Experience Implementing the NEI 18-04 Process for the Xe-100 Advanced Reactor Design

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Risk-Informed, Performance-based Principles and Policy Committee, Community of Practice Presentation
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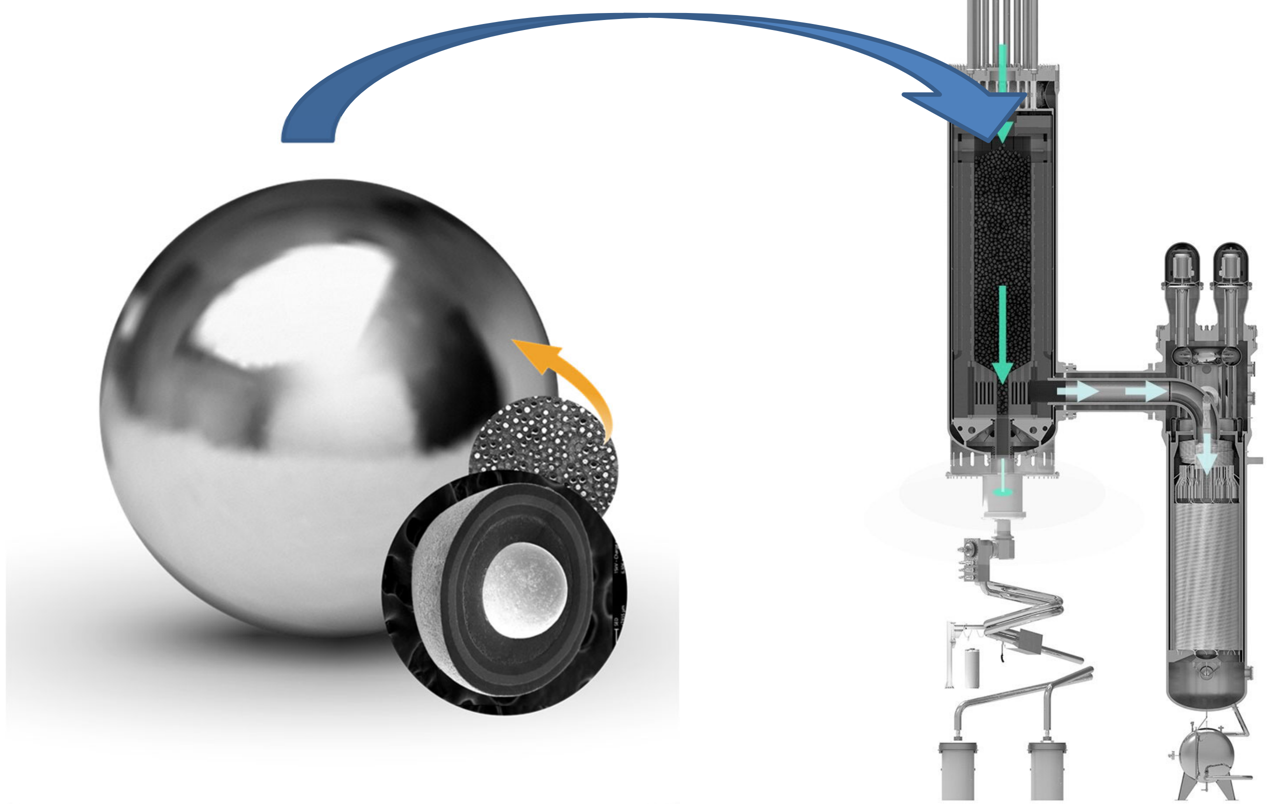
The Xe-100 Design Solution

Pebble Benefits:

- Tested up to 1800 °C
- Burnup up to 165,000 MWd/t-hm
- Long-term robustness for thousands of years
- TRISO particle contains **99.999%** of fission products

Pebble: ~19,000 TRISO-coated particles
Reactor: ~ 220,000 Fuel pebbles
The primary safety goal: Maintain the geometry of the pebbles, reactor, and reactor building to ensure intrinsic control of heat generation and removal, keeping the fuel particles within their performance envelope and assuring fission product retention at the source.



This fuel allows engineers to think differently about reactor design, ultimate safety and rugged predictable long-term storage

Licensing Modernization Project (LMP)

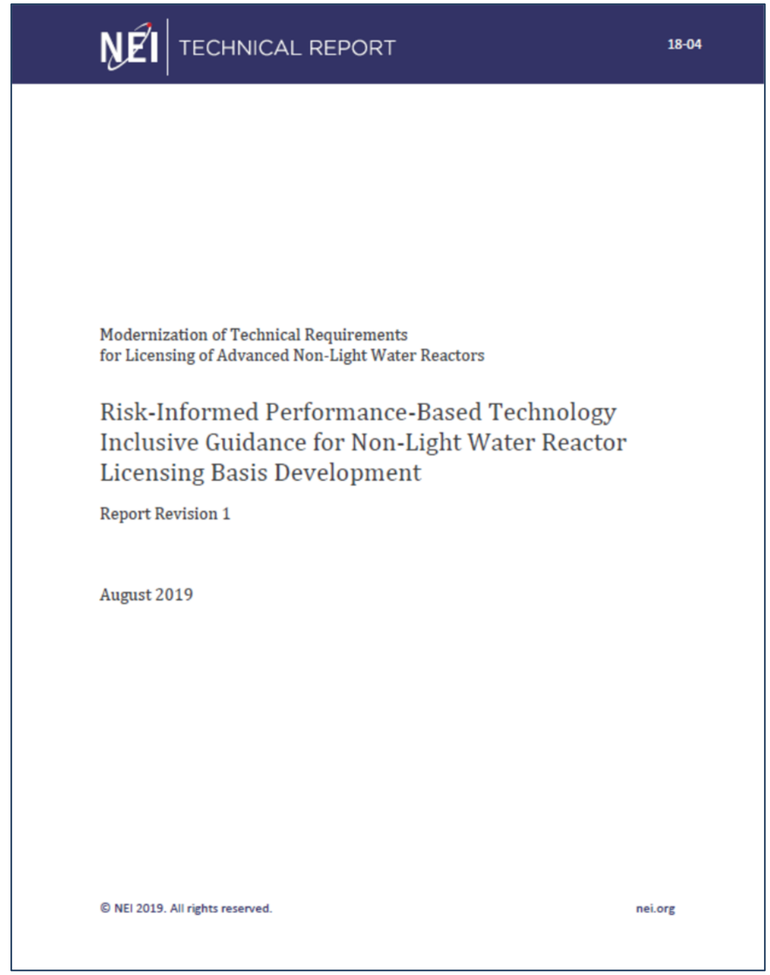
NEI 18-04 and Regulatory Guide 1.233

Outgrowth of licensing challenges of the U.S. Department of Energy's Next Generation Nuclear Plant (NGNP) Program

- What are the licensing-basis events, and how to systematically develop that set and select for analysis?
- How to classify the structures, systems, and components to credit them appropriately in analyses?
- How to evaluate the adequacy of defense-in-depth in a clear, logical, systematic, and consistent manner?

NEI 18-04 *Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development*
https://www.nrc.gov/docs/ML1924/ML19241A472.pdf

RG 1.233 *Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors*
https://www.nrc.gov/docs/ML2009/ML20091L698.pdf


NEI TECHNICAL REPORT 18-04

Modernization of Technical Requirements
for Licensing of Advanced Non-Light Water Reactors

Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development

Report Revision 1

August 2019

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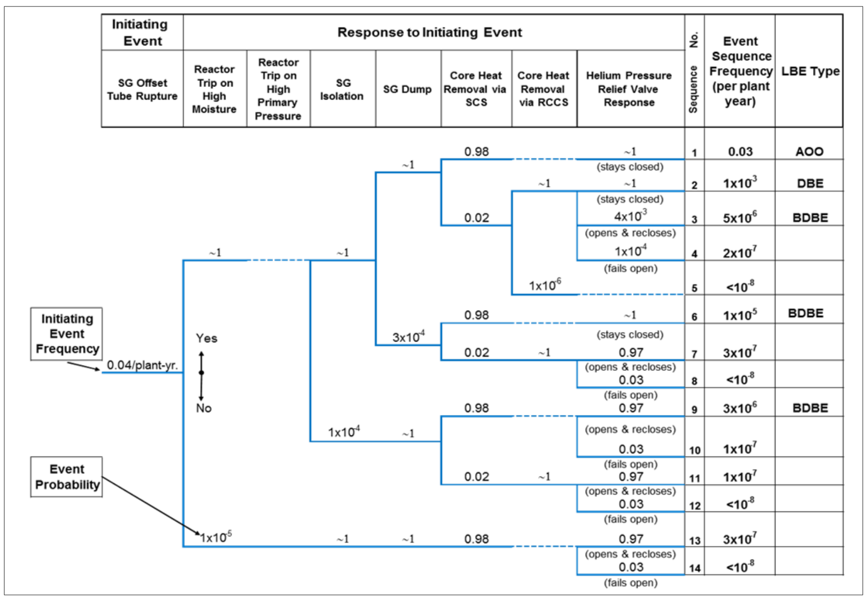
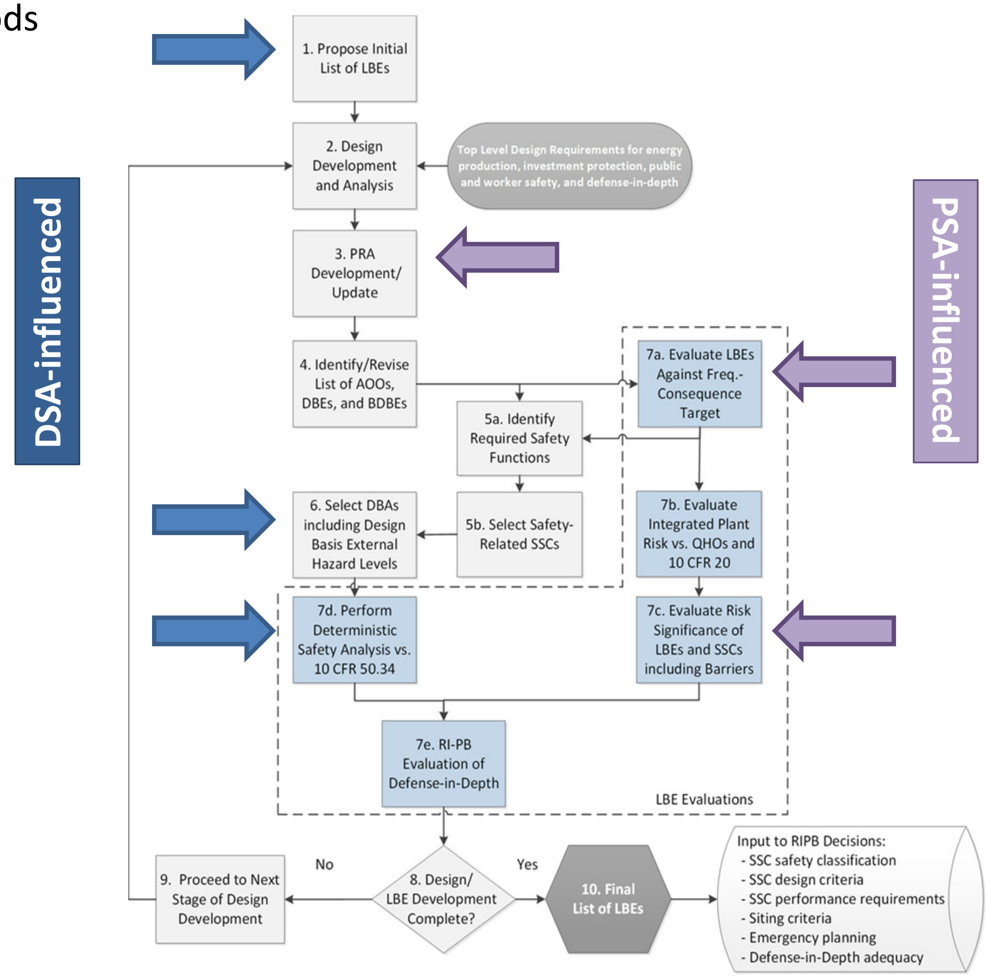
Licensing Basis Events

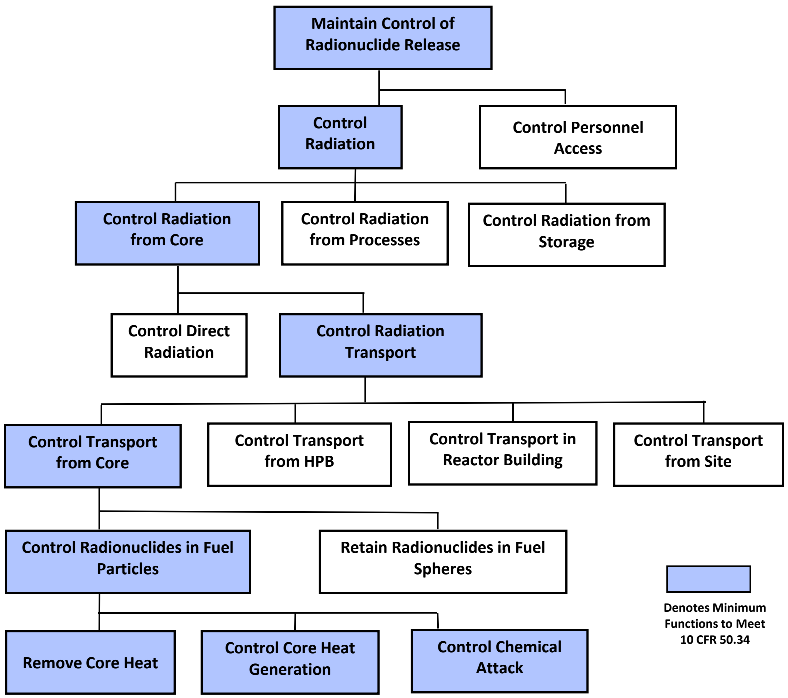
Approach that incorporates deterministic and probabilistic methods that is:

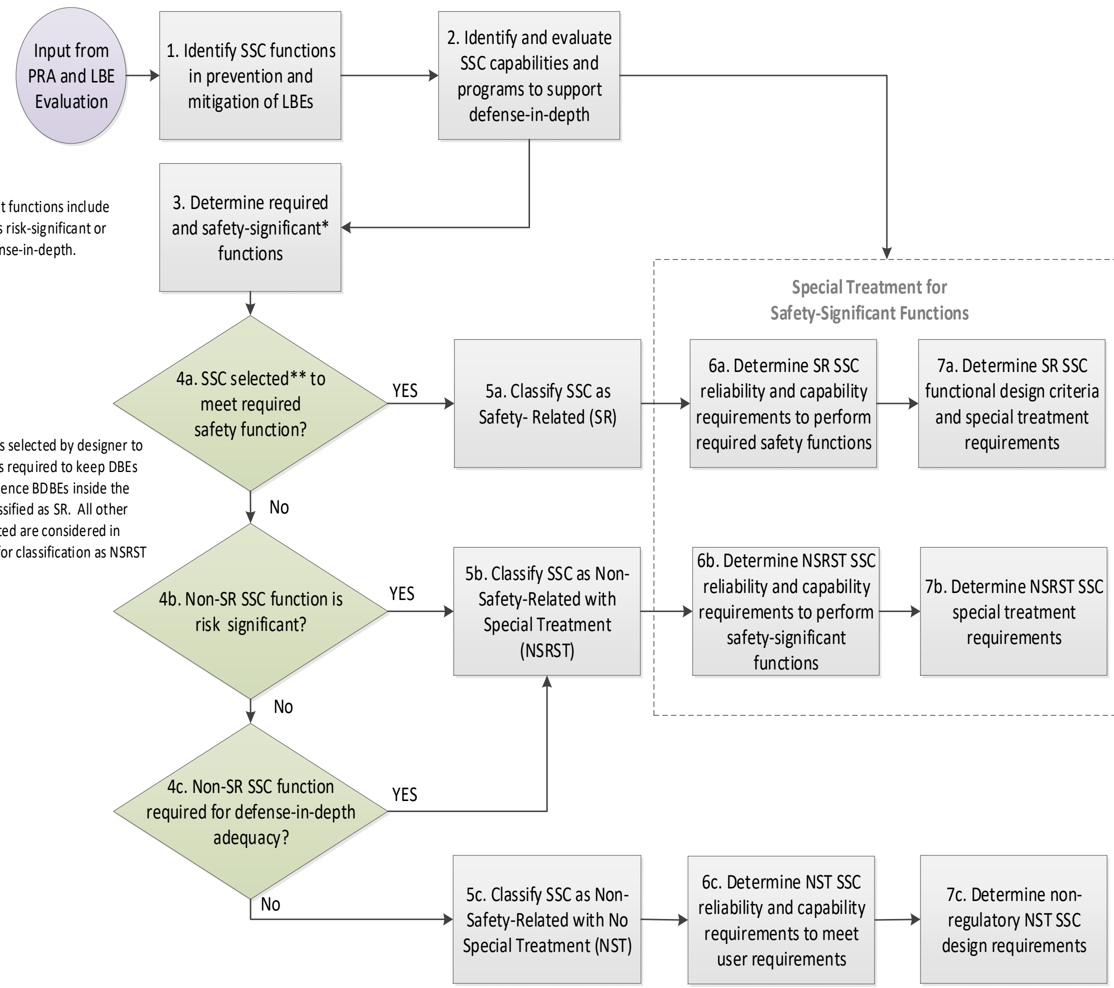
- Systematic and reproducible
- Sufficiently complete
- Available for timely input to design decisions
- Risk-informed and performance-based
- Reactor technology-inclusive
- Consistent with applicable regulatory requirements





Classification of Structures, Systems, and Components





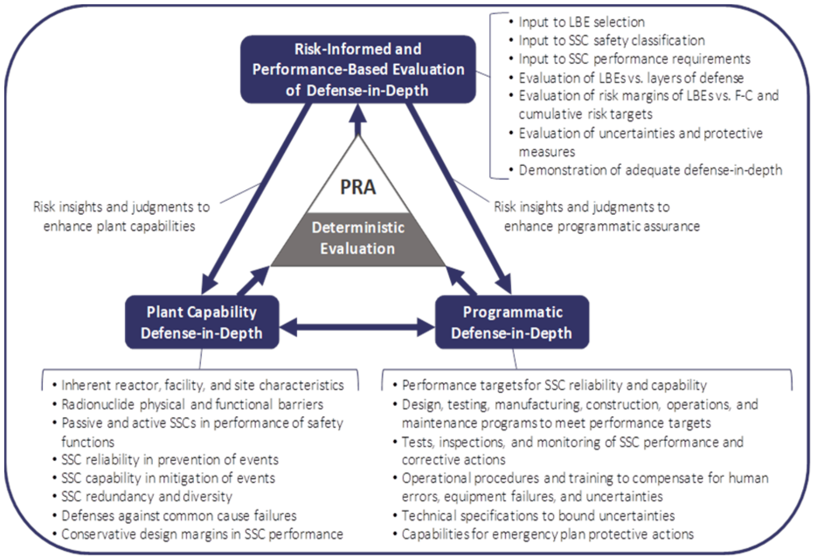
*Safety-significant functions include those classified as risk-significant or required for defense-in-depth.

** Only those SSCs selected by designer to perform functions required to keep DBEs and high consequence BDBEs inside the F-C target are classified as SR. All other SSCs not so selected are considered in Boxes 4b and 4c for classification as NSRST or NST.

Decomposing the Required Safety Functions across the spectrum of LBEs leads to a systematic process of assigning classifications to the functions & SSCs that perform them.

- Safety-related
- Non-safety-related, but with special treatment(s) applied
- Non-safety related

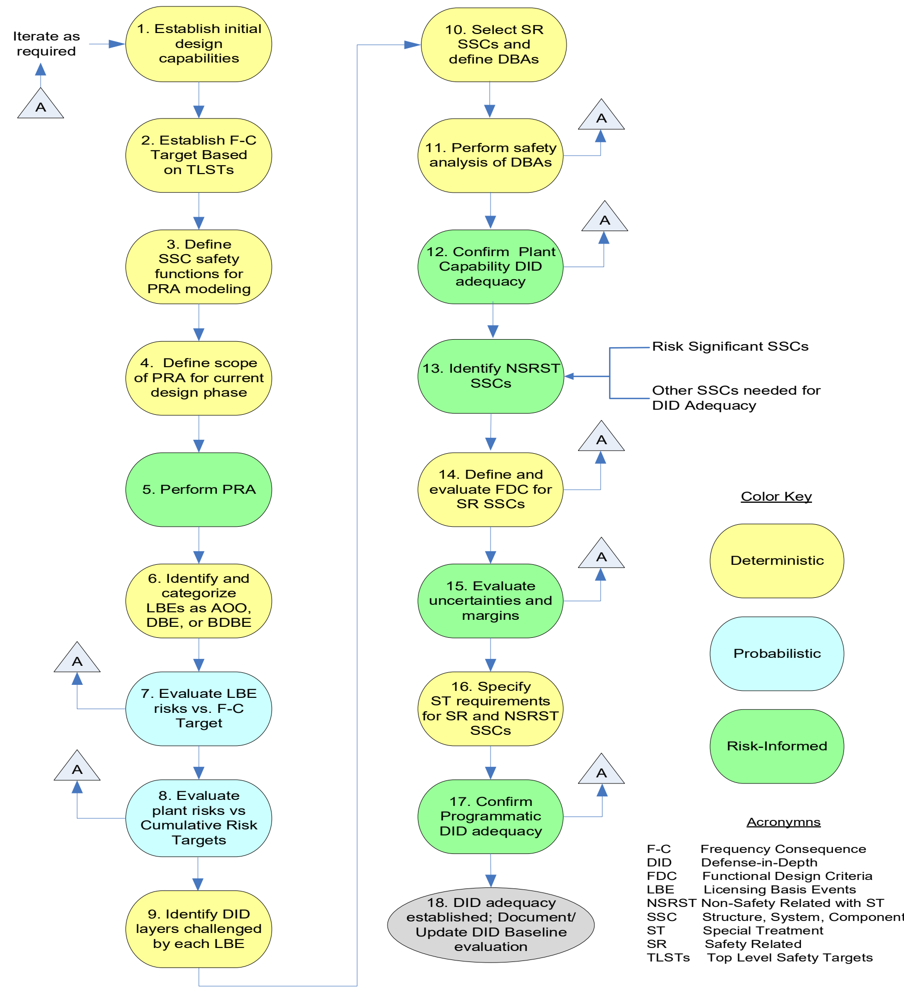
Evaluation of the Adequacy of Defense in Depth



Outcome: A systematic, reproducible, iterative means of evaluating Defense in Depth and representing that to the regulator

- Plant Functional Capability DID—This capability is introduced through systems and features designed to prevent occurrence of undesired LBEs or mitigate the consequences of such events.
- Plant Physical Capability DID—This capability is introduced through SSC robustness and physical barriers to limit the consequences of a hazard.

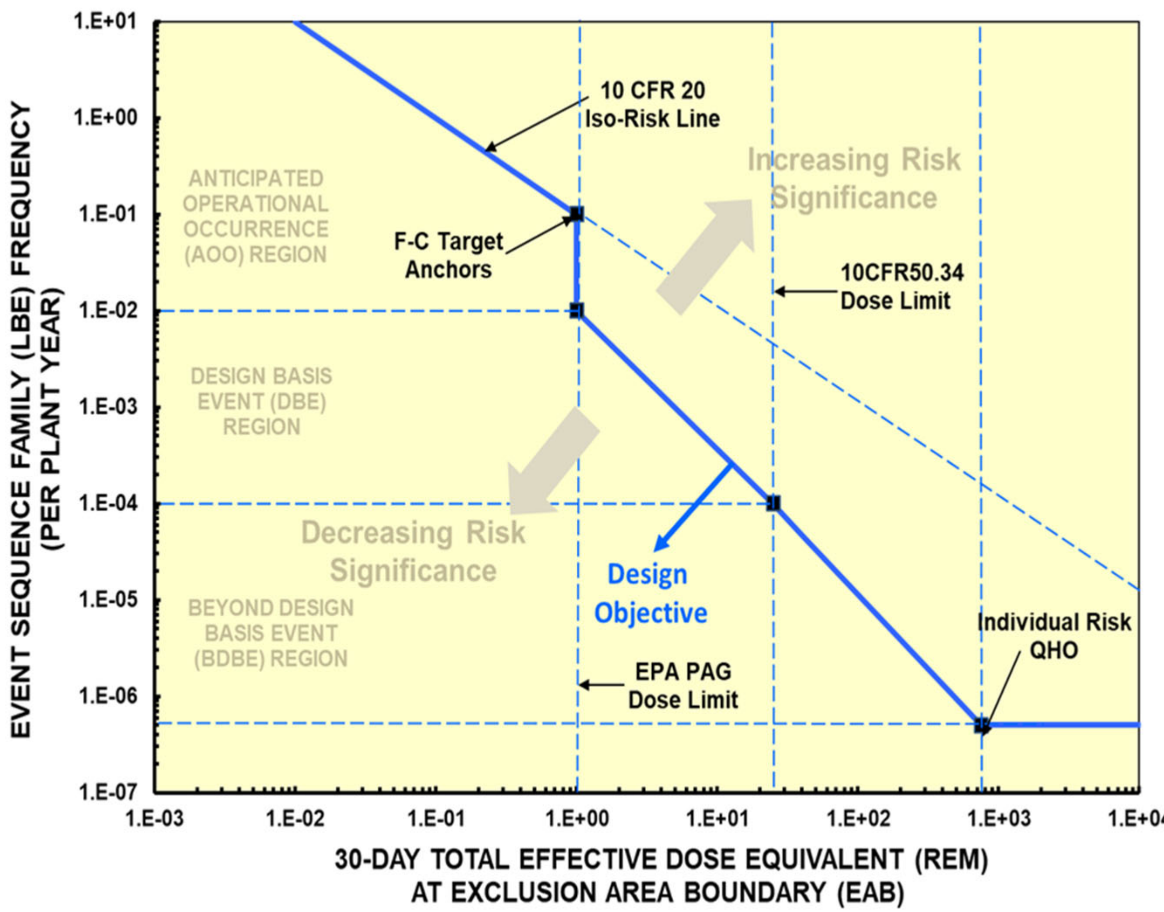
These capabilities when combined create layers-of-defense response to plant challenges.



Visualizing Safety: Frequency-Consequence Curve

In formulating the LMP F-C Target, a number of key inputs were considered including:
- 10 CFR 20 which limits public exposures from normal operation and anticipated events to 100 mrem/year
- The 1-rem EPA Protective Action Guide dose, which if exceeded would lead to offsite protective actions
- 10 CFR 50.34 which limits exposures from the most severe and least likely design basis accidents to 25 rem
- NRC Safety goal Quantitative Health Objectives which limit the individual risks to the population within 1 mile of the site boundary to 5×10^{-7}/year

Not the complete answer for licensing, but a means of systematically evaluating off-normal and unplanned events throughout plant life



PSA & DSA Insights from LMP

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Risk Triplet: Organizing the Information

Table 1. Phase 0 PRA Internal Initiating Events at Full Power

Internal Initiating Events
Turbine Trip (TT)
Reactor Trip (RT)
Circulator Trip (CT)
Loss of Primary Flow (LF)
Control Rod Withdrawal (CR)
Loss of Offsite Power (LO)
Steam Generator Feedwater Pump Trip (FW)
Small Helium Depressurization (SD)
Medium Helium Depressurization (MD)
Large Helium Depressurization (LD)
Steam Generator Tube Rupture (SG)

PSA
- Organized into LBE families (AOO & DBE shown)(34 total)
- Only considering internal postulated initiating events
- At pre-conceptual design phase, used scaled dose consequences & modified PRA
- Risk-insights used to inform SSC classifications

DSA
- Existing HTGR event families & phenomena
- Fresh and spent fuel accidents
- Consideration of chemical attack (air/water ingress)
- External hazards

Table 2. LBEs for the HTGC-PBR Demonstration Grouped by Event Sequence Frequency

LBE	PRA ID	LBE Description	Event Sequence Frequency, per plant-yr	Dose, WB rem	Dose Basis, M/P
Anticipated Operational Occurrences					
1	TT-01	Turbine trip, plant runback to reduced power level	1×10^{1}	$< 10^{-5}$	--
2	RT-01	Reactor trip, forced cooling via main-loop system	6×10^{0}	$< 10^{-5}$	--
3	CT-01	Circ. trip, forced cooling via main-loop system	4×10^{0}	$< 10^{-5}$	--
4	CT-02	Circ. trip, forced cooling via start-up/shutdown (SU/SD) system	4×10^{-1}	$< 10^{-5}$	--
5	RT-02	Reactor trip, forced cooling via SU/SD system	3×10^{-1}	$< 10^{-5}$	--
6	LO-01	Loss of Offsite Power, plant maintains house load	1×10^{-1}	$< 10^{-5}$	--
7	TT-02	Turbine trip, forced cooling via main-loop system	9×10^{-2}	$< 10^{-5}$	--
8	FW-01	FW trip, forced cooling via SU/SD system	5×10^{-2}	$< 10^{-5}$	--
9	SD-01	Sm. Helium Leak, isolated, plant maintains operation	5×10^{-2}	1×10^{-5}	P
10	SD-08	Sm. Helium Leak, no isolation, forced cooling via main-loop	5×10^{-2}	1×10^{-5}	P
11	CT-03	Circ. trip, forced cooling failure, passive cooling via Reactor Cavity Cooling System (RCCS)	2×10^{-2}	$< 10^{-5}$	--
Design Basis Events					
1	SG-01	SG (tube rupture), isolation, forced cooling via SU/SD system	9×10^{-3}	1×10^{-5}	--
2	CR-01	Rod withdrawal, forced cooling via main-loop	9×10^{-3}	$< 10^{-5}$	--
3	LO-02	Loss of Offsite Power < 3hr, forced cooling via SU/SD	5×10^{-3}	$< 10^{-5}$	--
4	TT-03	Turbine trip, forced cooling via SU/SD system	5×10^{-3}	$< 10^{-5}$	--
5	SD-09	Sm. Helium Leak, no isolation, forced cooling via SU/SD system	5×10^{-3}	1×10^{-4}	--
6	RT-03	Reactor trip, passive cooling via RCCS	3×10^{-3}	$< 10^{-5}$	--
7	FW-02	FW trip, passive cooling via RCCS	5×10^{-4}	$< 10^{-5}$	--
8	CR-02	Rod withdrawal, forced cooling via SU/SD	5×10^{-4}	$< 10^{-5}$	--
9	MD-01	Md. Helium Break, isolation, forced cooling via SU/SD	5×10^{-4}	3×10^{-5}	P
10	SD-02	Sm. Helium Leak, isolation, forced cooling via main-loop	5×10^{-4}	1×10^{-5}	P
11	SD-10	Sm. Helium Leak, passive cooling via RCCS, pump down successful	5×10^{-4}	2×10^{-4}	M
12	MD-02	Md. Helium Break, no isolation, forced cooling via SU/SD	5×10^{-4}	3×10^{-5}	P
13	LO-09	Loss of Offsite Power < 24 hr., forced cooling via SU/SD	4×10^{-4}	$< 10^{-5}$	--
14	LF-01	Loss of Offsite Power, passive cooling via RCCS	4×10^{-4}	$< 10^{-5}$	--
15	LO-05	Loss of Offsite Power < 3 hr., passive cooling via RCCS	4×10^{-4}	$< 10^{-5}$	--
16	LO-03	Loss of Offsite Power < 3 hr., passive cooling via RCCS	3×10^{-4}	$< 10^{-5}$	--
17	LO-16	Loss of Offsite Power > 24 hr., forced cooling via SU/SD	2×10^{-4}	$< 10^{-5}$	--

Design Basis Events vs. Design Basis Accidents

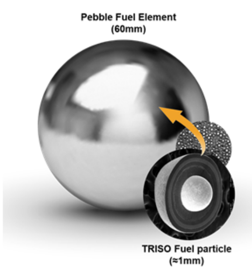
LBEs:

Design Basis Events (DBEs)

- Defined by frequency range
- Analyzed in the PRA against a consequence target
- Considered during the risk-significance process in SSC safety classification

Design Basis Accidents (DBAs)

- Analyzed in the DSA considering only the safety-related SSCs to assess success criteria and event consequences
- SR-SSCs evaluated against external hazard event levels they are designed to withstand



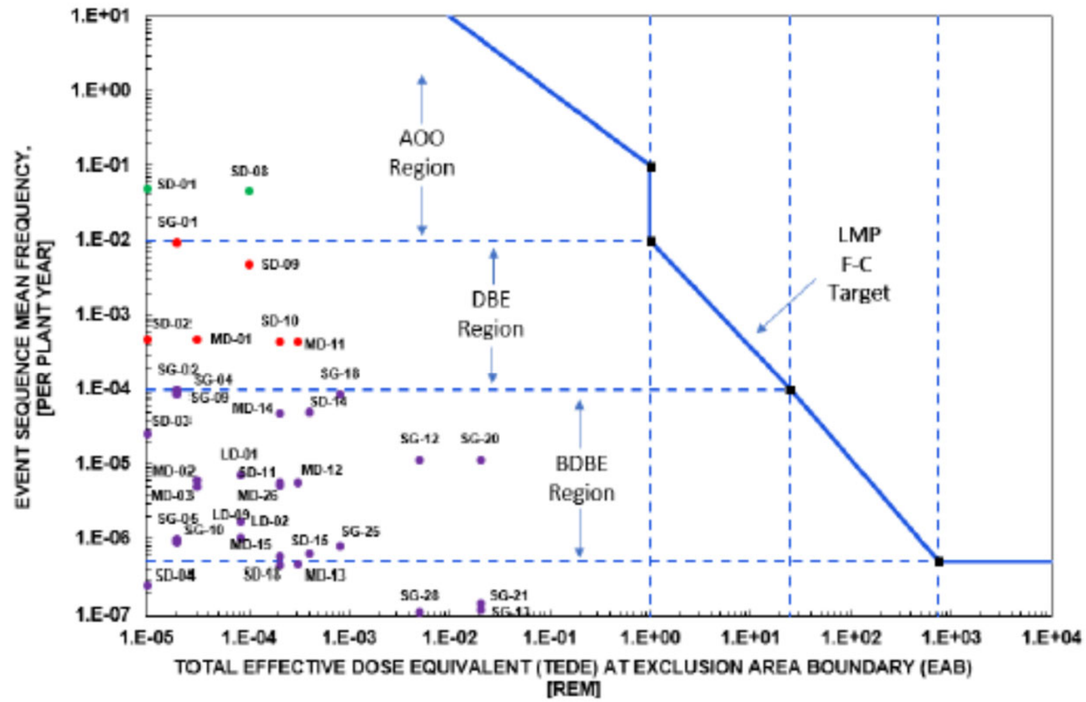


Figure 4. Xe-100 LBEs Plotted Against the LMP F-C Target

SSC Classification

Three SSC classifications:

- Safety related (SR)
- Non-safety related with special treatment (NSRST)
- Non-safety related with no special treatment (NST)

Selection of Safety-Related SSCs determined by those SSCs which are needed to meet Required Safety Functions in the DBE region

NSRST SSCs selected based on risk-significance or contribution to ensure adequacy of defense in depth

- For Xe-100, expect NSRST systems to arise from defense in depth only

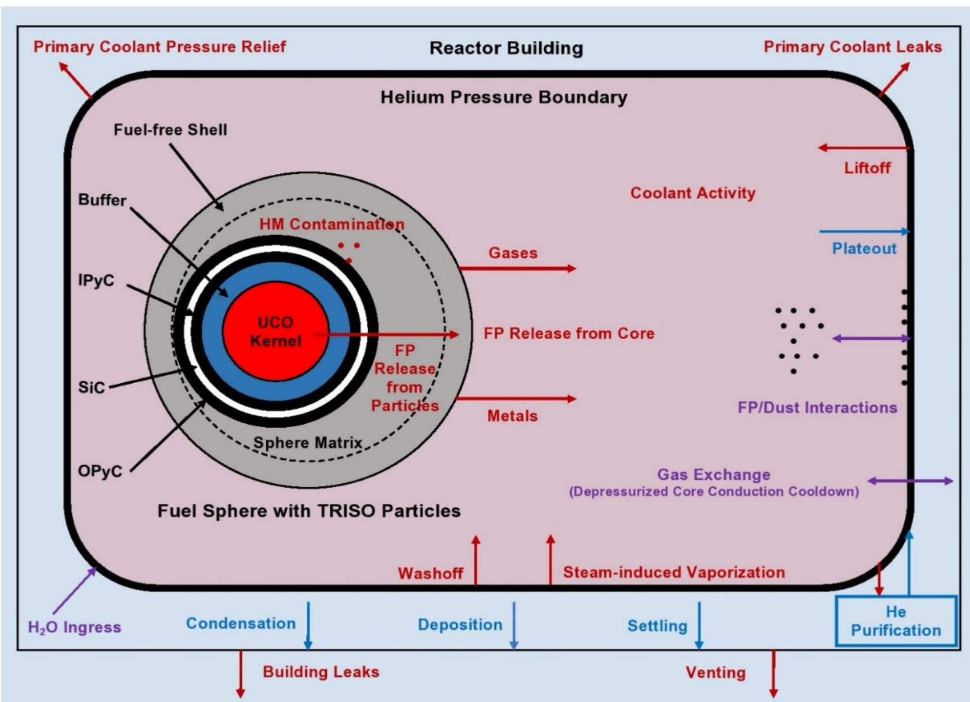
Need to consider implicit assumptions in event tree!

Table 4. Available Candidate SSCs for Required Safety Function to Remove Core Heat over DBE

Alternate Sets of SCCs	Small Helium Depressurizations																	Option for Required Safety Function?
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
• Reactor Core • Steam Generator + Circulation • ML Forced Cooling	N	Y	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	No
• Reactor Core • Steam Generator + Circulation • SU/SD - Active	Y	Y	Y	Y	Y	N	N	Y	Y	Y	N	N	Y	N	N	N	Y	No
• Reactor Core • Reactor Vessel • RCCS - Active	Y	Y	Y	Y	Y	N	N	Y	Y	Y	N	N	Y	Y	Y	Y	Y	No
• Reactor Core • Reactor Vessel • RCCS - Passive	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Yes
• Reactor Core • Reactor Vessel • RB/Ground + Air Heat Sinks	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Yes

Mechanistic Source Term Evaluation

X-energy uses an integrated suite of codes (XSTERM) to demonstrate via analysis the performance criteria across the spectrum of LBEs and all radionuclide release phenomena



Determine release from TRISO fuel particles

↓

Determine release from fuel pebbles

↓

Release from Helium Pressure Boundary

↓

Release from Reactor Building

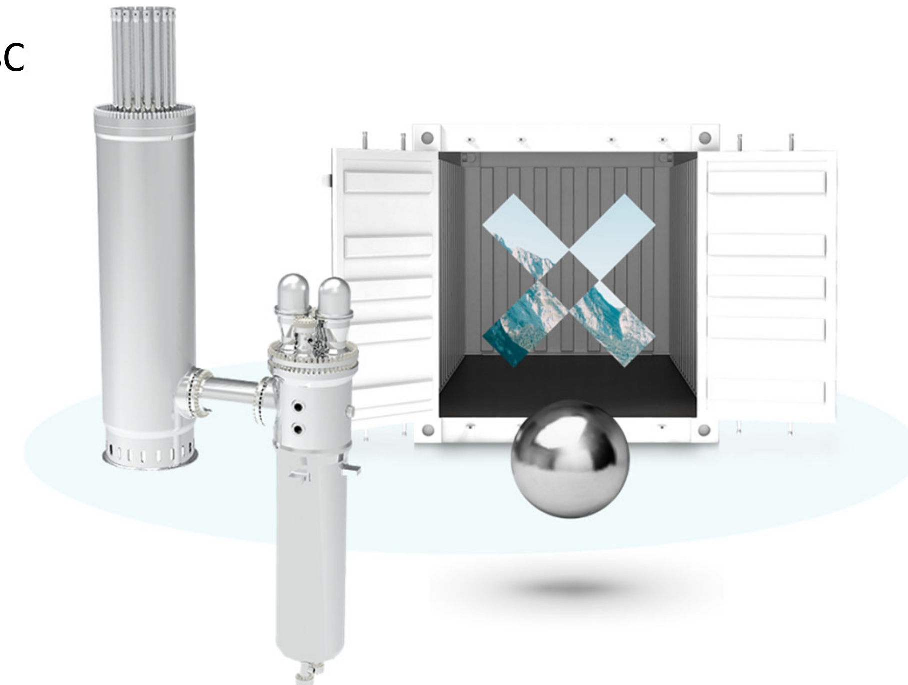
↓

Mechanistic Source Term

Dose Consequence to Receptor

Implementing NEI 18-04: The Good Side

- Credibility
  - Logically consistent framework to establish LBEs, assign SSC classifications, and evaluate defense in depth
- Early implementation of risk insights / use of risk information
- Performance-based framework
  - Dose and integrated risk figures of merit in application
- Ability to readily implement other risk-informed initiatives



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The Challenges

Early Design Stage: Where Do You Begin?

- Capability and framework to develop risk-insights
- Effort to establish and maintain an iterative PRA model
- "Graded approach" with respect importance to safety and to application of QA for a particular design phase

Special Treatment Identification and Selection

- 50.69 process experience does not necessarily lead to easy decisions, particularly for early design phases
- Training and qualification of the IDP team
- Defining what is industrial practice and, therefore, what is beyond?

Quality Assurance

- Industry experience with Appendix B and Important to Safety
- Limited approaches to apply graded quality assurance for NSRST SSCs
    - X-energy has developed a graded QA approach intended to meet both US and Canadian requirements

Communication

- Integration with design organization
- Education on new terminology (i.e., LBEs vs. DBAs)

Creating a *single* process

The Potential

- Alignment between CNSC and NRC on acceptability of the NEI 18-04 approach
  - Generally acceptable methodology in each regulatory framework
  - Applicant must address some elements, such as:
    - Plant vs. Reactor risk metrics
    - Definitions of AOOs, DBAs, BDBAs
    - F-C differences
- Improvements in change control (risk-informed)
- Use of NEI 21-07 for SAR format

Regulatory agencies in the U.S. and Canada continue to work together to create a favorable environment for nuclear design vendors like X-energy. This led to the first joint review report for an advanced reactor technology provided to X-energy in July 2021.


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