GT-MHR Source Term Overview

Presented to
Nuclear Regulatory Commission Staff
28 January 2003

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General Atomics

GENERAL ATOMICS

Outline

- Radionuclide Containment System
  - Multiple release barriers
  - Defense-in-depth
- Controlling Radionuclide Transport Phenomena
- Methodology for Deriving Barrier Performance Requirements (e.g., Fuel Product Specification)
- Example Derivation of Fuel Quality Requirements
- Methodology for Identifying Design Data Needs (DDNs) Required to Validate Source Term

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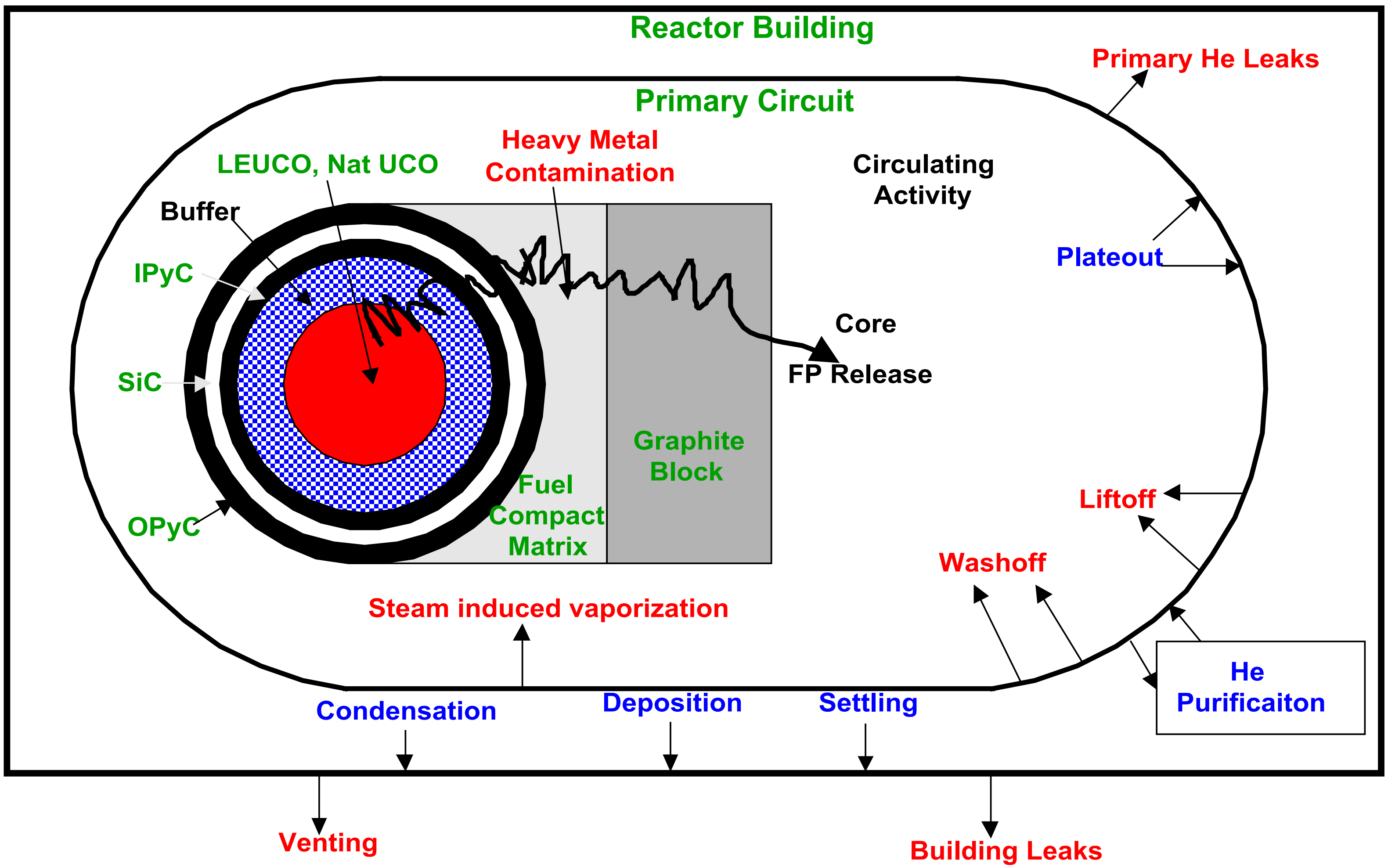
Radionuclide Control Methodology

- Design Selections to Limit Fuel Temperatures
  - Limited core thermal power
  - Low power density
  - Annular core geometry
- Multiple Radionuclide Release Barriers
  - TRISO-coated fuel particles
  - Inherent properties of ceramic core
  - Natural removal mechanisms in vessel & building
- Fuel Product Specifications
  - As-manufactured fuel attributes
  - Allowable heavy-metal contamination
  - Allowable coating defects
- He Purification System
  - Limits circulating noble gas and H-3 activities
  - Limited effect on condensible radionuclides

DOMINANT RADIONUCLIDES IN GT-MHR

Nuclide	Half Life	Primary Impact
I-131	8 Day	Offsite Dose, O&M Doses
Cs-134	2.1Year	O&M Doses, Offsite Dose
Cs-137	30 Year	O&M Doses, Offsite Dose
Ag-110m	250 Day	O&M Doses
Sr-90	29 Year	Offsite Dose
Kr & Xe	--	Normal Gaseous Effluent
H-3	12 Year	Normal Liquid Effluent

GT-MHR
Radionuclide Containment System



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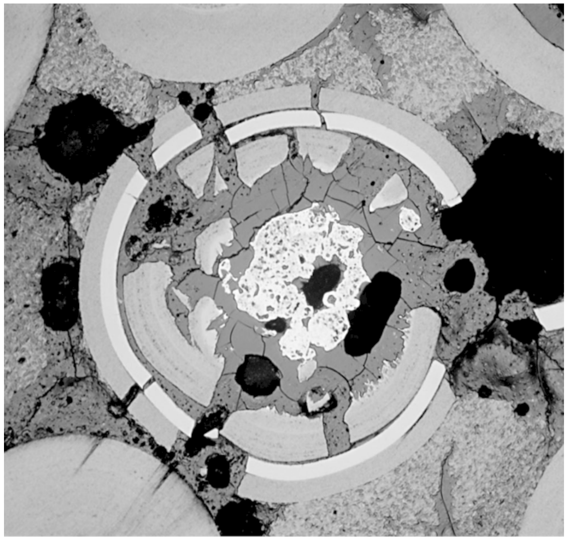
THE COATINGS ON THE FUEL PARTICLES ARE THE MOST IMPORTANT BARRIER

- GT-MHR Design Employs a Multiple-barrier, Radionuclide (RN) Containment System to Meet Radionuclide Control Requirements
  - Fuel kernels
  - Particle coatings
  - Compact matrix/fuel element graphite
  - Primary circuit
  - Reactor building
- Performance Criteria for Each Barrier Derived using a Top-down Allocation Process

Radionuclide Release Barriers
Fuel Kernels



- POTENTIAL RELEASE MECHANISMS
  - Fission recoil
  - Diffusion
  - Hydrolysis (reaction with H_2O)
- CONTROLLING PARAMETERS
  - Fuel temperatures
  - Time
  - H_2O concentration
  - Burnup (metal diffusivities Increase)
- KERNEL RETENTION
  - Fractional gas release function of time/temperature history
  - Increased gas release in case of hydrolysis
  - Partial diffusive release of volatile fission metals
  - Other radionuclides, including actinides, completely retained

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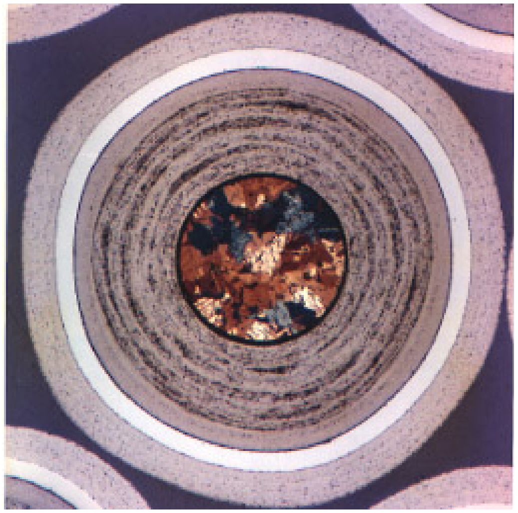
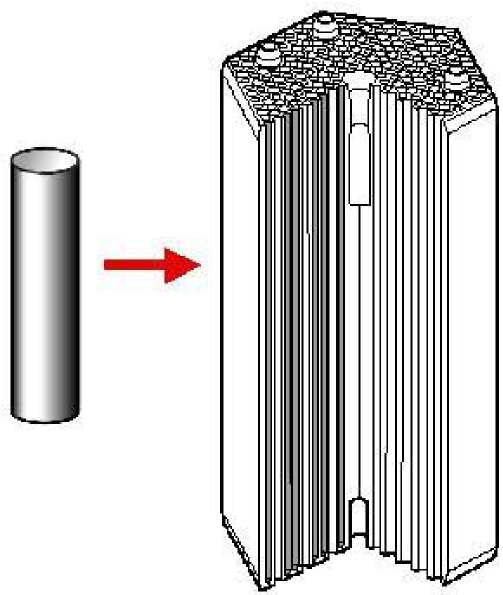
Radionuclide Release Barriers Particle Coatings



- POTENTIAL RELEASE MECHANISMS
  - Diffusion through intact coatings
  - In-service coating failure
  - SiC corrosion by fission products
  - SiC thermal decomposition
- CONTROLLING PARAMETERS
  - Fuel temperatures
  - Time
  - Fast neutron fluence (Increased FP Diffusivities)
- COATING RETENTION
  - Only Ag Released by Diffusion from Intact Particles
  - No Pressure-Induced Failure of Standard Particles
  - SiC Thermochemical failure function of time/temperature
  - Gases Retained by OPyC with Defective/Failed SiC

Radionuclide Release Barriers
Core Matrix/Graphite

- POTENTIAL RELEASE MECHANISMS
  - Diffusion/vaporization
  - Matrix/graphite oxidation
- CONTROLLING PARAMETERS
  - Temperature
  - Time
  - Fast neutron fluence
  - H_2O Concentration



- MATRIX/GRAPHITE RETENTION
  - Cs and Sr partially released at hotter locations
  - Released Cs and Sr partially resorb on cooler graphite
  - Sorbed metals assumed to be released by oxidation

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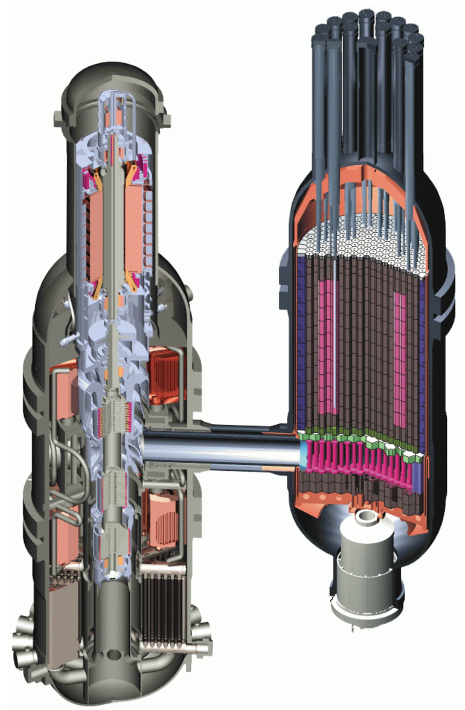
Radionuclide Release Barriers
Primary Circuit



- **POTENTIAL RELEASE MECHANISMS**
  - **Primary coolant leaks**
  - **Liftoff** (mechanical reentrainment)
  - **Steam-Induced vaporization**
  - **Washoff** (removal by liquid H_2O)
- **CONTROLLING PARAMETERS**
  - **Temperatures in primary circuit**
  - **Size/location of coolant leaks**
  - **Particulate matter in primary circuit**
  - **Steam/Liquid H_2O ingress and egress**
- **PRIMARY CIRCUIT RETENTION**
  - **Condensible RNs plate out during normal operation**
  - **Circulating Kr, Xe and H-3 limited by HPS**
  - **Plateout largely retained during rapid blowdowns**
  - **RN holdup due to thermal contraction of gas in vessel**

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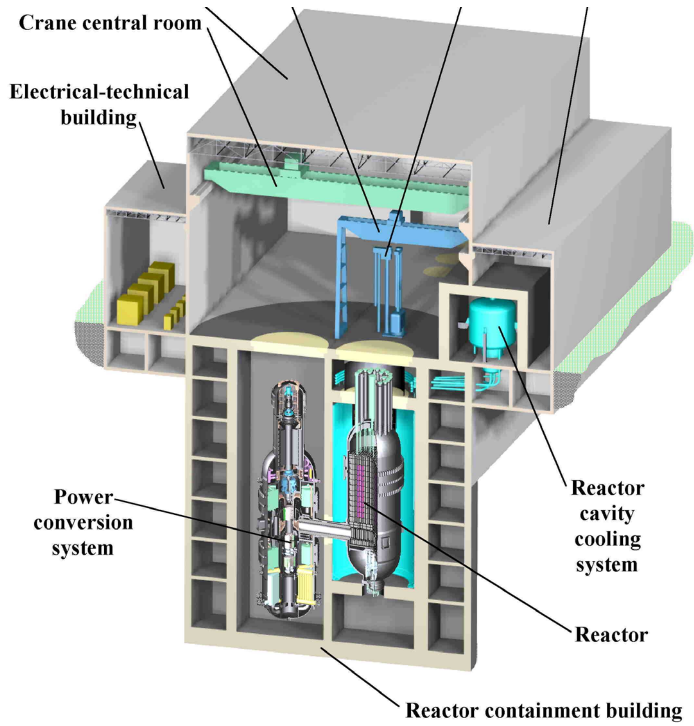
Radionuclide Release Barriers
Reactor Building

- POTENTIAL RELEASE MECHANISMS
  - Venting through louvers
  - Building leakage
- CONTROLLING PARAMETERS
  - Leak path(s) and rates
  - Contaminated steam/liquid H_2O
  - Contaminated particulate matter
  - Temperatures along leak path(s)
- REACTOR BUILDING RETENTION
  - Noble gases decay during holdup
  - Condensible fission products, including I, deposit
  - Contaminated steam condenses
  - Contaminated dust settles out and deposits



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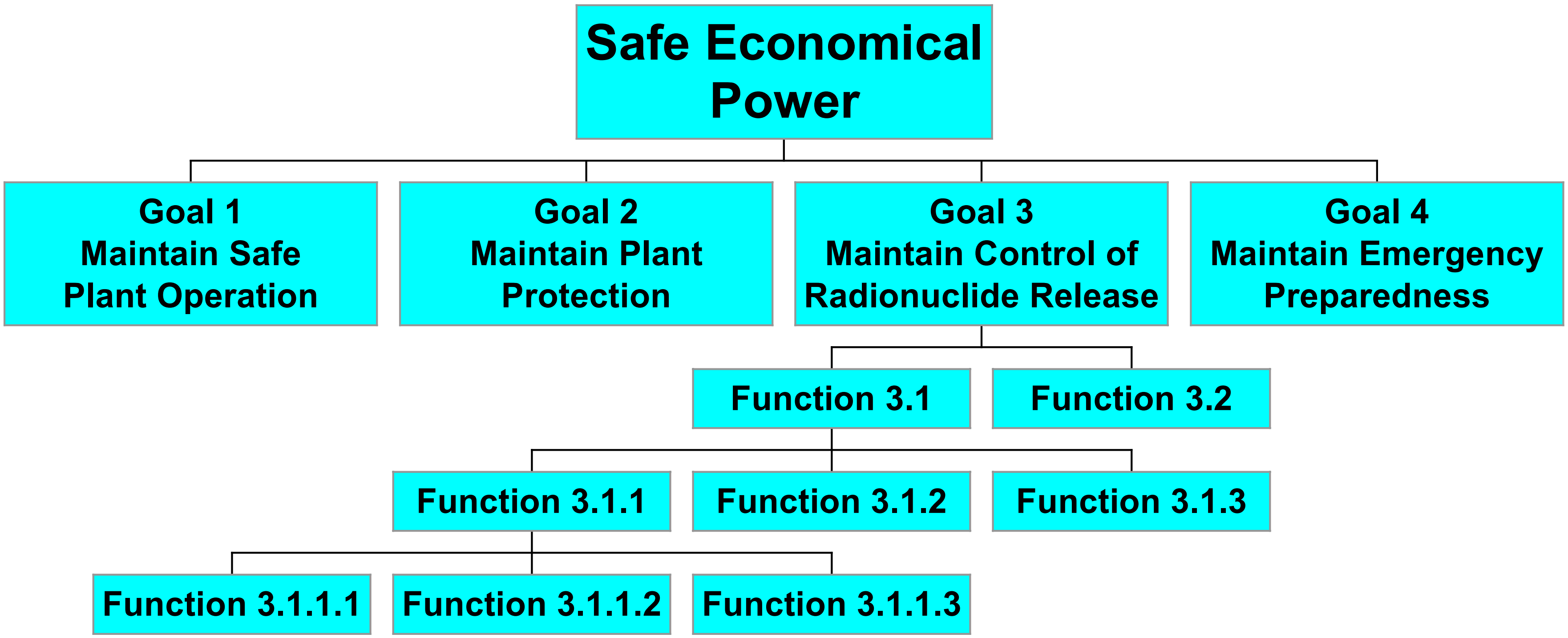
A Top-Down Functional Analysis Used to Develop MHR Design Basis



Requirements Are Specified and Design Selections Made for Each Function; These Requirements and Design Selections Cascade Downward until the Design Basis Is Completely Defined

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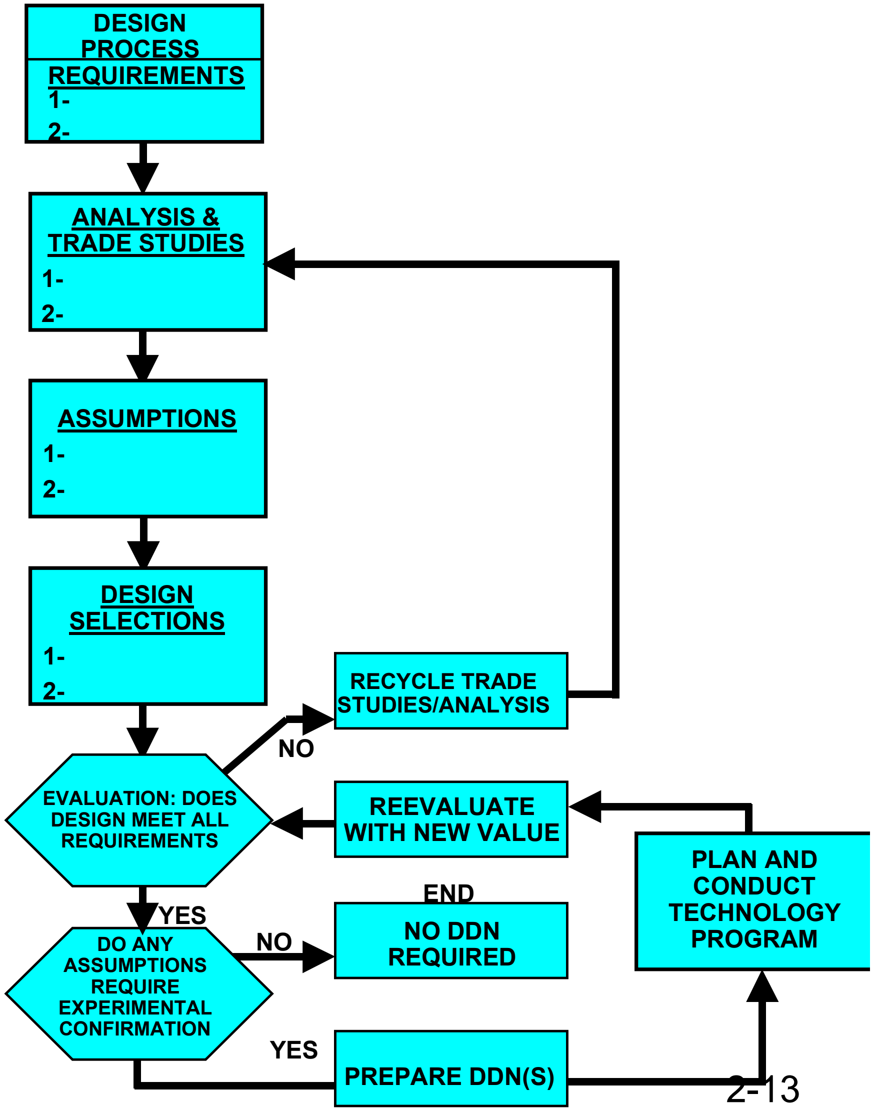
Methodology for Deriving Barrier Performance Requirements



- Requirements Specified to Quantify Each Function
- Analyses & Trade Studies Performed; Assumptions Made as Necessary
- Design Selections Made to Satisfy Requirements
- Certain Assumptions Require Technology Development before Validity Determined
- As Part of the Functional Analysis, Fuel Performance Requirements Are Derived from Top-Level Radionuclide Control Requirements

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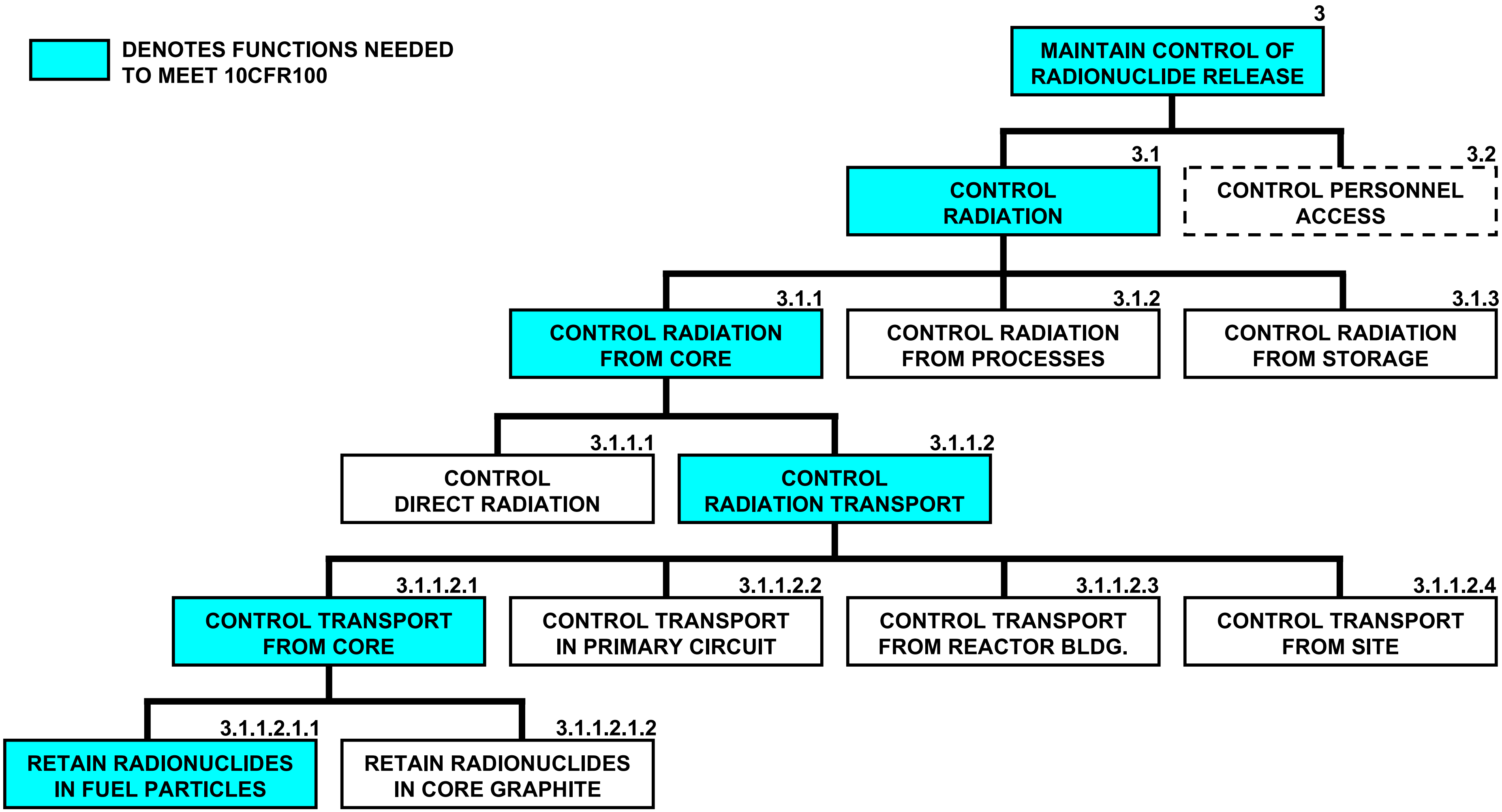
Example Derivation of Fuel Quality Requirements

- A Top-Down Functional Analysis Was Performed for the 350 MW(t) Steam-Cycle MHTGR in 1980s
- This Methodology Provides a Logical Basis for Deriving Fuel Requirements from Top-Level Radionuclide Control Requirements
  - In-service fuel failure limits
  - As-manufactured fuel quality requirements
- Example Derivation of Fuel Quality Requirements for the Steam-Cycle MHTGR Follows
- A Comparable Analysis Needs Be Done for the Direct-Cycle GT-MHR; Similar Results Anticipated

Key Top-level Radionuclide Control Requirements for Steam-Cycle MHTGR

- TOP-LEVEL REGULATORY CRITERIA
  - 10CFR50 App I and 40 CFR190 limits for radionuclides in effluents
  - 10CFR20 occupational doses
  - 10CFR100 offsite accident dose guidelines
  - EPA-520 protective action guides (PAG) for emergency planning
  - NRC safety goal risk limits
- UTILITY/USER REQUIREMENTS
  - Top-level regulatory criteria (including lower level PAG dose limits) without shelter or evacuation
  - Worker doses <10%of 10CFR20

MHTGR MEETS 10CFR100 BY RADIONUCLIDE RETENTION IN FUEL



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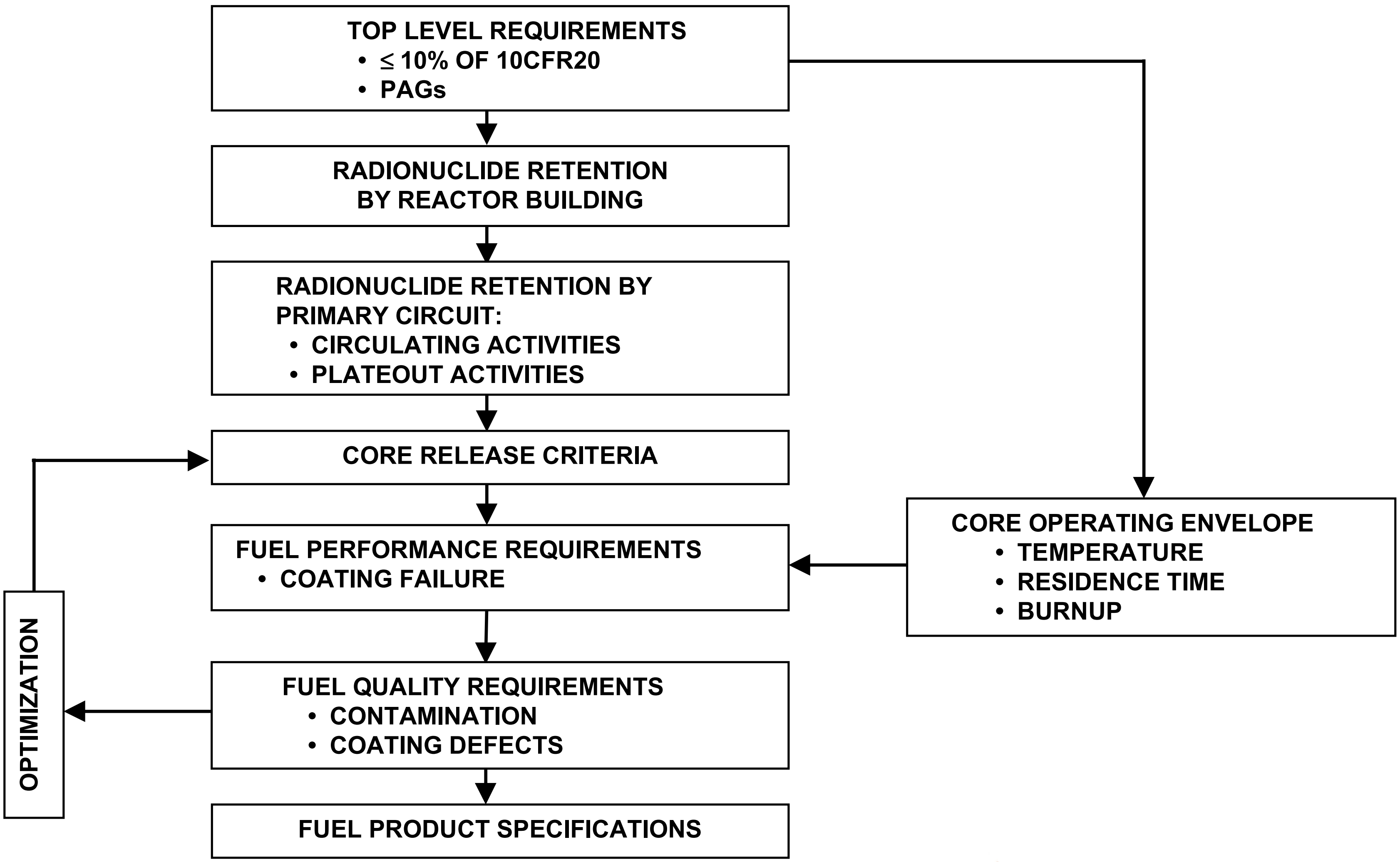
Logic for Deriving Key Fuel Product Specifications



Key Events in Deriving Fuel Quality Criteria for Steam-Cycle MHTGR

- Normal Plant Operation
  - Steady-state full-power operation
  - Normal operating transients
- Postulated Accidents
  - Primary coolant leak (rapid depressurization)
  - Large H_2O ingress plus pressure relief
  - Depressurized core conduction cooldown

Quantitative Example for Primary Coolant Leak Accident Follows; Most Constraining Event for Steam-Cycle MHTGR for Establishing As-Manufactured Fuel Quality Requirements

Example Derivation of Fuel Quality Allocation

- PART 1: DURING PRIMARY COOLANT LEAK ACCIDENT
  - Use offsite dose limit of 5 Rem thyroid from PAG
  - Event Summary: rapid primary coolant leak with forced cooling
  - Use Reg. Guide weather/breathing rates:
    5 Rem → 4 Ci iodine-131 releasable from reactor building
  - Allocate no retention in reactor building
  - Assume conservatively that 5%of normal operation "Design" level plateout in primary circuit is released due to liftoff:
  - 4 Ci allowable I-131 release → 80 Ci "Design" level plateout in primary circuit during normal operation

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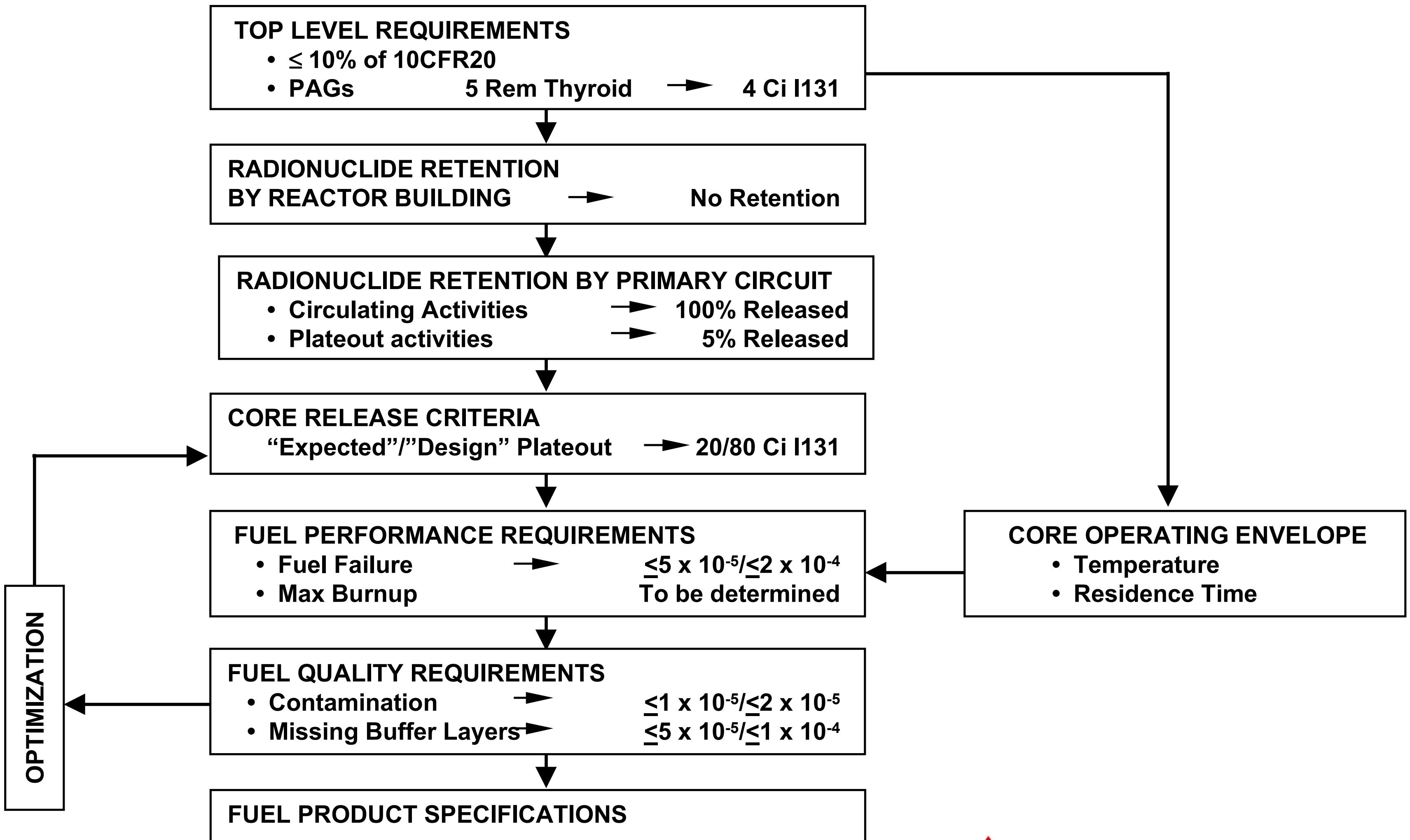
Example Derivation of Fuel Quality Allocation - Cont.

- **PART 2: DURING NORMAL OPERATION**
  - Assume that "Expected" plateout is factor of 4 less: 80 Ci design plateout → 20 Ci "Expected" plateout
  - Assume no holdup of iodine in graphite
  - Assume design methods for predicting gas release accurate to within 4x at 95%confidence ($R_{95\%}/R_{50\%} \leq 4$)
  - Allocate equal contributions from exposed kernels and contamination: 20 Ci → 10 Ci from each
  - Assume 0.1 fractional release from contamination and 10 million Ci iodine core inventory: 10 Ci → 10/10 million/ 0.1 = 1×10^{-5} allowable fraction of contamination
  - Assume 0.02 fractional release from exposed kernels: 10 Ci → 10/10 million/.02 = 5×10^{-5} fraction of exposed kernels

Example Derivation of Fuel Quality Allocation - Cont.

- PART 3: QUALITY AFTER MANUFACTURE
  - Assume design methods for predicting fuel failure are accurate to within 4x at 95%confidence ($F_{95\%}/F_{50\%} \leq 4$)
  - Assume that particles with missing buffers are dominant contributor to exposed kernels: 5×10^{-5} fraction of exposed kernel ⟶ 5×10^{-5} allowable fraction of missing buffers from manufacturer

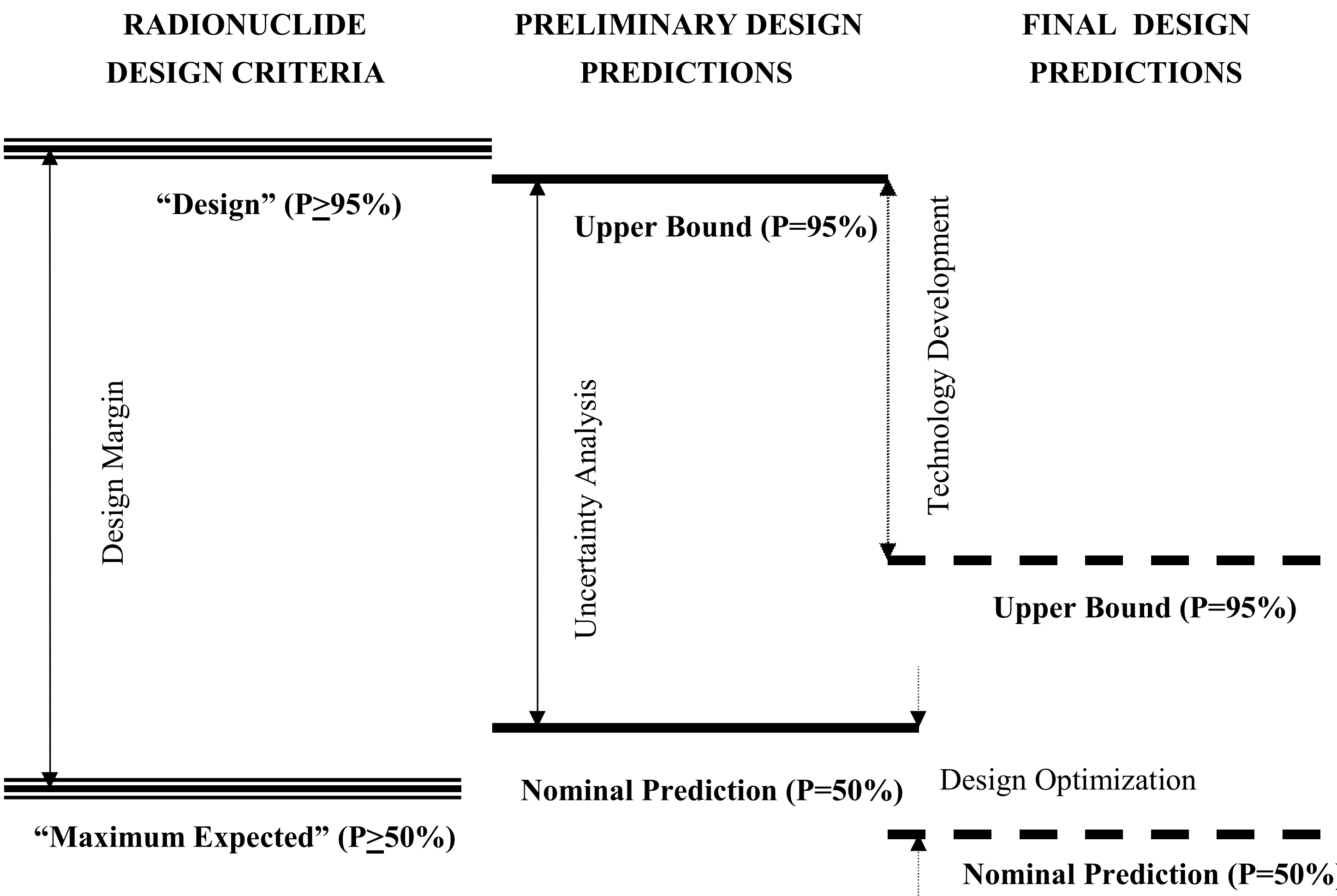
Allocated Barrier Performance Criteria for Rapid Depressurization Event



Functional Analysis Provides Design Basis for Radionuclide Containment System

- Barrier Performance Requirements Derived
  - Retention by reactor building
  - Retention by primary circuit
  - Retention by core (“RN Design Criteria”)
- Design Margins for each Barrier Quantified
- Predictive Accuracy Goals for Radionuclide Transport Methods Established
- Fuel Design Requirements
  - In-service fuel performance requirements
  - As-manufactured fuel quality requirements
- Design Data Needs to Validate RN Containment System Performance Identified

Design Margins Are Explicitly Included in Radionuclide Containment System



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Summary Basis for Key Steam-Cycle MHTGR Fuel Quality Requirements

- U contamination fraction allocated from PAG thyroid dose limit during rapid depressurization
- Missing buffer fraction allocated from exposed kernel limit derived from PAG thyroid dose limit during rapid depressurization
- SiC defect fraction allocated from allowable core Cs release derived from occupational exposure limit

Fuel Requirements May Be Optimized as Design Evolves

- Initial Functional Analysis ("Back-of-the-Envelope") Provides Logical Point of Departure at Beginning of Preliminary Design:
  - To establish provisional fuel requirements
  - To identify Design Data Needs and attendant technology development programs
- These Fuel Provisional Requirements Must Be Confirmed by Detailed Design Evaluation and Safety Analyses
  - PRA to confirm dominant events identified
  - Detailed deterministic consequence analyses
- Design Process Is Iterative: some Re-allocation of Barrier Performance Requirements Should Be Anticipated
- Nevertheless, Detailed Consequence Analysis for Steam-Cycle MHTGR largely Validated Provisional Fuel Requirements

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GT-MHR Fuel Design Basis

- GT-MHR Fuel Requirements Are Comparable to Steam-Cycle MHTGR for Preliminary Design
  - Identical radionuclide control requirements
  - Modest impact of plant design differences (~2x)
- MHTGR Fuel Requirements Adopted for GT-MHR
  - Exception: missing buffer fraction reduced 5x
- DDNs Revised to Reflect GT-MHR Design
  - Priority of H_2O ingress DDNs reduced
  - Higher temperatures, etc., in core and primary circuit
- Fuel Requirements and DDNs Will Be Revisited during GT-MHR Preliminary Design

Summary of GT-MHR Fuel Requirements

FUEL ATTRIBUTE	P $\geq$ 50%	P $\geq$ 95%
<u>As-Manufactured Fuel Quality</u>		
Heavy metal contamination fraction	$\leq 1.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-5}$
Missing buffer fraction	$\leq 1.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-5}$
SiC coating defection fraction	$\leq 5.0 \times 10^{-5}$	$\leq 1.0 \times 10^{-4}$
<u>In-Service Performance</u>		
Failure fraction (normal operation)	$\leq 5.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-4}$
Incremental failure during accident	$\leq 1.5 \times 10^{-4}$	$\leq 6.0 \times 10^{-4}$

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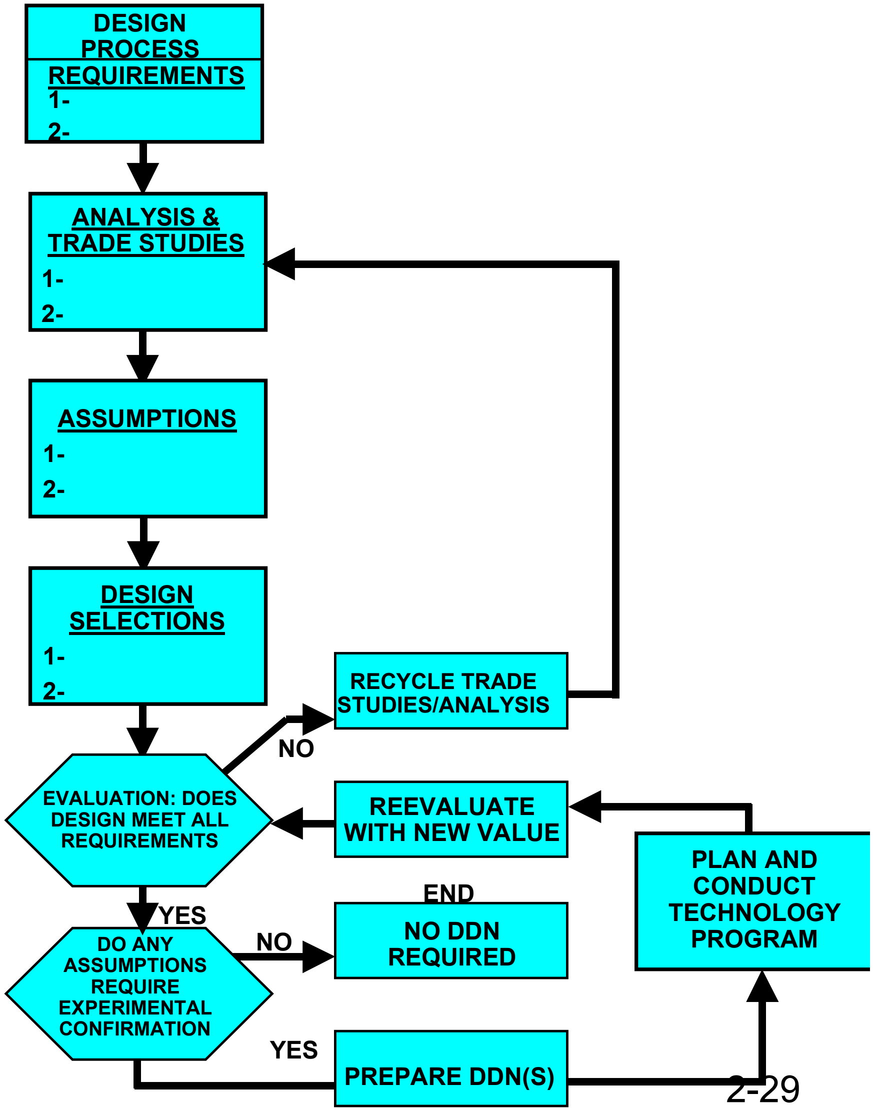
Methodology for Identifying Design Data Needs



- DDNs Are Identified as Part of the Functional Analysis Process
- Assumptions Are Made when Making Design Selections to Satisfy Requirements
- Certain Assumptions Require Technology Development before their Validity Can Be Determined

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GT-MHR Design Data Needs

- A Preliminary Set of Design Data Needs Have Been Identified for the 600 Mw(t) GT-MHR, including:
  - Fuel process development DDNs
  - Fuel materials development DDNs
  - Fission product transport DDNs
- The Fuel/Fission Product DDNs Will Be Summarized during the Remainder of the Current Meeting
- Only the ***High*** Priority Fission Product Transport DDNs Will Be Presented
- As the GT-MHR Design Matures, Additional DDNs May Be Identified, and the Existing DDNs May Be Modified
- Major Additions And/or Changes Are Not Anticipated

GT-MHR Design Data Needs
Fuel Process Development

DDN No.	DDN Title	Priority
C.07.01.01	UCO Kernel Process Development	Medium
C.07.01.02	**Fuel Particle Coating Process Development**	**High**
C.07.01.03	**Fuel Compact Fabrication Process**	**High**
C.07.01.04	**Quality Control Test Techniques Development**	**High**
C.07.01.05	Fuel Product Recovery Development	Medium

GT-MHR Design Data Needs
Fuel Materials Development

DDN No.	DDN Title	Priority
C.07.02.01	**Coating Material Property Data**	**High**
C.07.02.02	Defective Particle Performance Data	Medium
C.07.02.03	Thermochemical Performance Data for Fuel	Medium
C.07.02.04	Fuel Compact Thermophysical Properties	Low
C.07.02.05	**Normal Operation Fuel Performance Validation Data**	**High**
C.07.02.06	**Accident Fuel Performance Validation Data**	**High**
C.07.02.07	**Fuel Proof Test**	**High**

GT-MHR Design Data Needs Radionuclide Transport

DDN No.	DDN Title	Priority
C.07.03.01	**Fission Gas Release from Core Materials**	**High**
C.07.03.02	Fission Metal Diffusivities in Fuel Kernels	Medium
C.07.03.03	**Fission Product Diffusivities in Particle Coatings**	**High**
C.07.03.04	**Fission Product Diffusivities/Sorptivities in Graphite**	**High**
C.07.03.05	Tritium Permeation in Heat Exchanger Tubes	Low
C.07.03.06	Tritium Transport in Core Materials	Low
C.07.03.07	**RN Deposition Characteristics for Structural Materials**	**High**
C.07.03.08	Decontamination Protocols for Turbine Alloys	Medium
C.07.03.09	**RN Reentrainment Characteristics for Dry Depressurization**	**High**

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GT-MHR Design Data Needs
Rn Transport - Continued

DDN No.	DDN Title	Priority
C.07.03.10	RN Reentrainment Characteristics for Wet Depressurization	Low
C.07.03.11	Characterization of the Effects of Dust on RN Transport	Medium
C.07.03.12	**Fission Product Transport in Vented Low-Pressure Containment**	**High**
C.07.03.13	Decontamination Efficiency of Depressurization Train Filter	Medium
C.07.03.14	**Fission Gas Release Validation Data**	**High**
C.07.03.15	**Fission Metal Release Validation Data**	**High**
C.07.03.16	**Plateout Distribution Validation Data**	**High**
C.07.03.17	**Radionuclide "Liftoff" Validation Data**	**High**
C.07.03.18	Radionuclide "Washoff" Validation Data	Medium

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Conclusions

- GT-MHR Uses Multiple-Barrier Radionuclide Containment System to Meet Radionuclide Control Requirements
- Fuel Particle Coatings Are the Most Important Barrier
  - Coatings alone are sufficient to meet 10CFR100 limits
  - Additional barriers needed to meet User requirements (e.g., PAGs at EAB)
- Certain Assumptions Made in the Assessment of the RN Containment System Must Be Validated
  - Fabrication of high-quality fuel meeting specifications
  - Coating integrity during normal operation and LBEs
  - Accuracy of codes for modeling release barriers

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Outcome Objectives

- NRC concurs with adequacy and logic of approach for defining fuel requirements
  - In-service fuel failure limits
  - As-manufactured fuel quality
- NRC concurs with adequacy and logic of approach for identifying DDNs relevant to validating source term

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