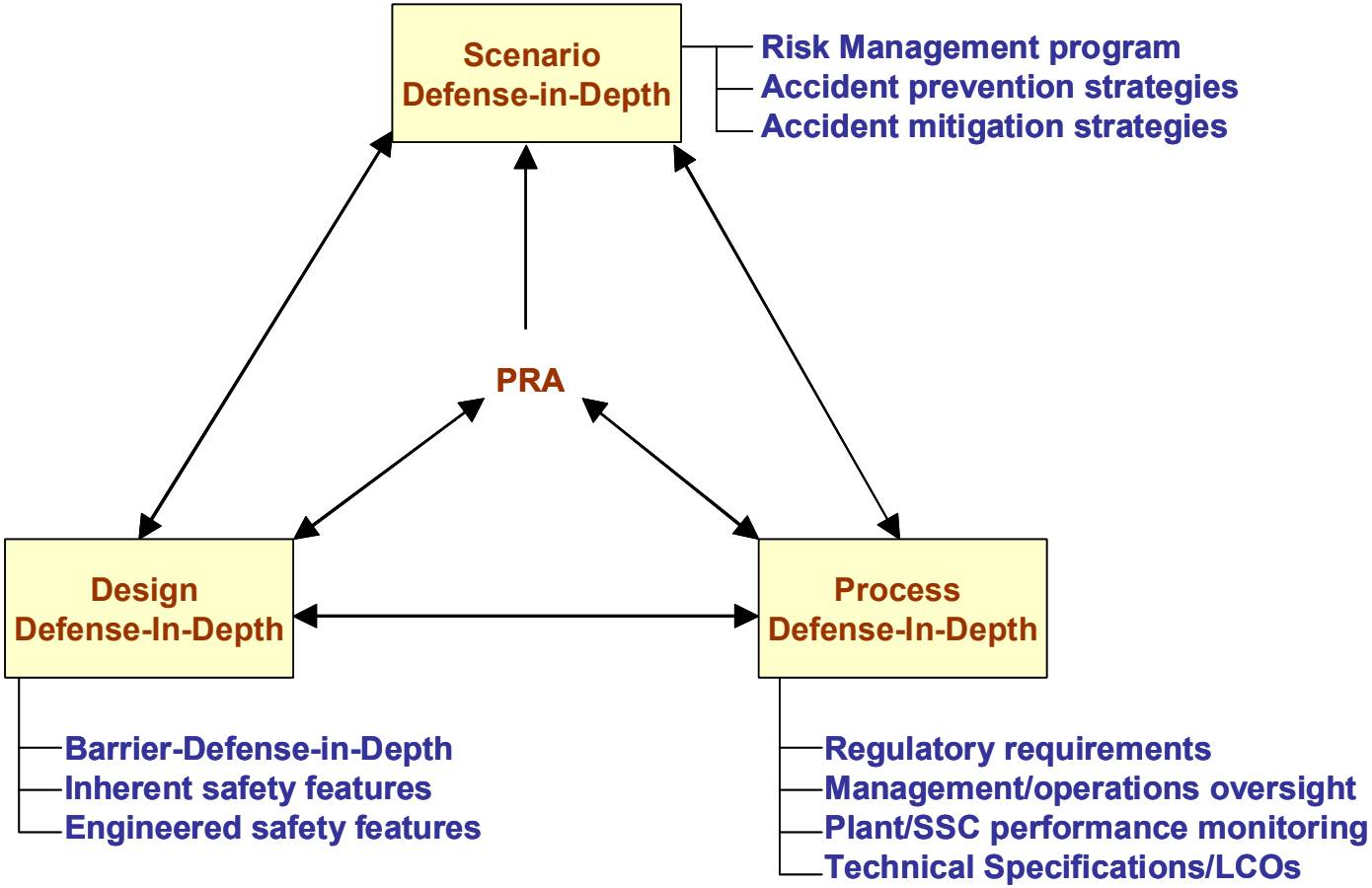
# Schematic of Defense-in-Depth Aspects




PRA – Probabilistic Risk Assessment
RM – Risk Management
LCO – Limited Condition for Operation
SSC – Structure, System, Component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# Relation of Licensing Approach Elements to Defense-in-Depth

- **What must be met?**
  - TLRC
- **When must TLRC be met?**
  - LBEs
- **How must TLRC be met?**
  - Safety Functions
  - SSC Safety Classification
  - Regulatory Design Criteria
  - DBA Design Conditions
- **How well must TLRC be met?**
  - Regulatory Special Treatment

- **Scenario Defense-in-Depth**
  - TLRC
  - LBEs
- **Design Defense-in-Depth**
  - Safety Functions
  - SSC Safety Classification
  - Regulatory Design Criteria
  - DBA Design Conditions
- **Process Defense-in-Depth**
  - All of above plus
  - Regulatory Special Treatment


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# Approach to Regulatory Special Treatment

- **Selection of and treatment of safety-related SSCs follows regulatory practice**
  - DBE consequences shown to be acceptable using only safety-related SSCs
  - High consequence BDBEs have acceptably low frequencies assured with reliable safety-related SSCs
  - Safety-related SSCs receive special treatment during design, fabrication, construction, operation and maintenance
- **The special treatment requirements for safety-related SSC are developed based on the required function for each DBE.**
- **Clear basis is established for safety-related equipment selection and the corresponding regulatory special treatment.**
- **Design conditions for and special treatment of safety-related SSC provide assurance as to *how well* the TLRC are satisfied.**


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# Example Special Treatment Choices

- **Design**
  - Technology choices with their inherent properties
  - Blend of active and passive engineered safety features
  - Redundancy/diversity
  - Development testing
  - Conservative margins
  - Independent verification
- **Manufacturing**
  - Material procurement
  - Quality inspection
  - Testing
- **Construction**
  - Independent verification procedures
  - NDE
  - QA
- **Operation & Maintenance**
  - Monitoring
  - training
  - Maintenance procedures
  - Trending
  - ISI/IST


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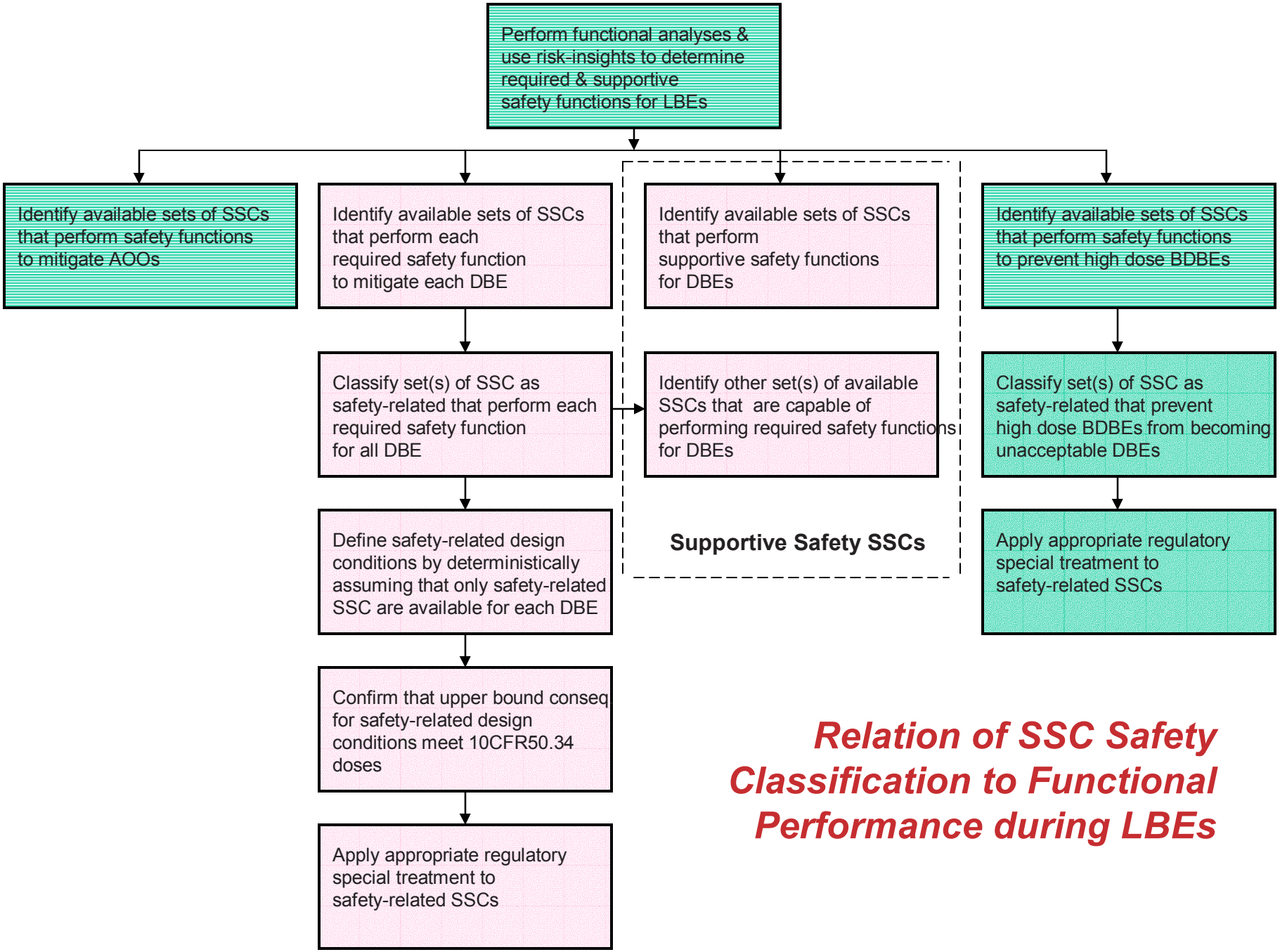


## *Relation of SSC Safety Classification to Functional Performance during LBEs*

# Issue Focus

- **Safety Classification**
  - a means to focus regulatory attention and resources on a subset of the plant's SSCs to provide added assurance that required safety functions are accomplished for offsite public protection

- **SSCs classified as safety-related**
  - proposed by applicant and conservatively shown to provide sufficient mitigation to meet dose criteria during DBEs and to provide sufficient prevention of high-dose BDBEs
  - receive regulatory special treatment during design, manufacturing /construction, operation, and maintenance

- **SSCs not classified as safety-related**
  - may also perform functions that provide safety margins and defense-in-depth, in addition to primary functions needed for the owner
  - are also within the regulator's purview and receive treatment as needed for performance assurance, availability, and operational requirements


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# Issue Focus

- **Issues with SSC safety classification include:**
  - Linkage to events leading to classification of equipment
  - Events for which the safety-related SSCs are sufficient for prevention or mitigation
  - Selection of which SSCs are classified as safety-related
  - Special treatment alternatives for safety-related SSCs
  - Role of SSCs that provide safety margins and defense-in-depth
  - Treatment needed for SSCs not classified as safety-related
  - Best means to harmonize the PBMR process with the Staff's technology-neutral licensing framework


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# Licensing Approach Terms Used

- Required Safety Functions
- Supportive Safety Functions
- Safety-Related SSCs
- Supportive Safety SSCs
- Not Safety SSCs
- Design Basis Accidents
- Design Basis Accident Design Conditions
- Regulatory Design Criteria
- Regulatory Special Treatment
- Design DiD
- Process DiD
- Scenario DiD


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# Example Terms Not Used

- Important to Safety
- Non Safety-Related SSCs


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# Discussion Outline

- June Meeting Review
- Communication Information
- Details for Planning
- ➔ Exelon RAIs
- Suggested Sequence of Activities
- References


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# Exelon RAIs

| Area of Review | Timing | Pre-application Work Item(s) |
|---|---|---|
| ***White Papers*** | | |
| **PBMR Operational Modes and States** | | |
| **RAI 7.1.1** | **1** | |
| ***Licensing Approach*** | | |
| **RAIs 1-9** | **1** | |


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# Discussion Outline

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# Proposed Strategy

- Submittal of SSC classification and DiD white paper with PBMR detailed approach; propose DCA specification
- Workshop on proposed SSC safety classification method and Defense-in-Depth approach, after the LBE-PRA Workshop
- RAI from NRC on above
- Revise the white paper and resubmit for NRC final consideration
- Confirm DCA content specification


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# References

- **Exelon pre-application interactions**
  - Exelon letter dated March 15, 2002, "Revision of Exelon Generation Company's Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," Section 5.
  - Exelon presentation to ACRS, "Proposed Licensing Approach for the Pebble Bed Modular Reactor in the United States," October 2001.

- **DOE submittal to NRC, "Preliminary Safety Information Document for the Standard MHTGR," Volume 1, Section 3, August 1992, Amend 11.**

- **NRC Request For Additional Information (RAI) Related To Exelon's March 15, 2002, Document Titled "Proposed Licensing Approach for the Pebble Bed Modular Reactor (PBMR) In The United States," June 3, 2002.**

- **Karl Fleming and Fred Silady, Technology Insights, "A Risk Informed Defense-in-Depth Framework For Existing and Advanced Reactors," Reliability Engineering and System Safety Journal, 2002.**


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