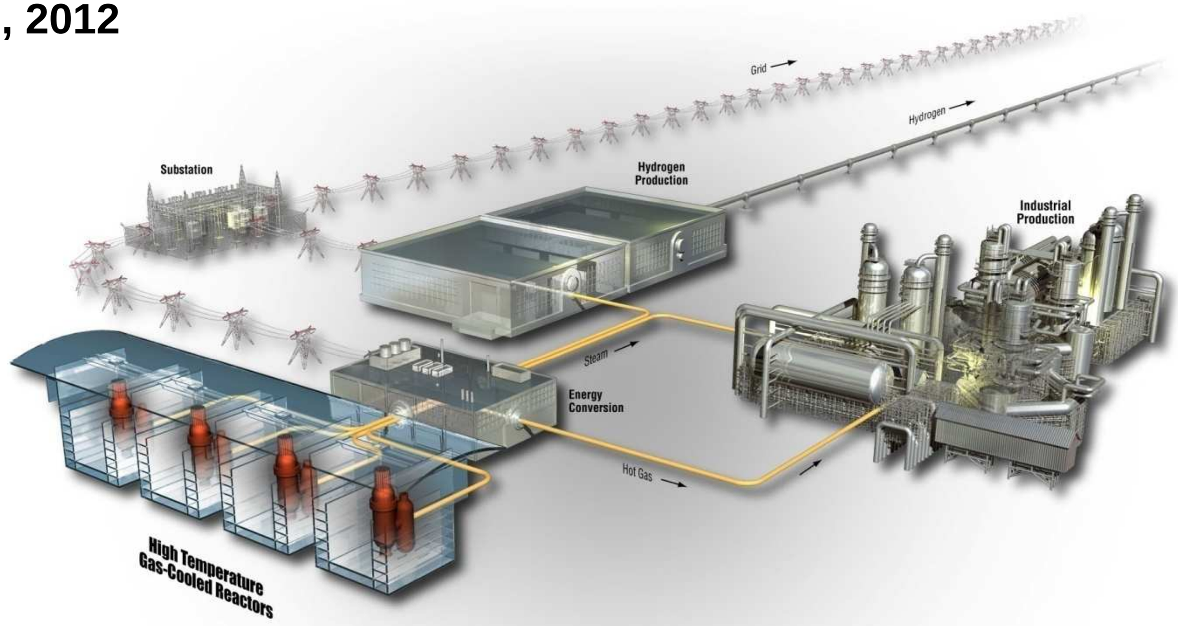
Next Generation Nuclear Plant

Risk-Informed Performance-Based Licensing Approach

Probabilistic Risk Assessment White Paper

July 10, 2012



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Meeting Outline

- PRA White Paper Introduction
  - HTGR PRA background
  - Regulatory foundation
- NGNP Approach to PRA
  - PRA objectives/motivations
  - PRA scope
  - Compare/contrast with LWR PRA
  - PRA challenges for HTGRs
- Event Sequence Modeling
  - MHTGR station blackout example involving multiple modules
- Approach to Modular HTGR Challenges and Technical Adequacy
- Review of Outcome Objectives
- Meeting Summary

PRA White Paper Introduction

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Outcome Objectives

1. **Scope** of HTGR PRA is appropriate for intended uses in NGNP COLA including
   - **Evaluation of design alternatives and incorporation of risk insights into design**
   - **Input to selection of LBEs**
   - **Input to safety classification of SSCs**
   - **Risk-informed evaluation of defense-in-depth**
2. Approaches to **initiating event selection, event sequence development, end-state definition, and definition of risk metrics** are appropriate.
3. Approach to **treatment of inherent characteristics and passive SSCs** is reasonable and consistent with current state-of-the-art PRAs.
4. Approach to use of deterministic engineering analyses to provide technical basis for predicting plant response to initiating events and event sequences, success criteria, and mechanistic source terms yields **appropriate blend of deterministic and probabilistic** approaches

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Outcome Objectives ***(Continued)***

5. Approach to **development of PRA database**, including use of applicable data from LWRs, use of expert opinion, and treatment of uncertainty is reasonable
6. Process for **representing uncertainties and quantification of mechanistic source terms** is a reasonable approach for purpose of developing and analyzing results
7. Approach for PRA treatment of **single and multiple reactor accidents** is sufficient to support certification of single HTGR module and for multi-module configurations
8. Approach to using available **guides and standards for PRA quality and independent peer review** is acceptable for determining adequacy for its intended uses
9. Approach to **treatment of uncertainties** is adequate for intended PRA applications
10. Approach used to support the risk-informed **evaluation of defense-in-depth** in the design, construction, and operation of an HTGR is adequate.

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The Principal Challenges

- Lack of design and operational details for reactors that are still in the conceptual design stage
- Lack of relevant service experience from which to derive a PRA data base
- Increased emphasis on the use of passive systems to perform safety functions in advanced reactors
- Need to address events and event sequences within and beyond the design basis
- Inapplicability of risk metrics such as core damage frequency to reactors with inherent reactor characteristics that are fundamentally different than those of LWRs
- Lack of experience by reviewers and regulators who are familiar with PRA as it has been applied to non-LWRs

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Use of PRA to Support HTGRs

- Began in mid 70’s with DOE Accident Initiation and Progression Analysis (AIPA) study on large HTGRs to guide and prioritize technology development
  - Introduced Beta Factor Method for common cause failures
  - First ever PRA of internal fires
- Insights from AIPA on 3000MWt large HTGR guided the U.S. development of the modular HTGR with its size, shape, power density and configuration for passive core heat removal
- Used as a design tool for all HTGR designs after ~1975:
  - GT-MHR under development by DOE and Russian Federation
  - PBMR in South Africa and for NGNP
  - AREVA-HTR (ANTARES) under development in France, USA, and Germany
  - SC-MHR for NGNP
  - HTRs in China and Korea

Examples of HTGR Design Decisions Supported by PRAs

- Design features of modular HTGRs
  - Core size, power level and shape requirements for passive heat removal
- Design features to define core cooling system reliability and capability
  - Decay heat removal capability for power conversion system
  - Redundancy and reliability of active cooling systems for maintenance and investment protection
  - Design options for reactor cavity cooling system
- Selection of design basis events involving depressurization
  - Limiting size and location of depressurization events
  - In-service inspection and leak detection requirements
  - Control and protection system inputs and set-points
- Risk impacts of reactor building (RB) design options
  - Pros and cons of leak tight containment
  - Requirements for physical protection, venting, and filtration
  - Capability of pressure relief and leak management systems
  - Allocation of radionuclide retention capabilities of fuel, HPB, and RB

Regulatory Foundation

- 10 CFR 52 Requirements for PRAs in COL
- NRC PRA Policy Statement (1995)
- Policy Issues for Non-LWRs (SECY 03-0047)
  - Issue 1 on level of safety included integrated risk issue
  - Issue 4 is the use of PRA input to licensing basis
  - Issue 5 involves use of mechanistic source terms
- NRC Regulatory Guides
  - RG 1.206 addresses PRA input to Chapter 19 of COL and use of CDF and LRF goals, DID considerations (prevention/mitigation balance
  - RG 1.174 address use of PRA in risk informed decision making with deterministic considerations, e.g. DID, PRA quality attributes
  - RG 1.200 address PRA technical adequacy and endorsement of industry PRA standards

Regulatory Foundation and Industry Initiatives – Modular HTGRs

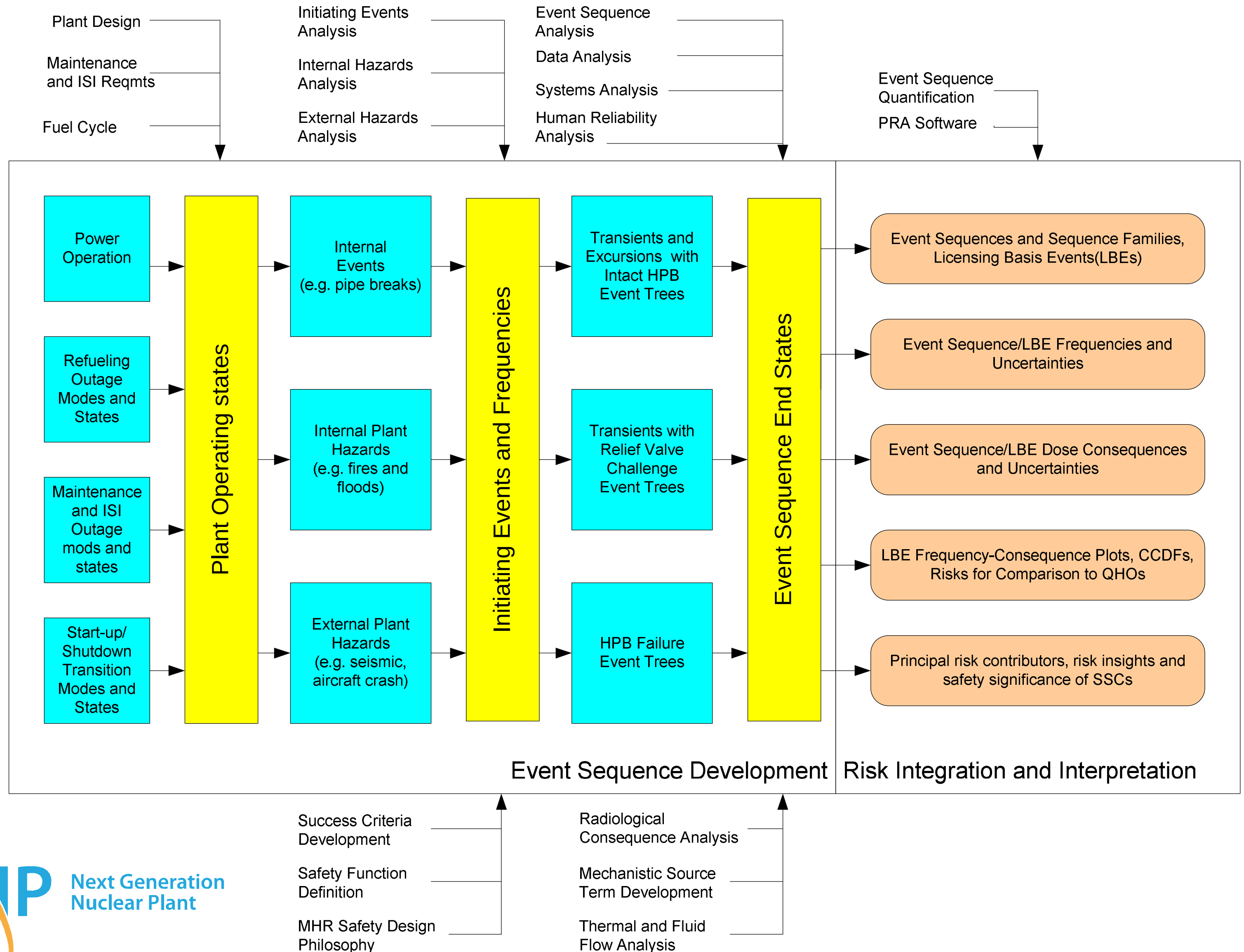
- NUREG-1338 NRC Pre-Application Review of MHTGR (‘85-92)
  - Review of MHTGR-specific PRA including integrated risk aspects
  - Risk-informed licensing approach similar to that proposed by NGNP
  - Safety information document including deterministic safety analyses
- Exelon PBMR Pre-application Review and PBMR design certification (‘01-’09)
  - NRC supportive of using PRA and further standards development
  - NRC suggested including spent fuel pool in PRA scope
- ANS 53.1 Nuclear Safety Design Standard for MHRs
- ASME Section XI Division for MHRs and Reliability Integrity Management Program
- ASME/ANS Technology-Neutral PRA Standard for Advanced non-LWR Plants

NGNP Approach To PRA

Elements of the NGNP Full-Scope PRA

- Definition of plant operating states
- Initiating events analysis
- Event sequence development
- Success criteria development
- Thermal and fluid flow analysis
- Systems analysis
- Data analysis
- Human reliability analysis
- Internal flooding analysis
- Internal fire analysis
- Seismic risk analysis
- Other external events analysis
- Event sequence frequency quantification
- Mechanistic source term analysis
- Radiological consequence analysis
- Risk integration and interpretation of results
- Peer review

Flow of PRA Elements



Unique Features Of Modular HTGR PRA

- All sources of radioactive material addressed
- Success criteria reflect reactor's unique features;
  - Reactor specific criteria to establish safe, stable end states
  - Breaches in HPB do not result in loss of cooling (e.g., no LOCA)
  - Need functional basis for long system mission times
  - Plant response to ATWS and SBO fundamentally different than for LWR
- Smaller number of systems to model
- Integrated event sequence model for treatment of internal and external events and all operating and shutdown modes
- Source term phenomena unique to HTGRs
- Absence of severe core damage LWR-specific phenomena
- No "core damage" or "large early release" pinch points; CDF and LERF not applicable
- No need for Level 1/Level 2/Level 3 framework
- Unique HTGR end states covering a range of radionuclide release categories
- Need to address integrated risk of multi-reactor plant
- Need to process more sequences to support applications and ensure no cliff edge effects
- Need to address hazards from nearby industrial processes

Event Sequence Modeling

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Identification of Sources and Barriers (Table 3-2)

Radioactive Material Source	Barriers to Radionuclide Transport
Fuel elements in the core	- Fuel particle kernel - Silicon carbide & pyrocarbon coatings of fuel particle - Fuel matrix & fuel element graphite - HPB (primary circuit) - Reactor building
Fuel elements outside the core	- Fuel particle kernel - Silicon carbide & pyrocarbon coatings of fuel particle - Fuel matrix & fuel element graphite - Fuel handling & storage systems - Reactor building
Non-core sources within the HPB	- HPB - Reactor building
Other sources	- Various tanks, piping systems and containers - Reactor building or ancillary buildings housing waste management equipment

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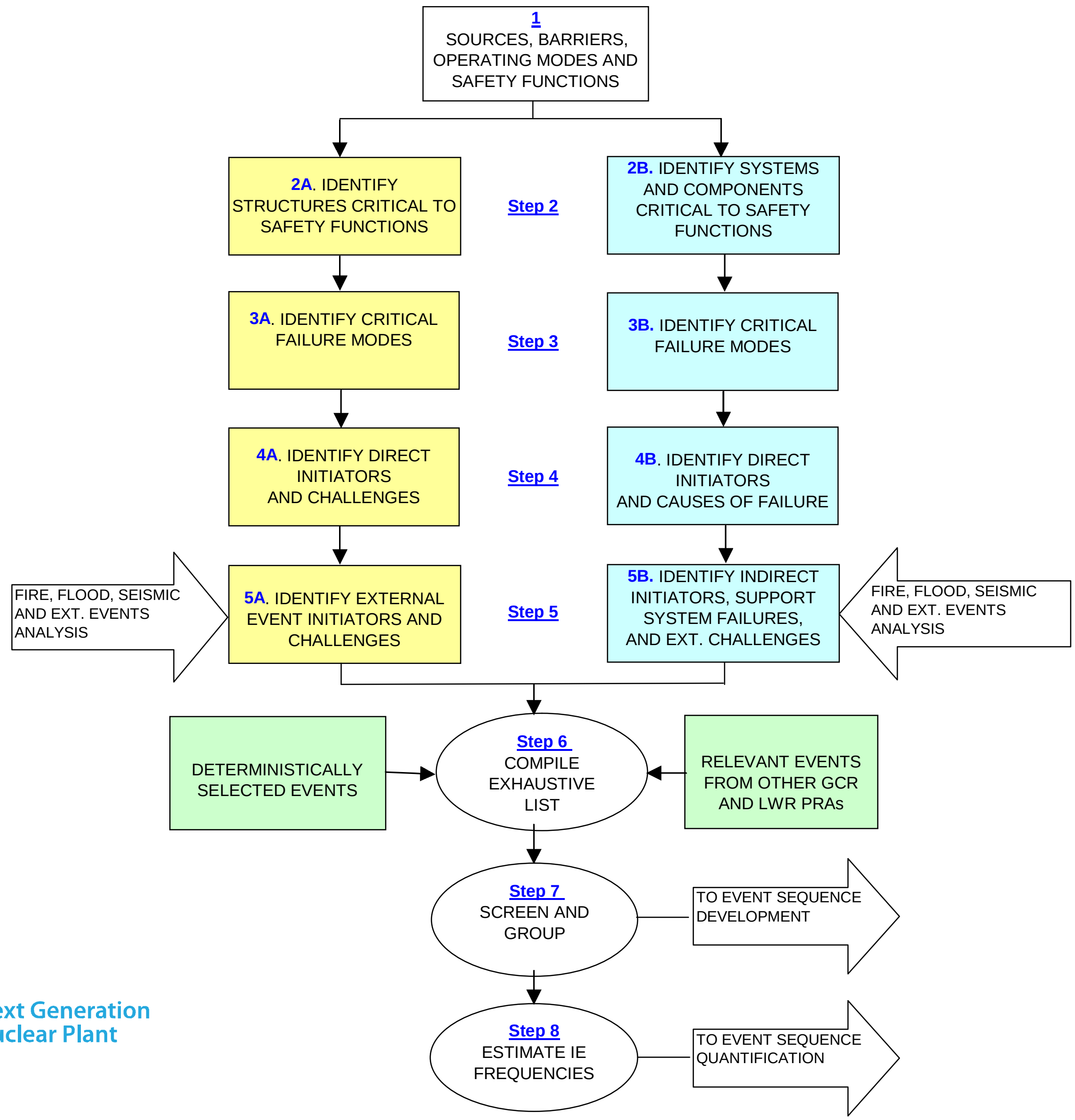
Master Logic Diagram For Selecting Initiating Events



Event Sequence Development Step-by-Step Procedure

Step 1: Define functional initiating event categories for each plant operating state
(additional steps repeated for each category)

Step 2: Define event sequence end states

Step 3: Define safety functions, systems, and operator Actions

Step 4: Develop dependency matrices

Step 5: Develop event sequence models
- Event Sequence Diagrams
- Event Trees

Step 6: Define success criteria for each event tree top event

Step 1: Define Functional Initiating Event Categories for Each Plant Operating State

- Defined in conjunction with initiating event task
- For HPB sources of radioactive material
  - Transient functional categories
  - HPB break categories
  - SG failure categories
  - External event categories (defined in separate task)
  - Internal plant hazard categories (defined in separate tasks)
- For other sources of radioactive material
  - Spent fuel storage
  - HPS
  - Radwaste systems

Step 2: Define Scenario End States HTGR End State Considerations

- Purpose of end states is to classify event sequences with respect to potential for offsite radiological consequences
- Need to consider events within and outside the design basis
- End states with releases are functionally similar to Level 3 PRA release categories for LWRs
- If there is no HPB failure postulated as an initiating event, in nearly all cases the HPB will remain intact throughout event due to absence of core-coolant-pressure boundary interactions; in most cases primary relief valves are not challenged; if there is no HPB breach, there is no release. Non-release end states are needed to support design decisions.
- End state factors defined to process many sequences with small variations in source terms; number of different end states dictated by how finely the consequences need to be resolved

NGNP Plant Safety Functions*

- Maintain fuel integrity
- Control heat generation (reactivity)
- Control heat removal
- Control chemical attack (from water or air ingress)
- Maintain core and reactor vessel structural integrity
- Control HPB
  - Maintain HPB Integrity (controls chemical attack)
  - Depressurize/pump-down the primary HTS
  - Isolate HPB leaks from HPB (isolation valves)
  - Isolate HPB leaks and breaks from Reactor Vessel
- Control Reactor Building (RB) Functions
  - Maintain RB structural integrity
  - Control Primary-RB-outside air gas-exchange
  - Provide filtration/retention inside RB

For Primary Helium Pressure Boundary Sources

Step 3: Define Functions, Systems, Actions

- Mitigation functions for HPB leaks and breaks
  - Detection of leak via control and protection systems
  - Isolation of leak
  - Pump-down of primary system
  - Reactor trip/manual shutdown
  - Core heat removal via active or passive systems
  - RB functions
- Mitigation functions for steam generator (SG) leaks and breaks
  - Detection of moisture in primary system
  - Isolation of leaking SG
  - Dump of leaking SG
  - Reactor trip/manual shutdown
  - Primary relief valve response
  - Core heat removal via active or passive systems
  - RB functions

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Step 4: Dependency Matrices

- Divide system list into three categories
  - Front line when system directly performing a safety function
  - Support when system provides a support function to one or more front line systems
  - Not modeled
- Develop matrices for
  - Support to front line systems
  - Support to support systems
  - Initiating events to support and front line systems

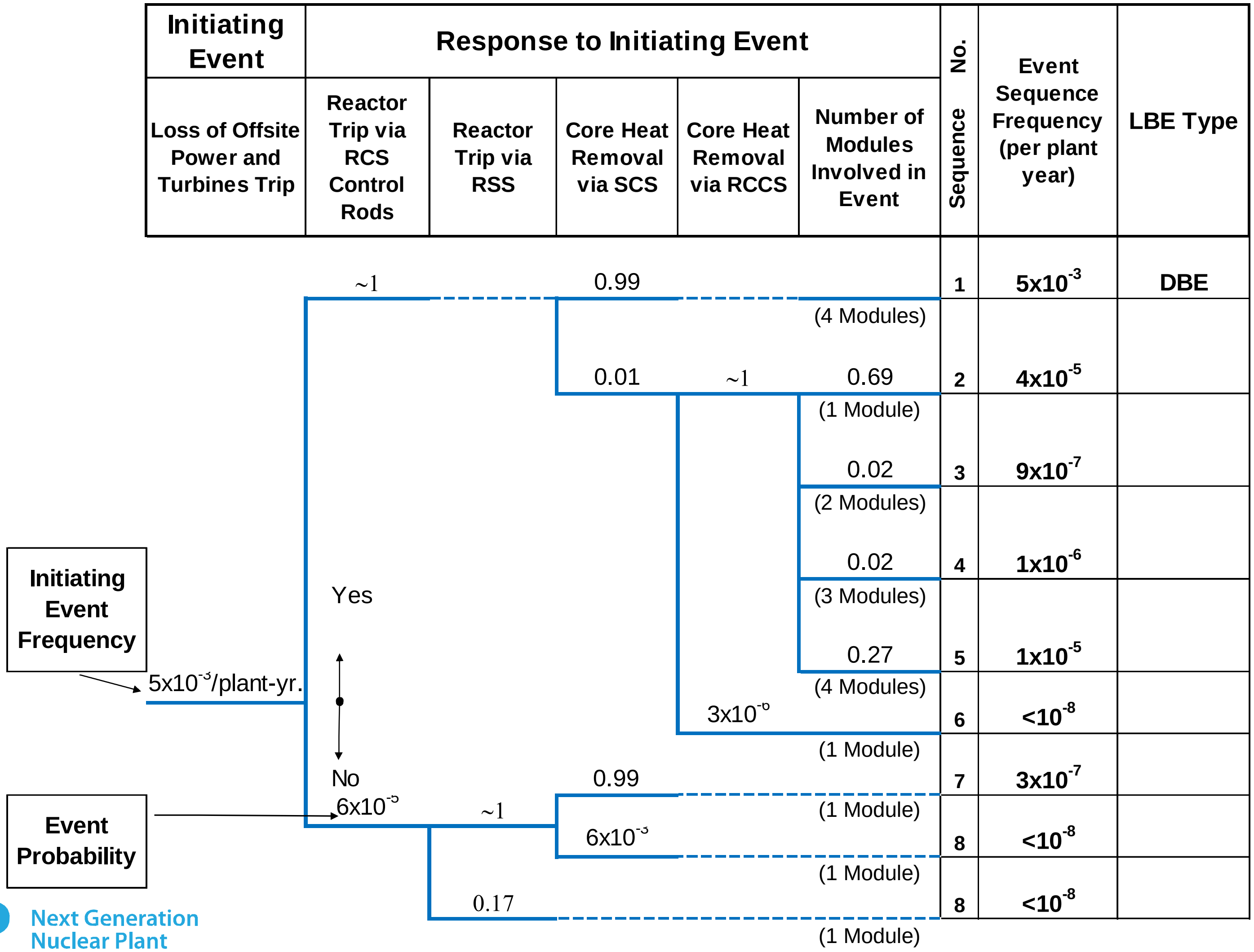
Step 5: Develop Event Sequence Models

- Thought process
  - Define most likely or expected sequence of events from an assumed initiating event occurrence
    - Perform/review plant transient and response analysis
    - Understand response of control and protection systems and all automatic actions
    - Define the safety functions and which systems are available to support them
    - Apply/develop basic mitigation and termination strategy and operator actions to be expected all the way to repairs and return to power
  - Systematically identify alternative outcomes for each developed sequence
  - Consider which questions need to be resolved to assign the end state codes
- Event Sequence Diagrams and Event Trees

Framework for Definition of HTGR Event Sequences

- Definition of initial plant conditions (i.e., plant operating states)
- Initiating event characterization
  - Cause of the Initiating Event
  - Initiating Event functional category
  - Reactor module impact
- Response of main circulator and valve to Initiating Event
- Status of the HPB including any mitigating actions
- Response of the systems for reactivity control
- Response of the core heat removal systems
- Status of fuel
- Response of the reactor building
  - Early response to initiating event
  - Long term response including mitigating actions
- Oxidation status
- Source term characteristics

Example Selection of DBE from MHTGR Loss of Offsite Power Event Tree Involving Multiple Reactor Modules



Approach to Modular HTGR Challenges and Technical Adequacy

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PRA Data Parameter Categories

- Initiating event frequencies for energy conversion area (ECA) failure modes (turbo compressors, gas-turbine generators)
- Initiating event frequencies for the same internal and external plant hazards found in full-scope LWR PRAs (fires, floods, seismic events, transportation accidents).
- Initiating event frequencies for HPB passive component failure modes (e.g., pipes, pressure vessels, weldments, and pressure relief valves)
- Failure rates and maintenance terms for active components common to LWRs (e.g., pumps and valves in water systems, water-to-water heat exchangers, diesel generators, breakers, and instrumentation and control components)
- Failure rates and unavailabilities for active components unique to gas-cooled reactors (GCRs) (e.g. gas blowers, gas-to-gas and gas-to-water heat exchangers, GCR control rod drives, and gas system valves)
- Common cause failure parameters for a limited set of redundant components, mostly in common cause groups of components common to LWRs

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PRA Treatment of Inherent and Passive Features (1/2)

HTGR Inherent and Passive Features	PRA Treatment
Negative temperature coefficient of reactivity	Deterministic accident simulation models will treat this realistically; uncertainties in core reactivity and thermal response addressed as part of mechanistic source term and associated uncertainty analysis.
High thermal heat capacity (low-power density) of core and reflector	Deterministic accident simulation models will treat this realistically; uncertainties in core thermal response addressed as part of mechanistic source term and associated uncertainty analysis.
Passive core cooling capability	Event trees will define success and failure combinations of core heat removal systems, including the RCCS; seismic events and other external events will be defined that challenge and exceed the RCCS capability; fragilities assessed; potential for blockage of the RCCS cooling flow path because of common cause failure mechanisms to be addressed; uncertainties in passive heat transfer during conduction cool-down events to be assessed as part of mechanistic source term uncertainty analysis.
Fuel particle capabilities during normal and accident conditions	Failed fuel fraction from manufacture treated probabilistically based on manufacturing, operating, and heat-up test data; failed fuel during burn-up and accident modelled probabilistically as part of fuel failure model in source term analysis; source term uncertainties quantified, including those associated with fuel performance and other transport mechanisms.

PRA Treatment of Inherent and Passive Features (2/2)

HTGR Inherent and Passive Features	PRA Treatment
Core, vessel, and associated support structures	Full seismic and external event analysis will be performed that consider events that challenge or exceed design basis capabilities of all active and passive SSCs modelled in the PRA. Fragilities will be assessed for these hazards.
Helium Pressure Boundary integrity and capability to limit air ingress	LWR piping experience and pipe reliability models are applied for expected HTGR applicable pipe damage mechanisms to quantify HPB failure initiating event frequencies; leak before break approaches being factored into the design will be accounted for in these estimates. Event trees will cover a range of HPB failure sizes and failure modes; consequence analysis will include a quantification of the impacts of any air ingress and oxidation reactions as part of the core thermal transient analysis, and will be addressed as part of the mechanistic source term and associated uncertainty analysis.
Reactor Building structure including pressure relief features	Event trees will develop a spectrum of sequences that define a range of challenges and responses of blow-out panels. The uncertainty analysis will treat the response of the reactor building pressure relief features probabilistically

PRA Treatment of Seismic and External Events

- Consistency in selection of LBEs requires a PRA treatment of external hazards
- NGNP seismic PRA will address
  - Full range of seismic hazard curves for COL site
  - Seismically induced fires and floods
  - Seismic fragility correlation
  - Consideration of multi-reactor and multi-source effects

Technical Adequacy of PRA

- PRA technical adequacy defined by
  - Experience and qualifications of PRA team
  - In-depth knowledge of the plant design and how it responds to transients and accidents
  - PRA technical quality attributes
  - PRA standards and regulatory guides
  - PRA peer reviews
- NGNP PRA will make use of existing PRA guides and standards
  - White paper discusses how then current LWR standard would be used – these are useful but require extensive interpretation and adaptation for applicability to HTGRs
  - NGNP has supported the completion of the ASME/ANS Technology Neutral PRA Standard for Advanced Non-LWR Nuclear Power Plants

PRA Quality Attributes

- PRA attributes
  - Completeness in coverage of risk contributors
    - Completeness in PRA scope relative to applications
    - Completeness in level of detail
  - Model to plant fidelity
    - As built and as-operated plant
    - Configuration management program to track changes
  - Realism in the quantification of risk metrics
    - Adequate technical basis for best estimates
    - Appropriate use of conservatisms that do not mask risk insights
    - Identification and Quantification of Uncertainties
  - Adequate treatment of dependencies
  - Transparency of documentation
  - Use of appropriate methods and data
  - Independent peer review
- PRA application attributes
  - Delineation of cause and effect relationships to applications
  - Selection of appropriate risk metrics and decision criteria

Review of Outcome Objectives

Outcome: Objective 1

1. **Scope** of HTGR PRA is appropriate for intended uses in NGNP COLA including
   - Evaluation of design alternatives and incorporation of risk insights into design
   - Input to selection of LBEs
   - Input to safety classification of SSCs
   - Risk-informed evaluation of defense-in-depth

NGNP Approach: A full-scope, all modes, and all hazards PRA for the NGNP COLA consistent with requirements of 10 CFR 52. Risk insights will be used for selecting LBEs, safety classification of SSCs, and risk-informed evaluation of defense-in-depth consistent with those described in Issue 4 of SECY 2003-0047 and are generally consistent with NRC's technology neutral licensing framework initiative.

Outcome: Objective 2

2. Approaches to **initiating event selection, event sequence development, end-state definition, and definition of risk metrics** are appropriate

NGNP Approach: NGNP HTGR-specific accident families and release categories will be used as a basis to define NGNP HTGR-specific risk metrics that relate directly to safety design approach of NGNP HTGR and are expressed in terms of frequency of offsite radiological consequences.

Outcome: Objective 3

3. Approach to **treatment of inherent characteristics and passive SSCs** is reasonable and consistent with current state-of-the-art PRAs.

NGNP Approach: NGNP HTGR PRA is characterized by systematic identification of NGNP HTGR-specific initiating events, definition and analysis of NGNP HTGR safety functions, delineation of all SSCs that provide either required or supportive safety functions, technically sound deterministic engineering analyses, and mechanistic source terms.

Outcome: Objective 4

4. Approach to use of deterministic engineering analyses to provide technical basis for predicting plant response to initiating events and event sequences, success criteria, and mechanistic source terms yields **appropriate blend of deterministic and probabilistic** approaches

NGNP Approach: NGNP HTGR safety design approach is deeply rooted in deterministic engineering principles. NGNP HTGR PRA will be developed on a foundation of technically sound deterministic engineering analyses similar to that in LWR PRAs. Deterministic analyses will play a role in the definition of NGNP HTGR safety functions and success criteria, the prediction of the plant response to initiating events, and the development of mechanistic source terms. Deterministic and probabilistic analyses will be done in a coordinated and integrated manner. Once LBEs and safety classifications of SSCs have been established, the licensing approach will include conservative safety analysis of DBEs to demonstrate that the selection of safety-related SSCs is sufficient, and in this respect similar to that found in Chapter 15 for current LWRs.

Outcome: Objective 5

5. Approach to **development of PRA database**, including use of applicable data from LWRs, use of expert opinion, and treatment of uncertainty is reasonable

NGNP Approach: A technically sound database for the PRA will be developed by:

- Identifying SSCs that are the same or similar to SSCs and events in LWRs
- Utilizing PRA data developed for these items
- Identifying other SSCs and events such as the pressure boundary components that are made of same materials and use same design codes as LWRs and applying corresponding service data after considering applicable failure mechanisms
- Identifying SSCs and events that are similar to those with applicable HTGR or GCR service experience and using that information
- Identifying SSCs and events that are unique to the NGNP HTGR design and carefully applying expert judgement in accordance with PRA standards
- Assessing uncertainties and including them in PRA data

Outcome: Objective 6

6. Process for **representing uncertainties and quantification of mechanistic source terms** is a reasonable approach for purpose of developing and analyzing results

NGNP Approach: NGNP COLA will include mechanistic source terms and a treatment of uncertainty in development of these mechanistic source terms as part of the COL. These source terms will account for reliability of fuel manufacturing process and for fuel performance during normal plant operation and burn-up, and during transient and accident conditions. Also reflected in mechanistic source terms are core reactivity behaviour, diffusion and oxidation phenomena, heat transport phenomena, fluid flow phenomena, and all relevant radionuclide transport phenomena. Uncertainties in estimation of these source terms will be addressed.

Outcome: Objective 7

7. Approach for PRA treatment of **single and multiple reactor accidents** is sufficient to support certification of single HTGR module and for multi-module configurations

NGNP Approach: PRA will be developed in a way that supports both single and multi-module designs; however PRA to be provided with the COLA will be based on a single reactor design. Event sequences involving single reactor and multiple reactor source terms will be explicitly developed for multi-module design. Event sequence frequencies will be calculated on a per multi-module plant-year basis. Capabilities to support a fully integrated risk assessment will be available pending outcome of on-going policy discussions among NRC Commissioners, staff, and ACRS on integrated risk issue.

Outcome: Objective 8

8. Approach to using available **guides and standards for PRA quality and independent peer review** is acceptable for determining adequacy for its intended uses

NGNP Approach: An approach to using existing LWR PRA standards and guidance and an independent peer review will be used to help ensure the adequacy of the PRA for the use in NGNP COLA. NGNP project will advise NRC on how existing standards were interpreted for application to the NGNP HTGR PRA. Certain requirements in PRA standards and guidance that require knowledge of the as-operated design details and accumulation of service experience will not be met until after a licensed NGNP HTGR is built and operated. This will be taken into account in the PRA treatment of uncertainties.

Outcome: Objective 9

9. Approach to **treatment of uncertainties** is adequate for intended PRA applications

NGNP Approach: PRA that is submitted for COLA will be adequate to support selection of LBEs for future operating NGNP HTGRs. PRA itself is based on a deterministic foundation that is expected to be fundamental to future operating plants. PRA uncertainties may be larger than for an existing operating plant to account for fact that plant is not yet operating.

These uncertainties will be reflected in relatively large error bands in the PRA results. It is expected (based on HTGR experience) that there will be sufficient margins between PRA results and the frequency-dose criteria that will be used to select the LBEs. LBE selection process also has deterministic elements to make final decisions on LBEs rather insensitive to numerical changes in PRA results.

As a result of conservative treatment of uncertainties, use of deterministic elements in the PRA and LBE selection process, and expected large margins between the PRA results and the frequency dose criteria for selecting the LBEs, there is confidence that design and site assumptions will not impact selection of LBEs. A design review is expected to be required to verify appropriateness of LBEs and SSC safety classification during significant updates and upgrades of PRA.

Outcome: Objective 10

10. Approach used to support the risk-informed **evaluation of defense-in-depth** in the design, construction, and operation of an HTGR is adequate.

NGNP Approach: Information from PRA will be used to identify roles of each NGNP HTGR SSC responsible for preventing or mitigating each LBE that makes a significant contribution to risk of a release of radioactive material. Prevention will be analysed in terms of how the reliability characteristics of SSCs contribute to frequency of initiating events and the probability of failure of SSCs that fail to perform their functions in response to an initiating event. Mitigation will be analysed in terms of the retention fractions of the radionuclide source inventories within each of barriers to release including fuel particle, graphite matrix, plate-out surfaces, HPB, and reactor building SSCs. The roles that redundancy, diversity, independence, and safety margins play in managing risks of event sequences will be examined in this investigation. Deterministic approaches that are taken to address uncertainties will also be identified.

Meeting Summary

- PRA is a key part to the NGNP design and the RIPB approach
- PRA is critical to the key issues
  - Licensing Basis Event (LBE) selection
  - Source terms
  - Containment functional performance
  - Emergency planning
- We understand that the staff review is underway, NGNP is ready to provide review assistance with additional information, phone calls, meetings, etc., as needed