C.I.4. Reactor

Chapter 4 of the final safety analysis report (FSAR) should provide an evaluation and supporting information to establish the capability of the reactor to perform its safety functions throughout its design lifetime under all normal operational modes, including transient, steady-state, and accident conditions. This chapter should also include information to support the analyses presented in Chapter 15, "Accident Analyses."

C.I.4.1 *Summary Description*

Provide a summary description of the mechanical, nuclear, and thermal and hydraulic designs of the various reactor components, including the fuel, reactor vessel internals, and reactivity control systems. This summary description should indicate the independent and interrelated performance and safety functions of each component. (Information on control rod drive systems and reactor vessel internals presented in Sections 3.9.4 and 3.9.5 of the FSAR may be incorporated by reference.) In addition, this description should include a summary table of the important design and performance characteristics, as well as a tabulation of analysis techniques used and load conditions considered (including computer code names).

C.I.4.2 *Fuel System Design*

The fuel system is defined as consisting of guide tubes or thimbles; fuel rods with fuel pellets, insulator pellets, cladding, springs, end closures, fill gas, and getters; water rods; burnable poison rods; spacer grids and springs; assembly end fittings and springs; channel boxes; and the reactivity control assembly. In the case of the control rods, this section should cover the reactivity control elements that extend from the coupling interface of the control rod drive mechanism. In addition, this section should present the design bases for the mechanical, chemical, and thermal designs of the fuel system, which can affect or limit the safe, reliable operation of the plant.

The description of the fuel system mechanical design should include the following aspects:

(1) mechanical design limits, such as those for allowable stresses, deflection, cycling, and fatigue
(2) capacity for fuel fission gas inventory and pressure
(3) listing of material properties
(4) considerations for radiation damage, cladding collapse time, materials selection, and normal operational vibration

Details for seismic loadings should be presented in Section 3.7.3 of the FSAR; however, this section should present shock loadings [associated with a loss-of-coolant accident (LOCA)] and the effects of combined shock and seismic loads.

The chemical design should consider all possible fuel cladding-coolant interactions. The description of the thermal design should include such items as maximum fuel and cladding temperatures, clad-to-fuel gap conductance as a function of burnup and operating conditions, and fuel cladding integrity criteria.

C.I.4.2.1 Design Bases

Explain and substantiate the selection of design bases from the perspective of safety considerations. Where the limits selected are consistent with proven practice, a referenced statement to that effect will suffice; however, where the limits exceed present practice, this section should provide an evaluation and explanation based on developmental work or analysis. These design bases may be expressed as either explicit numbers or general conditions. In addition, the discussion of design bases should include a description of the functional characteristics in terms of desired performance under stated conditions. This should relate systems, components, and materials performance under normal operating, anticipated transient, and accident conditions. The discussion should consider the following with respect to performance:

(1) Cladding
  (a) mechanical properties of the cladding (e.g., Young's modulus, Poisson's ratio, design dimensions, strength, ductility, and creep rupture limits), and effects of design temperature and irradiation on those properties
  (b) stress-strain limits
  (c) vibration and fatigue
  (d) chemical properties of the cladding

(2) Fuel Material
  (a) thermal-physical properties of the fuel (e.g., melting point, thermal conductivity, density, and specific heat), and effects of design temperature and irradiation on those properties
  (b) effects of fuel densification and fission product swelling
  (c) chemical properties of the fuel

(3) Fuel Rod Performance
  (a) analytical models and conservatism in the input data
  (b) ability of the models to predict experimental or operating characteristics
  (c) standard deviation or statistical uncertainty associated with the correlations or analytical models

(4) Spacer Grid and Channel Boxes
  (a) mechanical, chemical, thermal, and irradiation properties of the materials
  (b) vibration and fatigue
  (c) chemical compatibility with other core components, including coolant

(5) Fuel Assembly
  (a) structural design
  (b) thermal-hydraulic design

(6) Reactivity Control Assembly and Burnable Poison Rods
  (a) thermal-physical properties of the absorber material
  (b) compatibility of the absorber and cladding materials
  (c) cladding stress-strain limits
  (d) irradiation behavior of absorber material

(7) Surveillance Program
  (a) requirements for surveillance and testing of irradiated fuel rods, burnable poison rods, control rods, channel boxes, and instrument tubes/thimbles

C.I.4.2.2 Description and Design Drawings

Provide a description and final (FSAR) design drawing of the fuel rod components, burnable poison rods, fuel assemblies, and reactivity control assemblies showing arrangements, dimensions, critical tolerances, sealing and handling features, methods of support, internal pressurization, fission gas spaces, burnable poison content, and internal components. In addition, include a discussion of design features that prevent improper orientation or placement of fuel rods or assemblies within the core.

Provide the following fuel system information and associated tolerances:

- type and metallurgical state of the cladding
- cladding outside diameter
- cladding inside diameter
- cladding inside roughness
- pellet outside diameter
- pellet roughness
- pellet density
- pellet resintering data
- pellet length
- pellet dish dimensions
- burnable poison content
- insulator pellet parameters
- fuel column length
- overall rod length
- rod internal void volume
- fill gas type and pressure
- sorbed gas composition and content
- spring and plug dimensions
- fissile enrichment
- equivalent hydraulic diameter
- coolant pressure
- design-specific burnup limit

Also provide the following design drawings:

- fuel assembly cross-section
- fuel assembly outline
- fuel rod schematic
- spacer grid cross-section
- guide tube and nozzle joint
- control rod assembly cross-section
- control rod assembly outline
- control rod schematic
- burnable poison rod assembly cross-section
- burnable poison rod assembly outline
- burnable poison rod schematic
- orifice and source assembly outline

C.I.4.2.3 Design Evaluation

Present an evaluation of the fuel system design for the physically feasible combinations of chemical, thermal, irradiation, mechanical, and hydraulic interactions. The evaluation of these interactions should include the effects of normal reactor operations, anticipated operational occurrences, anticipated transients without scram, and postulated accidents. In particular, the fuel system design evaluation should include the following considerations:

(1) Cladding
- (a) vibration analysis
- (b) fuel element internal and external pressure and cladding stresses during normal and accident conditions, with particular emphasis on temperature transients or depressurization accidents
- (c) potential for chemical reaction, including hydriding, fission product attack, and crud deposition
- (d) fretting and crevice corrosion
- (e) stress-accelerated corrosion
- (f) cycling and fatigue
- (g) material wastage due to mass transfer
- (h) rod bowing due to thermal, irradiation, and creep dimensional changes
- (i) consequences of power-coolant mismatch
- (j) irradiation stability of the cladding
- (k) creep collapse and creepdown

(2) Fuel
- (a) dimensional stability of the fuel
- (b) potential for chemical interaction, including possible waterlogging rupture
- (c) thermal stability of the fuel, including densification, phase changes, and thermal expansion
- (d) irradiation stability of the fuel, including fission product swelling and fission gas release

(3) Fuel Rod Performance
- (a) fuel-cladding mechanical interaction
- (b) failure and burnup experience, including the thermal conditions for which the experience was obtained for a given type of fuel and the results of long-term irradiation testing of production fuel and test specimens
- (c) fuel and cladding temperatures, both local and gross, with an indication of the correlation used for thermal conductivity, gap conductance as a function of burnup and power level, and the method of employing peaking factors
- (d) an analysis of the potential effect of sudden temperature transients on waterlogged elements or elements with high internal gas pressure
- (e) an analysis of temperature effects during anticipated operational transients that may cause bowing or other damage to fuel, control rods, or structure
- (f) an analysis of the energy release and potential for a chemical reaction in the event of a physical burnout of fuel elements[1]
- (g) an analysis of the energy release and resulting pressure pulse should waterlogged elements rupture and spill fuel into the coolant[1]
- (h) an analysis of fuel rod behavior in the event that coolant flow blockage is predicted[1]

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[1]If this information is included in Chapter 15 of the FSAR, it may be incorporated in this section by reference.

(4) Spacer Grid and Channel Boxes
   (a) dimensional stability considering thermal, chemical, and irradiation effects
   (b) spring loads for grids

(5) Fuel Assembly
   (a) loads applied by core restraint system
   (b) analysis of combined shock (including LOCA) and seismic loading
   (c) loads applied in fuel handling, including misaligned handling tools

(6) Reactivity Control Assembly and Burnable Poison Rods
   (a) internal pressure and cladding stresses during normal, transient, and accident conditions
   (b) thermal stability of the absorber material, including phase changes and thermal expansion
   (c) irradiation stability of the absorber material, taking into consideration gas release and swelling
   (d) potential for chemical interaction, including possible waterlogging rupture

When conclusive operating experience is not available, discuss any prototype testing associated with the fuel design, with a particular focus on any of the following prototype tests that have been performed:

- spacer grid structural tests
- control rod structural and performance tests
- fuel assembly structural tests (lateral, axial and torsional stiffness, frequency, and damping)
- fuel assembly hydraulic flow tests (lift forces, control rod wear, vibration, and assembly wear and life)
- in-reactor testing of design features and lead assemblies of a new design, which may include one or more of the following:
  - fuel and burnable poison rod growth
  - fuel rod bowing
  - fuel assembly growth
  - fuel assembly bowing
  - channel box wear and distortion
  - fuel rod ridging (PCI)
  - crud formation
  - fuel rod integrity
  - hold down spring relaxation
  - spacer grid spring relaxation
  - guide tube wear characteristics

Also discuss the following phenomenological models:

- radical power distribution
- fuel and cladding temperature distribution
- burnup distribution in the fuel
- thermal conductivity of the fuel, cladding, cladding crud, and oxidation layers
- densification of the fuel
- thermal expansion of the fuel and cladding
- fission gas production and release
- solid and gaseous fission product swelling
- fuel restructuring and relocation
- fuel and cladding dimensional changes
- fuel-to-cladding heat transfer coefficient
- thermal conductivity of the gas mixture

- thermal conductivity in the knudsen domain
- fuel-to-cladding contract pressure
- heat capacity of the fuel and cladding
- growth and creep of the cladding
- rod internal gas pressure and composition
- sorption of helium and other fill gases
- cladding oxide and crud layer thickness
- cladding-to-coolant heat transfer coefficient

In addition, provide the following information:

(1) Fuel system damage criteria for all known mechanisms:
  (a) stress, strain, or loading limits for spacer grids, guide tubes, thimbles, fuel rods, control rods, channel boxes, and other fuel system structured members
  (b) commutative number of strain fatigue cycles
  (c) fretting wear at contact points on structural members
  (d) oxidation, hydriding, and the buildup of corrosion production
  (e) dimensional changes, such as rod bowing or irradiation growth on fuel rods and guide tubes (discuss associated analyses)
  (f) fuel and burnable poison rod internal gas pressures
  (g) "worst case" hydraulic loads for normal operations
  (h) maintaining control rods "watertight" to control rod reactivity

(2) Regarding fuel rod failure, the design evaluation should include the following:
  (a) analysis of maximum linear heat generation rate anywhere in the core, including all hot spots and hot channel factors, and the effects of burnups and composition on the melting point
  (b) calculation of the cladding swelling and rupture resulting from the temperature distribution in the cladding and pressure differences between the inside and outside of the cladding [this should be included in the evaluation model for the emergency core cooling system (ECCS)]

(3) Regarding fuel coolability, the design evaluation should include the following:
  (a) how the analysis of the core flow distribution accounts for the burst strain and flow blockage caused by ballooning (swelling)
  (b) whether the analyses of other accidents involving systems depressurization include burst strain and flow blockage caused by ballooning (swelling)

C.I.4.2.4 <u>Testing and Inspection Plan</u>

Describe the testing and inspections to be performed to verify the design characteristics of the fuel system components, including cladding integrity; dimensions; fuel enrichment; burnable poison concentration; absorber composition; and characteristics of the fuel, absorber, and poison pellets. This section should also include descriptions of radiographic inspections, destructive tests, fuel assembly dimensional checks, and the inspection program for new fuel assemblies and new control rods to ensure mechanical integrity after shipment. Where testing and inspection programs are essentially the same as for previously accepted plants, a statement to that effect should be provided, along with an identification of the fabricator and a table summarizing the important design and performance characteristics.

In addition, describe the online fuel rod failure monitoring methods and post-irradiation surveillance package, as well as surveillance of control rods containing boron carbide (B_4C).

C.I.4.3 *Nuclear Design*

C.I.4.3.1 Design Bases

Provide and discuss the design bases for the nuclear design of the fuel and reactivity control systems, including nuclear and reactivity control limits such as excess reactivity, fuel burnup, negative reactivity feedback, core design lifetime, fuel replacement program, reactivity coefficients, stability criteria, maximum controlled reactivity insertion rates, control of power distribution, shutdown margins, stuck rod criteria, rod speeds, chemical and mechanical shim control, burnable poison requirements, and backup and emergency shutdown provisions.

C.I.4.3.2 Description

Describe the nuclear characteristics of the design, including the information indicated in the following sections.

C.I.4.3.2.1 *Nuclear Design Description*

List, describe, or illustrate features of the nuclear design that are not discussed in specific subsections for appropriate times in the fuel cycle. Include such areas as fuel enrichment distributions, burnable poison distributions, other physical features of the lattice or assemblies relevant to nuclear design parameters, delayed neutron fraction and neutron lifetimes, core lifetime and burnup, plutonium buildup, soluble poison insertion rates, and the relationship to cooldown, xenon burnout, or other transient requirements.

C.I.4.3.2.2 *Power Distribution*

Present full quantitative information on calculated "normal" power distributions, including distributions within typical assemblies, axial distributions, gross radial distributions (XY assembly patterns), and nonseparable aspects of radial and axial distributions. This should include a full range of both representative and limiting power density patterns related to representative and limiting conditions of such relevant parameters as power, flow, flow distribution, rod patterns, time in cycle (burnup and possible burnup distributions), cycle, burnable poison, and xenon. Cover these patterns in sufficient detail to ensure that normally anticipated distributions are fully described and the effects of all parameters important in affecting distributions are displayed. This should include details of transient power shapes and magnitudes accompanying normal transients, such as load following, xenon buildup, decay or redistribution, and xenon oscillation control. Describe the radial power distribution within a fuel pin and its variation with burnup if this is used in thermal calculations.

Discuss and assign specific magnitudes to errors or uncertainties that may be associated with these calculated distributions, and present the experimental data, including results from both critical experiments and operating reactors that support the analysis, likely distribution limits, and assigned uncertainty magnitudes. Also, discuss experimental checks to be performed on this reactor, as well as the criteria for satisfactory results.

Present detailed descriptions of the design power distributions (shapes and magnitudes) and design peaking factors to be used in steady-state limit statements and transient analysis initial conditions. Include all relevant components and such variables as maximum allowable peaking factors vs. axial position or changes over the fuel cycle. Justify the selections by discussing the relationships of these design assumptions to the previously presented expected and limiting distributions and uncertainty analysis.

Describe the relationship of these distributions to the monitoring instrumentation, discussing in detail the adequacy of the number of instruments and their spatial deployment (including allowed failures); required correlations between readings and peaking factors, calibrations and errors, operational procedures and specific operational limits; axial and azimuthal asymmetry limits; limits for alarms, rod blocks, scrams, etc., to demonstrate that sufficient information is available to determine, monitor, and limit distributions associated with normal operation to within proper limits. Describe in detail all calculations, computer codes, and computers used in the course of operations that are involved in translating power distribution-related measurements into calculated power distribution information. Provide the frequency with which the calculations are normally performed and execution times of the calculations. Also describe the input data required for the codes. In addition, present a full quantitative analysis of the uncertainties associated with the sources and processing of information used to produce operational power distribution results. This should include consideration of allowed instrumentation failures.

C.I.4.3.2.3 ***Reactivity Coefficients***

Present full quantitative information on calculated reactivity coefficients, including the fuel Doppler coefficient, moderator coefficients (density, temperature, pressure, and void), and power coefficient. State the precise definitions or assumptions related to parameters involved (e.g., effective fuel temperature for Doppler, distinction between intra- and inter-assembly moderator coefficients, parameters held constant in the power coefficient, spatial variation of parameters, and flux weighting used). The information should primarily take the form of curves covering the full applicable range of parameters (density, temperature, pressure, void, and power) from cold startup through limiting values used in accident analyses. Include quantitative discussions of both spatially uniform parameter changes and those nonuniform parameter and flux weighting changes appropriate to operational and accident analyses, as well as the methods used to treat nonuniform changes in transient analyses.

Present sufficient information to illustrate the normal and limiting values of parameters appropriate to operational and accident states, considering cycle, time in cycle, control rod insertions, boron content, burnable poisons, power distribution, moderator density, etc. Discuss potential uncertainties in the calculations and experimental results that support the analysis and assigned uncertainty magnitudes and experimental checks to be made in this reactor. Where limits on coefficients are especially important (e.g., positive moderator coefficients in the power range), experimental checks on these limits should be fully detailed.

Present the coefficients actually used in transient analyses, and show (by reference to previous discussions and uncertainty analyses) that suitably conservative values are used (1) for both beginning of life (BOL) and end of life (EOL) analyses, (2) where most negative or most positive (or least negative) coefficients are appropriate, and (3) where spatially nonuniform changes are involved.

C.I.4.3.2.4 ***Control Requirements***

Provide tables and discussions related to core reactivity balances for BOL, EOL, and (where appropriate) intermediate conditions. Include consideration of such reactivity influences as control bank requirements and expected and minimum worths, burnable poison worths, soluble boron amounts and unit worths for various operating states, “stuck rod” allowances, moderator and fuel temperature and void defects, burnup and fission products, xenon and samarium poisoning, pH effects, permitted rod insertions at power, and error allowances. Also, present and discuss the required and expected shutdown margin as a function of time in cycle, along with uncertainties in the shutdown margin and experimental confirmations from operating reactors.

Fully describe all methods, paths, and limits for normal operational control involving such areas as soluble poison concentration and changes, control rod motion, power shaping rod (e.g., part length rod) motion, and flow change. Include consideration of cold, hot, and peak xenon startup, load following and xenon reactivity control, power shaping (e.g., xenon redistribution or oscillation control), and burnup.

C.I.4.3.2.5 ***Control Rod Patterns and Reactivity Worths***

Present full information on control rod patterns expected to be used throughout a fuel cycle. Include details concerning separation into groups or banks if applicable; order and extent of withdrawal of individual rods or banks; limits (with justification) to be imposed on rod or bank positions as a function of power level and/or time in cycle or for any other reason; and expected positions of rods or banks for cold critical, hot standby critical, and full power for both BOL and EOL. Describe allowable deviations from these patterns for misaligned or stuck rods or for any other reason (such as spatial power shaping). For allowable patterns (including allowable deviations), indicate for various power, EOL, and BOL conditions, the maximum worth of rods that might be postulated to be removed from the core in an ejection or drop accident, as well as rods or rod banks that could be removed in rod withdrawal accidents. Also give the worths of these rods as a function of position, describe any experimental confirmations of these worths, and present maximum reactivity increase rates associated with these withdrawals. Describe fully and give the methods for calculating the scram reactivity as a function of time after scram signal, including consideration for Technical Specification scram times, stuck rods, power level and shape, time in cycle, and any other parameters important for bank reactivity worth and axial reactivity shape functions. In addition, for boiling-water reactors (BWRs), provide criteria for control rod velocity limiters and control rod worth minimizers.

C.I.4.3.2.6 ***Criticality of Reactor During Refueling***

State the maximum value of K_{eff} for the reactor during refueling. Describe the basis for assuming that this maximum value will not be exceeded.

C.I.4.3.2.7 ***Stability***

Define the degree of predicted stability with regard to xenon oscillations in both the axial direction and the horizontal plane. If any form of xenon instability is predicted, include evaluations of higher-mode oscillations. Describe in detail the analytical and experimental bases for the predictions, and include an assessment of potential error in the predictions. Also, show how unexpected oscillations would be detectable before safety limits are exceeded.

Provide unambiguous positions regarding stability or lack thereof. That is, where stability is claimed, provide corroborating data from sufficiently similar power plants, or provide commitments to demonstrate stability. Indicate criteria for determining whether the reactor will be stable. Where instability or marginal stability is predicted, provide details of how oscillations will be detected and controlled, as well as provisions for protection against exceeding safety limits.

In addition, present analyses of overall reactor stability against power oscillations (other than xenon).

C.I.4.3.2.8 *Vessel Irradiation*

Provide the neutron flux distribution and spectrum in the core, at core boundaries, and at the pressure vessel wall for appropriate times in the reactor life for NVT determinations. Clearly state the assumptions used in the calculations, including power level, use factor, type of fuel cycle, and vessel design life. Also, discuss the computer codes used in the analysis database for fast neutron cross-sections, geometric modeling of the reactor, support barrel, water annulus, and pressure vessel, as well as the calculation uncertainties.

C.I.4.3.3 Analytical Methods

Describe in detail the analytical methods used in the nuclear design, including those for predicting criticality, reactivity coefficients, and burnup effects. This detailed description should include the computer codes used, including the code name and type, how it is used, its validity (based on critical experiments or confirmed predictions of operating plants), and methods of obtaining nuclear parameters (such as neutron cross-sections). In addition, the detailed descriptions of analytical methods should include estimates of the accuracy of each method.

C.I.4.3.4 Changes

List any changes in reactor core design features, calculational methods, data, or information relevant to determining important nuclear design parameters that depart from prior practice of the reactor designs, and identify the parameters affected by each change. Details regarding the nature and effects of these changes should be treated in appropriate subsections.

C.I.4.4 *Thermal and Hydraulic Design*

C.I.4.4.1 Design Bases

Provide the design bases for the thermal and hydraulic design of the reactor. Include such items as maximum fuel and clad temperatures and cladding-to-fuel gap characteristics as a function of burnup (at rated power, at design overpower, and during transients), critical heat flux ratio (at rated power, at design overpower, and during transients), flow velocities and distribution control, coolant and moderator voids, hydraulic stability, transient limits, fuel cladding integrity criteria, and fuel assembly integrity criteria.

C.I.4.4.2 Description of Thermal and Hydraulic Design of the Reactor Core

Describe the thermal and hydraulic characteristics of the reactor design. Include information indicated in the following sections.

C.I.4.4.2.1 *Summary Comparison*

Present a summary comparison of the reactor's thermal and hydraulic design parameters with previously approved reactors of similar design. This should include, for example, primary coolant temperatures, fuel temperatures, maximum and average linear heat generation rates, critical heat flux ratios, critical heat flux correlations used, coolant velocities, surface heat fluxes, power densities, specific powers, surface areas, and flow areas.

C.I.4.4.2.2 ***Critical Heat Flux Ratios***

Provide the critical heat flux ratios for the core hot spot at normal full power and design overpower conditions. State the critical heat flux correlation used, analysis techniques, method of use, method of employing peaking factors, and comparison with other correlations.

C.I.4.4.2.3 ***Linear Heat Generation Rate***

Provide the core-average linear heat generation rate (LHGR), as well as the maximum LHGR anywhere in the core. Also, indicate the method of utilizing hot channel factors and power distribution information to determine the maximum LHGR.

C.I.4.4.2.4 ***Void Fraction Distribution***

Provide curves showing the predicted radial and axial distributions of steam quality and steam void fraction in the core. State the predicted core average void fraction, as well as the maximum void fraction anywhere in the core.

C.I.4.4.2.5 ***Core Coolant Flow Distribution***

Describe and discuss the coolant flow distribution and orificing, as well as the basis on which orificing is designed (relative to shifts in power production during core life).

C.I.4.4.2.6 ***Core Pressure Drops and Hydraulic Loads***

Identify core pressure drops and hydraulic loads during normal and accident conditions, which are not addressed in Chapter 15 of the FSAR.

C.I.4.4.2.7 ***Correlations and Physical Data***

Discuss the correlations and physical data employed in determining important characteristics such as heat transfer coefficients and pressure drop.

C.I.4.4.2.8 ***Thermal Effects of Operational Transients***

Evaluate the capability of the core to withstand thermal effects resulting from anticipated operational transients.

C.I.4.4.2.9 ***Uncertainties in Estimates***

Discuss the uncertainties associated with estimating the peak or limiting conditions for thermal and hydraulic analysis (e.g., fuel temperature, clad temperature, pressure drops, and orificing effects).

C.I.4.4.2.10 ***Flux Tilt Considerations***

Discuss the margin provided in the peaking factor to account for flux tilts to ensure that flux limits are not exceeded during operation. Describe plans for power reduction in the event of flux tilts, and provide criteria for selecting a safe operating power level.

C.I.4.4.3 Description of the Thermal and Hydraulic Design of the Reactor Coolant System

Describe the thermal and hydraulic design of the reactor coolant system. Include the information indicated in the following sections.

C.I.4.4.3.1 *Plant Configuration Data*

Provide the following information on plant configuration and operation:

(1) a description of the reactor coolant system, including isometric drawings that show the configuration and approximate dimensions of the reactor coolant system piping

(2) a listing of all valves and pipe fittings (elbows, tees, etc.) in the reactor coolant system

(3) total coolant flow through each flow path (total loop flow, core flow, bypass flow, etc.)

(4) total volume of each plant component, including ECCS components, with sufficient detail to define each part (downcomer, lower plenum, upper head, etc.) of the reactor vessel and steam generator [for pressurized-water reactors (PWRs)]

(5) the length of the flow path through each volume

(6) the height and liquid level of each volume

(7) the elevation of the bottom of each volume with respect to some reference elevation (preferably the centerline of the outer piping)

(8) the lengths and sizes of all safety injection lines

(9) minimum flow areas of each component

(10) steady-state pressure and temperature distribution throughout the system

C.I.4.4.3.2 *Operating Restrictions on Pumps*

State the operating restrictions that will be imposed on the coolant pumps to meet net positive suction head requirements.

C.I.4.4.3.3 *Power-Flow Operating Map (BWR)*

For BWRs, provide a power-flow operating map, indicating the limits of reactor coolant system operation. This map should indicate the permissible operating range, as bounded by minimum flow, design flow, maximum pump speed, and natural circulation.

C.I.4.4.3.4 *Temperature-Power Operating Map (PWR)*

For PWRs, provide a temperature-power operating map. This map should indicate the effects of reduced core flow due to inoperative pumps, including system capability during natural circulation conditions.

C.I.4.4.3.5 ***Load-Following Characteristics***

Describe the load-following characteristics of the reactor coolant system, as well as the techniques employed to provide this capability.

C.I.4.4.3.6 ***Thermal and Hydraulic Characteristics Summary Table***

Provide a table summarizing the thermal and hydraulic characteristics of the reactor coolant system.

C.I.4.4.4 Evaluation

Present an evaluation of the thermal and hydraulic design of the reactor and the reactor coolant system. This evaluation should include the information indicated in the following sections.

C.I.4.4.4.1 ***Critical Heat Flux***

Identify the critical heat flux, departure from nucleate boiling, or critical power ratio correlation used in the core thermal and hydraulic analysis. Describe the experimental basis for the correlation (preferably by reference to documents available to the NRC), and discuss the applicability of the correlation to the proposed design. Place particular emphasis on the effect of the grid spacer design, the calculational technique used to determine coolant mixing, and the effect of axial power distribution.

C.I.4.4.4.2 ***Core Hydraulics***

The core hydraulics evaluation should include (1) a discussion of the results of flow model tests (with respect to pressure drop for the various flow paths through the reactor and flow distributions at the core inlet), (2) the empirical correlation selected for use in analyses for both single-phase and two-phase flow conditions and applicability over the range of anticipated reactor conditions, and (3) the effect of partial or total isolation of a loop.

C.I.4.4.4.3 ***Influence of Power Distribution***

Discuss the influence of axial and radial power distributions on the thermal and hydraulic design. Include an analysis to determine which fuel rods control the thermal limits of the reactor.

C.I.4.4.4.4 ***Core Thermal Response***

Evaluate the thermal response of the core at rated power, at design overpower, and during expected transient conditions.

C.I.4.4.4.5 ***Analytical Methods***

Describe the analytical methods and data used to determine the reactor coolant system flow rate. This should include classical fluid mechanics relationships and empirical correlations, and should address both single-phase and two-phase fluid flow, as applicable. In addition, this description should provide estimates of the uncertainties in the calculations, as well as the resultant uncertainty in reactor coolant system flow rate.

Present a comprehensive discussion of the analytical techniques used in evaluating the core thermal-hydraulics, including estimates of uncertainties. This discussion should include such items as hydraulic instability, application of hot spot factors and hot channel factors, subchannel hydraulic analysis, effects of crud (in the core and reactor coolant system), and operation with one or more loops isolated. Descriptions of computer codes may be included by reference to documents available to the NRC.

C.I.4.4.5 Testing and Verification

Discuss the testing and verification techniques used to ensure that the planned thermal and hydraulic design characteristics of the core and reactor coolant system have been provided and will remain within required limits throughout the core lifetime. This discussion should address the applicable portions of Regulatory Guide 1.68, "Initial Test Programs for Water-Cooled Nuclear Power Plants." References to the appropriate portions of Chapter 14 of the FSAR are acceptable.

C.I.4.4.6 Instrumentation Requirements

Discuss the functional requirements for instrumentation to be employed in monitoring and measuring those thermal-hydraulic parameters that are important to safety. For example, this discussion should include the requirements for in-core instrumentation to confirm predicted power density distribution and moderator temperature distributions. Details of the instrumentation design and logic should be presented in Chapter 7 of the FSAR.

Also, describe the vibration and loose-parts monitoring equipment to be provided in the plant. In addition, discuss the procedures to be used to detect excessive vibration and the occurrence of loose parts.

C.I.4.5 *Reactor Materials*

C.I.4.5.1 Control Rod Drive System Structural Materials

For the purpose of this section, the control rod drive system includes the control rod drive mechanism (CRDM) and extends to the coupling interface with the reactivity control (poison) elements in the reactor vessel. It does not include the electrical and hydraulic systems necessary to actuate the CRDMs. This section should provide the information described in the following subsections.

C.I.4.5.1.1 *Materials Specifications*

Provide a list of the materials, including weld materials, and their specifications for each CRDM component. Furnish information regarding the mechanical properties of any material not included in either Appendix I to Section III of the Boiler and Pressure Vessel (B&PV) Code promulgated by the American Society of Mechanical Engineers (ASME), or Regulatory Guide 1.84, "Design, Fabrication, and Materials Code Case Acceptability, ASME Section III, Division 1," and provide justification for the use of such materials.

State whether the CRDM design uses any materials that have a yield strength greater than 90,000 psi, such as cold-worked austenitic stainless steels, precipitation hardenable stainless steels, or hardenable martensitic stainless steels. If such materials are used, identify their usage and provide evidence that stress-corrosion cracking will not occur during service life in components fabricated from the materials.

C.I.4.5.1.2 *Austenitic Stainless Steel Components*

Describe the processes, inspections, and tests used to ensure that austenitic stainless steel components are free from increased susceptibility to intergranular stress-corrosion cracking caused by sensitization. If special processing or fabrication methods subject the materials to temperatures between 800–1,500EF (427–816EC), or involve slow cooling from temperatures over 1500EF (816EC), describe the processing or fabrication methods and provide justification to show that such treatment will not cause susceptibility to intergranular stress-corrosion cracking. Indicate the degree of conformance to the recommendations of Regulatory Guide 1.44, "Control of the Use of Sensitized Stainless Steel," as well as Position C.5 of Regulatory Guide 1.37, "Quality Assurance Requirements for Cleaning of Fluid Systems and Associated Components of Water-Cooled Nuclear Power Plants," as it relates to controls for abrasive steel surfaces. Provide justification for any deviations from these recommendations.

C.I.4.5.1.3 ***Other Materials***

Describe the tempering temperature of hardenable martensitic stainless steels and the aging temperature and aging time of precipitation-hardening stainless steels. Also, describe the processing and treatment of other special purpose materials, such as cobalt-base alloys (Stellites), nickle-based alloys (Inconel), titanium, colmonoys, and graphitars.

C.I.4.5.1.4 ***Cleaning and Cleanliness Control***

Provide details regarding the steps that will be taken to protect austenitic stainless steel materials and parts of these systems during fabrication, shipping, and onsite storage to ensure that all cleaning solutions, processing compounds, degreasing agents, and detrimental contaminants are completely removed and all parts are dried and properly protected following any flushing treatment with water. Indicate the degree of conformance to the recommendations of Regulatory Guide 1.37, "Quality Assurance Requirements for Cleaning of Fluid Systems and Associated Components of Water-Cooled Nuclear Power Plants." Provide justification for any deviations from these recommendations.

C.I.4.5.2 <u>Reactor Internals and Core Support Materials</u>

Discuss the materials used for reactor internals and core support materials. Include the information described in the following subsections.

C.I.4.5.2.1 ***Materials Specifications***

List the materials, including weld materials, and their specifications for components of the reactor internals and core support structures. Include materials treated to enhance corrosion resistance, strength, and hardness. Furnish information regarding the mechanical properties of any material not included in Appendix I to Section III of the ASME B&PV Code and provide justification for the use of such materials.

C.I.4.5.2.2 ***Controls on Welding***

Indicate the methods and controls that will be used when welding reactor internals components and core support structures, and provide assurance that such welds will meet the acceptance criteria of Article NG 5000 in Section III of the ASME B&PV Code.

C.I.4.5.2.3 ***Nondestructive Examination***

Indicate that the nondestructive examination procedures used to examine tubular products conform to the requirements of the ASME B&PV Code. Provide justification for any deviations from these

requirements.

C.I.4.5.2.4 ***Fabrication and Processing of Austenitic Stainless Steel Components***

Indicate the degree of conformance to the recommendations of Regulatory Guide 1.44, "Control of the Use of Sensitized Stainless Steel"; and Regulatory Guide 1.37, "Quality Assurance Requirements for Cleaning of Fluid Systems and Associated Components of Water-Cooled Nuclear Power Plants." If alternative measures are used, show that they will provide the same assurance of component integrity as would be achieved by following the recommendations of the listed regulatory guides. Indicate the maximum yield strength of all cold-worked stainless steels used in the reactor internals.

C.I.4.5.2.5 ***Other Materials***

Submit information on the mechanical properties, corrosion resistance, and fabrication, of any materials other than austenitic stainless steels. In particular, discuss the tempering temperature of hardenable martensitic stainless steels and the aging temperature and aging time of precipitation-hardening stainless steels. Also, discuss the processing and treatment of other special purpose materials, such as cobalt-base alloys (Stellites), nickel-based alloys (Inconel), Titanium and Colmonoys.

C.I.4.6 ***Functional Design of Reactivity Control Systems***

Present information to establish that the control rod drive system (CRDS), which includes the essential ancillary equipment and hydraulic systems, is designed and installed to provide the required functional performance and is properly isolated from other equipment. Also, present information to establish the bases for assessing the combined functional performance of all the reactivity control systems to mitigate the consequences of anticipated transients and postulated accidents.

In addition to the CRDS and ECCS, these reactivity control systems include the chemical and volume control system (CVCS) and the emergency boration system (EBS) for PWRs, and the standby liquid control system (SLCS) and the recirculation flow control system (RFCS) for BWRs.

C.I.4.6.1 <u>Information for CRDS</u>

Information submitted should include drawings of the rod drive mechanism, layout drawings of the collective rod drive system, process flow diagrams, piping and instrumentation diagrams, component descriptions and characteristics, and a description of the functions of all related ancillary equipment and hydraulic systems. This should also include the control rod drive cooling system for plants that have this system. This information may be presented in conjunction with the information requested for Section 3.9.4 of the FSAR.

C.I.4.6.2 <u>Evaluations of the CRDS</u>

Failure mode and effects analyses of the CRDS should be presented in tabular form, with supporting discussion to delineate the logic employed. The failure analysis should demonstrate that the CRDS, which for purposes of these evaluations includes all essential ancillary equipment and hydraulic systems, can perform the intended safety functions with the loss of any single active component.

These evaluations and assessments should establish that all essential elements of the CRDS are identified and provisions made for isolation from nonessential CRDS elements. In addition, this discussion should establish that all essential equipment is amply protected from common-mode failures (such as failure of moderate- and high-energy lines).

C.I.4.6.3 Testing and Verification of the CRDS

Describe the functional testing program. This should include rod insertion and withdrawal tests, thermal and fluid dynamic tests simulating postulated operating and accident conditions, and test verification of the CRDS with imposed single failures, as appropriate.

Present preoperational and initial startup test programs. Include the test objectives, methods, and acceptance criteria.

C.I.4.6.4 Information for Combined Performance of Reactivity Systems

Other sections of the FSAR (e.g., 9.3.4 and 9.3.5) present piping and instrumentation diagrams, layout drawings, process diagrams, failure analyses, descriptive material, and performance evaluations related to specific evaluations of the CVCS, SLCS, and RFCS. This section should include sufficient plan and elevation layout drawings to provide bases for establishing that the reactivity control systems (CRDS, ECCS, CVCS, SLCS, RFCS, and EBS) are not vulnerable to common-mode failures when used in single or multiple redundant modes.

Evaluations pertaining to the plant's response to postulated process disturbances and equipment malfunctions or failures are presented in Chapter 15 of the FSAR. This section should list all postulated accidents evaluated in Chapter 15 that take credit for two or more reactivity control systems to prevent or mitigate each accident. In addition, this section should tabulate the related reactivity systems.

C.I.4.6.5 Evaluations of Combined Performance

Evaluate the combined functional performance for accidents where two or more reactivity systems are used. The neutronic, fluid dynamic, instrumentation, controls, time sequencing, and other process-parameter-related features are presented primarily in Chapters 4, 7, and 15 of the FSAR. This section should include failure analyses to demonstrate that the reactivity control systems are not susceptible to common-mode failures when used redundantly. These failure analyses should consider failures originating within each reactivity control system, as well as those originating from plant equipment other than reactivity systems, and should be presented in tabular form with supporting discussion and logic.

C.I.4.6.3 Testing and Verification of the CRDS

Describe the functional testing program. This should include rod insertion and withdrawal tests, thermal and fluid dynamic tests simulating postulated operating and accident conditions, and test verification of the CRDS with imposed single failures, as appropriate.

Present preoperational and initial startup test programs. Include the test objectives, methods, and acceptance criteria.

C.I.4.6.4 Information for Combined Performance of Reactivity Systems

Other sections of the FSAR (e.g., 9.3.4 and 9.3.5) present piping and instrumentation diagrams, layout drawings, process diagrams, failure analyses, descriptive material, and performance evaluations related to specific evaluations of the CVCS, SLCS, and RFCS. This section should include sufficient plan and elevation layout drawings to provide bases for establishing that the reactivity control systems (CRDS, ECCS, CVCS, SLCS, RFCS, and EBS) are not vulnerable to common-mode failures when used in single or multiple redundant modes.

Evaluations pertaining to the plant's response to postulated process disturbances and equipment malfunctions or failures are presented in Chapter 15 of the FSAR. This section should list all postulated accidents evaluated in Chapter 15 that take credit for two or more reactivity control systems to prevent or mitigate each accident. In addition, this section should tabulate the related reactivity systems.

C.I.4.6.5 Evaluations of Combined Performance

Evaluate the combined functional performance for accidents where two or more reactivity systems are used. The neutronic, fluid dynamic, instrumentation, controls, time sequencing, and other process-parameter-related features are presented primarily in Chapters 4, 7, and 15 of the FSAR. This section should include failure analyses to demonstrate that the reactivity control systems are not susceptible to common-mode failures when used redundantly. These failure analyses should consider failures originating within each reactivity control system, as well as those originating from plant equipment other than reactivity systems, and should be presented in tabular form with supporting discussion and logic.