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Safety Analysis of U.S. Research Reactors

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Introduction (1/2)

- This presentation will focus on the following areas of safety analysis of research reactors in the U.S.
  - Reactor characteristics
  - Accident analysis
  - Technical specifications
- There are many other important topics included in a complete safety analysis

Introduction (2/2)

Safety Analysis Documents (1/2)

- Final Safety Analysis Report (FSAR) prepared by the operating organization
- Technical Specifications (TS) are limits on operation of the reactor based on the analysis in the FSAR
- The FSAR may reference technical reports prepared by vendors, the regulatory body, or other operating organizations

Safety Analysis Documents (2/2)

- The operating organization prepares other documents that support the FSAR:
  - Emergency Plan
  - Security Plan
  - Operator Training and Requalification Plan
  - Quality Assurance Plan
  - Environmental Report
  - Startup Plan

Final Safety Analysis Report (1/2)

- Provides technical information and analyses related to the facility site, design, operation, accidents, radiological impact, and financial qualifications
- NUREG-1537, “Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors: Format and Content”

Final Safety Analysis Report (2/2)

- Purpose of the FSAR
  - Show that the reactor is designed to operate safely
  - Show that accidents will not cause undue risk to people or the environment
  - Provide the basis for the TS
  - Explain to the regulator and the public why the reactor is safe

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Reactor Characteristics (1/2)

- Reactor characteristics are the design features and operating parameters of the reactor
- Reactor characteristics should be chosen so the reactor can be operated and shut down safely under all conditions

Reactor Characteristics (2/2)

- Reactor characteristics are the input to the accident analyses
- Many reactor characteristics are required by the TS
  - Safety Limits
  - Limiting Safety System Settings
  - Limiting Conditions for Operation
  - Design Features

Reactor Fuel (1/2)

- Chemical composition, enrichment, uranium loading
- Description of the design
- Material and structural information
- Material parameters that could affect fuel integrity
- Physical properties

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Reactor Fuel (2/2)

- Any special features for pulse operation
- History of the fuel type and fuel development program
- Effects of operation in the reactor

Reactivity Control Systems (1/1)

- Number, types, and locations of rods
- Structural and geometric description
- Reactivity worth and reactivity rates
- Design of supports and drive mechanisms
- Control circuits and interlocks
- Effects of operation in the reactor

Core Support Structure (1/1)

- Design features to support all loads
- Structural and geometric description
- Construction materials
- Design features for positioning fuel, control rods, and other systems
- Design features for movable core support structures
- Effects of operation in the reactor

Nuclear Design (1/4)

- Normal Operating Conditions
  - Number, types, and locations of all core components
  - Reactivity worths of core components
  - Description of planned core configurations
  - Reactor operating characteristics
  - Changes in reactivity with fuel burnup

Nuclear Design (2/4)

- Normal Operating Conditions
  - Reactor kinetic behavior
  - Reactor criticality physics
  - Core reactivity

Nuclear Design (3/4)

- Reactor Core Physics Parameters
  - Neutron lifetime and delayed neutron fraction
  - Coefficients of reactivity (must be negative)
    - fuel temperature
    - moderator temperature
    - voids
  - Axial and radial neutron flux distributions

Nuclear Design (4/4)

- Operating Limits
  - Limiting core configuration
  - Excess reactivity
  - Shutdown margin

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Thermal-Hydraulic Design (1/3)

- Coolant Hydraulic Characteristics
  - Flow rates
  - System pressures
  - Pressure changes at coolant channel entrances and exits
  - Frictional forces and buoyant forces
  - Change from forced-flow to natural convection

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Thermal-Hydraulic Design (2/3)

- Thermal power distribution in the fuel
- Power peaking factors
- Heat flux out of the fuel
- Special conditions for pulse operation of the reactor

Thermal-Hydraulic Design (3/3)

- Heat transfer methods
- Heat Transfer Limits
  - Onset of nucleate boiling
  - Departure from nucleate boiling
  - Onset of flow instability
  - Onset of significant voiding
  - Critical heat flux

Overview of Accident Analysis (1/2)

- The accident analysis is an analysis of reactor accidents to show that the reactor characteristics and TS will protect the fuel from damage
- The accident analysis is an analysis of accident consequences to show that the reactor characteristics and TS will protect reactor personnel and the public from radiation

Overview of Accident Analysis (2/2)

- The accident analysis shall contain acceptance criteria
  - No fuel damage
  - No radiological consequences that exceed the regulatory requirements
- The accident analysis shall demonstrate that the acceptance criteria are met

Accident Analysis Method (1/10)

- State the initial conditions of the reactor
  - Initial conditions should be conservative
  - Initial conditions should be requirements in the TS
  - Discuss why the initial conditions are correct and conservative for the accident

Accident Analysis Method (2/10)

- Identify the cause of the accident
  - equipment malfunction
  - operator error
  - natural event, such as an earthquake or flood
  - intentional damage to the reactor
  - The cause of the accident should be a single failure

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Accident Analysis Method (3/10)

- List the sequence of events
- Discuss equipment or systems that function or malfunction
  - the systems that function should be required in the TS
- Discuss actions performed by the reactor operator and other personnel
  - the actions should be specified in written procedures

Accident Analysis Method (4/10)

- Describe all damage caused by the accident
  - Damage to the fuel
  - Damage to equipment and systems
  - Damage to the reactor building
  - Damage to barriers that are designed to prevent the release of radioactive material to the environment

Accident Analysis Method (5/10)

- Analyze the accident
  - Quantitative evaluation of the accident sequence
  - Analysis should be realistic and conservative
  - Analysis should include assumptions, approximations, methodology, uncertainties, degree of conservatism, safety margins, and transport of radioactive material to the environment, if applicable

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Accident Analysis Method (6/10)

- Analyze the accident
  - Justify the assumptions, approximations, methodology, uncertainties, degree of conservatism, and safety margins
  - Demonstrate the validation of computational models, codes, assumptions, and approximations
    - comparison with experiments
    - comparison with measured data

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Accident Analysis Method (7/10)

- Analyze the accident
  - Describe all computer models and codes in detail
    - name of the code
    - type of code
    - how the code is used
    - the verification and validation of the code, including benchmark testing

Accident Analysis Method (8/10)

- Analyze the accident
  - Include estimates of the accuracy of all analytical methods
  - The analysis must contain enough information to allow the results to be independently reproduced or confirmed

Accident Analysis Method (9/10)

- Define and derive radiation source terms
  - Quantity and type of radionuclides
  - Physical and chemical forms of radionuclides
  - The duration of radioactive releases
  - Include direct and scattered radiation sources

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Accident Analysis Method (10/10)

- Evaluate the potential radiological effects
  - Use methods that are realistic and conservative
  - Include all radiation dose mechanisms
    - internal exposure
    - external exposure
    - environmental exposure pathways including water and food

Accident Categories (1/2)

- Maximum hypothetical accident
- Reactivity accident
  - ramp reactivity insertion
  - step reactivity insertion
- Loss of coolant
- Loss of coolant flow

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Accident Categories (2/2)

- Mishandling or malfunction of fuel
- Experiment malfunction
- Loss of electrical power
- External events
- Mishandling or malfunction of equipment

Maximum Hypothetical Accident (1/1)

- The maximum hypothetical accident (MHA) is an accident with consequences that bound all other accidents
  - Fuel damage
  - Release of fission products to the environment
- The MHA does not always have a credible initiating event

Reactivity Accidents (1/1)

- Ramp reactivity insertion
  - Continuous withdrawal of a control rod
- Step reactivity insertion
  - Rapid removal of a control rod
  - Rapid insertion of a fuel element
  - Failure of an experiment
  - Rapid change in operating parameters, such as a sudden decrease in coolant temperature

Loss of Coolant Accident (1/1)

- Generally a concern for reactors with a power level greater than 2 megawatts
- Failure or malfunction of a component in the primary coolant system
- Failure or malfunction of an experimental facility
- Failure or leak of the primary coolant boundary

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Loss of Coolant Flow Accident (1/1)

- Generally associated with reactors that have forced flow cooling systems
- Consider flow reversal if forced cooling flow is downward through the core
- Loss of electrical power
- Failure of a pump or other component in the primary coolant system
- Blocked coolant channel

Mishandling or Malfunction of Fuel (1/1)

- Overheating the fuel
- Dropping the fuel
- Dropping, impact, or other malfunction of a component that damages the fuel
- Operation with damaged fuel
- Accidental criticality in fuel in storage

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Experiment Malfunction (1/1)

- Loss of experiment cooling
  - Release of fissile material or fission products
  - Rapid change in reactivity
- Improper placement of an experiment
- Release of chemically reactive materials
- Release of corrosive materials
- Explosion

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Loss of Electrical Power (1/1)

- Generally, U.S. research reactor are designed so that they do not require electricity to shut down or remain safely shutdown
- Failure of offsite power
- Failure of emergency power

Malfunction of Equipment (1/1)

- Operator errors at the controls and during other activities
- Malfunction or loss of safety instruments or controls
- Electrical faults in control systems
- Malfunction of containment or confinement building
- Rapid leak of contamination

Technical Specifications (1/8)

- The TS are part of the reactor license issued by the regulator
- The TS are based on the safety analysis
- The TS should include all reactor characteristics that are used in the accident analysis

Technical Specifications (2/8)

- Specifies the safety limits, limiting safety system settings, limiting conditions for operation, and design features necessary for safe operation of the facility
- Specifies surveillance requirements for limiting conditions for operation
- Includes administrative controls for the operating organization

Technical Specifications (3/8)

- Safety Limits (SL) are limits necessary to protect the principal barriers that prevent the uncontrolled release of radioactivity
  - Fuel cladding
  - Primary coolant pressure boundary
- SL shall be established for fuel temperature, reactor power level, coolant flow, or coolant temperature, as needed

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Technical Specifications (4/8)

- Limiting Safety System Settings (LSSS) are settings for the reactor safety system that protect the safety limit
- LSSS shall be established for the reactor
- LSSS shall include uncertainties in reactor characteristics and safety channels

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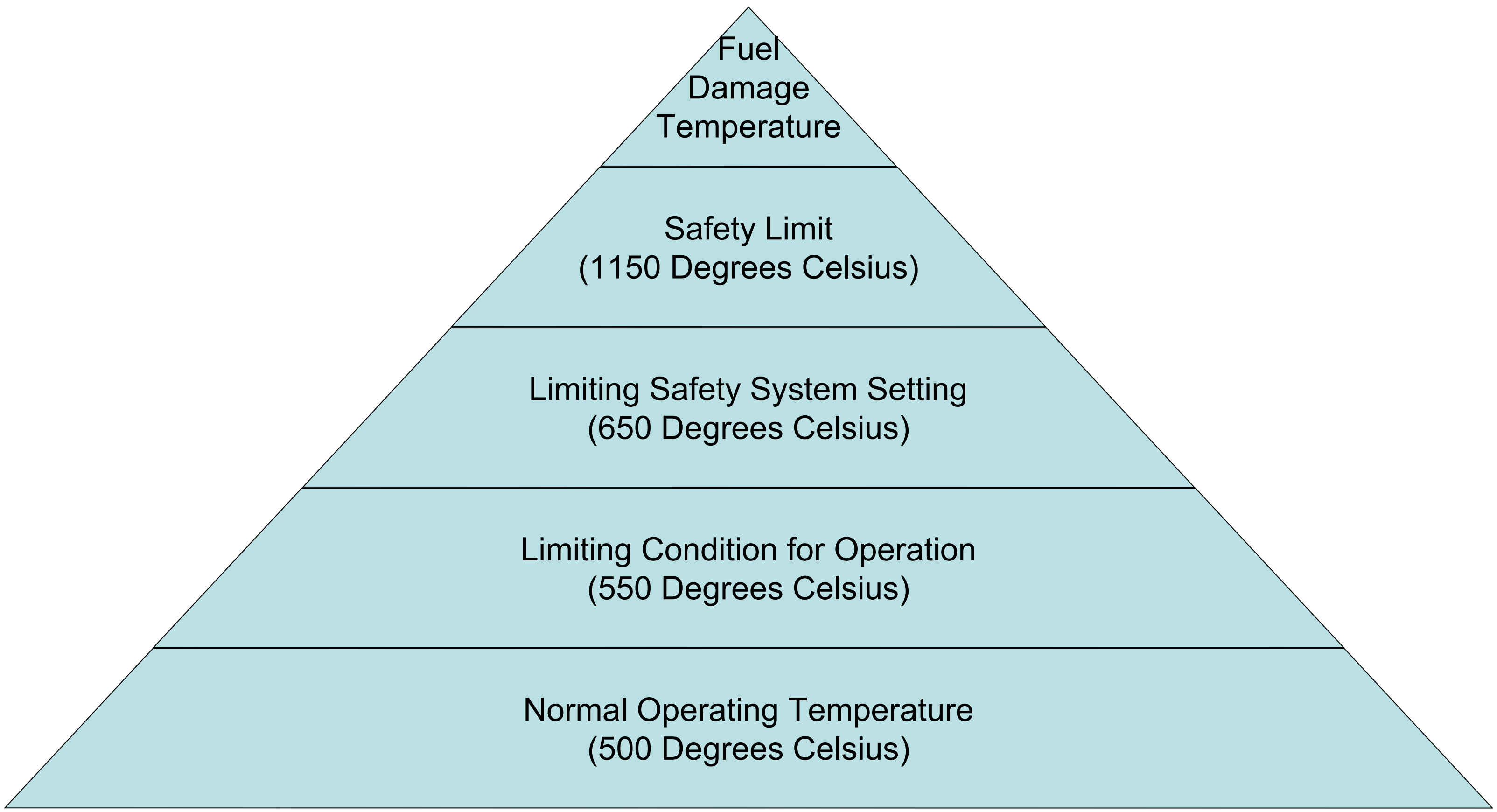
Technical Specifications (5/8)

- Limiting Conditions for Operation (LCO) are limits on reactor operation that ensure the reactor can be operated and shut down safely in all situations
- Each LCO usually has a surveillance requirement for inspection, testing, calibration, or maintenance

Technical Specifications (6/8)

- U.S. Requirements for LCO
  - Reactor characteristics that are used in the accident analysis
  - Instrumentation that detects damage to the reactor
  - Systems that prevent or reduce the consequences of accidents
  - Systems that are important to public safety

Technical Specifications (7/8)



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Technical Specifications (8/8)

- Guidance Documents
  - ANSI/ANS-15.1, “The Development of Technical Specifications for Research Reactors”
  - NUREG-1537, Part 1, Appendix 14.1, “Format and Content of Technical Specifications for Non-Power Reactors”

Conclusion (1/1)

- Questions?

- Thank you for your attention.