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High-Temperature Gas-Cooled Reactor Safety Research Plan

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Outline

- NRC HTGR Safety Research Plan Goals
- HTGR Safety Research Plan Development Process
- Major Safety Research Areas for Infrastructure Development
- Discussion of Major Safety Research Areas

HTGR Safety Research Plan Goal:
An Integrated License Application Review Infrastructure

Examples of Infrastructure Components:

- Experimental Data and Information
- Independent Analytical Tools and Analysis Methods
- Endorsed Codes & Standards and Safety Review Plans/Procedures
- Staff Expertise and Skills
- Specialized Expert Contractor Support

Examples of Infrastructure Technical Areas:

- High Temperature Materials and Graphite Behavior
- HTGR Fuels Performance
- Nuclear, Thermal-Fluid and Containment Analysis
- Accident Scenarios
- Radiation Protection, Fuel Cycle Safety
- Probabilistic Risk Assessment
- Instrumentation and Controls, Human Performance

HTGR Safety Research Plan Development Process

Phase 1 Identify Infrastructure Needs:

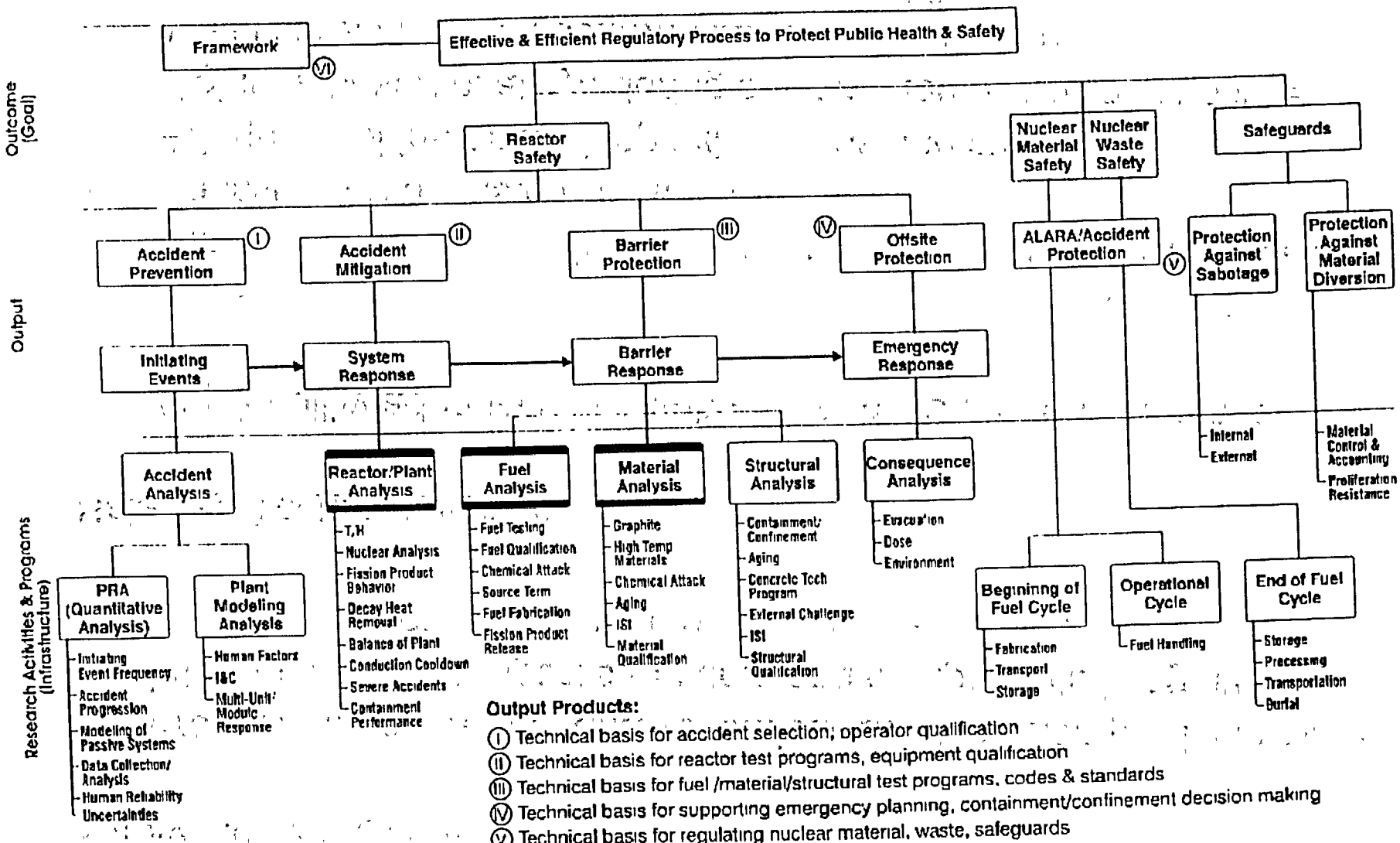
- Workshops on Adv Reactor Safety and Research Issues
- Pre-Application Reviews (e.g., MHTGR, PBMR, GT-MHR)
- Domestic and International Exchange of Research and Experience
- Training and Seminars
- Stakeholder Interactions

Phase 2 Identify Significant Technical Issues and User Needs

- Prioritize and Streamline Research Needs
- Utilize PIRT Process
- Interact with Stakeholders
- Establish Working Groups

Phase 3 Integrate, Implement and Maintain

Advanced Reactor Research Infrastructure
Key Research Areas and Areas for Examination



Output Products:

(I) Technical basis for accident selection; operator qualification
(II) Technical basis for reactor test programs, equipment qualification
(III) Technical basis for fuel /material/structural test programs, codes & standards
(IV) Technical basis for supporting emergency planning, containment/confinement decision making
(V) Technical basis for regulating nuclear material, waste, safeguards
(VI) Technical basis for risk-informed, performance based regulations

Fig 1. Key research areas for examination.

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High-Temperature Materials [HTR-M]

Safety-Related Issues:

- Pressure boundary Integrity (chemical attack, fission product release)
- Internal metallic support structures and components integrity
- Internal composite (core) support structure integrity

Selected Technical Issues:

- Applicability/adequacy of databases and ASME code cases to HTGRs
- Adverse impacts of coolant impurities and concentrating in crevices
- Data bases for calculating fatigue, creep, creep-fatigue interactions
- Sensitization of austenitic steels
- Adequacy of in-service inspection plans and methods
- Aging behavior of alloys during elevated temperature exposures
- Metal carburization, decarburization and oxidation
- Vessel/pipe and component failure probabilities for PRAs

High-Temperature Materials (Cont.) [HTR-M]

Examples of Planned Research:

- Creep-fatigue and stress corrosion cracking data
- Environmental characterizations
- Aging and embrittlement
- Sensitization
- Carburization, de-carburization and oxidation
- In-service inspection plans and methods, continuous monitoring
- Information, data from previous international research and experience

Nuclear-Grade Graphite [HTR-M]

Safety-Related Issues:

- Functionality of active shutdown systems
- Core coolant bypass leakage
- Integrity of core structures and core support structures
- Maximum fuel temperatures during normal operation and accidents
- Contribution of graphite dust to accident source term
- Potential reactivity events

Nuclear-Grade Graphite (Cont.) [HTR-M]

Selected Technical Issues:

- Effect of new coke sources and fabrication process on properties
- Structural qualification:
  - Unirradiated properties data
  - Irradiation effects (e.g., growth/shrinkage, strength, conductivity)
  - Irradiation behavior prediction models
  - Structural analysis methods and acceptance criteria
  - PBMR side reflector "exhaustion" and need for replacement
- Oxidation during loss of pressure boundary events (e.g., air, water)
- In-service inspection plans and methods

Nuclear-Grade Graphite (Cont.) [HTR-M]

Examples of Planned Research:

- Structural design codes and structural analysis methods
- Properties versus irradiation, temperature, etc. for selected graphites
- Oxidation rate and effects on physical characteristics, strength
- Dust generation rate, dust heat generation rate and dust deposition
- Variability of properties across thick versus thin-walled components
- Consensus standards for material, design and fabrication
- In-service inspection and surveillance methods
- Information and data from international research and experience

Fuel Performance [HTR-F]

Safety-Related Issues:

- TRISO coated fuel particle (CFP) behavior:
  - CFP defects from manufacture
  - CFP failures during normal operation
  - CFP failures during postulated accidents
  - Fission product release (gases and solids)
- Accident source term
- Release of ^{110m}Ag from fuel

Fuel Performance (Cont.) [HTR-F]

Selected Technical Issues:

- Applicability of earlier fuel performance data to new fuels and plants
- Q/A used for earlier fuel performance and qualification test programs
- Completeness of earlier fuel performance tests (conditions, margins)
- Prompt supercritical reactivity pulse accident fuel behavior and limits
- Chemical attack accident fuel performance and limits
- Design and licensing-basis events for the new HTGR plant designs
- Fission product release data for mechanistic source term calculation
- Effects of accelerated versus real-time irradiation testing
- Conservatism of traditional time-temperature accident test profiles
- Key fabrication process variables/values for fuel quality/performance
- Product characteristics and statistical methods for fuel fabrication QA
- Availability and reliability of fuel performance models and methods
- Availability of required test data for fuel performance models
- Ability to predict maximum local fuel operating/accident temperatures

Fuel Performance (Cont.) [HTR-F]

Examples of Planned Research:

- Fuel irradiation test data for PBMR and GT-MHR production fuel
- Fuel irradiation/accident tests beyond the licensing basis (margins)
  - max operating temperature, max burnup
  - severe accidents: reactivity insertion, chemical attack, >1600°C
  - fission product release and CFP failures during testing
- Conservatism of traditional fuel qualification test conditions:
  - Accelerated versus real time irradiation
  - "Ramp and hold" versus actual temperature-time accident profile
- Knowledge of key fabrication process variables/limits for fuel quality and performance
- Fuel performance models, methods, materials property, irradiation data
- Information, data from previous international research and experience

Nuclear Analysis [HTR-N]

Reactor Safety-Related Issues:

- Passive shutdown during heat-up events
- Reactivity addition and prompt supercritical reactivity pulse events
- Transient and accident shutdown margins
- Global power distributions; localized power peaking
- Pebble burn-up measurement and discharge criteria
- PBMR side reflector degradation, loss of function, due to fast fluence

Nuclear Analysis (Cont.) [HTR-N]

Selected Technical Issues:

- Nuclear data libraries for core physics analysis
- Neutronic and decay heat analysis modeling of annular graphite cores
- For PBMRs: modeling multi-pass refueling, statistical pebble packing, varying burnups, fuel pebble and graphite pebble mixing
- For GT-MHRs: modeling of burnable poisons, fissile and fertile CFPs
- Reactivity effects of moisture ingress, control rod ejection, shutdown system withdrawal and seismic pebble-bed compaction
- Analysis of mis-loading events, anomalous pebble packing/clustering
- Local power density contributions to operating local hot spots and decay-power hot spots
- Effect of pebble statistical burnup distribution on pebble fission power
- Prototype testing (what can and can't be done)

Nuclear Analysis (Cont.) [HTR-N]

Examples of Planned Research:

- Create and verify state-of-the-art nuclear data libraries for reactor safety (and materials safety) analyses
- Become familiar with pre-applicant 's codes and methods
- Conduct exploratory studies with available independent codes
- Establish spacial kinetics models for HTGRs
- Review/use databases to validate/test reactor neutronics models
- Review/use databases to validate depletion and decay heat analyses

Thermal-Fluid Dynamic Analysis [HTR-TBD]

Safety-Related Issues:

- SSC (e.g., CFPs, RPV, structural concrete) high temperatures and failure during normal operation and postulated accidents
- SSC (e.g, fuel, graphite core structures) chemical attack for loss of RCPB events

Thermal-Fluid Dynamic Analysis (Cont.) [HTR-TBD]

Selected Technical Issues:

- Design and licensing-basis events for the new HTGR plant designs
- Selecting optimal suite of codes for analyzing spectrum of DBEs/LBEs
- Identifying key model issues:
  - temperature/fluence dependent graphite properties
  - pebble-pebble statistical geometry
  - He mixing at core outlet
  - predicting local (pebble) hot spots (e.g., AVR melt-wire tests)
  - coupling to reactor kinetics (e.g., seismic compaction, water ingress
  - compressible flow modeling
  - reactor cavity cooling: heat transfer and temperature distributions
  - experimental data for code validation
  - prototype testing (what can and can't be done)

Thermal-Fluid Dynamic Analysis (Cont.) [HTR-TBD]

Examples of Planned Research:

- Become familiar with applicant's codes and methods
- Use NRC's past HTGR codes to help establish needed analysis capabilities within the current NRC code suite
- Conduct exploratory and sensitivity studies with available codes
- Use CFD as higher-order method to check individual models in analysis code suite
- Participate in cooperative code-to-data and code-to-code bench marking activities
- Assess issues and uncertainties associated with limited applicable test data and scaling issues

Severe Accident and Source Term Analysis [HTR-TBD]

Accident Source Term Issues:

- Elevated CFP failure rate (fission product release) events, and/or
- Fission product transport mechanisms, and
- Containment (or confinement) bypass or failure

Selected Severe Accident Code Technical/Modeling Issues and Research:

- "Severe accident" scenarios
- Fuel fission product release, transport mechanisms and timing
- Effects of oxidation on CFP failures and fission product transport
- Contribution of graphite dust to source term
- Deposition of fission products in the reactor vessel and containment
- Material properties for Graphite

Examples of Planned Research:

- Revise accident progression codes to address model issues
- Assess code against Experimental data and other codes

New Generic NRC Regulations Framework for Advanced Reactors [HTR-L]

Background and Issues:

- Current NRC regulations are based on current generation LWRs with limited application to HTGRs
- New NRC regulations framework will have a more rational structure, utilize PRA insights and apply deterministic and probabilistic methods
- New framework will need to apply to advanced LWRs and non-LWRs
- New framework will need to be supported by an infrastructure of regulatory guidance, inspection guidance, staff review plans, etc.
- New regulations framework will start with a "fresh sheet of paper"

New Generic NRC Regulations Framework (Cont.) [HTR-L]

Examples of Planned Research:

- Establish a structured approach for developing the framework and infrastructure of guidance
- Develop the global architecture for the new regulations framework and infrastructure of guidance, and the process for formulating the new regulations, the use of defense in depth, the handling uncertainties, etc.
- Systematically identify the supporting infrastructure needed by staff for licensing reviews
- Develop the generically applicable regulations
- Develop the design-specific regulations and regulatory guides that account for design-specific aspects of the generically applicable regulations

Probabilistic Risk Assessment

HTGR Risk Assessment Issues:

- Probability & consequences insights are central to proposed licensing approaches
- Very Limited PRA experience (Levels 1, 2 or 3)

Selected Technical Issues:

- Lack of risk metrics (core damage, LERF not `applicable)
- Lack of methods, data and tools for modeling HTGRs
- Little experience for low power and shutdown conditions

Probabilistic Risk Assessment (Cont.)

Examples of Planned Research:

- Develop risk metrics
- Identify and quantify initiating events
- Determine accident progression and containment performance
- Identify passive system failure modes and develop models; develop digital I&C models; establish uncertainties
- Collect and analyze applicable SSC data; determine uncertainties
- Conduct human reliability analysis for long-term operator actions
- Conduct independent PRA (PBMR or GT-MHR) designs;other states
- Conduct PRA for multiple modules
- Develop staff PRA review guidance

Structural Analysis

Structural Analysis Issues:

- Maintain function of safety-related structures, systems and components
- Ensure containment/confinement resistance to external challenges
- Ensure confinement of radioactive materials during accidents

Selected Technical Issues and Planned Research:

- Assess applicability of industry codes/standards to HTGR safety-related design/construction features; compare foreign to U.S. codes and stds
- Assess and include effects of HTGR fabrication, construction, operating environment and load history on construction and ISI code criteria
- Assess and include effects of long term high temperatures on concrete design and fabrication practices and associated code criteria

Human Factors

Safety-Related Issues:

- Role and reliability of human actions:
  - Operations, accident initiation/prevention
  - Maintenance activities
  - Accident mitigation
- Staffing requirements for multi-module control room

Examples of Planned Research:

- Obtain insights on the impact of human performance on HTGRs
- Evaluate automation & concept of operations on human performance
- Review applicability of existing requirements
- Develop/adapt function and task analysis tools and techniques
- Evaluate staffing for off-normal conditions
- Evaluate training and qualifications for operators
- Assess human system interface issues

Instrumentation and Control

Safety-Related Issues:

- Extensive use of automation for process controls
- Control room designs for controlling multiple modules
- Failures must not prevent operators or automated systems from performing their intended safety function

Selected Technical Issues:

- New technologies: smart transmitters, wireless communications, advanced predictive maintenance, diagnostics and on-line monitoring methods and enhanced cyber security

Instrumentation and Control (Cont.)

Examples of Planned Research:

- Assess lesson learned from development, current practices and operating experiences for ABWR and N4 control systems
- Develop failure models for new I&C systems to assess potential safety issues and integration into plant PRA models
- Use of I&C in multi-module HTGRs
- Analyze potential issues/requirements for HTGR instruments (e.g., high temperature applications)

Material Accountability and Control

Safeguards-Related Issue:

- Potential for diversion of PBMR fresh or irradiated fuel pebbles

Selected Technical Issue:

- Tracking identical pebbles without unique identifiers

Examples of Planned Research:

- Review industrial methods and literature for state-of-the-art tracking methods and capabilities

Radiation Protection

Personnel Exposure (ALARA) Issues:

- Maintenance of power conversion system equipment with ^{110m}Ag surface contamination; streaming

Technical Issues:

- Potential streaming paths due to side reflector graphite block (shielding) distortion over time
- Transport of ^{110m}Ag from fuel and plate-out on equipment surfaces

Examples of Planned Research:

- Evaluate extent of ^{110m}Ag radiation hazard
- Evaluate plans for controlling personnel exposures
- Evaluate potential streaming and other HTGR-unique hazards

Transportation

Transportation Issue:

- Adequacy of existing casks to HTGR fuel designs

Technical Issues

- Geometry and physical properties of ceramic fuel designs

Example of Planned Research:

- Assess applicability of analyses supporting existing cask regulations; perform new analysis as needed