

SECTION 4

REACTOR

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
4.1	SUMMARY DESCRIPTION	4.1-1
4.1.1	Reference for Section 4.1	4.1-4
4.2	MECHANICAL DESIGN	4.2-1
4.2.1	Fuel	4.2-2
4.2.1.1	Design Bases	4.2-2
4.2.1.1.1	Fuel Rods	4.2-3
4.2.1.1.2	Fuel Assembly Structure	4.2-5
4.2.1.2	Design Description	4.2-8
4.2.1.2.1	Fuel Rods	4.2-10
4.2.1.2.2	Fuel Assembly Structure	4.2-11
4.2.1.3	Design Evaluation	4.2-14
4.2.1.3.1	Fuel Rods	4.2-14
4.2.1.3.2	Fuel Assembly Structure	4.2-24
4.2.1.3.3	Operational Experience	4.2-28
4.2.1.3.4	Test Rod and Test Assembly Experience	4.2-28a
4.2.1.4	Testing and Inspection Plan	4.2-28a
4.2.1.4.1	Quality Assurance Program	4.2-28a
4.2.1.4.2	Quality Control	4.2-29
4.2.1.4.3	Onsite Inspection	4.2-32
4.2.2	Reactor Vessel Internals	4.2-33
4.2.2.1	Design Bases	4.2-33
4.2.2.2	Description and Drawings	4.2-34
4.2.2.3	Design Loading Conditions	4.2-40a
4.2.2.4	Design Loading Categories	4.2-42
4.2.2.5	Design Criteria Basis	4.2-43
4.2.3	Reactivity Control System	4.2-44

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Title</u>	<u>Page</u>
4.2.3.1	Design Bases	4.2-44
4.2.3.1.1	Design Stresses	4.2-44
4.2.3.1.2	Material Compatibility	4.2-45
4.2.3.1.3	Reactivity Control Components	4.2-45
4.2.3.1.4	Control Rod Drive Mechanisms	4.2-48
4.2.3.2	Design Description	4.2-49
4.2.3.2.1	Reactivity Control Components	4.2-51
4.2.3.2.2	Control Rod Drive Mechanism	4.2-56
4.2.3.3	Design Evaluation	4.2-63
4.2.3.3.1	Reactivity Control Components	4.2-63
4.2.3.3.2	Control Rod Drive Mechanism	4.2-73
4.2.3.4	Tests, Verification, and Inspections	4.2-77
4.2.3.4.1	Reactivity Control Components	4.2-77
4.2.3.4.2	Control Rod Drive Mechanism	4.2-79
4.2.4	References for Section 4.2	4.2-81
4.3	NUCLEAR DESIGN	4.3-1
4.3.1	Design Bases	4.3-1
4.3.1.1	Fuel Burnup	4.3-2
4.3.1.2	Negative Reactivity Feedbacks (Reactivity Coefficient)	4.3-3
4.3.1.3	Control of Power Distribution	4.3-4
4.3.1.4	Maximum Controlled Reactivity Insertion Rate	4.3-6
4.3.1.5	Shutdown Margins	4.3-7
4.3.1.6	Stability	4.3-8
4.3.1.7	Anticipated Transients Without Trip	4.3-9
4.3.2	Description	4.3-10
4.3.2.1	Nuclear Design Description	4.3-10
4.3.2.2	Power Distribution	4.3-13
4.3.2.2.1	Definitions	4.3-13
4.3.2.2.2	Radial Power Distribution	4.3-16

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Title</u>	<u>Page</u>
4.3.2.2.3	Assembly Power Distribution	4.3-17
4.3.2.2.4	Axial Power Distribution	4.3-17
4.3.2.2.5	Deleted	4.3-18
4.3.2.2.6	Limiting Power Distribution	4.3-20
4.3.2.2.7	Experimental Verification of Power Distribution Analysis	4.3-26
4.3.2.2.8	Testing	4.3-29
4.3.2.2.9	Monitoring Instrumentation	4.3-29
4.3.2.3	Reactivity Coefficients	4.3-30
4.3.2.3.1	Fuel Temperature (Doppler) Coefficient	4.3-30
4.3.2.3.2	Moderator Coefficients	4.3-31
4.3.2.3.3	Power Coefficient	4.3-34
4.3.2.3.4	Comparison of Calculated and Experimental Reactivity Coefficients	4.3-34
4.3.2.3.5	Reactivity Coefficients Used in Transient Analysis	4.3-35
4.3.2.4	Control Requirements	4.3-35
4.3.2.4.1	Doppler	4.3-36
4.3.2.4.2	Variable Average Moderator Temperature	4.3-36
4.3.2.4.3	Redistribution	4.3-37
4.3.2.4.4	Void Content	4.3-37
4.3.2.4.5	Rod Insertion Allowance	4.3-37
4.3.2.4.6	Burnup	4.3-38
4.3.2.4.7	Xenon and Samarium Poisoning	4.3-38
4.3.2.4.8	pH Effects	4.3-38
4.3.2.4.9	Experimental Confirmation	4.3-39
4.3.2.5	Control	4.3-39
4.3.2.5.1	Chemical Poison	4.3-39
4.3.2.5.2	Rod Cluster Control Assemblies	4.3-40
4.3.2.5.3	Burnable Absorbers	4.3-41
4.3.2.5.4	Peak Xenon Startup	4.3-41
4.3.2.5.5	Load Follow Control and Xenon Control	4.3-42

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Title</u>	<u>Page</u>
4.3.2.5.6	Burnup	4.3-42
4.3.2.6	Control Rod Patterns and Reactivity Worth	4.3-42
4.3.2.7	Criticality of Fuel Assemblies	4.3-45
4.3.2.8	Stability	4.3-46
4.3.2.8.1	Introduction	4.3-46
4.3.2.8.2	Stability Index	4.3-46
4.3.2.8.3	Prediction of the Core Stability	4.3-47
4.3.2.8.4	Stability Measurements	4.3-48
4.3.2.8.5	Comparison of Calculations with Measurements	4.3-50
4.3.2.8.6	Stability Control and Protection	4.3-51
4.3.2.9	Vessel Irradiation	4.3-52
4.3.3	Analytical Methods	4.3-53
4.3.3.1	Fuel Temperature (Doppler) Calculations	4.3-54
4.3.3.2	Macroscopic Group Constants	4.3-55
4.3.3.3	Spatial Few-Group Diffusion Calculations	4.3-57
4.3.4	References for Section 4.3	4.3-58
4.4	THERMAL AND HYDRAULIC DESIGN	4.4-1
4.4.1	Design Bases	4.4-1
4.4.1.1	Departure From Nucleate Boiling Design Basis	4.4-2
4.4.1.2	Fuel Temperature Design Basis	4.4-2a
4.4.1.3	Core Flow Design Basis	4.4-3
4.4.1.4	Hydrodynamic Stability Design Bases	4.4-4
4.4.1.5	Other Considerations	4.4-4
4.4.2	Description	4.4-5
4.4.2.1	Summary Comparison	4.4-5
4.4.2.2	Fuel Cladding Temperatures (Including Densification)	4.4-7
4.4.2.2.1	Uranium Dioxide Thermal Conductivity	4.4-9

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Title</u>	<u>Page</u>
4.4.2.2.2	Radial Power Distribution in UO Fuel Rods	4.4-10
4.4.2.2.3	Gap Conductance	4.4-10
4.4.2.2.4	Surface Heat Transfer Coefficients	4.4-12
4.4.2.2.5	Fuel Clad Temperatures	4.4-12
4.4.2.3	Critical Heat Flux Ratio or Departure from Nucleate Boiling Ratio and Mixing Technology	4.4-13
4.4.2.3.1	Departure from Nucleate Boiling Technology	4.4-14
4.4.2.3.2	Definition of Departure from Nucleate Boiling Ratio	4.4-15a
4.4.2.3.3	Mixing Technology	4.4-17a
4.4.2.3.4	Engineering Hot-Channel Factors	4.4-19
4.4.2.3.5	Effects of Rod Bow on DNER	4.4-21a
4.4.2.3.6	Transition Core DNB Methodology	4.4-21a
4.4.2.4	Flux Tilt Considerations	4.4-22
4.4.2.5	Void Fraction Distribution	4.4-22
4.4.2.6	Core Coolant Flow Distribution	4.4-23
4.4.2.7	Core Pressure Drops and Hydraulic Loads	4.4-23
4.4.2.7.1	Core Pressure Drops	4.4-23
4.4.2.7.2	Hydraulic Loads	4.4-24
4.4.2.8	Correlation and Physical Data	4.4-25
4.4.2.8.1	Surface Heat Transfer Coefficients	4.4-25
4.4.2.8.2	Total Core and Vessel Pressure Drop	4.4-26
4.4.2.8.3	Void Fraction Correlation	4.4-27
4.4.2.9	Thermal Effects of Operational Transients	4.4-28
4.4.2.10	Uncertainties in Estimates	4.4-29
4.4.2.10.1	Uncertainties in Fuel and Clad Temperatures	4.4-29
4.4.2.10.2	Uncertainties in Pressure Drops	4.4-30
4.4.2.10.3	Uncertainties Due to Inlet Flow Maldistribution	4.4-30
4.4.2.10.4	Uncertainty in DNB Correlation	4.4-30

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Title</u>	<u>Page</u>
4.4.2.10.5	Uncertainties in DNBR Calculations	4.4-30
4.4.2.10.6	Uncertainties in Flow Rates	4.4-31
4.4.2.10.7	Uncertainties in Hydraulic Loads	4.4-31
4.4.2.10.8	Uncertainty in Mixing Coefficients	4.4-32
4.4.2.11	Plant Configuration Data	4.4-32
4.4.3	Evaluation	4.4-33
4.4.3.1	Core Hydraulics	4.4-33
4.4.3.1.1	Flow Paths Considered in Core Pressure Drop and Thermal Design	4.4-33
4.4.3.1.2	Inlet Flow Distributions	4.4-34
4.4.3.1.3	Empirical Friction Factor Correlations	4.4-35
4.4.3.2	Influence of Power Distribution	4.4-36
4.4.3.2.1	Nuclear Enthalpy Rise Hot Channel Factor	4.4-37
4.4.3.2.2	Axial Heat Flux Distributions	4.4-38
4.4.3.3	Core Thermal Response	4.4-38
4.4.3.4	Analytical Techniques	4.4-39
4.4.3.4.1	Core Analysis	4.4-39
4.4.3.4.2	Fuel Temperatures	4.4-47
4.4.3.4.3	Hydrodynamic Instability	4.4-47
4.4.3.5	Hydrodynamic and Flow Power Coupled Instability	4.4-47
4.4.3.6	Temperature Transient Effects Analysis	4.4-50
4.4.3.7	Potentially Damaging Temperature Effects During Transients	4.4-51
4.4.3.8	Energy Release During Fuel Element Burnout	4.4-52
4.4.3.9	Energy Release or Rupture of Water- logged Fuel Elements	4.4-53
4.4.3.10	Fuel Rod Behavior Effects from Coolant Flow Blockage	4.4-53
4.4.4	Testing and Verification	4.4-55
4.4.4.1	Tests Prior to Initial Criticality	4.4-55

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Title</u>	<u>Page</u>
4.4.4.2	Initial Power and Plant Operation	4.4-55
4.4.4.3	Component and Fuel Inspections	4.4-56
4.4.4.4	Augmented Startup Test Program	4.4-56
4.4.5	References for Section 4.4	4.4-56
4.5	RELOAD ANALYSIS	4.5-1
4.5.1	References for Section 4.5	4.5-2

LIST OF TABLES

<u>Table</u>	<u>Title</u>
4.1-1	Thermal and Hydraulic Design
4.1-2	Analytic Techniques Incore Design
4.1-3	Design Loading Conditions for Reactor Core Components
4.2-1	Maximum Deflections Allowed for Reactor Internal Support Structures
4.2-2	Comparison of Single and Double Encapsulated Secondary Source Designs
4.3-1	Reactor Core Description
4.3-2	Nuclear Design Parameters
4.3-3	Reactivity Requirements for Rod Cluster Control Assemblies
4.3-4	Axial Stability Index-PWR Core With a 12-Foot Height
4.3-5	Typical Neutron Flux Levels at Full Power
4.3-6	Comparison of Measured and Calculated Doppler Defects
4.3-7	Benchmark Critical Experiments

LIST OF TABLES (Cont)

<u>Table</u>	<u>Title</u>
4.3-8	Saxton Core II Isotopics, Rod MY, Axial Zone 6
4.3-9	Critical Boron Concentrations, HZP, BOL
4.3-10	Comparison of Measured and Calculated Rod Worth
4.3-11	Comparison of Measured and Calculated Moderator Coefficients at HZP, BOL
4.4-1	Reactor Thermal and Hydraulic Design Parameters
4.4-2	(This text has been deleted)
4.4-3	Void Fractions at Nominal Reactor Conditions With Design Hot Channel Factors
4.4-4	Comparison of THINC-IV and THINC-I Predictions With Data From Representative Westinghouse Two and Three Loop Reactors
4.5-1	(This text has been deleted)
4.5-2	(This text has been deleted)

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>
4.2-1	Fuel Assembly Cross Section - 17 x 17
4.2-2	Standard Fuel Assembly Outline - 17 x 17
4.2-2A	17 x 17 Vantage+/Vantage 5H Fuel Assembly Comparison
4.2-2B	17 x 17 Standard Robust Fuel Assembly Outline
4.2-2C	17 x 17 RFA ZIRLO TM +2 Outline
4.2-3	Standard Fuel Rod Schematic
4.2-3A	17 x 17 Vantage+/Vantage 5H Fuel Rod Comparison
4.2-3B	17 x 17 Standard RFA Fuel Rod Schematic
4.2-3C	17 x 17 RFA ZIRLO TM +2 Fuel Rod Schematic
4.2-4	Typical Clad and Pellet Dimensions as a Function of Exposure
4.2-5	Plan View
4.2-6	Representative Fuel Rod Internal Pressure and Linear Power Density for the Lead Burnup Rod as a Function of Time
4.2-7	Top Grid to Nozzle Attachment
4.2-8	Lower Core Support Assembly
4.2-9	Elevation View, Grid to Thimble Attachment
4.2-10	Upper Core Support Structure
4.2-11	Guide Thimble to Bottom Nozzle Joint
4.2-12	Plan View of Upper Core Support Structure
4.2-13	Full Length Rod Cluster Control and Drive Rod Assembly With Interfacing Components

LIST OF FIGURES (Cont)

<u>Figure</u>	<u>Title</u>
4.2-14	Full Length Rod Cluster Control Assembly Outline
4.2-15	Full Length Absorber Rod
4.2-16	Burnable Absorber Assembly
4.2-17	Pyrex Burnable Poison Rod Cross Section
4.2-17A	WABA Rod Cross Section
4.2-18	Primary Source Assembly
4.2-19	Single Encapsulated Secondary Source
4.2-20	Thimble Plug Assembly (Optional Usage)
4.2-21	Full Length Control Rod Drive Mechanism
4.2-22	Full Length Control Rod Drive Mechanism Schematic
4.2-23	Nominal Latch Clearance at Minimum and Maximum Temperature
4.2-24	Control Rod Drive Mechanism Latch Clearance Thermal Effect
4.2-25	Schematic Representation of Reactor Core Model
4.3-1	Production and Consumption of Higher Isotopes
4.3-2	Boron Concentration vs Cycle Burnup (Typical)
4.3-3	Normalized Power Density Distribution At BOL, Unrodded Core, HFP, No Xenon (Typical)
4.3-4	Normalized Power Density, Distribution Near BOL, Unrodded Core, HFP, Equilibrium Xenon (Typical)

LIST OF FIGURES (Cont)

<u>Figure</u>	<u>Title</u>
4.3-5	Normalized Power Density Distribution Near BOL, Group D Inserted, HFP, Equilibrium Xenon (Typical)
4.3-6	Normalized Power Density Distribution Near Middle of Life, Unrodded Core, HFP, Equilibrium Xenon (Typical)
4.3-7	Normalized Power Density Distribution Near EOL, Unrodded Core, HFP, Equilibrium Xenon (Typical)
4.3-8	Typical Axial Power Shapes Occurring at Beginning of Life
4.3-9	Typical Axial Power Shapes Occurring at Middle of Life
4.3-10	Typical Axial Power Shapes Occurring at End of Life
4.3-11	Maximum F_0 -Power vs Axial Height During Normal Operation
4.3-12	Peak Power Density During Control Rod Malfunction Overpower Transients
4.3-13	Peak Linear Power During Boration/Dilution Overpower Transients
4.3-14	Comparison Between Calculated and Measured Relative Fuel Assembly Power Distribution
4.3-15	Comparison of Calculated and Measured Axial Shape
4.3-16	Measured Values of F_0 for Full Power Rod Configuration
4.3-17	Doppler Temperature Coefficient at BOL and EOL, (Typical)
4.3-18	Doppler Power Coefficient-BOL, MOL, EOL, (Typical)
4.3-19	Doppler Power Defect-BOL, MOL, EOL, (Typical)
4.3-20	Moderator Temperature Coefficient-BOL, ARO (Typical)

LIST OF FIGURES (Cont)

<u>Figure</u>	<u>Title</u>
4.3-21	Moderator Temperature Coefficient-EOL, ARO (Typical)
4.3-22	Moderator Temperature Coefficient as a Function of Boron Concentration, BOL, ARO (Typical)
4.3-23	Hot Full Power Moderator Temperature Coefficient vs Cycle Burnup (Typical)
4.3-24	Total Power Coefficient-BOL, EOL (Typical)
4.3-25	Total Power Defect-BOL, EOL (Typical)
4.3-26A	Rod Cluster Control Assembly Pattern - Unit 1
4.3-26B	Rod Cluster Control Assembly Pattern - Unit 2
4.3-27	Accidental Simultaneous Withdrawal of 2 Control Banks EOL, HZP, Banks D&B Moving in the Same Plane
4.3-28	Design Trip Curve
4.3-29	Normalized Rod Worth vs Percent Insertion All Rods But One
4.3-30	Axial Offset vs Time-PWR Core With a 12-Foot Height and 121 Assemblies
4.3-31	XY Xenon Test Thermocouple Response Quadrant Tilt Difference vs Time
4.3-32	Calculated and Measured Doppler Defect and Coefficients at BOL, Two-Loop Plant, 121 Assemblies, 12-Foot Core
4.3-33	Comparison of Calculated and Measured Boron Concentration for 2-Loop Plant, 121 Assemblies, 12-foot Core
4.3-34	Comparison of Calculated and Measured C_B 2-Loop with 121 Assemblies, 12-Foot Core

LIST OF FIGURES (Cont)

<u>Figure</u>	<u>Title</u>
4.3-35	Comparison of Calculated and Measured c_B 3-Loop Plant, 157 Assemblies, 12-Foot core
4.4-1	Peak Fuel Average and Surface Temperatures During Fuel Rod Lifetime vs Linear Power
4.4-1A	Peak Fuel Average and Surface Temperatures During Fuel Rod Lifetime vs Linear Power for Vantage-5H fuel
4.4-2	Peak Fuel Centerline Temperature During Fuel Rod Lifetime vs Linear Power
4.4-2A	Peak Fuel Centerline Temperatures During Fuel Rod Lifetime vs Linear Power for Vantage-5H fuel
4.4-3	Thermal Conductivity of UO_2 (Data Corrected to 95% Theoretical Density)
4.4-4	Axial Variation of Average Clad Temperature for Rod Operating at 5.43 kW/ft
4.4-5A	Comparison of Measured to Predicted 17 x 17 DNB Data
4.4-5B	Measured vs Predicted Critical Heat Flux - WRB-1 Correlation
4.4-5C	Measured Critical Heat Flux - WRB-2 Correlation
4.4-6	TDC vs Reynold's Number for 26-Inch Grid Spacing
4.4-7	Normalized Radial Flow and Enthalpy Distribution at 4-Foot Elevation
4.4-8	Normalized Radial Flow and Enthalpy Distribution at 8-Foot Elevation

LIST OF FIGURES (Cont)

<u>Figure</u>	<u>Title</u>
4.4-9	Normalized Radial Flow and Enthalpy Distribution at 12-Foot Elevation (Unit 2)
4.4-10	Void Fraction vs Thermodynamic Quality $H-H_{SAT}/H_g-H_{SAT}$
4.4-11	PWR Natural Circulation Test
4.4-12	Comparison of a Representative Westinghouse Two-Loop Reactor Incore Thermocouple Measurements With THINC-IV Predictions
4.4-13	Comparison of a Representative Westinghouse Three-Loop Reactor Incore Thermocouple Measurements With THINC-IV Predictions
4.4-14	Hanford Subchannel Temperature Data Comparison With THINC-IV
4.4-15	Hanford Subcritical Temperature Data Comparison With THINC-IV
4.4-16	Distribution of Incore Instrumentation - Unit 1
4.4-17	Distribution of Incore Instrumentation - Unit 2
4.5-1	Typical Salem Unit 1 Loading Pattern
4.5-2	Typical Salem Unit 1 Burnable Absorber Configuration
4.5-3	Typical Salem Unit 2 Loading Pattern
4.5-4	Typical Salem Unit 2 Burnable Absorber Configuration