Modular High Temperature Gas-cooled Reactor: Accident Analysis

Advanced Reactor Technologies

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ADVANCED REACTOR TECHNOLOGIES

Outline

- Licensing Modernization Project (LMP)
  - Risk Informed Approach
  - Selection of Licensing Basis Events (LBEs)
  - Frequency-Consequence Target
  - LBE Cumulative Risk Targets
  - Structures, Systems, and Components (SSC) Safety Categories Classification
  - Evaluation of Defense in Depth (DID)
- Use of Probabilistic Risk Assessment (PRA) in LMP Process
  - PRA Policy Statement
  - American Nuclear Society (ANS) Non-Light-Water Reactor (non-LWR) PRA Standard

Risk-Informed Approach

- NRC PRA Policy Statement motivates risk-informed, performance-based (RIPB) approach to modular High Temperature Gas-cooled Reactor (HTGR) licensing
- Complements traditional deterministic design approach to increase use of risk insights in design and licensing decisions
- Risk-informed approach:
  - Explicit consideration to a broader set of challenges
  - Logical prioritization of challenges
  - Consideration of broader set of resources to defend against challenges
  - Explicitly identifying and quantifying sources of uncertainty
  - Better decision making by testing for sensitivity to key assumptions
- Performance-Based Approach:
  - Measurable (or calculable) parameters for monitoring
  - Objective criteria to assess performance

PRA Development

- Early introduction of PRA into design process facilitates risk-informing design decisions
- Scope and level of detail consistent with scope and level of detail of design and site information and fit for purpose in RIPB decisions
- PRA event-sequences include those involving single and multiple reactor modules and risk significant non-reactor sources
- Non-LWR PRA standard specifically designed to support LMP PRA applications
- Limitations and uncertainties associated with PRA addressed in the evaluation of defense-in-depth adequacy

Objectives of the Licensing Modernization Project (LMP)

- From draft LMP Guideline Document (NEI 18-04):
  - The scope of this document is focused on establishing guidance for advanced (i.e., non-LWR) designs so license applicants can develop inputs that can be used to comply with applicable regulatory requirements, …
  - Technology inclusive
- Based on 10 CFR 50.34 and other regulatory requirements, an applicant must answer the following questions:
  - What are the plant initiating events, event sequences, and accidents that are associated with the design?
  - How does the proposed design and its SSCs respond to initiating events and event sequences?
  - What are the margins provided by the facility's response, as it relates to prevention and mitigation of radiological releases within prescribed limits for the protection of public health and safety?
  - Is the philosophy of DID adequately reflected in the design and operation of the facility?

LMP – Licensing Basis Events

- LBEs are defined broadly to include all the events used to support the safety aspects of the design and to meet licensing requirements
- They cover a comprehensive spectrum of events from normal operation to rare, off-normal events
- Categories defined as Normal Operations, including Anticipated Operational Occurrences (AOO), Design Basis Events (DBE), Beyond Design Basis Events (BDBE) and Design Basis Accidents (DBA)
- LBE definitions generally consistent with Next Generation Nuclear Plant (NGNP) white papers
- Draft LMP guidance document (NEI 18-04) includes glossary to clarify differences in terminology with regulatory terms

LBE Categories

Anticipated Operational Occurrences (AOOs). Anticipated event sequences expected to occur one or more times during the life of a nuclear power plant, which may include one or more reactor modules. Event sequences with mean frequencies of 1×10^{-2}/plant-year and greater are classified as AOOs. AOOs take into account the expected response of all SSCs within the plant, regardless of safety classification.

Design Basis Events (DBEs). Infrequent event sequences that are not expected to occur in the life of a nuclear power plant, which may include one or more reactor modules, but are less likely than an AOO. Event sequences with mean frequencies of 1×10^{-4}/plant-year to 1×10^{-2}/plant-year are classified as DBEs. DBEs take into account the expected response of all SSCs within the plant regardless of safety classification. The objective and scope of DBEs to form the design basis of the plant is the same as in the NRC definition.

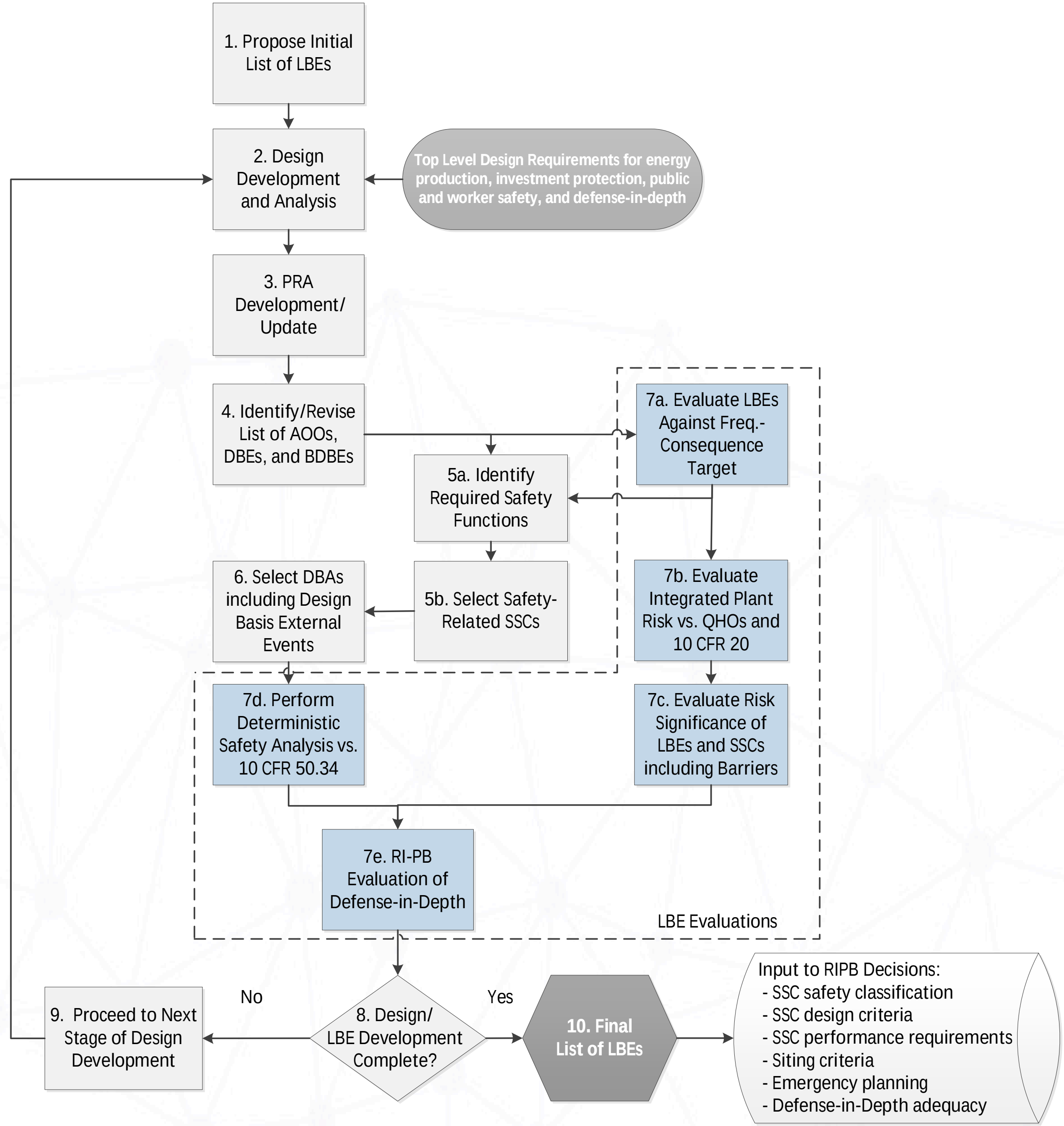
Beyond Design Basis Events (BDBEs). Rare event sequences that are not expected to occur in the life of a nuclear power plant, which may include one or more reactor modules, but are less likely than a DBE. Event sequences with mean frequencies of 5×10^{-7}/plant-year to 1×10^{-4}/plant-year are classified as BDBEs. BDBEs take into account the expected response of all SSCs within the plant regardless of safety classification.

Design Basis Accidents (DBAs). Postulated accidents that are used to set design criteria and performance objectives for the design and sizing of SSCs that are classified as safety-related. DBAs are derived from DBEs based on the capabilities and reliabilities of safety-related SSCs needed to mitigate and prevent accidents, respectively. DBAs are derived from the DBEs by prescriptively assuming that only SSCs classified as safety-related are available to mitigate postulated accident consequences to within the 10 CFR 50.34 dose limits.

LMP – Selection and Evaluation of LBEs

- AOOs, DBEs, and BDBEs are defined in terms of event sequence families from a design-specific PRA
- AOOs, DBEs, and BDBEs are evaluated:
  - Individually for risk significance using a Frequency-Consequence (F-C) chart
  - Collectively by comparing the total integrated risk against a set of cumulative risk targets
- DBEs and high consequence BDBEs are evaluated to define Required Safety Functions necessary to meet F-C Target
- Designer selects Safety Related SSCs to perform required safety functions among those available on all DBEs
- DBAs are derived from DBEs by assuming failure of all non-safety related SSCs and evaluating the consequences conservatively vs. 10 CFR 50.34

LBE Selection and Evaluation



LMP – Frequency-Consequence Target

- Purpose is to evaluate risk significance of individual LBEs and to help define the Required Safety Functions
- Derived from the NGNP F-C Target and frequency bins for AOOs, DBEs, and BDBEs
- Addressed the “staircase” issue with previous F-C targets (NGNP and NUREG-1860)
- F-C Target anchor points based on:
  - 10 CFR 20 annual dose limits and ISO-risk concept
  - Avoidance of offsite protective actions for lower frequency AOOs
  - 10 CFR 50.34 dose limits for lower frequency DBEs
  - Consequences based on 30 day TEDE dose at EAB
  - Doses at EAB are used to assure meeting QHO for prompt fatality individual risk

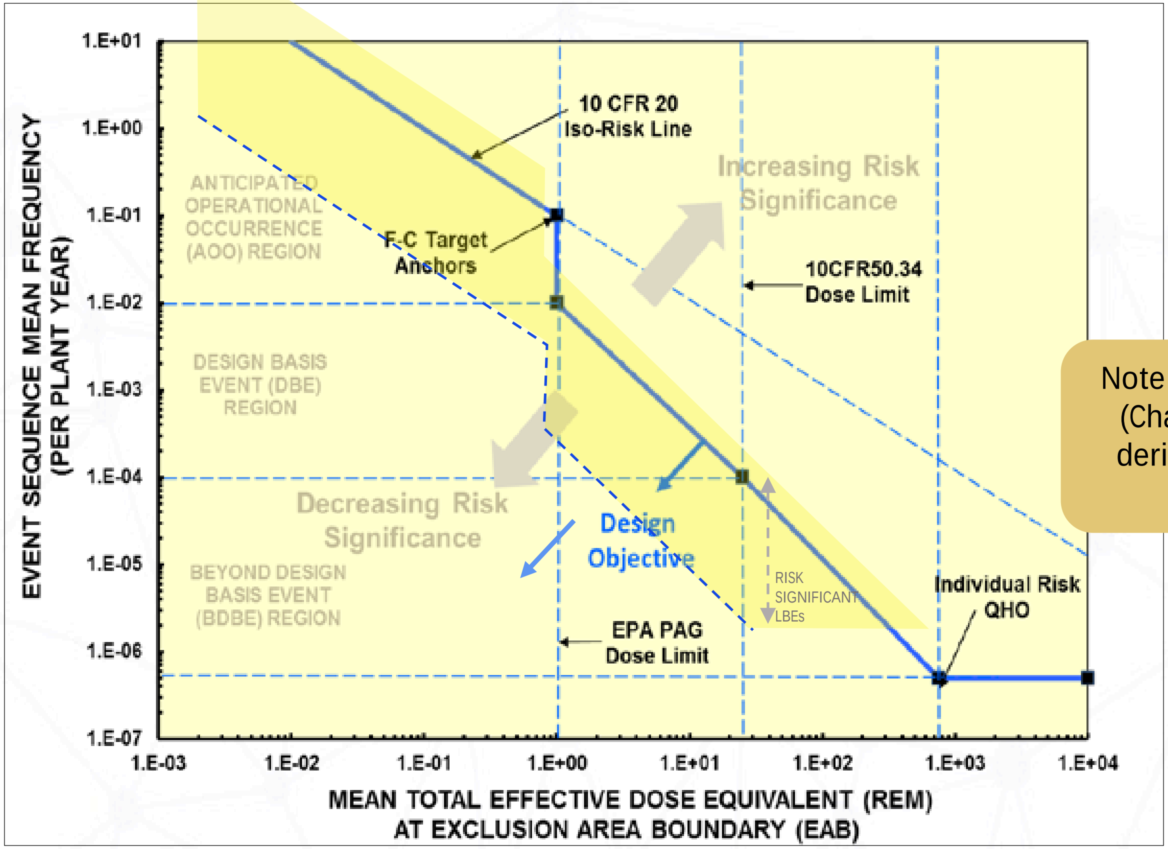
LMP – F-C Target

The F-C Target values shown in the figure should not be considered as a demarcation of acceptable and unacceptable results. The F-C Target provides a general reference to assess events, SSCs, and programmatic controls in terms of sensitivities and available margins.

AOOs

DBEs

BDBEs



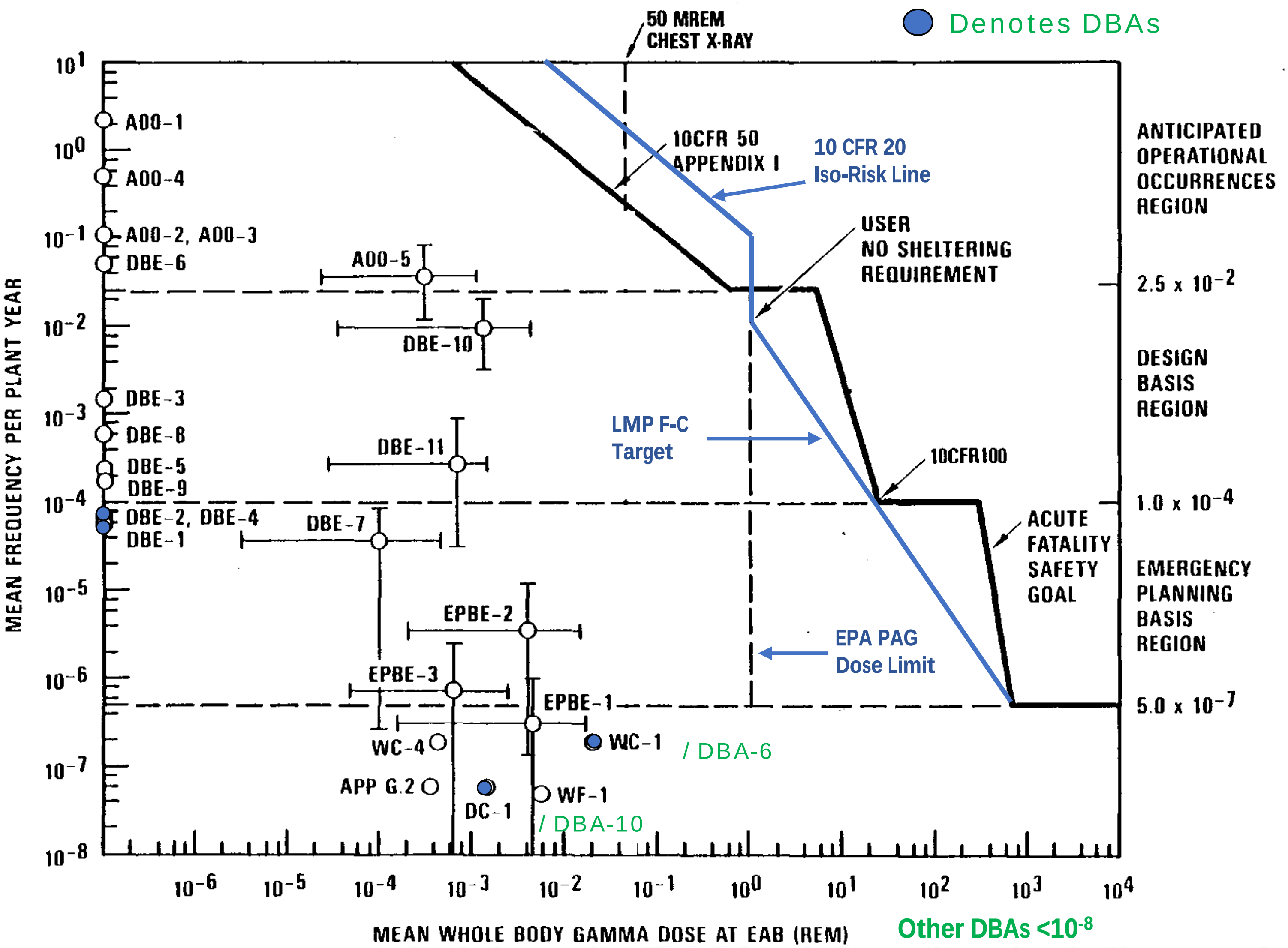
Note that DBAs (Chapter 15) derived from DBEs

* F-C Target considered along with cumulative risk metrics, safety classification, and assessment of defense in depth

LMP – LBE Cumulative Risk Targets

- The total frequency of exceeding an offsite boundary dose of 100 mrem shall not exceed 1/plant-year to ensure that the annual exposure limits in 10 CFR 20 are not exceeded
- The average individual risk of early fatality within the area 1 mile of the Exclusion Area Boundary (EAB) shall not exceed 5×10^{-7}/plant-year to ensure that the NRC Safety Goal Qualitative Health Objective (QHO) for early fatality risk is met
- The average individual risk of latent cancer fatalities within the area 10 miles of the EAB shall not exceed 2×10^{-6}/plant-year to ensure that the NRC safety goal QHO for latent cancer fatality risk is met

Historical Example: MHTGR DBEs, DBAs, and BDBEs on F-C Plot (circa 1987)



LMP – SSC Approach Highlights

- Adopts three SSC safety classification categories in NGNP SSC white paper
- Proposes criteria for SSC risk significance based on absolute risk metrics
- Incorporates concepts from 10 CFR 50.69 and NEI-00-04
- Includes SSC requirements to address single and multi-module risks
- Expands on guidance for deriving performance requirements beyond those in NGNP SSC white paper

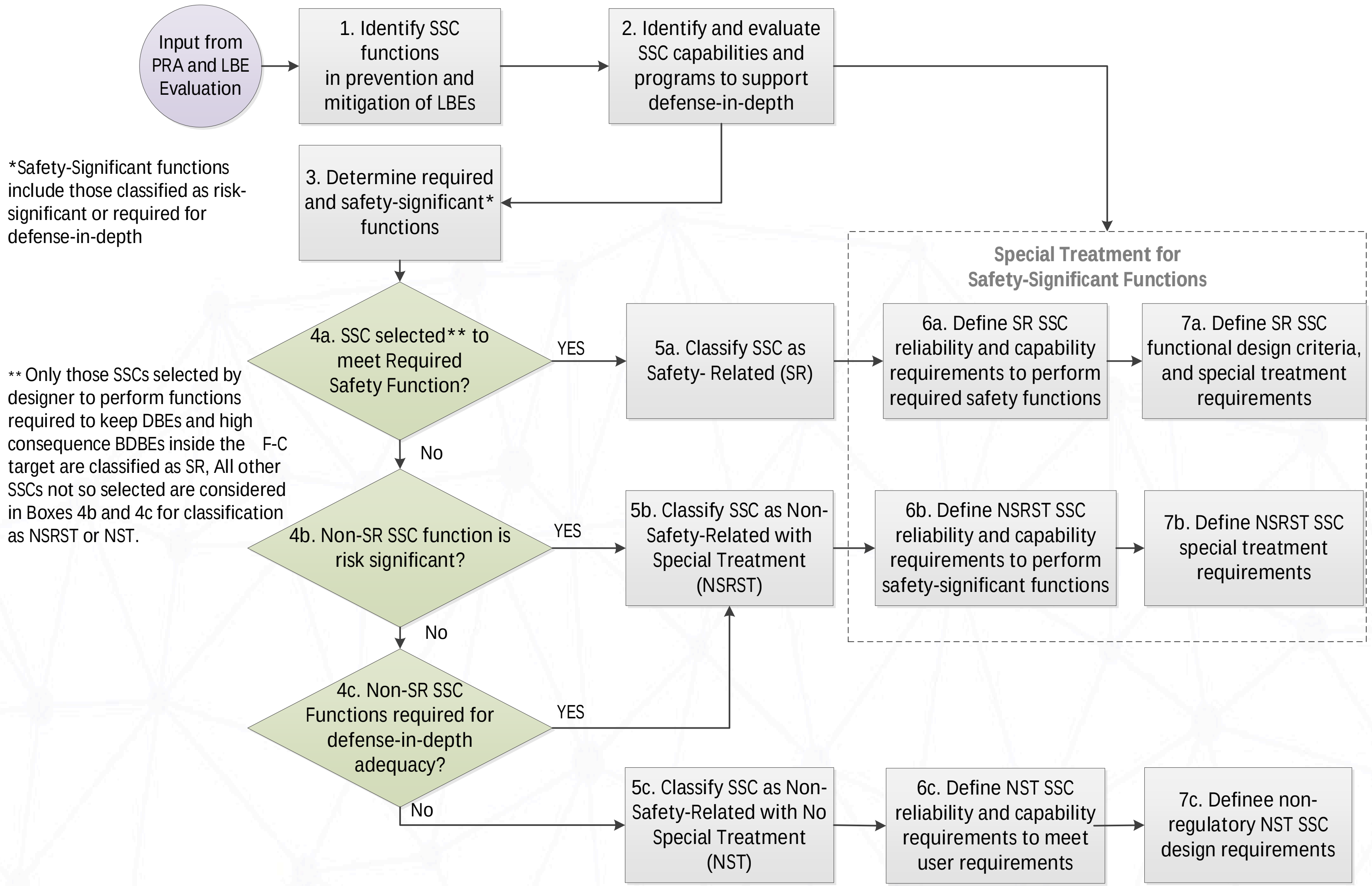
LMP – Proposed SSC Safety Categories

- Safety-Related (SR):
  - SSCs selected by the designer to perform required safety functions to mitigate the consequences of DBEs to within the F-C target, and to mitigate DBAs to meet the dose limits of 10 CFR 50.34 using conservative assumptions.
  - SSCs selected by the designer to perform required safety functions to prevent the frequency of BDBEs with consequences greater than 10 CFR 50.34 dose limits from increasing into the DBE region and beyond the F-C target.
- Non-Safety-Related with Special Treatment (NSRST):
  - Non-safety related SSCs relied on to perform risk significant functions. Risk significant SSCs are those that perform functions that keep LBEs from exceeding the F-C target, or make significant contributions to the cumulative risk metrics selected for evaluating the total risk from all analyzed LBEs.
  - Non-safety related SSCs relied on to perform functions requiring special treatment for DID adequacy.
- Non-Safety-Related with No Special Treatment (NST):
  - All other SSCs.

LMP – SSC Risk Significance

- A prevention or mitigation function of the SSC is necessary to meet the design objective of keeping all LBEs within the F-C target
  - The LBE is considered within the F-C target when a point defined by the upper 95%-tile uncertainty of the LBE frequency and dose estimates are within the F-C target
- The SSC makes a significant contribution to one of the cumulative risk metrics used for evaluating the risk significance of LBEs
  - A significant contribution to each cumulative risk metric limit is satisfied when total frequency of all LBEs with failure of the SSC exceeds 1% of the cumulative risk metric limit. The cumulative risk metrics and limits include:
    - The total frequency of exceeding of a site boundary dose of 100 mrem < 1/plant-year (10 CFR 20)
    - The average individual risk of early fatality within 1 mile of the EAB $< 5\times10^{-1}$/plant-year (QHO)
    - The average individual risk of latent cancer fatalities within 10 miles of the EAB shall not exceed 2×10^{-6}/plant-year (QHO)

LMP – SSC Safety Classification Approach



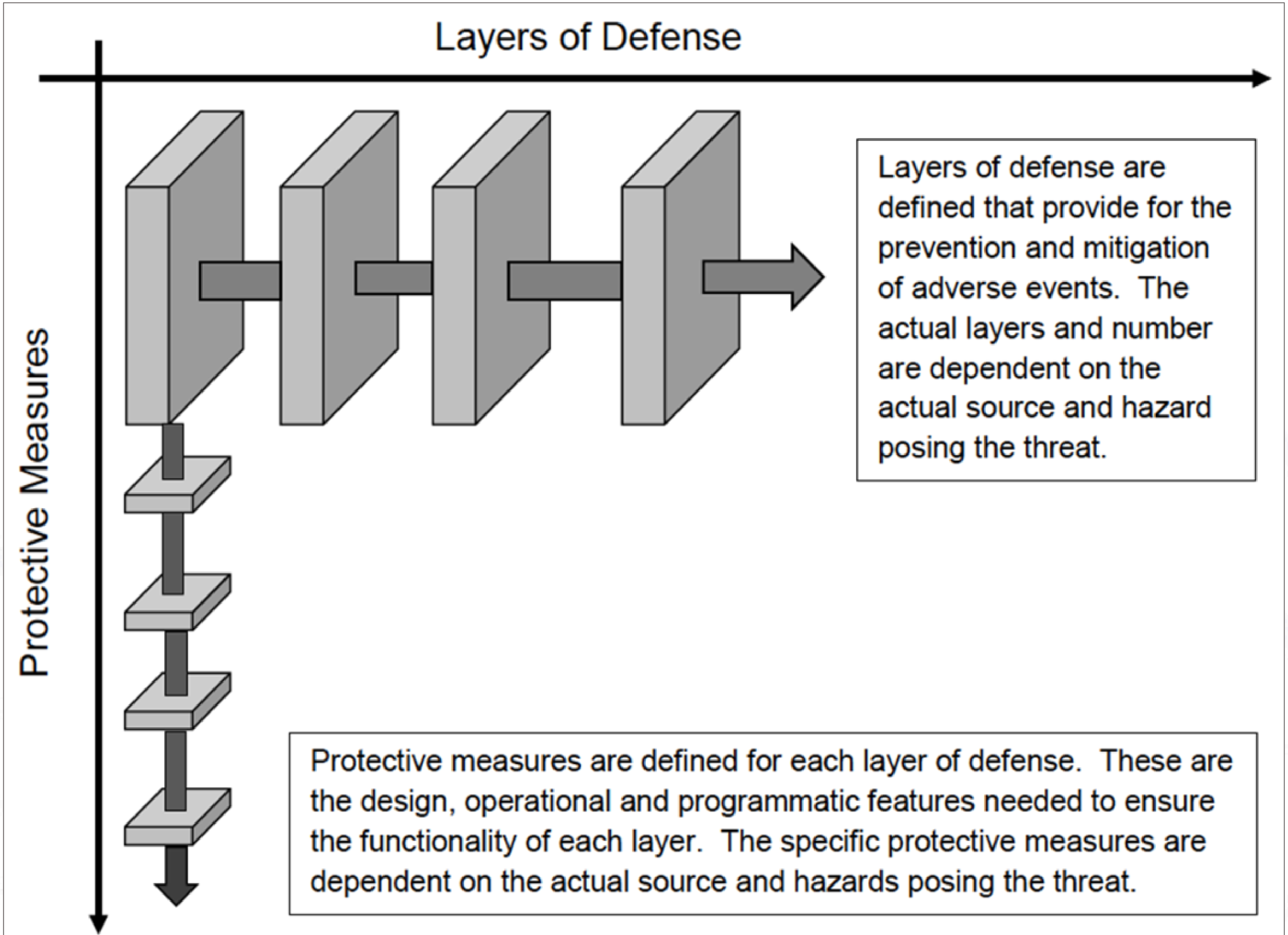
LMP – Derivation of Special Treatment Requirements

- SR SSCs:
  - Functional Design Criteria derived from required safety functions
  - Lower level design criteria derived from SRDC
- SR and NSRST SSCs:
  - SSC reliability and capability performance targets
  - Focus on prevention and mitigation functions from LBEs
  - Integrated decision making process to derive specific special treatment requirements
  - Reflects concepts from 10 CFR 50.69 and NEI-00-04
  - Reflects Commission’s expectations for risk-informed and performance based regulation from SRM to SECY 98-0144

LMP – SSC Classification Summary

- LMP retains the NGNP SSC safety categories of SR, NSRST, and NST
- All safety significant SSCs classified as SR or NSRST
- Absolute risk metrics proposed for SSC and LBE risk significance
- All SR SSCs are classified as risk significant
- NSRST SSCs include other risk significant SSCs and SSCs requiring some special treatment for Defense In Depth (DID) adequacy
- Specific special treatment for capabilities and reliabilities in the prevention and mitigation of accidents
- Special treatment defined via integrated decision panel

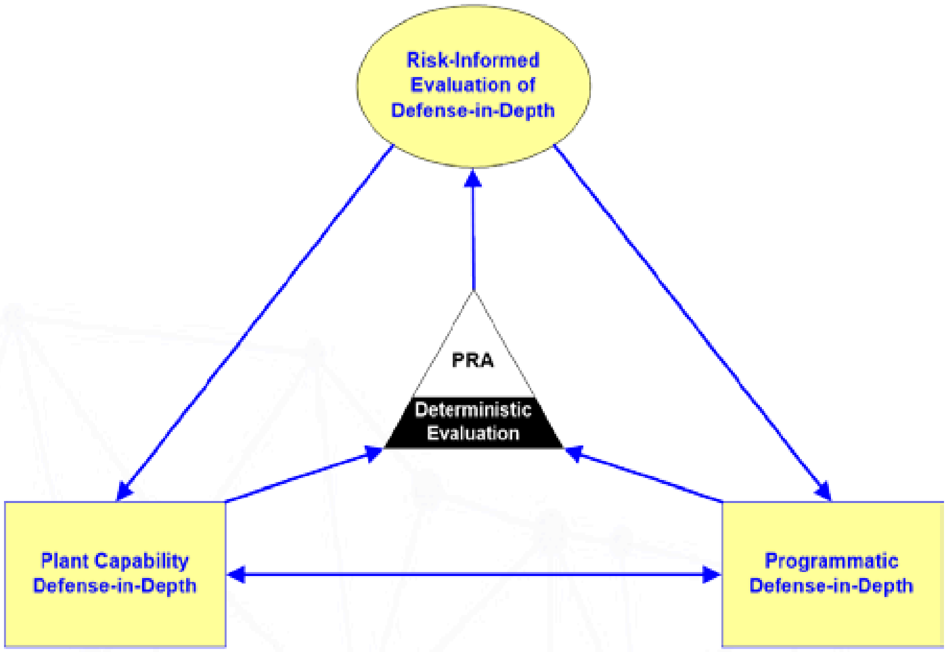
DID Concept from NUREG/KM-0009



LMP – DID Adequacy Approach

- Builds on NGNP DID approach also reflected in ANS-53.1
- Evaluation of DID adequacy is both risk-informed and performance-based
- The “layers of defense” and attributes of the NRC and IAEA DID frameworks are more visibly represented
- DID attributes for plant capability and programmatic DID have been enhanced for consistency with the measures defined in the LMP Guidance Document
- This process is used to evaluate each LBE and to identify the DID attributes that have been incorporated into the design to prevent and mitigate accident sequences and to ensure that they reflect adequate SSC reliability and capability
- Those LBEs with the highest levels of risk significance are given greater attention in the evaluation process
- The practicality of compensatory actions for DID purposes are considered in the context of the individual LBE risk significance and in a cumulative manner across all LBEs

LMP – Defense In Depth Adequacy Basic Structure



Plant Capability DID

<u>Plant Functional Capability DID</u> - This capability is introduced through systems and features designed to prevent occurrence of undesired LBEs or mitigate the consequences of such events.

<u>Plant Physical Capability DID</u> - This capability is introduced through SSC robustness and physical barriers to limit the consequences of a hazard.

Programmatic DID

Programmatic DID addresses uncertainties when evaluating plant capability DID. It incorporates special treatment during design, manufacturing, constructing, operating, maintaining, testing, and inspecting of the plant and the associated processes to ensure there is reasonable assurance that the predicted performance can be achieved and verified throughout the lifetime of the plant.

Risk-Informed Evaluation of DID

This element provides a systematic, holistic, integrated, and transparent process for examining the DID adequacy achieved by the combination of plant capability and programmatic elements. This evaluation is performed by a risk-informed integrated decision-making (RIDM) process to assess and establish whether DID is sufficient to enable consideration of different alternatives for achieving commensurate safety levels at reduced burdens.

DID Adequacy Evaluation Process

- DID Baseline Evaluation documented by Integrated Decision Panel (IPD) and updated at each design/licensing stage
- Defense-in-depth is deemed by IDP as adequate when:
  - Plant capability DID is deemed to be adequate
  - Plant capability DID guidelines in Table 5-2 (NEI 18-02) are satisfied
  - Review of LBEs is completed with satisfactory results
  - Programmatic DID is deemed to be adequate
  - Performance targets for SSC reliability and capability are established
  - Sources of uncertainty in selection and evaluation of LBE risks are identified
  - Special treatment for all SR and NSRST SSCs is sufficient

Commission Policy: Use of PRA Methods in Nuclear Regulatory Activities

"The Commission believes that the use of PRA in regulatory activities should be increased to the extent supported by the state-of-the-art PRA methods and data in a manner that complements the NRC deterministic approach."

"[T]he expanded use of PRA technology will continue to support the NRC's defense-in-depth philosophy by allowing quantification of the levels of protection and by helping to identify and address weaknesses or overly conservative regulatory requirements applicable to the nuclear industry. Defense-in-depth is a philosophy used by NRC to provide redundancy for facilities with 'active' safety systems, e.g., a commercial nuclear power (sic), as well as the philosophy of a multiple-barrier approach against fission product releases."

(FR, Vol. 60, No. 158, pg. 42622-42629, August 16, 1995)

The Commission’s 1995 PRA Policy Statement

- “A probabilistic approach to regulation enhances and extends this traditional, deterministic approach, by:
  1) Allowing consideration of a broader set of potential challenges to safety,
  2) Providing a logical means for prioritizing these challenges based on risk significance, and
  3) Allowing consideration of a broader set of resources to defend against these challenges.”
- The LMP approach is consistent with this policy

Non-LWR PRA Standard

- ASME/ANS started the development of a non-LWR PRA standard in 2006 and produced a trial use standard ASME/ANS-Ra-S-1.4-2013
- Approximately 80% of the technical requirements are common to the LWR PRA standards; remaining 20% address:
  - Risk metrics appropriate for all advanced non-LWRs
  - PRAs on multi-module plants
  - PRAs that support event sequence frequencies and consequences
  - PRAs that are performed at early stages in design
- Trial use standard is currently being revised towards a ballot for an ASME/ANS standard in 2019

LMP – Treatment of Passive Systems

- The PRA standard requires a quantitative uncertainty analysis of phenomena to quantify the failure probability of passive systems
- NEI 18-04 (draft) does not require assuming complete failure of passive SSCs or inherent features. However, NEI 18-04 does require SSC failure mode determinations by the developer as part of safety case development, and also requires the definition of Required Safety Functions and plant features responsible for fulfilling them.
- This topic is covered in other available references, including:
  - ASME/ANS-RA-S-1.4 Probabilistic Risk Assessment Standard for Advanced Non-LWR Nuclear Power Plants
  - NUREG-0800 Standard Review Plan Chapter 19, and
  - Other regulatory guidance such as NUREG-1855

Suggested Reading

- NEI 18-04, Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development, Draft Report Revision N
- Draft Regulatory Guide 1353, Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Inform the Content of Applications for Licenses, Certification, and Approvals for Non-Light-Water Reactors (ML18271A164)
- Draft SECY, Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Inform the Content of Applications for Licenses, Certification, and Approvals for Non-Light-Water Reactors (ML18270A334)
- NGNP Licensing Strategy Report to Congress describes a risk-informed approach for NGNP Licensing, 2008.
- ASME/ANS RA-S-1.4-2013, Probabilistic Risk Assessment Standard for Advanced Non-LWR Nuclear Power Plants, 2013.
- ANSI/ANS-53.1-2011 – Nuclear Safety Design Process for Modular Helium-Cooled Reactor Plants.

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