Exelon[SM]

Method for Safety Classification and Development of Regulatory Design Criteria for the PBMR in the US

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Presentation Purpose

- To describe the risk-informed process for selection of safety-related equipment and the development of regulatory design criteria

- To illustrate the method with examples from the application of the similar process utilized for the MHTGR in the mid-80's

- To compare the process with current regulatory practice

- To obtain NRC feedback and identify next steps

Presentation Outline

- Background
  - Top Level Regulatory Criteria (TLRC)
  - Selection of Licensing Basis Events (LBE)
- Derivation of Required Functions
- Selection of Safety-Related Equipment
- Development of Regulatory Design Criteria
- Comparison with Current Regulatory Practice
  - Advanced Reactor Policy
  - Risk-Informed Guidance (RG 1.174)
    - Defense-in-depth
    - Balance between prevention and mitigation
    - Safety Margins
    - Monitoring
  - Special Treatment Guidance
- Outcome Objectives

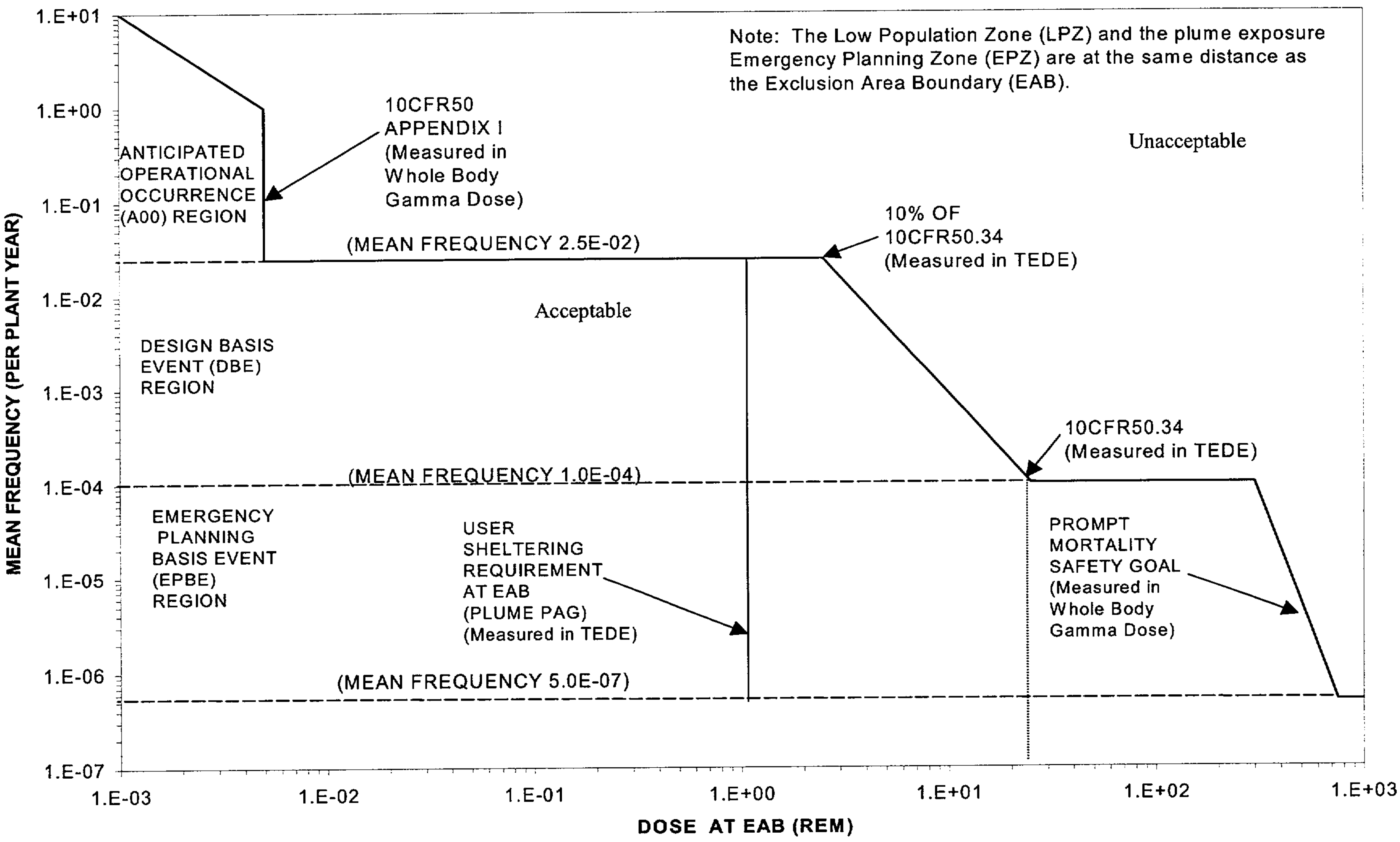
Relation of Risk-Informed Licensing Bases

- Top Level Regulatory Criteria (TLRC) provide *what* must be achieved
- Licensing Basis Events (LBE) provide *when* the TLRC must be met
- Regulatory design criteria (RDC) and equipment safety-related classification provide *how* it will be assured that the TLRC are met
- Requirements (special treatment) for the safety-related Systems, Structures, and Components (SSC) provide *how well* the TLRC are assured

Limiting Top Level Regulatory Criteria for the PBMR

- 10CFR50 Appendix I annualized offsite dose guidelines
  - 5 mrem/yr whole body
- 10CFR100/50.34 accident offsite doses
  - 25 rem total effective dose equivalent
- EPA-400-R-92-001 protective action guideline doses
  - 1 rem total effective dose equivalent
- 51FR130 individual acute and latent fatality risks
  - $5x10^{-7}$/yr and $2x10^{-6}$/yr, respectively

PBMR Risk Criteria Chart with Top Level Regulatory Criteria



Licensing Basis Events

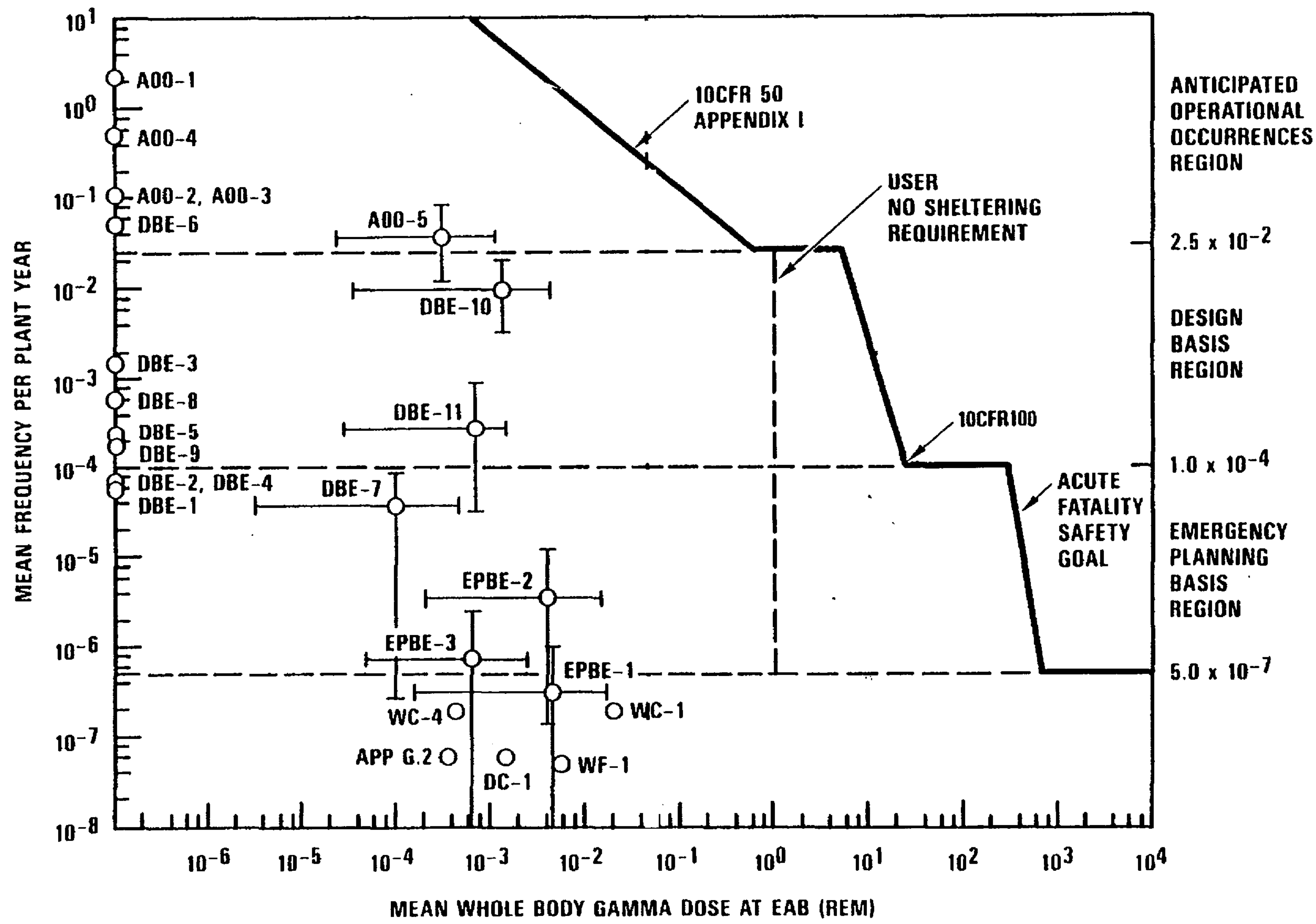
- Off-normal or accident events used for demonstrating design compliance with the Top Level Regulatory Criteria

- Collectively, analyzed in PRA for demonstrating compliance with the safety goal

- Encompass following event categories
  - Anticipated Operational Occurrences
  - Design Basis Events
  - Emergency Planning Basis Events

- Example of selection process provided for MHTGR preapplication submittals

MHTGR Licensing Basis Events



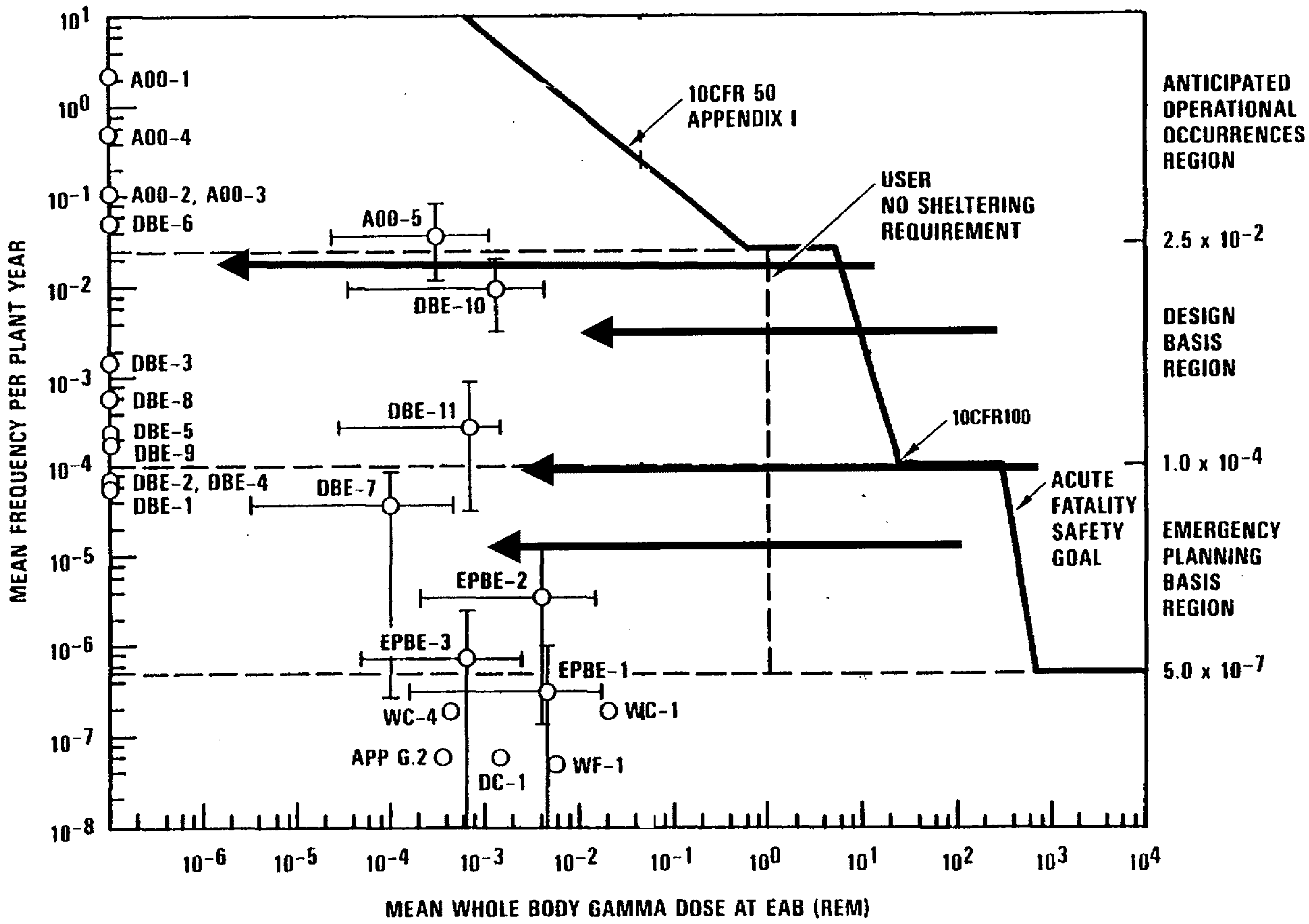
Design Basis Events

- Events of lower frequency than AOOs, not expected to occur in the lifetime of the plant
  - for a plant lifetime of 40 years, less than 1% chance
  - lower frequency of 10^{-4}/plant year

- Identified as families of events in (or close to) DBE region that could exceed 10CFR50.34 *if certain equipment or design features had not been selected*

- Mean values and uncertainty range of consequences are evaluated to provide high confidence of compliance with and safety margin to 10CFR50.34

MHTGR Example for Selection of DBE

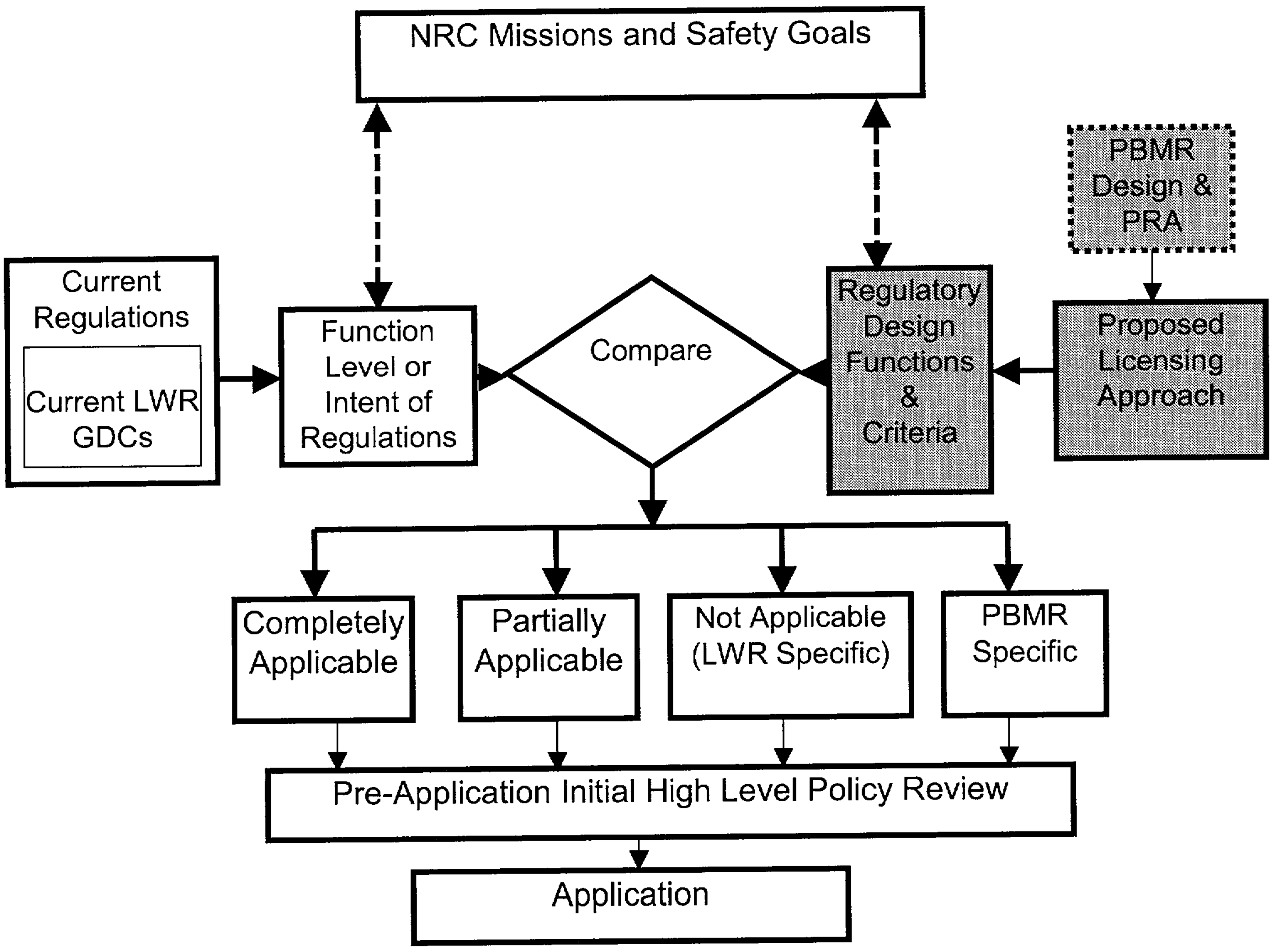


DBE Examples from MHTGR

Designation	Design Basis Events
DBE-1	Loss of main loop and shutdown forced cooling
DBE-2	Main loop transient w/o control rod trip
DBE-3	Control rod withdrawal w/o main loop cooling
DBE-4	Control rod withdrawal w/o forced cooling
DBE-5	Earthquake with reactor trip and shutdown cooling
DBE-6	Moisture inleakage
DBE-7	Moisture inleakage without forced cooling
DBE-8	Moisture inleakage with moisture monitor failure
DBE-9	Moisture inleakage w/ steam generator dump failure
DBE-10	Moderate primary coolant leak w/o forced cooling
DBE-11	Small primary coolant leak w/o forced cooling

Shaded LBE not expected for PBMR

Use of PRA Insights for Regulatory Document Review

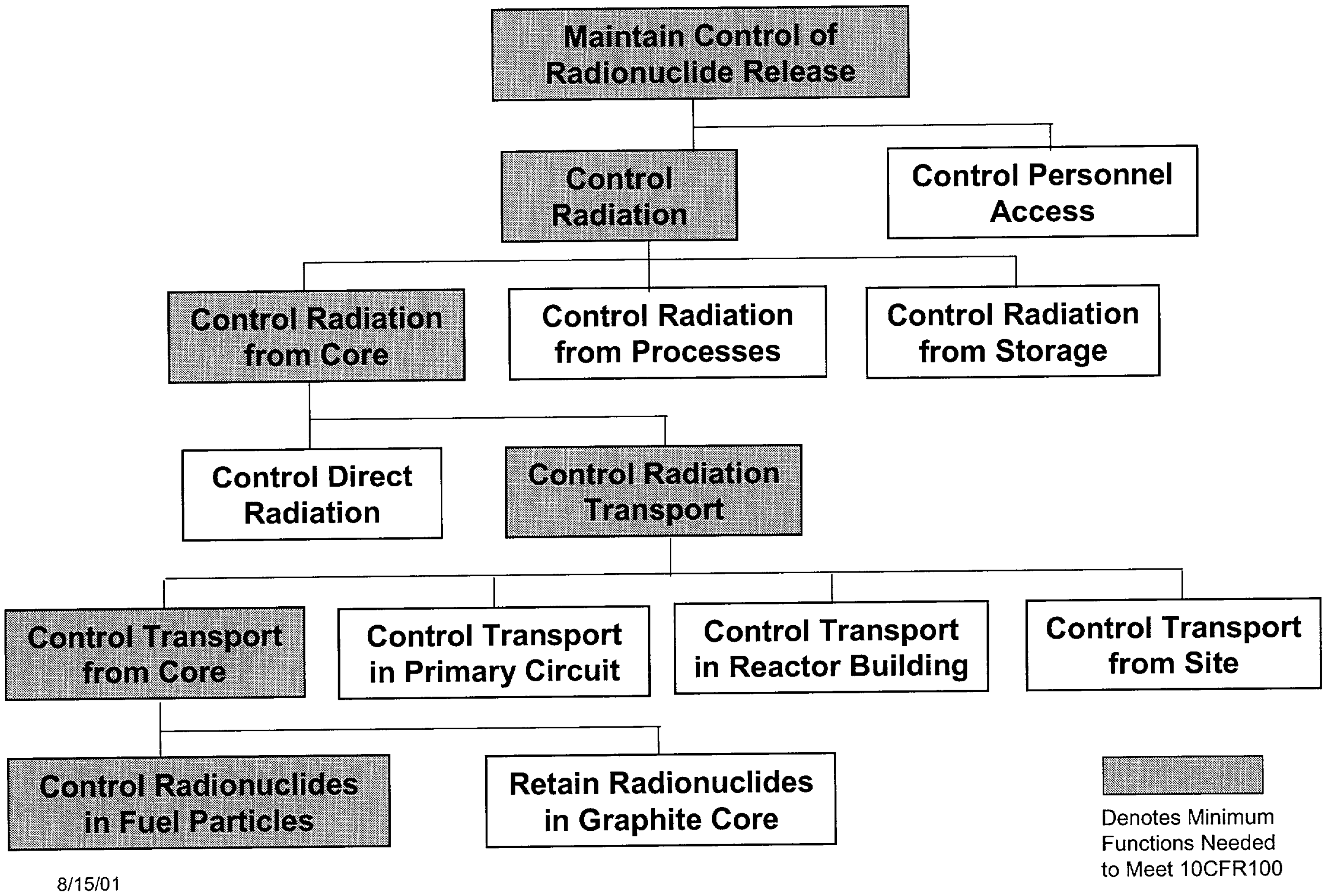


Required Safety Functions

- Required safety functions developed from review of LBE versus TLRC

- PBMR required safety functions will be similar to those for the MHTGR
  - for compliance with 10CFR100/50.34:
    - radionuclide retention within fuel particles
      - control of heat generation
      - core heat removal
      - control of chemical attack

MHTGR Example of Radionuclide Retention Functions



MHTGR Example of 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.

PBMR Regulatory Design Criteria

- RDC to be developed with risk insights for each required safety function
- Risk-informed RDC to be compared to guidance in LWR GDC to supplement areas where PBMR specific criteria are needed
- Many of the RDC will be similar to those developed for MHTGR; others will differ due to
  - Adjustments in TLRC
  - Differences in design
  - Different LBE
  - Different required safety functions

Risk-Informed Selection of Safety-Related SSC

- Equipment relied on to perform the required safety functions
  - Consequence mitigation: for DBE, SSC that are available and sufficient to perform the required safety functions to assure that the DBE dose criteria are met
  - High consequence prevention: for EPBE with doses greater than DBE dose criteria, SSC that are available and sufficient to perform the required safety functions to assure that the frequency of the event is below the DBE frequency criteria

- Method illustrated with MHTGR examples

MHTGR Selection of Safety-Related Equipment for Removal of Core Heat

SSC Available & Sufficient to Remove Core Heat During DBE?						
SSC	DBE 1	DBE 4	DBE 5	DBE 7	DBE 10	Safety-Related?
Main Loop Cooling	No	No	No	No	No	
Shutdown Cooling System	No	No	Yes	No	Yes	
Reactor Cavity Cooling System	Yes	Yes	Yes	Yes	Yes	Yes
Reactor Cavity & Surroundings	Yes	Yes	Yes	Yes	Yes	

MHTGR Equipment Safety Classification for Core Heat Removal

- Two options are available and sufficient for core heat removal for all DBEs: RCCS and conduction to reactor cavity structures and surroundings

- Both rely on core geometry and properties and vessel properties to transfer heat from the reactor

- RCCS selected as safety-related based on ability to specify, analyze, monitor and demonstrate adequacy

MHTGR Selection of Safety-Related Equipment for Control of Heat Generation

SSC Available & Sufficient to Control Heat Generation During DBE?							
SSC	DBE 2	DBE 3	DBE 4	DBE 5	DBE 6	DBE 7	Safety-Related?
Control Rods	No	Yes	Yes	Yes	Yes	Yes	Yes
Reserve Shutdown Equipment	Yes	Yes	Yes	Yes	No	No	Yes

MHTGR Equipment Safety Classification for Control of Core Heat Generation

- Two components are available and together sufficient for control of core heat generation for all DBEs: Control rods and reserve shutdown equipment

- Both rely on core/fuel geometry and neutronic properties

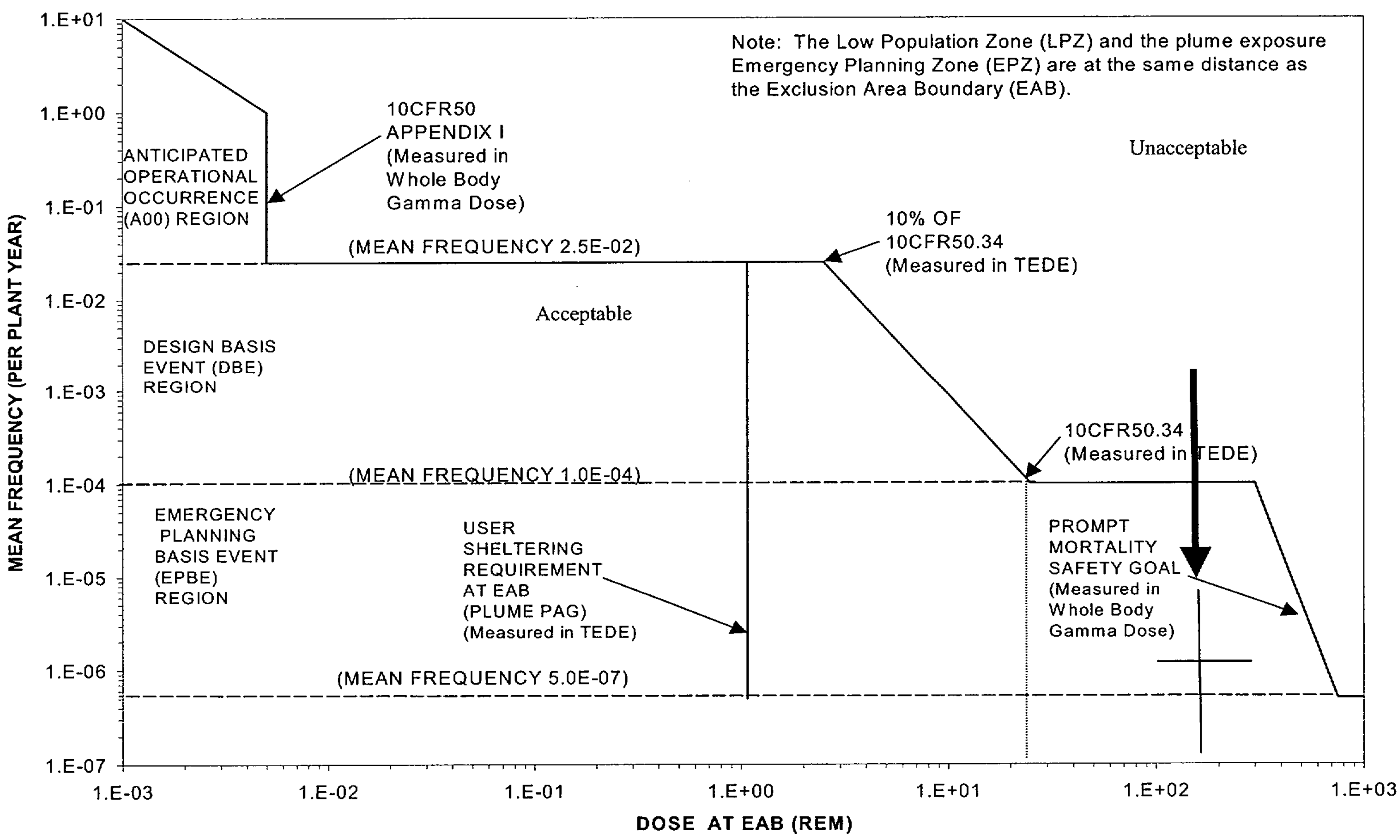
SSCs Selected as Safety-Related with EPBE

- Above MHTGR examples examined DBEs required to assure *consequences* are acceptable

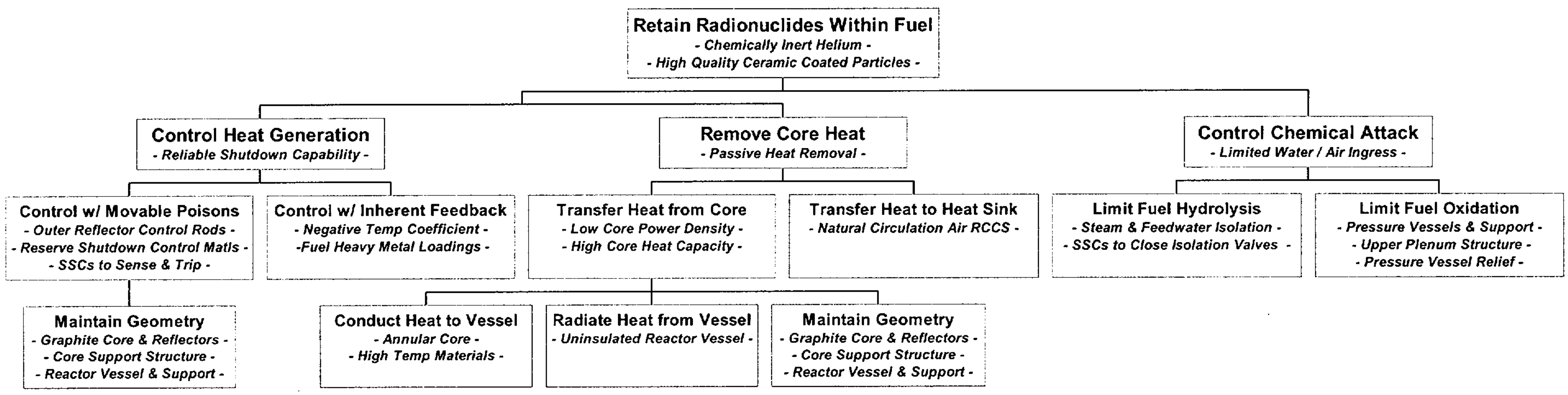
- Safety classification method also requires that *frequencies* of EPBE with consequences greater than 10CFR50.34 are acceptable

- MHTGR had no EPBE with high consequences

Hypothetical Example of High Consequence EPBE Leading to Safety-Related SSC



Relation of Safety-Related Equipment to MHTGR Safety Functions



- Similar functional tree for PBMR to be developed showing SSC classified as safety-related

Safety-Related Design Conditions (SRDC)

- Deterministic conditions derived from the selected DBEs that non-mechanistically rely solely on the safety-related equipment to meet 10CFR50.34
- SAR accident analyses provide
  - best estimate and upper bound doses for DBE to show margin
  - best estimate and upper bound doses for SRDC to show margin if only selected equipment is relied on
- SRDC are examined to set the quantitative requirements for the safety-related equipment in terms of temperatures, pressures, stresses, heat loads, etc.

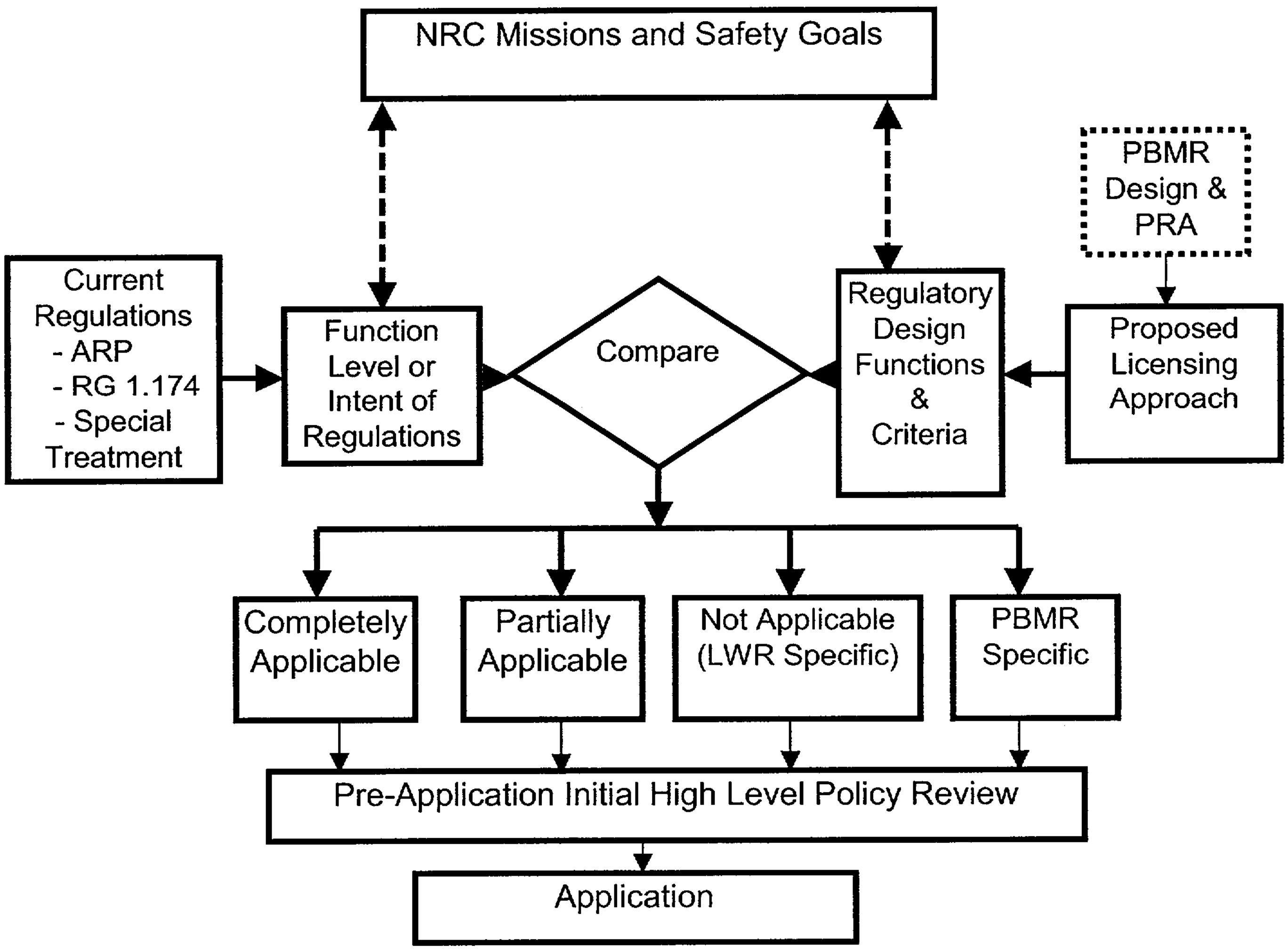
MHTGR Example of Safety-Related Design Conditions

- Reactor pressure vessel selected as safety-related for the following required safety functions
  - radiate core heat from vessel wall
  - maintain core geometry
  - limit air ingress to core

- With regard to maintain core geometry, examination of following SRDC led to quantitative requirements
  - pressurized conduction cooldowns (DBE 1 & 4--reactivity events)
  - depressurized conduction cooldowns (DBE 10 & 11---primary coolant leaks)

- Determined that an ASME Code Case required for limited durations of the vessel material at elevated temperatures

Consistency of PBMR Risk-Informed Licensing Bases with Regulatory Practice



Comparison to NRC Advanced Reactor Policy

- **Early Interactions**

  Policy encourages " the earliest possible interactions of applicant, vendor and government agencies with the NRC."

- **Safety Criteria**

  Policy states that " the Commission expects, as a minimum, at least the same degree of protection of the public and the environment that is required of current generation LWRs."

- **Licensing Approach**

  "Advanced reactor designers are encouraged as part of their design submittals to propose specific review criteria of novel regulatory approaches which NRC might apply to their designs."

- **Design Features**

  Policy states that "the Commission expects that advanced reactors will provide enhanced margins of safety and/or utilize simplified, inherent, passive, or other innovative means to accomplish their safety functions."

PBMR Preliminary Design Features and Advanced Reactor Policy (1 of 4)

NRC's Definition of Advanced Reactor Characteristics	Corresponding PBMR Preliminary Design Features
Highly reliable and less complex shutdown and decay heat removal systems; The use of inherent or passive means to accomplish this objective....(negative temperature coefficient, natural circulation)	• Low excess reactivity and negative temperature coefficient provide passive shutdown capability • Two diverse active systems provided to insert negative reactivity to assure long term subcriticality • Redundant, diverse and independent active forced cooling systems to remove core decay heat • Conduction/radiation cooldown capability without forced or natural convection of the primary coolant • No requirement for maintaining an inventory of primary coolant inside the reactor vessel.
Longer time constants and sufficient instrumentation to allow for more diagnosis and management prior to reaching safety systems challenge and/or exposure of vital equipment to adverse conditions.	• Low power density and large heat capacity of core fuel and graphite provides long time constants for power/temperature transients over full range of accident conditions • Low stored energy and single phase of primary coolant prevents rapid thermal and mechanical energy transfer to primary boundary and to confinement structures; eliminates fuel coolant interactions that could challenge barrier integrity. • Capability to monitor circulating primary system radioactivity to confirm integrity of the fuel is within design limits

PBMR Preliminary Design Features and Advanced Reactor Policy (2 of 4)

NRC's Definition of Advanced Reactor Characteristics	Corresponding PBMR Preliminary Design Features
Simplified safety systems which, where possible, reduce required operator actions, equipment subjected to severe environmental conditions, and components needed for maintaining safe shutdown conditions.	• Capability to limit consequences of accidents independent of any prompt operator actions; and reliant on passive safety features. • Safety systems are few, simple, and have few components needed to operate
Designs that minimize the potential for severe accidents and their consequences by providing sufficient inherent safety, reliability, redundancy, diversity and independence in safety systems	• The inherent capabilities of the fuel particles to retain their structural integrity over the range of normal and accident conditions with margins limit the source terms to very small levels; operation of active systems not required to support this capability • Long time constants of any releases and absence of any adverse physical and chemical processes • Any sequence with the primary system boundary intact results in no release of radioactivity • Design features that limit the potential for air or water ingress.

PBMR Preliminary Design Features and Advanced Reactor Policy (3 of 4)

NRC's Definition of Advanced Reactor Characteristics	Corresponding PBMR Preliminary Design Features
Designs that provide reliable equipment in the balance of plant, (or safety system independence from balance of plant) to reduce the number of challenges to safety systems	• The entire plant is very simple with a small number of components and support systems;
Designs that provide easily maintainable equipment and components	• Fuel elements are continuously monitored via on-line refueling and monitoring of circulating activity; broken and spent fuel elements replaced on-line • Power conversion equipment (turbo-generator, turbo-units, etc.) can be maintained without compromising ability to support key safety functions
Designs that reduce the potential radiation exposures to plant personnel	• Performance of the fuel greatly reduces level of circulating primary coolant activity • Inert helium provides no impurities for activation products

PBMR Preliminary Design Features and Advanced Reactor Policy (4 of 4)

NRC's Definition of Advanced Reactor Characteristics	Corresponding PBMR Preliminary Design Features
Designs that incorporate defense-in-depth philosophy by maintaining multiple barriers against radiation release and by reducing potential for consequences of severe accidents	• Fuel particles, fuel spheres, primary pressure boundary, citadel structure, confinement envelope serve as concentric, independent barriers (See more detailed discussion in Section 7.2.1) • Design features employ balance between accident prevention and mitigation (See more detailed discussion in Section 7.2.2)
Design features that can be proven by citation of existing technology or which can be satisfactorily established by commitment to suitable technology development program	• Innovation of earlier designs: extensive experience with gas cooled reactors, HTGRs, and significant experience with pebble bed reactors to provide confidence in performance of fuel and major components. • New and unique PBMR features important for power production but not needed to support key safety functions • experimental evidence to support confidence in the integrity of the fuel under normal and adverse conditions • Formula for proven fuel manufacturing process and quality assurance testing that ensure manufacturing reliability • Plan to feedback operating experience from early PBMRs to refine technology

Comparison to RG 1.174, Framework for Risk-Informed Changes

- Applicable to LWRs
- Principles for risk-informed changes include the following
  - Consistent with defense-in-depth and balance between prevention and mitigation
  - Maintain sufficient safety margins
  - Changes small and consistent with Safety Goals
  - Changes monitored
- Provides useful guidance to evaluating the risk-informed aspects of the PBMR licensing approach

PBMR Designed With Defense-in-Depth

- Multiple, concentric, independent radionuclide retention barriers
  - fuel (ceramic particles and pebble bed spheres)
  - primary pressure boundary
  - containment (citadel structure and filtered confinement)

- Reliable design selections to maintain barriers with emphasis on
  - high quality
  - passive, intrinsic characteristics
  - appropriate redundancy, diversity and independence
  - design margins
  - continuously monitored
  - structured licensing bases process

Preliminary PBMR Design Features Supporting Defense-in-Depth of Fuel Barrier (1 of 2)

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

Preliminary PBMR Design Features Supporting Defense- in-Depth of Fuel Barrier (2 of 2)

Safety Functions Supporting Fuel Barrier Integrity	Elements of Defense-in-Depth in Supporting Safety Functions	
	Inherent features and attributes	**Engineered active and passive features**
Control chemical attack	• Ceramic fuel particles and graphite matrix • Design limitations on extent of air or water ingress • Self limiting aspect of reactions • Inert gas coolant	• Low pressure cooling water sources limits potential for water ingress • design interfaces with high pressure primary system • High quality primary vessels & piping with robust seismic capability
Maintain core geometry	• Use of refractory ceramics for structural materials exposed to high temperatures • Use of high temperature alloys for reactor vessel and core barrel components	• High quality reactor vessel and PPB components designed to large seismic margins • Robust citadel structure provides strength and protection from external missles • Forced convection of Helium maintains vessel and core barrel metal components at relatively low temperatures

Preliminary PBMR Design Features Supporting Defense in Depth of PPB

Safety Functions Supporting PPB Integrity	Elements of Defense-in-Depth in Supporting Safety Functions	
	Inherent features and attributes	**Engineered active and passive features**
Maintain PPB integrity	• Use of chemically inert single phase coolant • Inherently low pressurization potential due to low stored energy, large pressure gradients during normal operation, and limited pressurization capacity of HICS • Immediate reduction in PPB pressure on cessation of Brayton cycle	• Maintenance of high chemical purity by operation of helium purification system • Use of high quality reactor vessel and PPB components • PPB capability to retain PTG missiles • Use of a Citadel structure to protect the PPB • Forced convection flow paths maintain PPB components at relatively low temperatures. • Capability of HICS to pump down inventory to reduce driving head for releases from PPB.

Preliminary PBMR Design Features Supporting Defense in Depth of Containment

Safety Functions Supporting Containment Integrity	Elements of Defense-in-Depth in Supporting Safety Functions	
	Inherent features and attributes	**Engineered active and passive features**
Maintain integrity of containment	• Low stored energy and inert primary coolant • Completely envelopes PPB boundary • Events evolve slowly allowing for manual compensating measures	• HVAC filtration system to reduce exposures • Blowout panels for large depressurization events prevent pressure loads • Re-closable vent for an elevated release • Robust construction to protect equipment from external hazards • Partially below grade

Preliminary PBMR Design Features Supporting Defense in Depth of Emergency Planning

Safety Functions Supporting Emergency Planning	Elements of Defense-in-Depth in Supporting Safety Functions	
	Inherent features and attributes	**Engineered active and passive features**
Provide ample warning time for effective protective actions	• Large thermal capacity provides ample time for implementing emergency plans • Low source terms reduce EP contingencies	• Features relied upon in conservative EP strategy are solely sufficient to limit radiological doses at the site boundary below Protective Action Guidelines levels for all LBEs.

PBMR Equipment Classification Addresses Defense-in-Depth

- Prior representative slides are a composite of features available for required safety functions for *barrier* defense-in-depth
- Features available for specific events vary from one DBE to another
- Once safety-related SSC selected, *process* defense-in-depth employed with special treatment for
  - quality assurance
  - procurement
  - fabrication
  - monitoring
  - maintenance
  - ISI/IST

Prevention-Mitigation Balance

- Available guidance assumes an LWR with focus on core damage prevention and mitigation
- NUREG 1150 acknowledges that there is no single prevention-mitigation balance
- To judge PBMR prevention-mitigation, a spectrum of accident families must be examined with distinctive frequencies and consequence characteristics
- Examined role of SSC in two MHTGR accident families
  - initiating event
  - response of supporting active SSC
  - response of supporting passive SSC
  - response of radionuclide barriers
  - emergency plan measures

Prevention/Mitigation Analysis of MHTGR DBE-10

Elements of Event Sequence	Prevention Aspects	Mitigation Aspects
Initiating event	• Moderate **PPB** failure (1 in^2 to 13 in^2 leak with frequency of about $8x10^{-3}$ per year)	
Response of active systems supporting key safety functions	• No system failures for this sequence	• Successful forced cooling via the **HTS** with reliability of .83 • Successful insertion of **control rods** • Pumpddown of Helium ineffective due to size of PPB failure
Response of passive features supporting key safety functions	• No additional failures of passive features	• Initially intact **fuel particles** remain intact • Initial circulating and plateout primary coolant activity is very low due to **fuel performance during normal operation**
Fraction of source term released from fuel into primary reactor coolant system PPB		• < $2x10^{-6}$ of I-131 inventory available for release from **circulating and plateout** activity due to fuel performance during normal operation .
Fraction of source term released from PPB into containment		• About $1x10^{-3}$ of the I-131 in the plateout and all of circulating activity escapes the **PPB** into the containment
Fraction of source term released from containment		• About 1/3 of the I-131 released into the **containment** from the PPB is released from the plant
Time available to implement emergency plan protective actions.		• Less than .01 Ci of I-131 is released from the plant during the depressurization event

Prevention/Mitigation Analysis of MHTGR DBE-11

Elements of Event Sequence	Prevention Aspects	Mitigation Aspects
Initiating event	• Small **PPB** failure (.03 to 1 in^2 leak with frequency of about $3x10^{-2}$ per year)	
Response of active systems supporting key safety functions	• Reliability of the failed **HTS** of .83 reduces the frequency by factor of 0.17. • Reliability of the assumed failed **SCS** of .97 reduces the frequency by a factor of 0.03	• Successful insertion of **control rods** • Successful **pumpdown** of Helium to reduce transport potential
Response of passive features supporting key safety functions	• No additional failures of passive features	• Successful operation of **RCCS** to remove heat conducted/radiated from core/reactor vessel • Conduction cooldown transient resulting in elevated core temperatures • Initially intact **fuel** particles remain intact • Initial circulating primary coolant activity is very low
Fraction of source term released from fuel into PPB		• < $2x10^{-5}$ of I-131 inventory released from fuel over a period of several days; release limited to part of the inventory of **initially failed/ fuel** particles and of circulating activity
Fraction of source term released from PPB into containment		• About ½ of the I-131 released from the fuel released from the **PPB**
Fraction of source term released from containment		• About 4% of the I-131 released into the **containment** is released from the plant.
Time available for emergency protective actions.		• Less than 3 Ci of I-131 is released from the plant over a period of **50 to 150 hours**

PBMR Provides Prevention/Mitigation

- SSC serve a preventative role in one accident family and a mitigative role in another
- Must be viewed over spectrum of event sequences
- SSC classification method explicitly considers availability of SSC for each DBE
- Consequence mitigation emphasized for DBE; frequency prevention emphasized for high consequence EPBE (if any)
- Approach considers events that have both prevention and mitigation within the DBE region

PBMR Approach to Safety Margins

- Included in the fundamental safety design approach that sets the configuration, geometry, rating, fuel quality, etc.
- Explicitly treated in the safety analyses of the DBE and the SRDC
- Confirmed in plant startup testing and during operation

PBMR Approach to Monitoring

- SSC monitored during normal operation
  - fuel performance
  - RCCS performance
  - reactor neutronics
- Actuation of equipment requiring power and motive forces minimized
- Scope of monitoring provides an on-line diagnostic of how the plant will respond during off-normal events

PBMR Approach to Special Treatment

- Once the DBE are selected, the PBMR approach to selection of safety-related equipment follows conventional practice
  - accident analyses shown to be acceptable with only safety-related equipment
  - classified equipment receives special treatment during design, fabrication, operation and maintenance
- The special treatment requirements will be developed on a case-by-case basis from the DBE
- In this manner, a clear "blueprint" is available for the rationale for the equipment selection and the requirements

Outcome Objectives from NRC to Exelon

- Comments and feedback on the process for equipment classification and the development of regulatory design criteria
- Agreement on the equipment selection method as a key foundation of licensing approach
- Comments and feedback that PBMR is consistent with Advanced Reactor Policy and within RG 1.174 guidance (e.g., defense-in-depth and prevention/mitigation)
- Comments and feedback on the risk-informed approach to special treatment