OVERVIEW DESCRIPTION
OF THE
CORE OPERATING LIMIT SUPERVISORY SYSTEM
(COLSS)

CEN-312-NP

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Nuclear Power Systems

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ABSTRACT

A nuclear power plant must be maintained within its limiting conditions for operation as specified in the plant Technical Specifications to assure safe operation. The Core Operating Limit Supervisory System (COLSS) aids the operator in maintaining operating margin to limits on linear heat rate and departure from nucleate boiling. To do so, COLSS uses measurements of incore detector signals, CEA positions and plant thermal/hydraulic properties to determine the core power distribution and thermal performance.

This report provides a general description of the scope and methodology of the COLSS algorithms. It is provided solely for information to be used as a reference during future reviews of submittals on the dockets of C-E supplied NSSS's that utilize COLSS.

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GLOSSARY OF TERMS

AOO	-	Anticipated Operational Occurrence
ASI	-	Axial Shape Index
CEA	-	Control Element Assembly
CHF	-	Critical Heat Flux
COLSS	-	Core Operating Limit Supervisory System
CPC	-	Core Protection Calculator
CRT	-	Cathode Ray Tube (display)
DNB	-	Departure From Nucleate Boiling
DNBR	-	Departure From Nucleate Boiling Ratio
DNB-OPM	-	Departure From Nucleate Boiling Overpower Margin
DP	-	Differential Pressure
F_{xy}	-	Planar Radial Power Peaking Factor
KW/FT	-	Kilowatts per Foot
LCO	-	Limiting Condition for Operation
LHR	-	Linear Heat Rate
LOCA	-	Loss of Coolant Accident
LOF	-	Loss of Flow (event)
NSSS	-	Nuclear Steam Supply System
PDIL	-	Power Dependent Insertion Limit
POL	-	Power Operating Limit
RCP	-	Reactor Coolant Pump
RCS	-	Reactor Coolant System
RTD	-	Resistance Temperature Detector

[ ]

1.0 Introduction and Summary

Maintaining a nuclear power plant within its Limiting Conditions for Operation (LCO) is a necessary condition for safe operation and acceptable transient consequences. These LCOs are delineated in the Technical Specifications. There are many systems in a nuclear power plant that are used to help the operators maintain the limiting conditions for operation. One such system used in some C-E supplied NSSSs is the Core Operating Limit Supervisory System (COLSS). COLSS is a digital computer based on-line monitoring system that is used to provide information to aid the operator in complying with the Technical Specifications operating limits on total core power, peak Linear Heat Rate (LHR), Departure from Nucleate Boiling Ratio (DNBR), Axial Shape Index (ASI), and azimuthal power tilt. The C-E Standard Technical Specifications discuss the importance and purpose of these operating limits in the bases for Section 3.2. The system is used at the following plants:

1) Arkansas Nuclear One Unit 2,
2) San Onofre Nuclear Generating Station Units 2 and 3,
3) Waterford Unit 3, and
4) Palo Verde Nuclear Generating Station Units 1, 2, and 3.

COLSS uses input from selected sensors to determine the plant condition and displays this condition to the operator in a form which allows easy interpretation of reactor core status. Audible alarms and visual CRT messages are provided to alert the operator when an operating limit is exceeded. COLSS is a monitoring system and does not activate any safety equipment, initiate any automatic actions, or provide any direct input to safety systems. The major calculations performed by COLSS are:

1) Core Power,
2) Core Power Distribution,
3) Margin to Minimum Departure from Nucleate Boiling Ratio,
4) Margin to Linear Heat Rate Limit, and
5) Core Azimuthal Power Tilt Magnitude.

The purpose of this report is to provide a general description of COLSS for reference during future review of submittals on the dockets of C-E supplied NSSSs that utilize COLSS. To meet this purpose, the report describes:

1) COLSS monitoring and alarms which aid the operator in maintaining the appropriate Technical Specification operating limits,
2) sensor data and its processing for input to COLSS,
3) COLSS algorithm functions, and
4) determination of constants for use in COLSS.

The accuracy of the information supplied by COLSS to the operator was originally evaluated in Reference 1. Generic and plant specific documents such as References 5 and 8, have described updates to the uncertainty evaluation methods that have evolved since the issuance of Reference 1.

2.0 COLSS Description

2.1 Purpose of the COLSS System

The plant Technical Specifications specify Limiting Conditions for Operation of plant systems, components, and parameters. Monitoring systems are provided to assist the operator in meeting these Technical Specification requirements. COLSS is a monitoring system that assists the plant operator in maintaining the Limiting Conditions for Operation (LCO) specified in the following Technical Specifications:

1) 3.2.1 Linear Heat Rate,
2) 3.2.3 Azimuthal Power Tilt,
3) 3.2.4 DNBR Margin,
4) 3.2.7 Axial Shape Index, and, for some plants,
5) 3.3.3.2 Incore Detector Operability.

An audible alarm and a visual CRT alarm message is initiated whenever any of the parameters indicated above do not satisfy the LCO conditions required by the Technical Specifications.

COLSS monitoring is accomplished by performing calculations using incore detector signals, CEA positions, primary and secondary coolant pressure measurements, and various temperature measurements and flow measurements to monitor the following parameters:

1) margin to the peak Linear Heat Rate (LHR) limit,

2) margin to the Departure from Nucleate Boiling Ratio (DNBR) limit,

3) margin to the licensed total core power,

4) azimuthal tilt, and

5) Axial Shape Index (ASI).

The function of the COLSS in the overall plant monitoring and protection system is illustrated in Figure 2-1. The protection function is provided by the Core Protection Calculators (CPC) which cause a plant trip if necessary to avoid violation of fuel design limits on LHR or DNBR. The COLSS monitoring system reviews system behavior and alerts the plant operator to situations where LHR or DNBR have reached their monitoring limits. In addition, COLSS alerts the operator when other plant parameters (e.g., azimuthal tilt or axial shape) are at prespecified limits. The Technical Specifications require periodic review of specific aspects of the operation of both the monitoring and protection systems relative to detailed calculations or specific measurements to verify acceptable operation and recalibrate as required.

2.2 Overview of COLSS Operation

The COLSS algorithms provide an integrated approach to monitoring those system parameters important to the evaluation of LHR and DNBR. Rather than restricting each parameter individually, COLSS uses its inputs to simulate the core power distribution which is then used to directly evaluate the current LHR and DNBR. From this evaluation, the power margin to the DNBR limit, to the LHR limit, and to the licensed plant power are determined and compared to alarm setpoints which monitor the requirements of the Technical Specifications. Additional alarm limits are provided on Axial Shape Index (ASI) and azimuthal tilt. If an alarm setpoint is violated, an alarm sequence is initiated to alert the operator to the violation. The functional block diagram of Figure 2-2 illustrates the overall COLSS algorithm.

2.2.1 System Inputs

Table 2-1 provides a typical list of COLSS monitored variables. The specific number of sensors and the sensor ranges can vary from plant to plant depending on installed instrumentation. Figure 2-3 shows typical COLSS sensor locations. All COLSS sensors are sampled at one second intervals except for the CEA position indications, which are sampled at ten second intervals, and the incore detectors, which are sampled at two second intervals for some plants.

2.2.2 Process Measurement Processing

The plant computer process control executive program processes system inputs for use by COLSS. This processing includes taking the measurements, checking the values against transducer limits, and conversion of measurements to engineering units. If a measurement exceeds the associated transducer limits, it is identified as invalid for use in later algorithms.

Additional measurement validity checking is performed internal to COLSS including [ ]

This checking will alert the operator to the gradual deterioration of a sensor.

When data being obtained from a sensor is determined to be invalid, the operator is informed of the sensor failure by alarm and the data is marked within COLSS as being invalid.

[ ]

2.2.3 COLSS Calculations

Portions of the COLSS calculations are performed at one, ten, and thirty second intervals and are synchronized with data acquisition rates. (E.G., incore instruments are polled at 2 second intervals but used in COLSS power distribution synthesis at 10 second intervals.) Calculations performed at one second intervals include:

1) measurement processing,
2) reactor vessel volumetric flow calculation,
3) plant power calculation based on:
   a) turbine first stage pressure
   b) reactor coolant temperature rise across the core
4) update of the DNB power operating limit since the latest detailed calculation, and
5) comparison of the plant power to calculated limits.

Calculations performed at ten second intervals include:

1) axial power distribution synthesis,
2) azimuthal tilt calculations, and

3) local power density power operating limit calculations.

4) comparison of ASI and azimuthal tilt to allowed limits.

Calculations performed at thirty second intervals include:

1) secondary calorimetric calculations of reactor power, and

2) thermal margin power operating limit calculations.

2.2.3.1 Volumetric Flow Calculation

The volumetric flow for a single pump is based on differential pressure across the pump, pump rotational speed, and water properties from the measured values of cold leg temperature and primary system pressure. The total reactor coolant system flow is derived by summing the individual pump flows.

2.2.3.2 Core Power Calculation

Core power is determined by an auctioneering process between power values calculated by a primary side calorimetric and a correlation to turbine first stage pressure, both of which are calibrated periodically to the secondary side calorimetric. The primary calorimetric power is derived from the calculated volumetric flow and water properties based on measured values of cold leg temperature, hot leg temperature, and reactor coolant system pressure. The estimate of reactor power from turbine pressure is based on a third order polynomial fit to turbine first stage pressure. The secondary calorimetric power is derived from the measured values of feedwater flow*, feedwater temperature, steam flow*, and secondary steam pressure. Appropriate allowances for energy gains and losses are included.

2.2.3.3 Power Distribution Calculation

Signals from the fixed in-core neutron detectors and signals from the CEA pulse counter position indicators supply the input to the power distribution calculations. The calculations performed include:

1) Determination of planar radial peaking factors based on CEAs present in each axial plane,
2) Calculation of a normalized 40 node axial power distribution and a 3-D power peaking factor for use in the calculation of the LHR power operating limit,
3) Calculation of a core average axial shape index (ASI),
4) Determination of a [ ] node hot channel axial power distribution and associated integrated radial peak for use in the calculation of the thermal margin power operating limit to DNB, and
5) Calculation of azimuthal power tilt.

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*Both Feedwater flow and steam flow are determined from differential pressure measurement across known flow restrictions.

2.2.3.4 Secondary Calorimetric Power Calculation

Secondary calorimetric power is derived from measurements of steam header pressure, feedwater flow (as differential pressure), feedwater temperature, and steam flow (as differential pressure). These inputs are used to perform an energy balance on each steam generator and then the separate results are added. Corrections are made to the secondary calorimetric power for energy additions to and losses from the system, including letdown and charging pump flows, reactor coolant pump heat input, pressurizer heat input, and heat losses from NSSS components.

2.2.3.5 Linear Heat Rate Power Operating Limit Calculation

The power operating limit is based on the core average full power linear heat rate, the linear heat rate limits (historically set by the LOCA), the calculated 3-D power peaking factor, and the calculated azimuthal tilt. The LHR limit can be provided as a function of both inlet temperature and axial position.

2.2.3.6 Thermal Margin Power Operating Limit Calculation

The thermal margin power operating limit calculation is based on the same methods used in the C-E developed thermal margin design computer code (CETOP) and incorporates the CE-1 Critical Heat Flux (CHF) correlation (see References 2 and 3). This calculation uses measured data from cold leg temperature sensors and reactor coolant system pressure sensors along with the hot channel axial power distribution and the primary system volumetric flow calculated previously. This calculation contains an allowance for the margin required by the LCOs for AOOs. The detailed calculation is performed at 30 second intervals and is updated at one second intervals based on changes in reactor coolant system pressure, cold leg temperature, reactor coolant volumetric flow rate, azimuthal tilt, and integrated radial peaking factors to provide the operator with a smoother response to changes in plant conditions.

2.2.3.7 Core Power Margin Calculation

The core power margin calculation compares the actual power to the thermal margin and LHR power operating limits (POL) and to the licensed power limit. Two sets of checks are done. The first set consists of two margin calculations using the present value of the core power and two POLs. The second set consists of three margin calculations using running averages of both the power and the two POLs and includes calculation of the margin to the licensed power limit. These latter three margins are called "smoothed" margins. In all, five margins are calculated and compared to appropriate limits. The smallest of the smoothed margins is selected for display on the digital panel meter and the CRT display.

2.2.4 COLSS Outputs

A typical set of dedicated COLSS outputs to the plant operator are listed in Table 2-2. These outputs include displays of core power, power operating limits, the minimum margin to any power operating limit, the COLSS master alarm, and the azimuthal tilt alarm. The COLSS master alarm is activated when licensed power is exceeded, when either power operating limit is exceeded, or when a valid value of plant power or a power operating limit is unavailable. This alarm is also activated when COLSS has been bypassed for testing. Sample messages that can be displayed on the COLSS alarm CRT are given in Figure 2-4. Additional displays and reports are incorporated in COLSS to assist the operator in monitoring the operation of the NSSS and in evaluating COLSS alarms. These additional outputs are:

1) CRT displays of several hundred internal parameters (Figure 2-5 gives a sample of the types of parameters included),
2) a detailed printed report of all inputs and outputs,
3) an axial power distribution plot as illustrated in Figure 2-6,
4) a COLSS Failed Sensor Report listing all sensors inputs that have failed validity checking, and
5) a Test Mode Report to verify correct operation of the COLSS program.

TABLE 2-1

TYPICAL COLSS MONITORED PLANT VARIABLES

Measurement	Sensors	Typical Number	Typical Range & Units
Core volumetric flow	Reactor coolant pump rotational speed	2 per pump	100 - 1200 RPM
	Reactor coolant pump differential pressure	2 per pump	0 - 150 PSID
Core power			
Primary calorimetric	Cold leg temperature	1 per cold leg	
	Narrow range		525 - 625F
	Wide range		0 - 600F
	Hot leg temperature	1 per hot leg	525 - 675F
Secondary calorimetric	Feedwater flow	1 per generator	0 - 780 in water
	Steam flow ΔP	1 per generator	0 - 660 in water
	Feedwater temperature	1 per generator	0 - 100 - 500F
	Steam pressure	1 per generator	850 - 1050 PSIG
Core power distribution	In-core monitoring system	44 to 61 incore assemblies with 5 axially stacked detectors each	NA (power distribution is provided graphically)
	CEA position	1 per CEA	0 - 150 inches
Reactor coolant pressure	Pressurizer pressure	2 (on pressurizer)	1,500-2,500 PSIA
Turbine power	Turbine first stage steam pressure	2 (on turbine)	0-1,000 PSIA

TABLE 2-2

TYPICAL DEDICATED COLSS OUTPUTS

OUTPUT QUANTITY	TYPICAL DISPLAY RANGE	UNITS	UPDATE FREQUENCY	OUTPUT TYPE
Plant Power	0 to 125	% Power	1 Sec.	Analog
Power Operating Limit based on Linear Heat Rate	0 to 125	% Power	1 Sec.	Analog
Power Operating Limit based on Thermal Margin	0 to 125	% Power	1 Sec.	Analog
Minimum Margin to an Operating Limit	-50.0 to 125.9	% Power	1 Sec.	Digital 4 Digit
Axial Shape Index	-.7 to +.7	-	10 Sec.	Analog
Margin alarm	close - open	-	1 Sec.	Contact
CPC Azimuthal Tilt alarm	close - open	-	10 Sec.	Contact
Tech. Specification Azimuthal Tilt alarm	close - open	-	10 Sec.	Contact
Axial Shape Index out of limits alarm	close - open	-	10 Sec.	Contact

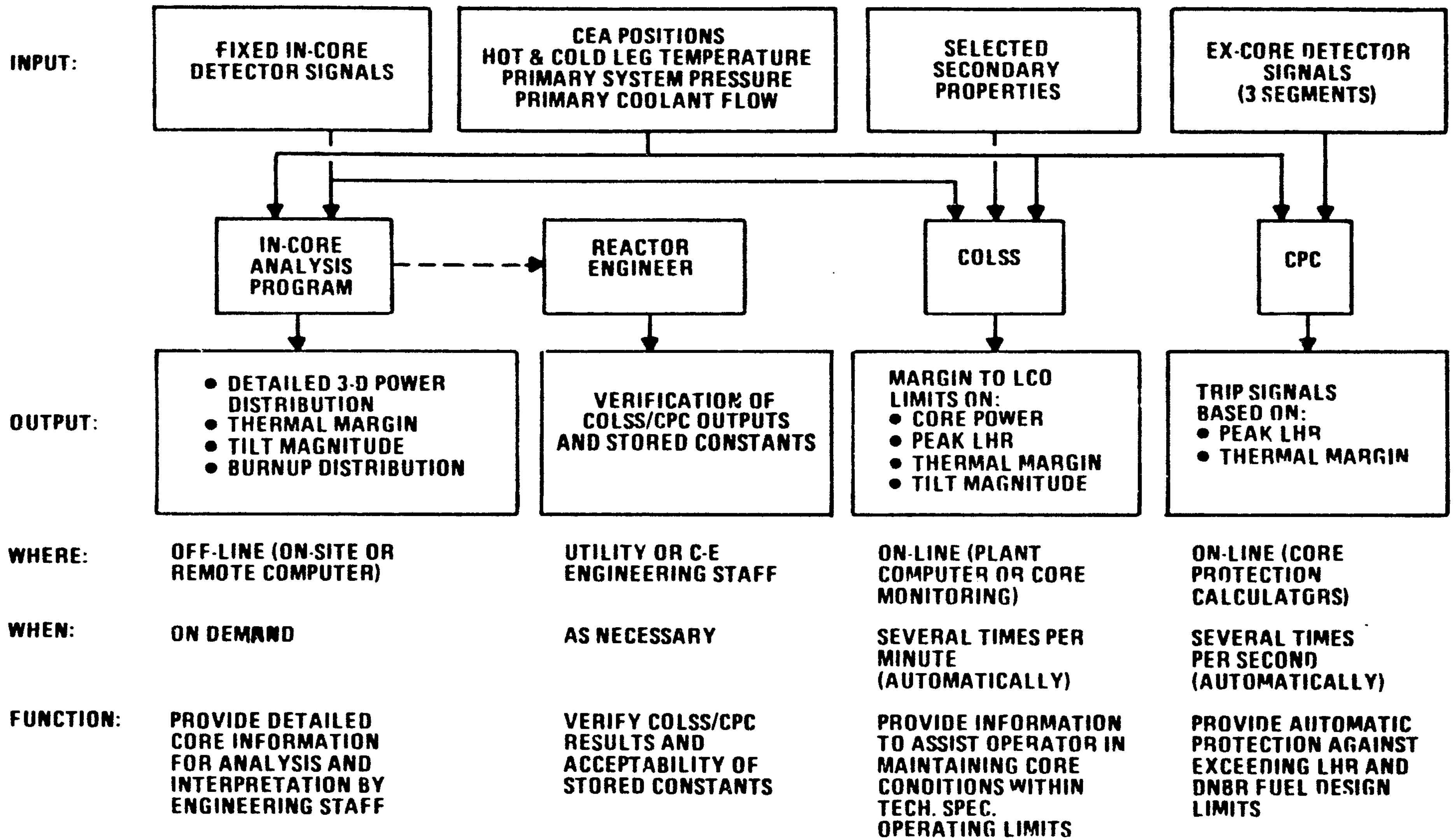


FIGURE 2-1
OVERVIEW OF C-E CORE MONITORING AND PROTECTION SYSTEMS

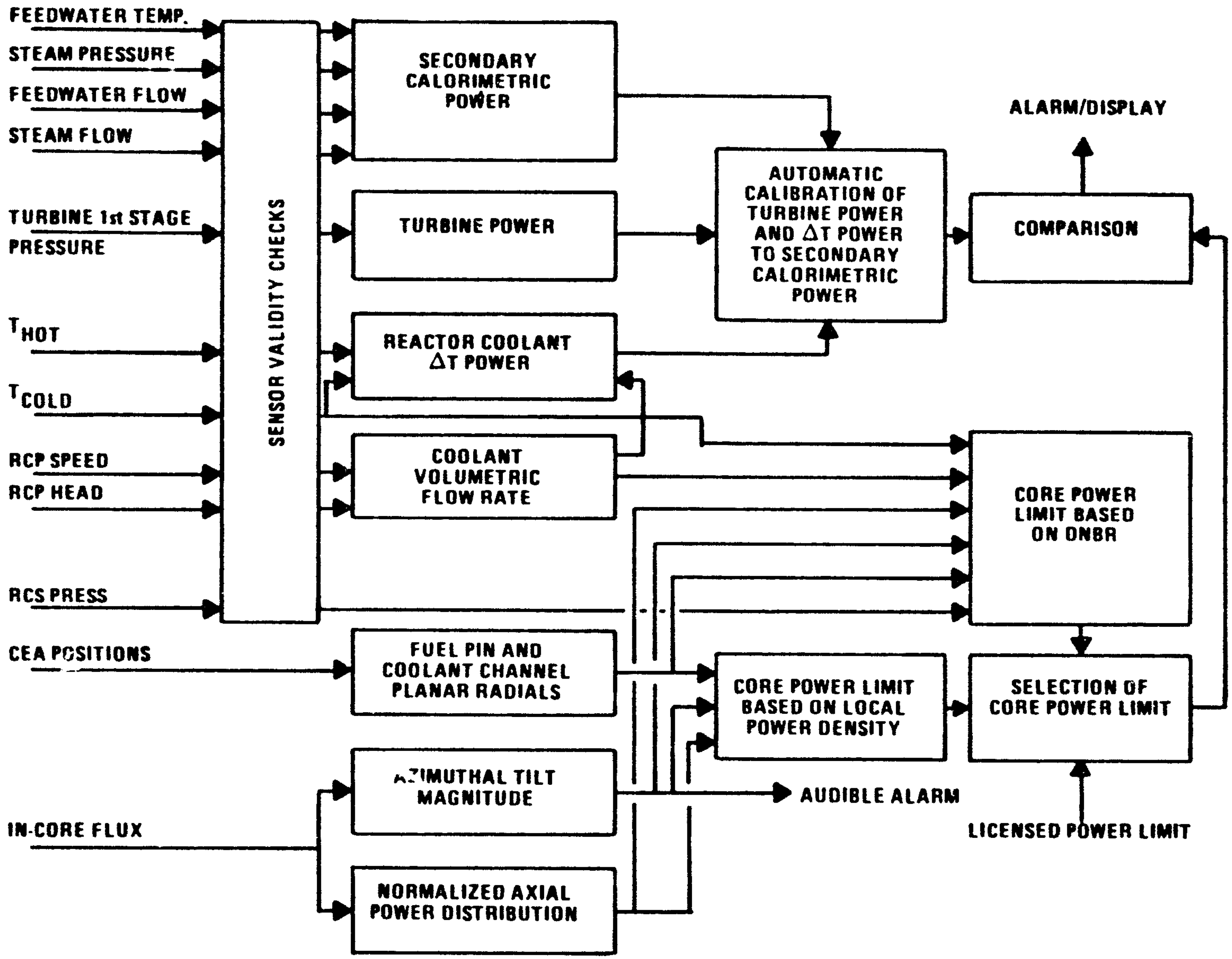
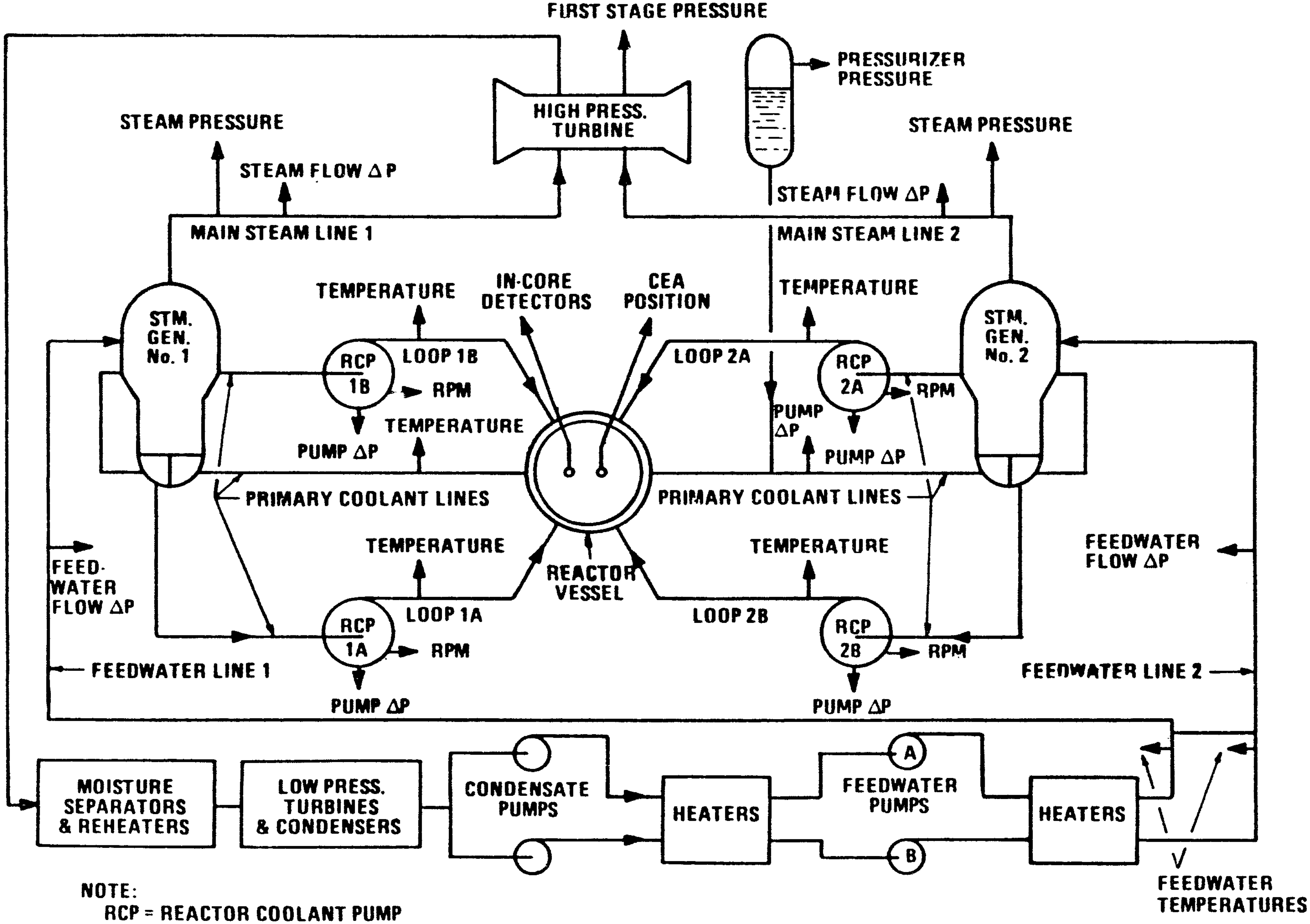


FIGURE 2-2
FUNCTIONAL DIAGRAM OF THE CORE OPERATING LIMIT SUPERVISORY SYSTEM

FIGURE 2-3
COLSS SENSOR LOCATIONS



NOTE:
RCP = REACTOR COOLANT PUMP

FIGURE 2-4

TYPICAL ALARM CRT MESSAGES

Alarm 1 Messages

(TIME)			
XX:XX:XX	ALARM	COLSS	DNBR POWER LIMIT EXCEEDED
XX:XX:XX	ALARM	COLSS	KW/FT POWER LIMIT EXCEEDED
XX:XX:XX	ALARM	COLSS	LICENSED POWER LIMIT EXCEEDED
XX:XX:XX	ALARM	COLSS	INSTANTANEOUS DNBR POWER LIMIT EXCEEDED
XX:XX:XX	ALARM	COLSS	INSTANTANEOUS KW/FT POWER LIMIT EXCEEDED
XX:XX:XX	ALARM	COLSS	LPL ALARM DURATION EXCEEDED
XX:XX:XX	ALARM	COLSS	DNBR ALARM DURATION EXCEEDED
XX:XX:XX	ALARM	COLSS	KW/FT ALARM DURATION EXCEEDED

ALARM 2 and ALARM 3 Messages

XX:XX:XX	ALARM	COLSS	CPC TILT LIMIT EXCEEDED
XX:XX:XX	ALARM	COLSS	TECH SPEC TILT LIMIT EXCEEDED
XX:XX:XX	ALARM	COLSS	CPC TILT ALARM DURATION EXCEEDED
XX:XX:XX	ALARM	COLSS	TECH SPEC TILT ALARM DURATION EXCEEDED

Alarm 4 Messages

XX:XX:XX	ALARM	COLSS	ASI OUT OF LIMITS
XX:XX:XX	ALARM	COLSS	ASI ALARM DURATION EXCEEDED

Other Alarm Messages

XX:XX:XX	ALARM	COLSS	REMOVED FROM SERVICE
XX:XX:XX	ALARM	COLSS	HOT LEG DEVIATION EXCEEDED

FIGURE 2-5

SAMPLE PARAMETERS FOR CRT DISPLAY

Parameter Description	Usage	Units
COLSS HOT LEG TEMP-LOOP 1	INPUT	DEG F
COLSS HOT LEG TEMP_LOOP 2	INPUT	DEG F
COLSS TURB 1ST STAGE PRES,PR	INPUT	PSIA
COLSS TURB 1ST STAGE PRES,AL	INPUT	PSIA
COLSS FW OUTLET TEMP, SG1	INPUT	DEG F
COLSS FW OUTLET TEMP, SG2	INPUT	DEG F
COLSS FEEDWATER FLOW DP,SG1	INPUT	IN H2O
COLSS FEEDWATER FLOW DP,SG2	INPUT	IN H2O
COLSS SECONDARY STEAM PR,SG1	INPUT	PSIG
COLSS SECONDARY STEAM PR,SG2	INPUT	PSIG
COLSS STEAM FLOW DP, SG1	INPUT	IN H2O
COLSS STEAM FLOW DP, SG2	INPUT	IN H2O
CEA REG GRP 1 MINIMUM POS	INPUT	IN
CEA REG GRP 2 MINIMUM POS	INPUT	IN
CEA REG GRP 3 MINIMUM POS	INPUT	IN
CEA REG GRP 4 MINIMUM POS	INPUT	IN
CEA REG GRP 5 MINIMUM POS	INPUT	IN
CEA REG GRP 6 MINIMUM POS	INPUT	IN
CEA REG GRP 1 MINIMUM POS	INPUT	IN
CEA REG GRP 2 MINIMUM POS	INPUT	IN
CEA S D GRP 1 MINIMUM POS	INPUT	IN
CEA S D GRP 2 MINIMUM POS	INPUT	IN
CEA REG GRP 1 DEVIATION	INPUT	IN
CEA REG GRP 2 DEVIATION	INPUT	IN
CEA REG GRP 3 DEVIATION	INPUT	IN
CEA REG GRP 4 DEVIATION	INPUT	IN
CEA REG GRP 5 DEVIATION	INPUT	IN
CEA REG GRP 6 DEVIATION	INPUT	IN
CEA P L GRP 1 DEVIATION	INPUT	IN
CEA P L GRP 2 DEVIATION	INPUT	IN
CEA S D GRP 1 DEVIATION	INPUT	IN
CEA S D GRP 2 DEVIATION	INPUT	IN
DET SENSTVTY CORR FLUX	INPUT	NV*E14
RCP 1A SPEED	OUTPUT	RPM
RCP 1B SPEED	OUTPUT	RPM
RCP 2A SPEED	OUTPUT	RPM
RCP 2B SPEED	OUTPUT	RPM
RCP 1A DIFF PRESS	OUTPUT	PSID
RCP 1B DIFF PRESS	OUTPUT	PSID
RCP 2A DIFF PRESS	OUTPUT	PSID
RCP 2B DIFF PRESS	OUTPUT	PSID
RCS PRESSRZR PRESS	OUTPUT	PSIA
RCS LOOP 1A COLD LEG TEMP	OUTPUT	DEG F
RCS LOOP 1B COLD LEG TEMP	OUTPUT	DEG F
RCS LOOP 2A COLD LEG TEMP	OUTPUT	DEG F
RCS LOOP 2B COLD LEG TEMP	OUTPUT	DEG F

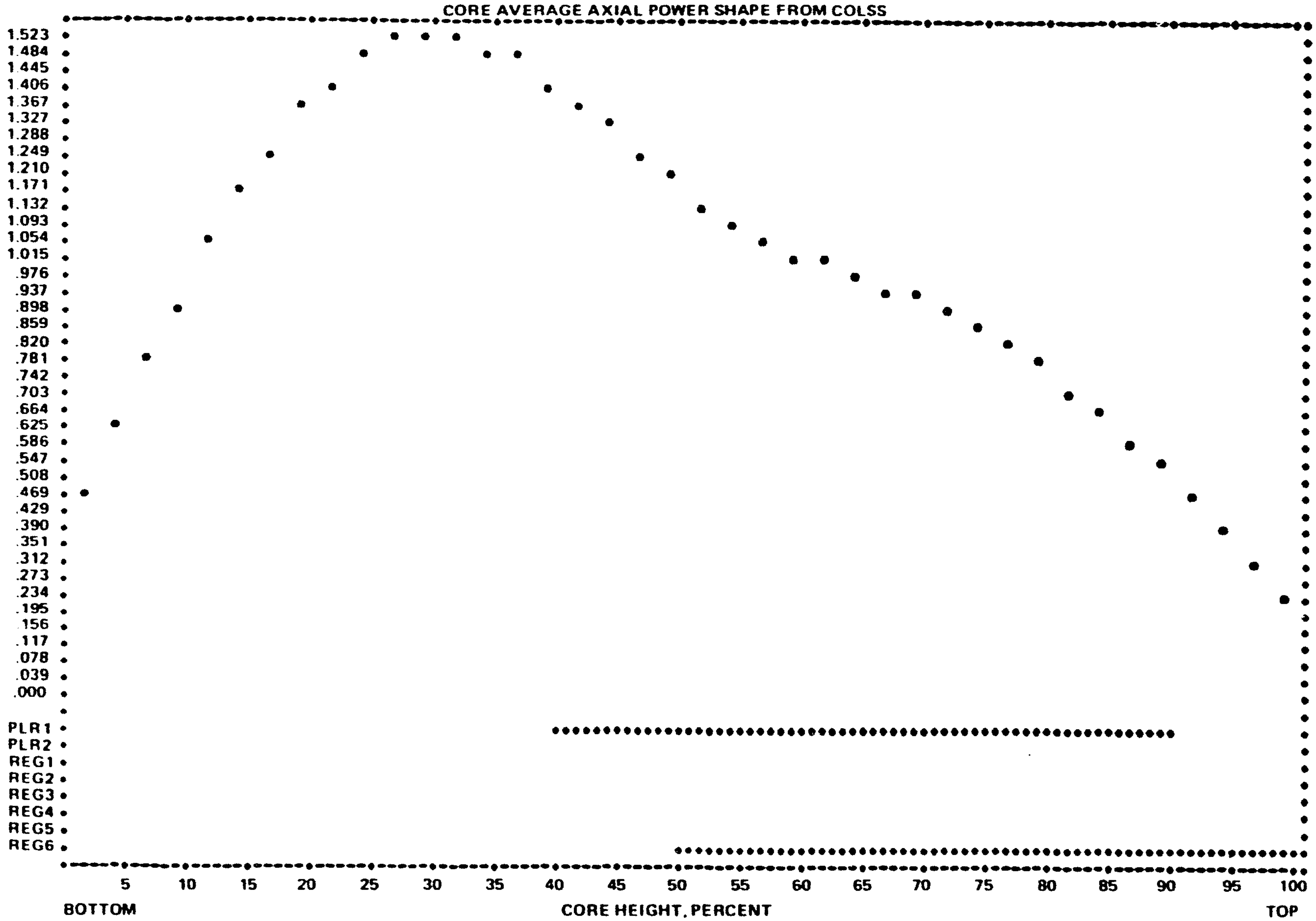


FIGURE 2-6
COLSS POWER DISTRIBUTION PLOT

2.3 Description of COLSS Algorithms

As discussed in the overview (section 2.2), COLSS performs the following major calculations:

1) calculation of reactor coolant system volumetric flow rate,
2) calculation of core power based on:
    a) reactor coolant temperature rise across the core,
    b) turbine first stage pressure, and
    c) secondary system calorimetric,
3) calculation of core power distribution parameters including:
    a) normalized core average axial power distribution.
    b) azimuthal tilt magnitude,
    c) hot channel integrated planar radial peaking factors and 3-D peaking factors, and
4) calculation of power limits based on linear heat rate and on the departure from nucleate boiling ratio (DNBR).

This section provides additional descriptions of these calculations. This material is intended to provide a general description of the scope and methodology implemented in the COLSS algorithms. References are provided, as appropriate, to more detailed reports.

2.3.1 Reactor Coolant System Volumetric Flow

The volumetric flow calculation is performed every second and provides the flow input needed for the calculation of primary calorimetric power and of the power operating limit based on DNBR. The flow through each pump is calculated based on sensor inputs of

1) pump rotational speed,
2) pump differential pressure,
3) cold leg temperature, and
4) Reactor Coolant System (RCS) pressure.

Following validity checking of sensor inputs, the specific volume of the water entering the reactor coolant pumps is determined from cold leg temperature and RCS pressure. The differential pressure is then converted to pump head and is adjusted for the fraction of rated pump speed at which the pump is operating. This result is then used to calculate volumetric flow in gallons per minute based on a polynomial fit to pump speed and the ratio of pump head divided by the square of the fractional pump speed. The coefficients of this fit are derived from pump testing. Total flow is then calculated as the sum of the flows from each of the four pumps*. A normalized vessel volumetric flow is also calculated.

The volumetric flows are also used to determine the mass flow rate for each cold leg as the ratio of the volumetric flow rate to the specific volume of the cold leg water. The total vessel mass flow which is the sum of the flows through the four cold legs, is provided for operator information. Also, a relative total mass flow is calculated and provided to the operator to assist in compliance with flow calibration requirements.

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*allowance is made for core bypass flow in the DNBR calculation

2.3.2 Primary Calorimetric Power

The primary calorimetric power calculation is performed every second. This calculation of power uses the volumetric flow already calculated for each pump plus sensor inputs of:

1) RCS pressure,
2) cold leg temperature, and
3) hot leg temperature.

The primary calorimetric power calculation begins with the compensation of each of the four cold leg temperature indications for sensor time response and plenum mixing time. For each cold leg the compensation uses a digital filter which is implemented using the present and previous values of cold leg temperature and the previous value of the compensated cold leg temperature. The coefficients of this filter are explicitly determined from the time responses and the period of the calculation.

The enthalpy of the water in each hot leg and cold leg is determined from polynomial fits to the measured hot leg temperatures, the compensated cold leg temperatures, and the reactor coolant system pressure. Power is then calculated from the enthalpy change between the cold and hot legs.

2.3.3 Turbine Power

The turbine power calculation is performed every second. The only measured input to this calculation is turbine first stage pressure. The calculated power is given by a third order polynomial fit to the turbine pressure. All coefficients in the fit are determined empirically.

2.3.4 Secondary Calorimetric Power

The secondary calorimetric calculation is performed once per 30 seconds using input values that are averaged over the previous 10 seconds to reduce the impact of sensor noise*. The measured inputs to this calculation for each steam generator are:

1) feedwater flow pressure drop,
2) steam flow pressure drop,
3) feedwater temperature, and
4) secondary steam pressure.

The calculated secondary calorimetric power is the sum of the power transferred to each steam generator and the energy lost from the system, less energy additions to the system.

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* For the Palo Verde COLSS, secondary calorimetric power itself is averaged over several calculations rather than using averaged input parameters.

2.3.4.2 Power Adjustments from the NSSS

The calculated secondary calorimetric power is adjusted for power losses and power credits to the NSSS. The power losses are determined from input constants. On-line measured data is not used directly. The power losses that are included are:

1) letdown mass flow rate and enthalpy,
2) reactor coolant pump seal cooling mass flow rate and enthalpy,
3) cooling water mass flow rate and enthalpy,
4) mass flow rate of other primary coolant water leaving the system and its enthalpy,
5) power loss from the pressurizer
6) power loss from primary coolant piping,
7) combined power loss from steam generators, and
8) other energy losses from the NSSS.

Similarly, the power credits to the system are also based on input constants. The power credits that are included are:

1) charging pump mass flow rate and enthalpy,
2) total power input from active reactor coolant pumps,
3) power input from pressurizer heaters,
4) other sources of power input from electrical equipment, and
5) all other power input to the NSSS.

2.3.4.1 Power in Each Steam Generator

The power transferred to each steam generator is calculated from feedwater enthalpy, feedwater pressure, feedwater mass flow rate, feedwater specific volume, steam mass flow rate, and steam generator pressure. The feedwater pressure (determined separately for each feed train) is either measured directly or calculated as the secondary steam pressure corrected for pressure losses from the feed injection point back to the pressure transducer.

The feedwater specific volume (derived from the feedwater temperature and pressure using standard water properties) is used to convert the measured feedwater flow pressure drop to mass flow for each feed train. A small temperature correction is provided in this conversion to account for changes in flow resistances.

Steam generator pressure for each steam generator is either measured directly or calculated as the measured secondary pressure corrected for pressure losses between the steam generator and the sensor. The steam mass flow rate is calculated as the feedwater flow minus the blowdown mass flow rate (an input constant or a measured quantity).

The power transferred to each steam generator is then calculated as the difference between enthalpy removal via the steam and blowdown mass flows, and enthalpy entry via the feedwater mass flow. The quality of both steam flow and blowdown flow are properly accounted for.

The final calculation of secondary calorimetric power is then simply the sum of the two steam generator powers plus the net NSSS power losses (i.e., total losses minus total gains).

2.3.5 Plant Power

Both primary calorimetric power and turbine power are calibrated using a correction factor based on the most recently performed secondary calorimetric calculation of power. [ ]

[†] The larger of the two calibrated powers is selected as plant power for display to the operator, for use in margin calculations, and for use by the Power Dependent Insertion Limit (PDIL) CEA Application Program. [ ]

[ ]

2.3.6 Core Power Distribution

The major steps in deriving the core power distribution include:

1) conversion of incore flux measurements to assembly relative power by axial region,
2) determination of planar radial peaking factors from CEA position,
3) synthesis of a core average axial power distribution,

4) calculation of azimuthal tilts, and

5) synthesis of a pseudo hot pin power distribution.

2.3.6.1 Conversion of Flux to Power

This algorithm converts incore detector compensated neutron flux to assembly relative power at each incore detector location at 10 second intervals. It uses methodology that is essentially identical to that used to perform the similar function in CECOR (Reference 4).

The flux to power conversion uses the incore detector compensated fluxes at each of the five axial levels of each of the incore detector strings along with the CEA group positions. The CEA group positions are used to provide an additive correction to the conversion factor to account for shadowing of a specific detector by a CEA in the same assembly.

For each string a power dependent correction factor is determined as a linear function of plant power. The final conversion factor for a string is then the sum of the CEA shadowing correction plus the product of the burnup dependent correction factor and the power dependent correction.

The burnup dependent component is calculated daily using the integrated power at a detector location. This "integration" is done stepwise assuming that the power has been constant over each 10 second interval. The depletion of fuel in the vicinity of a given detector location is taken to be proportional to the integrated power. The burnup dependent flux to power correction factor is then given by a polynomial in burnup.

2.3.6.2 Planar Radial Peaking Factors

The appropriate planar radial peaking factors are determined for each axial node by a table lookup process based on indicated CEA group positions. This calculation is performed once per ten seconds and is done in two parts.

1) Planar radial peaking factor tables are stored for each of the possible CEA configurations. For each configuration, the table contains the planar radial peaking factor [ ]

2) Penalty factors are applied to the radial peaking factors based on the determination of out-of-sequence CEA group insertion and excessive CEA deviations within any group. A pre-calculated CEA out-of-sequence penalty multiplier is applied if any out-of-sequence condition exists.

   A second penalty factor accounts for CEA deviations within a group. The penalty factor for each CEA group is determined as a piece-wise linear function of the size of the deviation. The final deviation penalty factor is the product, over all groups, of the individual penalty factors. The magnitude of the penalty factor applied depends on the CEA group in which the deviation is occurring.

2.3.6.3 Axial Power Distribution

A forty node core average axial power distribution is calculated based on in-core detector power signals using a five mode Fourier series expansion. This calculation is performed once per ten seconds to provide the power distribution used in the LHR calculation.

For each of the 5 detector levels, the assembly relative powers calculated previously (see section 2.3.6.1.) are averaged over all incore locations with valid signals. These average powers at each level are then normalized to have a sum of 100%. The normalized detector signals are transformed into five Fourier series weighting coefficients by evaluating the matrix product of a prestored "coefficient matrix" and the vector of detector signals. This prestored matrix depends only on the integral of the five Fourier modes over the axial length of the incore detectors. The 40 node power distribution is then constructed by forming the sum, at each axial node, of the Fourier functions (prestored in an array) times their respective coefficients. The axial power distribution is normalized so that the average value of the axial distribution is unity.

Once the axial power distribution is available, the core average ASI is determined as the difference between the lower and the upper half core power fractions.

[ ]

2.3.6.4 Hot-Pin Integrated Radial and ASI

A [ ] node hot pin power distribution is determined as the product of the axial power distribution and the planar radial peaking factor for each of the [ ] nodes. The integrated radial peaking factor is then calculated as the average of the hot pin power distribution over the [ ] axial nodes. The hot pin ASI is calculated in the same manner as the core average ASI except for the use of the hot pin power distribution.

2.3.6.5 Azimuthal Tilt

The core average azimuthal tilt is calculated from the assembly average powers once per 10 seconds using methodology that is essentially identical to that in CECOR (Reference 4). The incore detectors are divided into "tilt groups" of four detectors with appropriate symmetry properties. Depending on the plant, there are between nine and twelve tilt groups at each axial detector level. [ ] For each tilt group, the sum and difference of the signals in opposite quadrants are calculated. These sums and differences and a set of detector location dependent constants are used to calculate an azimuthal tilt for each group.

The average azimuthal tilt at each level is then calculated as an [ ] of the magnitude of the individual group tilts at that level. [ ]

The core average azimuthal tilt is calculated by averaging the 5 level tilts using a weighting factor for each level that is based on the number of valid sets of detectors at that level. If the calculated azimuthal tilt is higher than either the Technical Specification limit or the Core Protection Calculator (CPC) addressable tilt allowance, then an alarm is initiated.

2.3.6.6 Three-D Power Distribution

The 3-D power peaking factors are calculated for use in the linear heat rate power operating limit calculation. The 40 node 3-D power distribution is then determined as the product of the radial peaking factor (Section 2.3.6.2) and the value of the 40 node core average axial power distribution (Section 2.3.6.3) at each node. The maximum value of these products is the 3-D power peaking factor which is made available for operator information.

2.3.7 Linear Heat Rate Power Operating Limit

The core power operating limit based on the Linear Heat Rate (LHR) limit is calculated once per 10 seconds. This calculation is used to monitor the LHR limit normally established by Loss of Coolant Accident (LOCA) considerations.

The linear heat rate is calculated for each of the 40 nodes of the 3-D power distribution. This linear heat rate is the product of the normalized power fraction in the node, the core average linear heat rate at rated power, and the fraction of core power at which the plant is operating. Correction factors are applied to account for the azimuthal tilt and modeling uncertainties.

The power operating limit at each node is calculated as the product of plant power, a correction factor to account for failed incore detectors, and the LHR limit divided by the calculated linear heat rate for that node. The minimum value calculated in this manner is the LHR power operating limit. It is this value which is compared to the current value of plant power.

The LHR limit can be input as a function of inlet temperature, if desired.

2.3.8 Thermal Margin Power Operating Limit

The thermal margin power operating limit is based on maintaining the calculated DNBR above a specified minimum value (based on the CE-1 CHF correlation) and maintaining the fluid quality below a specified maximum value at the point of minimum DNBR. The thermal hydraulic model used to evaluate this limit is based on the C-E proprietary code CETOP and the CE-1 CHF correlation (see references 2 and 3). This calculation is performed once per 30 seconds with a dynamic update provided once per second.

The thermal-hydraulic modeling uses [

]

The calculation proceeds in an iterative manner in that an estimate of the power operating limit (POL) is used to determine the minimum DNBR and the quality at that point. If both the DNBR and the quality are within their respective limits, the algorithm raises the POL estimate and recalculates the DNBR and quality. Similarly, if either of DNBR or quality are not within their limits, the POL is lowered. This iteration continues until it finds the maximum POL that meets both DNBR and quality limits.

The details of this calculation have been described in references 2 and 3 and will not be repeated here. The calculation of the POL incorporates adjustments to account for the margin required by the LCOs for AOOs. These adjustments are discussed in Section 3.3.

2.3.9 Thermal Margin Power Operating Limit Update

The detailed thermal margin calculation is only performed once per 30 seconds. An approximate update to the most recent detailed calculation is performed once a second to provide the operator with a smoother indication of the core performance. The updated thermal margin power operating limit (POL) is based on changes in several measured and derived parameters including:

1) primary pressure,
2) maximum compensated cold leg temperature,
3) core flow rate,
4) integral radial peaking factor,

5) azimuthal tilt,

6) [ ]

7) quality at the node of minimum DNBR,

8) most recently calculated power operating limit,

9) POL derivative with respect to quality, and

10) POL derivative with respect to DNBR.

2.3.10 Core Power Margin

The core power margin calculation compares the actual power to the thermal margin and LHR power operating limits (POL) and to the licensed power limit. Two sets of checks are done. The first set consists of two margin calculations using the present value of the core power and the two POLs. The second set consists of three margin calculations using running averages of both the power and the two POLs and includes calculation of the margin to the licensed power limit. These latter three margins are called "smoothed" margins. In all, five margins are calculated and compared to appropriate limits. The smallest of the smoothed values is displayed on the digital panel meter and CRT display and is referred to as MARGIN. If any of the 5 calculated margins is less than its respective limit, an alarm is initiated.

Before being used in these comparisons, the calculated power operating limits are adjusted for power measurement biases. These biases are dependent on the measured power level and on which of the three calculated powers have been used to determine plant power (see section 2.4.1).

2.4 Uncertainties

The calculation of DNB and LHR power operating limits requires numerous measured inputs and calculated constants. Each of the measured inputs (i.e., temperature, pressure, etc.) and the calculated constants (i.e., fuel and poison rod bow, system parameters, etc.) can have some uncertainty associated with it. These uncertainties are applied in a conservative fashion to reduce the predicted power operating limits to ensure that adverse combinations of uncertainties do not prevent alarms when limiting conditions for operations are violated.

2.4.1 Power Measurement Bias

The accuracy of the power measurement is a function of the frequency of calibration and the method for determining the present power output. The secondary calorimetric is the most accurate measure of reactor power and generally has a net uncertainty of less than or equal to 2% of rated power near full power increasing to a value typically in the range of [ ] of rated power at low power. The primary calorimetric and the turbine first stage pressure determinations of power are less accurate having a typical uncertainty of 3.5%. Biases are applied to the POLs to account for these uncertainties. [ ]

The bias term is subtracted from the calculated power operating limits to obtain the biased power operating limits.

2.4.2 Power Operating Limit Uncertainties

Other uncertainties associated with the calculation of the power operating limits are accounted for at least at a 95/95 probability/confidence level in the power operating limit algorithms by applying

The uncertainty components considered in these adjustments to the DNBR and LHR power operating limit calculations include:

1) uncertainty in in-core detector signal measurement,
2) uncertainty in Control Element Assembly (CEA) position measurement,
3) uncertainties in temperature, pressure, and flow measurements,
4) uncertainty in verification of tabulated planar radial peaking factors (F_{xy}) using CECOR,
5) uncertainty in the COLSS power distribution algorithm modeling,
6) uncertainty in the thermal-hydraulic algorithm modeling,
7) computer processing uncertainties,
8) fuel and poison rod bow uncertainties,
9) LHR axial fuel densification factor,
10) engineering factors due to manufacturing tolerances,
11) other system parameter uncertainties, and
12) CE-1 CHF correlation uncertainties

The generation of these uncertainty terms is discussed in Section 3.4.

3.0 Constants and Supporting Data

To support the COLSS algorithms, numerous constants based on plant design characteristics must be generated for incorporation into COLSS. These constants can be divided into 5 major categories:

1) constants related to plant mechanical and thermal hydraulic design,
2) constants related to core design,
3) constants related to monitoring margin to limiting conditions for operation,
4) constants related to measurement and calculational uncertainties, and
5) constants required to support on-line DNBR calculations.

Each of these areas will be discussed to provide some background into the basis for the constants in that area. General descriptions of the types of analysis used to determine the constants will be provided where appropriate.

3.1 Basis for Mechanical and Thermal-Hydraulic Constants

Calculations of the RCS volumetric flow rate and calibrated power depend on constants which are based on the NSSS thermal hydraulic and mechanical design. The volumetric flow calculation is determined by a polynomial fit to measured values of RCP differential pressure and pump speeds. The constants for this calculation are based on a curve fit of experimental pump characteristic data obtained from operation of the RCP's in a test loop. RCS rated flow and RCP rated speed are also used in the flow calculation.

The primary calorimetric power is based on calculated fluid enthalpies and measured flows, temperatures, and pressures. No significant constants are required to support a strictly static primary calorimetric power calculation beyond standard water property tables. However, this calculation includes a dynamic compensation of variations in cold leg temperatures. The cold leg temperature compensation depends on the cold leg temperature sensor time constant and the calculated plenum time constant based on RCS design (sensor location, flow path, and flow rate). The core rated power is provided as a data base constant to permit normalization of the calculated power to percent of rated power.

The secondary calorimetric power is based on measurements of feedwater flow, steam flow, feedwater temperature, and steam pressure. Most of the constants used in the power calculation are derived from or confirmed by field data obtained during power ascension testing. These constants relate feedwater pressure to secondary steam pressure and steam flow, relate steam generator pressure to steam header pressure and steam flow, and quantify energy losses from and credits to the system (including the gain associated with operation of the RCP's).

The relationship of feedwater mass flow rate to feedwater temperature, feedwater flow, and feedwater specific volume is based on venturi characteristic test data. The calculated turbine power is based on a polynomial which is fit to the data obtained during power ascension testing.

3.2 Basis for Core Design Constants

3.2.1 Conversion of Flux to Power Constants

The conversion of the flux signal for each incore detector to relative power uses correlation coefficients that reflect detector location, local geometry, and local burnup. These coefficients are the same as those used in the CECOR off-line power distribution calculation (Reference 4). The System 80 plants require additional adjustments in those bundles which have both a CEA and an in-core detector string. Other C-E plants using COLSS do not have CEA's entering instrumented assemblies and do not require these adjustments.

3.2.2 Planar Radial Peaking Factor Look-up Tables

Prior to startup, neutronics calculations are performed to determine the maximum expected planar radial peak for each CEA configuration allowed by the CEA Power Dependent Insertion Limit (PDIL). Detailed calculations are generally performed for the unrodded core and for CEA configurations containing only the part length CEAs and the first two lead regulating banks. Conservative, bounding values are determined for other configurations including those which involve insertion of shutdown CEA banks.

The maximum expected radial peak for the current cycle is installed in COLSS for each configuration. During start-up testing, measurements are performed with CECOR to verify the unrodded peaking factor and, usually, the peaking factors for the CEA configurations that are permitted at higher powers. Adjustments to addressable radial peaking factor constants are made if appropriate. CECOR calculations are performed periodically during the cycle to verify the continued adequacy of the installed constants as required by the Technical Specifications.

Penalty factor constants for CEA banks out of sequence and CEA misalignment are determined to assure an alarm if the CEA misoperation degrades the margin below the allowed LCO. These constants are based on analyses using standard neutronics methods to determine the change in power distribution due to the CEA misoperation.

3.2.3 Axial Power Distribution Constants

The incore detector signals are converted into a 40 node core average power distribution using two arrays of constants. The first array converts the planar averages of the incore detector signals to amplitude coefficients of a Fourier series approximation of the axial power distribution. These constants depend only on the axial location and the length of the incore detectors, and on the Fourier modes used. The second array is a tabulation of Fourier mode values at each of the axial locations which are precalculated to reduce the COLSS calculation time.

3.2.4 Azimuthal Tilt Calculation Constants

The azimuthal tilt calculation requires detector location dependent constants for each "tilt group" of four detectors and appropriate averaging factors. These factors are used primarily to account for geometric effects (detector location) but also include an average radial tilt sensitivity from 3-D neutronics calculations. CECOR is run at regular intervals to verify the accuracy of the COLSS azimuthal tilt calculations.

3.2.5 LHR Limit Constants

The maximum allowed steady state LHR limit specified in the Technical Specifications and monitored by COLSS is typically based on the Loss Of Coolant Accident (LOCA). This limit is specified as a function of core inlet temperature in the COLSS of some plants.

3.3 Basis for DNB Margin Monitoring Constants

The Limiting Conditions for Operation (LCO) in the Technical Specifications assure that sufficient margin is available to cover the degradation in DNB margin that can occur during any Anticipated Operational Occurrence (AOO). Such a margin loss can be caused by an increase in local power or temperature, by a decrease in core flow or pressure, or by an adverse change in the core power distribution. The margin assured by the LCO is sufficient to cover continued adverse changes from the time the event begins until either corrective action is taken or a power reduction caused by a reactor trip begins to recover margin.

COLSS monitors the margin required by the LCOs through [ ]

3.3.1 Derivation of the [ ] from the Loss of Flow Analysis

For C-E plants, the Loss of Flow event has been among the most limiting with respect to thermal margin. During the few seconds after the pumps begin slowing down and prior to a significant power reduction due to the CEA insertion, the reduced flow causes a rapid decrease in DNB margin. Several seconds into the event the heat flux/flow combination results in the minimum DNBR that will be experienced during the transient. The specific time and value of this minimum is a function of the axial power distribution and the initial thermal and hydraulic conditions in the core. [ ]

Numerous power distributions and initial conditions are used to determine the [ ] over the ASI range of interest using the HERMITE (Reference 6) or CESEC (Reference 7) transient codes. The [ ] calculated in this manner is represented in COLSS by a piece-wise linear function of ASI which bounds the values determined in the transient cases. The ASI dependence is available to reflect the sensitivity of margin loss during a LOF event to the initial axial power distribution.

3.3.2 Derivation of [ ] from Analysis of Other AOOs

[ ] are derived from analysis of AOOs other than LOF. Typically, AOOs which are the most limiting with respect to margin requirements monitored by application of these [ ]

[ ] are the Asymmetric Steam Generator Transient (ASGT) and the CEA Drop. The final [ ] are chosen to bound the requirements of both transients.

An Asymmetric Steam Generator Transient may result from the inadvertent closure of a Main Steam Isolation Valve. The resulting asymmetric core inlet temperature distribution results in increased core power peaking on the cold side. This event is protected by an asymmetric steam generator transient trip on cold leg temperature difference (ΔT) in the CPC, but also requires that adequate thermal margin be available to cover temperature asymmetries that occur prior to trip actuation. This event is simulated by design transient codes for different values of the ΔT setpoint. The increase in the radial peak used in the safety analysis is calculated as a function of the temperature tilt using standard physics methodology. The selected ΔT setpoint and the margin monitored by COLSS using the [ ] must be adequate for the ASGT analysis to meet acceptance criteria.

Plants which include the Core Protection Calculator System as part of the Reactor Protection System have the capability to accommodate deviated CEAs via penalty factors generated by the CEA calculators. If a SAFDL violation is conservatively predicted by the CPCs following application of the penalty, then the reactor will trip. If not, operation can continue in accordance with the Technical Specifications. As a result, COLSS has not been required to verify that adequate margin has been set aside to cover margin degradation during a dropped CEA event when the CEA calculators in the CPCs are operable. In order to reduce the frequency of reactor trips, analyses have been performed to show that sufficient thermal margin can be reserved by the LCOs to preclude the need for a CPC trip for many CEA drop events. As a result, CEA drop events not protected by CPC are analyzed to calculate the [ ]

3.3.3 COLSS Penalty Factors Applied for CEA Calculators Inoperable

If the CEA calculators of the CPCs are not in operation, automatic trip protection for CEA deviation events is not provided. Therefore, adequate margin must be set aside per the Technical Specifications. In the COLSS calculation, this margin degradation during CEA related transients is accounted for by an addressable input constant to the DNB calculation. The value of this constant is determined by simulating the CEA misoperation distortion factor using neutronics codes.

3.4 Basis for Measurement and Calculational Uncertainty Constants

Three uncertainty penalty factors are calculated for COLSS, one which is used in calculating the linear heat rate power operating limit and two which are used in calculating the DNBR power operating limit.

The LHR adjustment accounts for the composite modeling uncertainty in the COLSS determination of the 3-D peak and for the various engineering factors. This modeling error is determined from a set of several thousand comparison cases between COLSS and design codes covering suitable ranges of power level, core burnup, CEA position, and primary system fluid properties. The overall adjustment factor accounts for the effects of fuel rod bow, poison rod bow, design code modeling uncertainty, COLSS power algorithm uncertainty, CECOR F_{xy} measurement uncertainty, and computer processing uncertainties. In the COLSS algorithm, this adjustment is applied as a multiplier to the core average linear heat rate. This has the effect of reducing the linear heat rate power operating limit.

Similarly, the DNBR adjustments account for the composite modeling uncertainty in the COLSS calculation of the power distribution and DNBR. This composite modeling error is based on the same set of comparison cases between COLSS and design codes used for the LHR uncertainty calculation. The overall adjustment factors include the effects of fuel rod bow, poison rod bow, design code modeling uncertainty, CECOR F_{xy} measurement uncertainty, COLSS DNB algorithm uncertainty, and computer processing uncertainties. [ ]

[ ]

For most COLSS plants, the system uncertainties are combined statistically and included in the minimum DNBR limit that is established for use with the CE-1 CHF correlation. The uncertainties accounted for include inlet flow distribution uncertainties, fuel pellet density uncertainties, fuel pellet enrichment uncertainties, fuel pellet diameter uncertainties, random and systematic uncertainties in fuel clad diameter, random and systematic uncertainties in fuel rod pitch, and CHF correlation uncertainties.

The original methodology for calculating uncertainty penalty factors was described in Reference 1. Generic and plant specific documents, such as References 5 and 8, have described updates to this methodology that have evolved since the issuance of Reference 1.

3.5 Basis for Constants Supporting On-Line DNB Calculations

The DNB calculations performed in COLSS use a simplified, faster running version of the design CETOP code called CETOP-1. Most of the constants used in CETOP-1 are identical to those in CETOP or are the product of CETOP constants which are provided to reduce computer calculation time. Three significant differences exist between CETOP-1 and CETOP to reduce the computer run time.

4.0 Conclusion

The preceding discussions have provided an overview of the COLSS program as used in recent C-E NSSS designs. This system uses measurements of incore detector signals, CEA positions, and plant thermal-hydraulic properties to provide an on-line determination of the core power distribution and thermal margin performance. The results of these calculations are provided to the plant operator through various displays to aid him in maintaining the plant within the Limiting Conditions for Operation as specified in the Technical Specifications.

5.0 References

1. "Assessment of the Accuracy of PWR Operating Limits as Determined by the Core Operating Limits as Determined by the Core Operating Limit Supervisory System (COLSS)", CENPD-169, July 1975.

*2. "CETOP-D Code Structure and Modeling Methods for San Onofre Nuclear Generating Station Units 2 and 3", CEN-160(S)-NP, September 1981.

3. "C-E Critical Heat Flux - Critical Heat Flux for C-E Fuel Assemblies with Standard Spacer Grids", Part 1 CENPD-162-A September 1976, Part 2 CENPD-207-A December 1984.

4. "INCA/CECOR Power Peaking Uncertainty", CENPD-153, Rev. 1-A, May 1980.

*5. "Statistical Combination of Uncerta nties - Uncertainty Analysis of Limiting Conditions for Operation of the San Onofre Nuclear Generating Station Units 2 and 3", Part 3, CEN-283(S)-NP, October 1984.

6. "HERMITE - A Multi-dimensional Space Time Kinetics Code for PWR Transients: CENPD-188, March 1976.

7. "CESEC - Digital Simulation of a Combustion Engineering Nuclear Steam Supply System" Enclosure 1-NP to LD-82-001, January 6, 1982.

*8. "Statistical Combination of Uncertainties for Waterford-3", CEN-343(C)-P, October 1986.

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*Plant specific references which are intended to be typical of similar references appropriate to other plants