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CECO PWR TRANSIENT ANALYSIS METHODOLOGY TOPICAL SUPPLEMENT

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By

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Reactor Safety Analysis

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Abstract

This document is a Supplement to the topical report describing the Commonwealth Edison Company (CECo) reload safety analysis methods for application to PWR nuclear generating stations. It describes the changes made to the CECo safety analysis methodology as a result of new technology acquired since the the original topical report analyses were performed. Sample calculations are presented to demonstrate CECo's ability to perform the safety analyses required for the licensing, operation, testing, and surveillance of a PWR reload cycle, including those utilizing Westinghouse Vantage 5 fuel designs.

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1.0 Introduction

The purpose of this topical report supplement is to document the changes made in the methods described in the original topical report (Reference 1) that have been implemented due to recent technology transfers with Westinghouse Electric Corporation. The methodology reported in Reference 1 reflects the use of the Westinghouse Standard Thermal Design Procedure (STDP) for Departure from Nucleate Boiling (DNB) limiting transients. This topical report presents analyses performed using the Westinghouse Revised Thermal Design Procedure (RTDP) for DNB limiting transients (Reference 2). The differences between the RTDP and the STDP will be discussed in this report. This methodology upgrade is being implemented to increase calculated DNB margin for the first two reloads of Vantage 5 fuel in Zion (Zion Unit 1 Cycle 13 and Zion Unit 2 Cycle 13), which will not contain Intermediate Flow Mixing (IFM) grids. The RTDP will be used for safety analysis for all CECo PWRs using Westinghouse Vantage 5 and OFA fuel.

Also, a description of CECo's use of the Westinghouse methodology for calculation of the Reactor Protection System overtemperature delta-T and overpower delta-T (OTΔT and OPΔT) safety analysis setpoints is included in this report.

The DNB limiting transients that are normally analyzed using the RTDP are listed below:

1. Uncontrolled RCCA Withdrawal at Power
2. Uncontrolled RCCA Withdrawal from Subcritical
3. Dropped Rod
4. Loss of Reactor Coolant Flow
5. Locked Rotor

6. Loss of External Electrical Load
7. Loss of Normal Feedwater
8. Excessive Heat Removal due to Feedwater System Malfunction
9. Excessive Load Increase

For this report, however, only the Locked Rotor and Loss of Flow events have been analyzed, since these are typically the most limiting DNB events, and the application of the RTDP will have a similar effect on the minimum DNBR (MDNBR) results for all of the applicable transients. This report is not intended to provide a detailed description of the transients analyzed under the RTDP, as this has been done in Reference 1, but will instead provide a brief description of the RTDP methodology and CECo's application.

It should be noted that some of the values of various parameters used for Vantage 5 fuel (e.g. RTDP uncertainties, nominal operating conditions, core bypass flow) are preliminary and thus have been used in the analyses in this report to demonstrate the application of the new methods that will be incorporated in CECo's reload safety analyses. The results presented in this report are not intended to be used for a particular plant application, but rather to demonstrate the calculational method employed. IFM grid inputs have not been included in these calculations, as this information is not yet available from Westinghouse. IFM grid inputs will be determined by Westinghouse and will be appropriately incorporated into the CECo licensing analyses when they become available.

Section 2 of this report contains descriptions of the methodologies presented. Section 3 provides the results of sample calculations performed to illustrate the applications presented in this report. Section 4 will summarize the conclusions of the analyses contained in this report.

2.0 Description of New Methods

2.1 Revised Thermal Design Procedure (RTDP)

The Westinghouse Revised Thermal Design Procedure (RTDP) will be used for the DNB limiting transients listed in Section 1. CECo's application of the RTDP is identical to the Westinghouse application described in the approved WCAP 11397-P-A (Reference 2), except that the VIPRE thermal-hydraulic code (Reference 3) is used instead of the Westinghouse THINC-IV code. As Reference 2 describes, the RTDP provides a more realistic prediction of the Design Limit DNBR (DLDNBR) which satisfies the DNB design criterion by statistically combining uncertainties in plant operating parameters, nuclear and thermal parameters, fuel fabrication parameters, and DNB correlation predictions to obtain an overall DNB uncertainty factor. This factor is then applied to give a limiting DNBR value (the DLDNBR) used in transient analyses. Since the uncertainties are included in the uncertainty factor, the transient analyses are performed using nominal values for the above mentioned parameters.

2.1.1 Description of RTDP Design Limit DNBR Calculation

The DLDNBR calculation is based on the results of sensitivity cases performed to determine the effect on DNBR of various operating and design parameters. The sensitivities are analyzed over a wide range of base operating conditions to bound any potential steady-state or transient operating condition. The sensitivity cases are then calculated by varying one parameter at a time, leaving all other parameters at their base values. Sensitivity factors are then calculated for each parameter as follows:

$$S_i = \frac{\ln(DNBR_{base_i}/DNBR_{sens_i})}{\ln(Y_{base_i}/Y_{sens_i})}$$

Where:

S_i = Sensitivity Factor for Parameter i
$DNBR_{base_i}$ = DNBR of Base Case Parameter i
$DNBR_{sens_i}$ = DNBR of Sensitivity Case for Parameter i
y_{base_i} = Base Value of Parameter i
y_{sens_i} = Sensitivity Value of Parameter i

Once all the sensitivity factors have been calculated for a case, the DLDNBR is calculated as follows:

DLDNBR = [ ] (a,c)

Where:

[ ] (a,c)

It should be noted that the DNB correlation statistics used in this calculation from Reference 4 have previously been reviewed and approved by the NRC (Reference 5).

2.1.2 Description of Safety Analysis Limit DNBR Calculation

After the DLDNBR is calculated, the Safety Analysis Limit DNBR (SALDNBR) is determined based on a desired amount of margin to the DLDNBR. The SALDNBR is calculated as follows:

$$SALDNBR = \frac{DLDNBR}{(1 - M)}$$

Where:

M = Amount of margin to DLDNBR desired
(e.g., for 10% margin M = 0.10)

The SALDNBR is used as the acceptance criteria for the DNB limiting transients that are analyzed using the RTDP. The calculated MDNBR for a transient must be greater than the SALDNBR in order to maintain margin to the DLDNBR. If a transient violates the SALDNBR, either available margin to the DLDNBR must be used to accomodate the results, or the bounding assumptions used in the analysis must be examined for possible restrictions. In most cases, if the violation is small, available margin will be used.

2.2 Overtemperature Delta-T and Overpower Delta-T Setpoints

The thermal overtemperature and overpower protection systems of the Reactor Protection System (the overtemperature delta-T (OTΔT) and overpower delta-T (OPΔT) trips) are designed to provide protection against the DNB design basis (OTΔT) and the fuel centerline temperature design basis (OPΔT) for Condition I and II events.

CECo will implement the Westinghouse methodology for calculating the safety analysis setpoints for the OTΔT and OPΔT trip functions of the Reactor Protection System. This methodology is described in WCAP 8745 (Reference 6). This methodology has been previously established by Westinghouse, so a detailed description of the Westinghouse methodology has been omitted. The CECo application of the methodology will be identical to that described in Reference 6, and is summarized in the following sections. The basis for the calculational procedure that follows has been established in Reference 6.

2.2.1 Calculation of Core Thermal Limit Lines

In order to develop the OTΔT and OPΔT setpoint equations, a set of core thermal limit lines must be generated. Core thermal limit lines are part of the technical specifications as reactor core thermal-hydraulic safety limits which are used to calculate the OTΔT and OPΔT setpoints. The core thermal limit lines consist of three lines that are calculated as a function of core inlet temperature vs. core power level at different system operating pressures. These are the DNB limit lines, the core exit boiling limit lines, and the core exit quality limit lines. These lines are then converted into core ΔT vs. T_{avg} space. A fourth line, the steam generator safety valve opening line, is also calculated as a function of ΔT vs. T_{avg}. The following sections describe

the calculational procedure for the core thermal limit lines and the overpower limit lines, which are inputs to the OTΔT and OPΔT setpoint calculations. Also included is the procedure for converting from T_{in} vs. power coordinates to core ΔT vs. T_{avg} coordinates. The overall calculational flow is shown in Figure 1.

2.2.1.1 Calculation of Core Exit Boiling Limit Lines

For a given reactor coolant system pressure the coolant saturation temperature and saturation enthalpy are known. Futhermore, the enthalpy rise across the reactor core can be calculated given the reactor power and coolant mass flow rate. Therefore the maximum inlet enthalpy that avoids core exit boiling is the saturation enthalpy minus the core average enthalpy rise. Once this maximum inlet enthalpy is determined, it may be used with the system pressure to obtain the corresponding core inlet temperature. This resulting inlet temperature along with the power level represents the core exit boiling limit at the given system pressure and reactor power level. In performing the mass-energy balance calculation, consideration must be made for the fact that the reactor volumetric coolant flow rate is constant, and therefore the reactor coolant mass flow rate is a function of coolant temperature. The following steps are taken to calculate the core exit boiling limits:

1. Calculate saturation temperature at the given pressure (T_{sat}).
2. Calculate saturation enthalpy from T_{sat} (H_{sat}).
3. Calculate sensitivity factors for power, flow, pressure, and T_{in}.
4. Calculate overall coefficient of variation (s/m), from the above calculated sensitivity factors and input values of individual parameter coefficients of variation, which are identical to those used in the RTDP DLDNBR calculation.
5. Calculate H_{max} = [ ]$^{(a,c)}$ where H_{max} is the saturation enthalpy which will be used to calculate the T_{in} values for the various power levels.
6. Assume an initial inlet temperature (T_{in}).

7. Calculate the coolant specific volume for the given pressure and core inlet temperature.

8. Calculate the mass flow rate (Mass flow rate = Volumetric flow rate / coolant specific volume).

9. Calculate the enthalpy rise (ΔH = Power/Mass flow rate).

10. Calculate the inlet enthalpy ($H_{in} = H_{max} - \Delta H$).

11. Calculate a new T_{in} based on H_{in}.

12. If calculated T_{in} is close enough to the previous T_{in} then stop the calculation, otherwise go back to step 7 using the new calculated T_{in} to repeat the calculation.

Typically, four different pressures (1775, 2000, 2250, and 2400 psia) with five different power levels (40, 60, 80, 100, and 120% of nominal power) are used to define the core exit boiling limits.

2.2.1.2 Calculation of DNB Limit Lines

DNB limit lines are calculated for a range of reactor operating conditions to ensure that the DNB design basis is met. For a given reactor power, system operating pressure, and coolant mass flow rate, there is a coolant inlet temperature above which the MDNBR reaches the safety analysis limit DNBR. These sets of inlet temperatures and power levels for a given operating pressure form a locus of points which define the DNB limit lines. Since these limits are dependent upon the thermal-hydraulic conditions of the core and the critical heat flux correlation, they are calculated using the VIPRE thermal-hydraulic code and the appropriate CHF correlation. VIPRE has the capability of automatically iterating inlet temperature until a specified MDNBR is reached. This capability is utilized in the CECo application.

2.2.1.3 Core Exit Quality Limit Lines

Core exit quality limit lines are calculated to ensure that coolant conditions stay within the range of applicability of the CHF correlation used for DNB analysis. The WRB-1 CHF correlation quality limit is 30%. The VIPRE code is used to calculate the core exit quality limit lines as described below.

Four different pressures (1775, 2000, 2250, and 2400 psia) and four different power levels (40, 60, 80, and 100% of nominal power) are chosen to define the core exit quality limits. For a given reactor operating pressure, coolant mass flow rate, and power level, there is an inlet temperature above which core exit quality exceeds 30%. This is done by increasing the inlet coolant temperature until any channel exit quality reaches 30% or until the inlet temperature reaches the saturation temperature. In most cases, the DNB limits and the core exit boiling limits bound the core exit quality limits, especially when the WRB-1 quality limit of 30% is used.

2.2.1.4 Conversion to Delta-T vs T-avg Coordinates

Once the core exit boiling limit lines, DNB limit lines, and core exit quality limit lines (sometimes referred to as simply "core limits") are obtained in a T_{in} vs. power coordinate system, they are converted into a ΔT vs. T_{avg} coordinate system to reflect plant measured parameters. This conversion is done in the following manner: For each point on the core thermal limit lines, the fractional core power, system pressure, core flow, and core inlet temperature are known. From this information, the inlet enthalpy may be determined thus allowing the core average enthalpy rise to be calculated. From the exit enthalpy, the exit temperature can be determined, and the core T_{avg} and ΔT are then easily determined.

In addition, in order to create core thermal limit lines that will bound the pressurizer high and low pressure trips, a calculation is performed to interpolate between pressures if one of the pressurizer pressure reactor trip setpoints falls between two of the pressures used in the calculations presented above. For example, the pressurizer low pressure trip setpoint is typically 1800 psia. An interpolation between the results of the 1775 psia and the 2000 psia calculations is performed to provide final core thermal limit lines at the 1800 psia pressure. The 1775 psia core limits calculations are done in order to account for possible small changes that may be made to the low pressure trip. As long as the setpoint does not fall below 1775 psia, the new OTΔT and OPΔT setpoints can be determined without re-calculating core limits.

2.2.1.5 Steam Generator Safety Valve Limit Line

The steam generator safety valve limit line is calculated from the log-mean-temperature difference equation as follows:

$$Q = UA \bullet \frac{T_{out} - T_{in}}{\ln \dfrac{T_{out} - T_{sv}}{T_{in} - T_{sv}}}$$

where:

Q = reactor power (btu/hr)

UA = overall heat transfer coefficient obtained from known performance of steam generator at nominal T_{avg} and nominal power.

T_{out} = reactor hot-leg temperature (°F)

T_{in} = reactor cold-leg temperature (°F)

T_{sv} = saturated temperature corresponding to 103% of the steam generator shell design pressure. (°F)

The intersections of the core thermal limit lines (combination of core exit boiling limit lines and DNB limit lines) and the steam generator safety-valve line are determined by taking points on the core thermal limit lines for each pressure until the above equation is satisfied. A point on each core thermal limit line satisfies the condition where the steam generator safety valves open. The safe operating range is the area above this line. A calculation is performed to obtain the intersections of the core thermal limit lines and the steam generator safety-valve line, given the nominal system pressure, power level, inlet and exit temperature of the reactor core as well as the complete core thermal limit lines. The parameter UA is calculated using the nominal T_{hot} as T_{out}, T_{cold} as T_{in}, and steam generator nominal saturation temperature as T_{sv} for the above equation. Next, the saturated temperature corresponding to 103% of the steam generator shell side design pressure (T_{sv}) is calculated.

After the nominal UA and T_{sv} are obtained, the remaining step is to find the intersection points on the core thermal limit lines for each pressure until the above equation is satisfied. Once this has been done, the OTΔT setpoint equation can be calculated.

2.2.1.6 Calculation of Thermal Overpower Limit Lines

The thermal overpower limit used in Westinghouse plants to prevent fuel melting is 118% of nominal power. The reactor is protected from exceeding this limit by the high-neutron flux trip. As mentioned earlier, the reactor operates at a constant volumetric coolant flow rate and therefore the temperature rise across the core has a slight dependence on pressure and inlet temperature. These lines are calculated by using the same mass-energy balance principle which was used to calculate core exit boiling limit lines. For a given pressure, 118% of nominal power, and a given coolant inlet temperature, the core exit temperature can be found. The thermal overpower limit lines are typically calculated at a variety of inlet temperatures at 118% of

nominal power. The intersection points of the core thermal limit lines and overpower limit lines are used to define a single overpower limit line and the OPΔT setpoint.

2.2.2 Calculation of OT-Delta-T and OP-Delta-T Equations

The thermal overtemperature protection function will trip the reactor when the compensated ΔT in any two channels exceeds the setpoint. The setpoint for each channel is continously calculated by analog circuitry programmed to evaluate according to the following equation:

$$\Delta T_{sp} = \Delta T_{nom}(K_1 - K_2(T-T') + K_3(P-P') - f(\Delta I))$$

The thermal overpower protection function will trip the reactor when the compensated ΔT in any two channels exceeds the setpoint. The setpoint for each channel is continuously calculated by plant protection system circuitry programmed to evaluate according to the following equation:

$$\Delta T_{sp} = \Delta T_{nom}(K_4 - K_6(T-T') - f(\Delta I))$$

The above two equations are expressed without any dynamic compensation terms for calculational simplicity. Actual OTΔT and OPΔT equations and a detailed explanation of nomenclature can be found in Reference 6. [

]$^{(a,c)}$ In order to determine proper nominal values for the plant trip setpoints, the constants are adjusted to account for appropriate allowances in plant instrumentation uncertainties and measurement errors.

After the core thermal limit lines have been calculated, they are used to generate the constants for the OTΔT and OPΔT setpoint equations. Since the purpose of this report is to present the CECo application of the methodology described in Reference 6, much of the technical description in this section is directly quoted from the reference.

2.2.2.1 OT-Delta-T Equation

The thermal overtemperature trip protects the core against DNB and hot-leg boiling (core exit boiling) for any power, pressure, and temperature condition. The equation form in Section 2.2.2 was chosen to conservatively represent the core limits (Reference 6). The following calculational procedure is used to determine the constants in the above equation:

1. Choose four intersection points which provide the basis for the calculation of the OTΔT equation. These four points define the intersections of:
   - Point A : the 118% overpower line and the core thermal limit line corresponding to the high-pressure trip
   - Point B : the 118% overpower line and the core thermal limit line corresponding to the low-pressure trip
   - Point C : the steam generator safety-valve line and the core thermal limit line corresponding to the high-pressure trip
   - Point D : the steam generator safety-valve line and the core thermal limit line corresponding to the low-pressure trip

   The points A, B, C, and D are illustrated in Figure 4, which represents the sample core thermal limit lines calculated for this report.

2. The OTΔT protection limit equation, neglecting pressure, is a straight line in ΔT vs. T_{avg} coordinates. The equation is as follows:

   $$\Delta T_{sp} = \Delta T_{nom}(K_1 - K_2(T_{avg} - T_{avgnom}))$$

   When the pressure effect is included, the OTΔT equation is a plane in three coordinates, ΔT, T_{avg}, and Pressure. The equation becomes:

   $$\Delta T_{sp} = \Delta T_{nom}(K_1 - K_2(T_{avg} - T_{avgnom}) + K_3(P - P_{nom}))$$

The slopes and constants for four different OTΔT protection limit equations are determined from the four intersection points (A,B,C, and D) by constructing:

- A line parallel to AC which intercepts B;
- A line parallel to AC which intercepts D;
- A line parallel to BD which intercepts A; and
- A line parallel to BD which intercepts C.

The constants K_1, K_2, and K_3 for each of these equations are determined by solving three of the equations simultaneously.

3. Each equation is tested at various pressures to ensure that all the core thermal limits are protected. Equations which do not protect all of the core thermal limits are discarded.
4. The final equation is selected based on optimizing operating margin (this is usually accomplished by maximizing K_1).

2.2.2.2 OP-Delta-T Equation

The overpower ΔT protection limit equation as shown in Section 2.2.2 is determined based on the intersection points of the overpower limit, plotted as a function of T_{avg} for fixed pressures, and the DNB core limits at corresponding pressures. The intersection points are lower on the DNB lines as pressure increases. When calculating the OPΔT limits, in consideration of this slight pressure dependence, a simplified first step is to remove any pressure dependence from the OPΔT limit equation. This is accomplished by defining a line which passes through the overpower - DNB core limit intersections at the high- and low-pressure trips, or by defining a constant ΔT which corresponds to the ΔT computed at the overpower - DNB core limit intersection at the high-pressure trip.

Either method would prevent the overpower limit from being exceeded for all combinations of pressure and temperature. However, to maximize operating margin, a combination of the two

approaches is used. The setpoint is a constant ΔT if T_{avg} is less than the nominal value; it is a diminishing ΔT if T_{avg} is greater than nominal.

The overpower limit ΔT equations are then:

$$\Delta T_{sp} = \Delta T_{nom} K_4 \qquad \text{for } T < T'$$

$$\Delta T_{sp} = \Delta T_{nom}(K_4 - K_6(T - T')) \qquad \text{for } T \geq T'$$

Where:

ΔT_{sp} = Setpoint value of ΔT, °F
ΔT_{nom} = Indicated ΔT at nominal plant conditions, °F
T = Measured average temperature, °F
T' = Nominal average temperature at rated power, °F
K_4 = Preset manually adjusted bias
K_6 = A constant that compensates for the change in density, flow, and heat capacity of water with change in temperature

Using the method described above, it can easily be shown that the preset manually adjusted bias term K_4 is:

$$K_4 = \Delta T_A / \Delta T_{nom}$$

where ΔT_A is the ΔT at point A

For T greater than nominal, the overpower ΔT protection limit is represented by an equation which defines the line from point A to point B, as shown in Figure 4. It is then apparent that the constant term which compensates for the change in temperature, K_6, is:

$$K_6 = (\Delta T_A - \Delta T_B)/(T_A - T_B)/\Delta T_{nom}$$

where ΔT_B is the ΔT at point B

The equations represent the maximum allowable ΔT during operation.

2.2.3 Calculation of the f(Delta-I) Function for the OT-Delta-T Equation

Since the CECo calculation of the $f(\Delta I)$ reset function for the OTΔT setpoint equation is identical to the Reference 6 procedure, the text in this section is paraphrased from the text in the reference.

The OTΔT trip equations developed in the previous sections were calculated based on the assumption that a cosine axial power shape is the limiting axial power shape. In order to account for other axial power shapes that may be more limiting, an $f(\Delta I)$ reset function is used to lower the trip setpoint by an amount that is dependent on the measured ΔI. This reset function is set to ensure that the core will not reach DNB for all expected normal operation power shapes as well as power shapes which might occur during certain limiting DNB transients such as the rod withdrawal at power and boration dilution events.

In order to calculate the $f(\Delta I)$ penalty function, axial offset DNB envelopes are calculated and are then used in conjunction with the core thermal limit lines. The axial offset DNB envelopes are intended to bound all possible normal operational and accident power shapes. Operational power shapes are those shapes which could occur during normal operation and load following maneuvers. Accident power shapes are those axial power shapes which are possible during transients having a strong influence on axial power distribution such as the rod withdrawal at power and boration/dilution events. To define a bounding axial offset DNB envelope, Westinghouse has performed extensive neutronic analyses considering approximately 150 cores and also examined limiting power shapes observed during operation to develop a set of power shapes (Reference 6). The shapes are verified to be limiting on a reload basis as part of the cycle

FAC analysis, which is performed in accordance with established Westinghouse methods (Reference 7).

2.2.3.1 *Calculation of the DNB Axial Offset Envelopes*

The DNB axial offset envelopes are typically calculated [

](a,c) must be iteratively determined using VIPRE. The VIPRE iterations on inlet core temperature are performed at the conditions listed above until the safety analysis DNBR limit is reached. The axial offset DNB envelopes are then calculated by performing a power level iteration with VIPRE for each shape using [

](a,c) The code iterations are terminated when the safety analysis DNBR limit is reached for each axial power shape. In the VIPRE analysis, iterations are done automatically, so the safety analysis limit DNBR chosen to iterate to is the more limiting between the typical cell limit and the thimble cell limits.

2.2.3.2 *Calculation of the f(Delta-I) Reset Function*

Once the axial offset DNB envelopes are developed, the f(ΔI) reset function may be calculated. The procedure for calculating the reset function is described in detail in Reference 6, but is summarized below.

(a,c)

[ ](a,c)

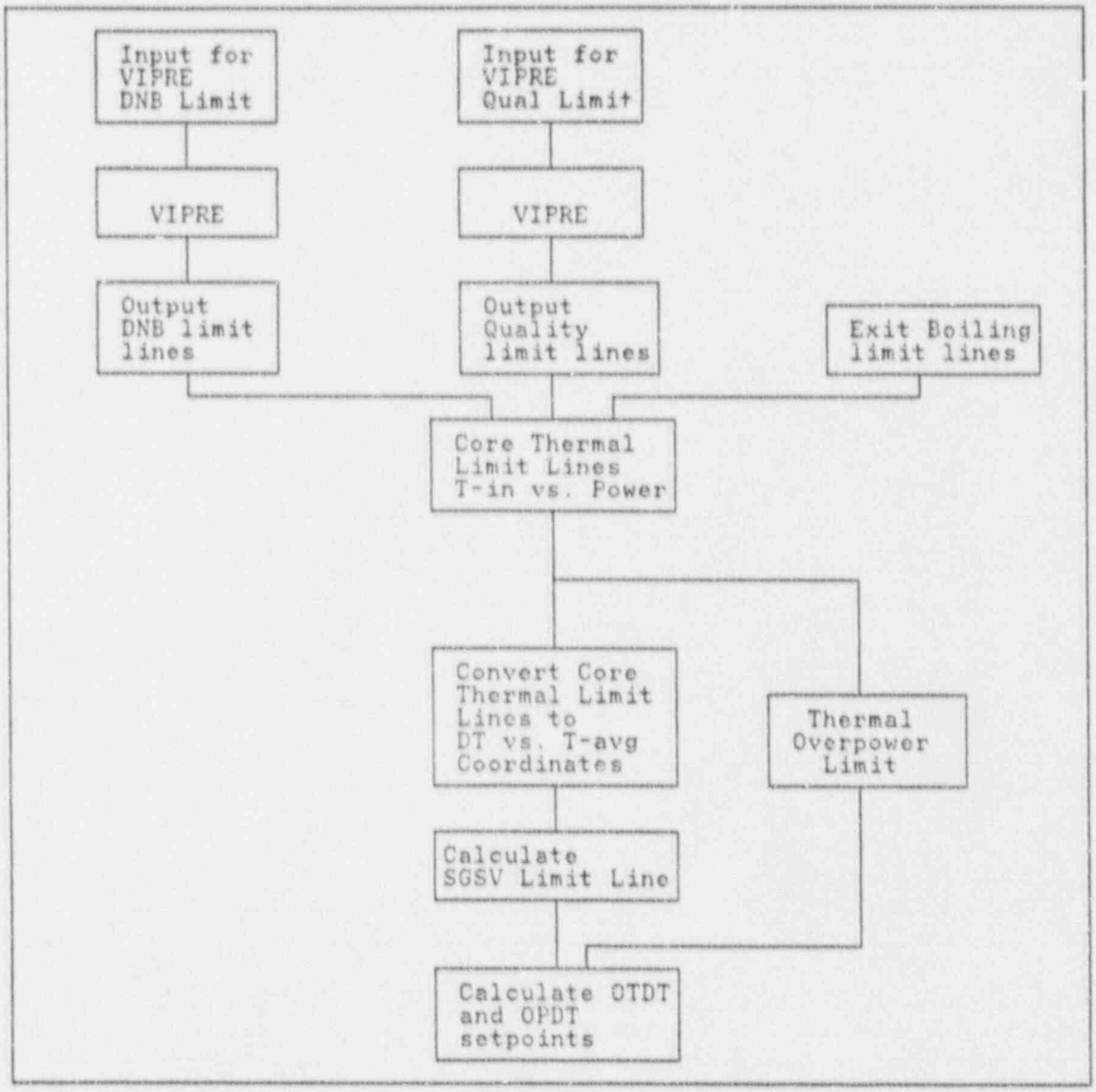

Figure 1. Core Thermal Limit Lines Calculational Flow

3.0 Results of Sample Calculations

3.1 DLDNBR and Safety Analysis Limit DNBR Calculations

3.1.1 DLDNBR Calculation

Several VIPRE jobs were run to determine the sensitivities on DNBR to various operating and fuel design parameters. The parameters that sensitivities were performed on were:

1. Core Power
2. Core Inlet Coolant Temperature
3. Reactor Coolant System Pressure
4. Reactor Vessel Flow (Core Flow plus Bypass Flow)
5. Hot Channel $F_{\Delta H}$
6. Engineering Hot Channel Factor (FDHE)

Base cases were set up to run the sensitivities in order to bound a conservative range of operating conditions. [ ]$^{(a,c)}$

[ ]$^{(a,c)}$

Each case required iteration of an operating parameter until a MDNBR near the expected DLDNBR was reached. An assumption was made that the DLDNBR would be somewhere near [ ]$^{(a,c)}$ which is a typical initial value. For each case the iterated parameter was as follows: [ ]$^{(a,c)}$

[ ] (a, c)

The base case flow rate used for all cases except case 6 was the preliminary Minimum Measured Flow (MMF) of 357000 GPM. This is the original Thermal Design Flow (TDF), which is 350000 GPM, plus the calculated flow uncertainty of 2%. This is a total reactor vessel flow rate, which includes the core bypass flow. In order to determine the reactor core flow rate, the core bypass flow must be subtracted out. A core bypass fraction of 5% was used for this calculation. This bypass fraction is based on preliminary information on the effects of 15x15 Vantage 5 fuel on core bypass flow. The core flow with 5% bypass corresponds to a mass flux of 2.5364 Mlb/HR-FT^2 at nominal conditions. The 2% flow uncertainty is based on installed plant instrumentation and the assumption that a detailed flow calorimetric measurement will be performed at the beginning of each cycle to calibrate the cold-leg elbow taps to provide a more accurate measure of vessel flow.

As mentioned in Section 2, the uncertainties used in these calculations are preliminary values for Zion, and are only used to demonstrate the calculational procedure. When the uncertainties are finalized by Westinghouse, they will be incorporated into the DLDNBR calculations. The uncertainties used for this analysis are included as sigma values in Table 3. The 4% DNBR uncertainty applied to the VIPRE code calculation, and the 1% DNBR uncertainty applied to the RETRAN code calculation are the same as those applied to the THINC and LOFTRAN

codes for Westinghouse. These uncertainties were required by the NRC Safety Evaluation Report (SER) for the Improved Thermal Design Procedure (ITDP) Topical Report (Reference 8).

After the base cases were run, sensitivity cases were run by varying each parameter by a few percent, one parameter at a time, to determine its sensitivity on MDNBR. Table 1 shows the values of the sensitivity parameters used for each case. Table 2 shows the MDNBR results of the [ ]$^{(a,c)}$ base and sensitivity cases analyzed.

The results shown in Table 2 were then used to calculate the sensitivity factors and the DLDNBR for each case. The results of the calculations for Case 1, which gave the limiting DLDNBR value, are shown in Table 3. The limiting DLDNBRs shown are [ ]$^{(a,c)}$

3.1.2 Safety Analysis Limit DNBR (SALDNBR) Calculation

With the DLDNBR known for each cell type, the SALDNBR can now be calculated. The SALDNBR should provide enough margin to the DLDNBR to account for any possible cycle design variations that may require available DNB margin to be used. However, the SALDNBR should not be so high as to cause possibly frequent reload DNB acceptance criteria violations. Therefore, a balance must be struck between DLDNBR margin and margin to analysis results. For the purposes of this report, 12% margin to the DLDNBR will be selected to calculate the SALDNBR. This will provide ample margin to accomodate any cycle margin penalties that may be required, and should not encroach on any analysis results. The SALDNBR is then calculated as follows:

Limit = [ ]$^{(a,c)}$

Limit = [ ]$^{(a,c)}$

These values will be used as the acceptance criteria for the sample locked rotor and loss of flow analyses presented in the following section. It should be noted that the SALDNBR is not a licensing requirement, it is a way of ensuring that adequate DNB margin is maintained.

3.1.3 Locked Rotor and Loss of Flow MDNBR Calculations

As stated in Section 1, the DNB events analyzed for this report are the Loss of Flow and Locked Rotor events. The results of the RTDP analyses show that the effect of the incorporation of the RTDP is to raise the MDNBR from the STDP results. This is expected, since the transient is initiated from nominal conditions, and the hot channel $f_{\Delta H}$ engineering uncertainty is not directly applied in the thermal hydraulic DNB calculation. In fact, the MDNBR for the cases analyzed in this report are greater than the cases analyzed in Reference 1, which had lower peak $f_{\Delta H}$ values. The MDNBRs calculated were 1.73 for the Locked Rotor event and 1.84 for the Loss of Flow event. The MDNBR vs time responses are shown in Figure 2. These MDNBRs are greater than the Reference 1 results of 1.65 for the Locked Rotor event and 1.77 for the Loss of Flow event. The Locked Rotor MDNBR, which is limiting, is still far above the typical channel Safety Analysis Limit DNBR of [ ]$^{(a,c)}$ which shows ample margin to the DLDNBR. When IFM grid data is incorporated, it is expected that the calculated MDNBR will be even greater, due to the increased turbulent mixing they will provide.

3.2 OT-Delta-T and OP-Delta-T Setpoint Calculations

The following sections present the calculations performed to determine the core thermal limit lines, the OTΔT and OPΔT setpoint equations, and the f(ΔI) reset function for the OTΔT trip function. The fuel parameters used in the calculations are representative of 15x15 Vantage 5 fuel without IFM grids, which will be the first application of Vantage 5 fuel at the Zion station. The calculational procedure, however, would be the same for 15x15 Vantage 5 with IFM grids, 17x17 Vantage 5, and OFA fuel as well. This report is intended to illustrate the calculational procedure, not necessarily to serve as the basis for a particular plant application.

3.2.1 Core Thermal Limit Lines Calculation

The core thermal limit lines are calculated as described in Section 2 of this report. The following sections present the results of the calculations.

3.2.1.1 Core Exit Boiling Limit Lines

The core exit boiling limits were calculated using the calculational procedure outlined in Section 2.2.1.1. Table 4 presents the results of the calculations.

3.2.1.2 DNB Limit Lines

The DNB limit limits were calculated with VIPRE using the calculational procedure outlined in Section 2.2.1.2. Table 5 presents the results of the calculations.

3.2.1.3 Core Exit Quality Limit Lines

The core exit quality limits were calculated with VIPRE using the calculational procedure outlined in Section 2.2.1.3. Table 6 presents the results of the calculations. The exit quality limits, DNB limits, and the core exit quality limits are shown in Figure 3.

3.2.1.4 Steam Generator Safety Valve Lines

The steam generator safety valve limit calculations followed the calculational procedure outlined in Section 2.2.1.4. The results of the calculations were used to determine the intersection points to the exit boiling or the DNB limit lines at the different specified pressures. The intersections of the steam generator safety valve lines with the core limits lines can be seen in Figure 4 which illustrates the finalized core thermal limit lines.

3.2.1.5 Overpower Limit Lines

The overpower limit line calculations followed the calculational procedure outlined in Section 2.2.1.5. The results of the calculations were used to determine the intersection points to the DNB limit lines at the different specified pressures. The intersections of the overpower limit lines with the DNB limit lines can be seen in Figure 4.

3.2.2 OTDT and OPDT Setpoint Calculations

The OTΔT and OPΔT setpoint equations were calculated using the calculational methodology outlined in Section 2.2.2 of this report and in Reference 6. The results of the calculations are presented below.

3.2.2.1 OTDT Setpoint Calculation

The following equation represents the OTΔT equation that protects all of the core thermal limits while maximizing operating margin:

$$OT\Delta T = 62.9(1.73979 - 0.018047(T_{avg} - 562.2) + 0.00109114(P - 2250.0))$$

The constants K_{1max}, K_2, and K_3 are 1.73979, 0.018047, and 0.00109114, respectively.

3.2.2.2 OPDT Setpoint Calculation

The following equations represent the OPΔT equation that provides the most operating margin:

$OP\Delta T = 72.54$ when T_{avg} is less than 562.16

$OP\Delta T = 62.92(1.15297 - 0.00189117(T_{avg} - 562.2))$ when T_{avg} is greater than 562.2

The constants K_{4max} and K_6 are 1.15297 and 0.00189117, respectively.

Figure 5 shows the OTΔT and OPΔT setpoints overlayed onto the core thermal limit lines to show that they provide protection for all of the core limits. The OTΔT lines are at 1800, 2000, 2250, and 2400 psia.

3.2.3 f(Delta-I) Reset Function Calculation

3.2.3.1 Axial Offset DNB Envelopes

The axial offset DNB envelopes were calculated with VIPRE using the calculational procedure outlined in Section 2.3.4. First, the inlet temperature searches to a [ ](a,c) MDNBR were calculated. The cases iterated to a T_{in} of [ ](a,c) The axial shapes used are illustrated in Figure 6. The power iteration results are shown in Table 7, and are illustrated in Figure 7.

3.2.3.2 f(Delta-I) Reset Function

The results of the axial offset DNB envelopes calculations were used to calculate the f(ΔI) deadbands and the slopes of the positive and negative wings of the reset function as described in Section 2.2.3.2. [ ](a,c) The effect of the f(ΔI) reset function on the setpoint is illustrated in Figure 8.

(a,c)

PARAMETER VALUE (BASE) (SENS)
POWER (%)
T-IN (°F)
PRESSURE (PSIA)
FLOW(Mlb/HR-FT²)
F-DELTA-H
FDHE

Table 1. Values of Operating Parameters used in DLDNBR Cases

(a,c)

PARAMETER VARIED
BASE CASE
POWER
T-IN
PRESSURE
FLOW
F-DELTA-H
FDHE

Table 2. MDNBR Results of Base and Sensitivity Cases

PARAMETER	MEAN (m)	SIGMA (s)	BASE VALUE	SENSITIVITY VALUE	DNBR (TYP)	DNBR (THM)
BASE						
POWER	1.00					
T-IN	530.70					
PRESSURE	2250.00					
FLOW	1.00					
EFF	0.95					
FDHE	1.00					
FNDH	1.59					
T/H CODE	1.00					
TRANS CODE	1.00					

(a,c)

PARAMETER	S (TYP)	S (THM)	$(S(s/m))^2$ (TYP)	$(S(s/m))^2$ (THM)
POWER				
T-IN				
PRESSURE				
FLOW				
EFF				
FDHE				
FNDH				
T/H CODE				
TRANS CODE				

(a,c)

(a,c)

Table 3. Sample DLDNBR Calculation Results

POWER LEVEL (%)	Core Exit Boiling Limits Inlet Temperature (°F)			
	1775 psia	2000 psia	2250 psia	2400 psia
40.0	595.17	613.04	631.53	642.08
60.0	583.06	601.36	620.40	631.35
70.0	576.99	595.47	614.76	625.87
80.0	570.91	589.56	609.08	620.35
90.0	564.83	583.64	603.36	614.78
100.0	558.75	577.70	597.62	609.18
120.0	546.59	565.81	586.08	597.88

Table 4. Core Exit Boiling Limit Lines Calculation Results

POWER LEVEL (%)	DNB Limits Inlet Temperature (°F)			
	1775 PSIA	2000 PSIA	2250 PSIA	2400 PSIA
80.0	596.27	607.65	622.44	632.00
100.0	564.85	579.24	595.57	605.34
120.0	526.29	542.22	558.88	568.83

Table 5. DNB Limit Lines Calculation Results

POWER LEVEL (%)	Core Exit Quality Limits Inlet Temperature (°F)			
	1775 psia	2000 psia	2250 psia	2400 psia
40.0	619.0	635.0	652.0	662.0
60.0	619.0	635.0	652.0	662.0
80.0	619.0	635.0	652.0	661.0
100.0	619.0	634.0	643.0	648.0

Table 6. Core Exit Quality Limits

AXIAL SHAPE	VIPRE CALCULATED POWER (%)
1	
2	
3	
4	
5	
6	
7	

(a,c)

Table 7. Power Iteration Results

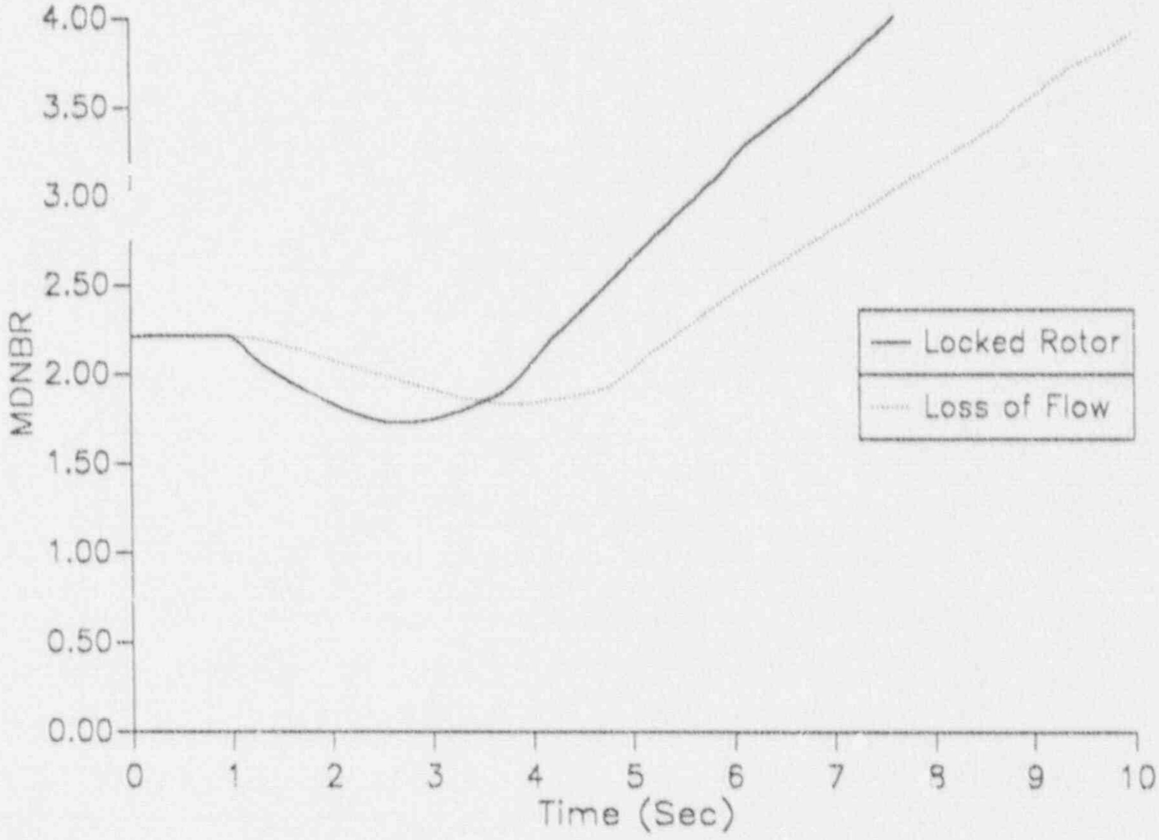

Figure 2. MDNBR Response for Sample Cases

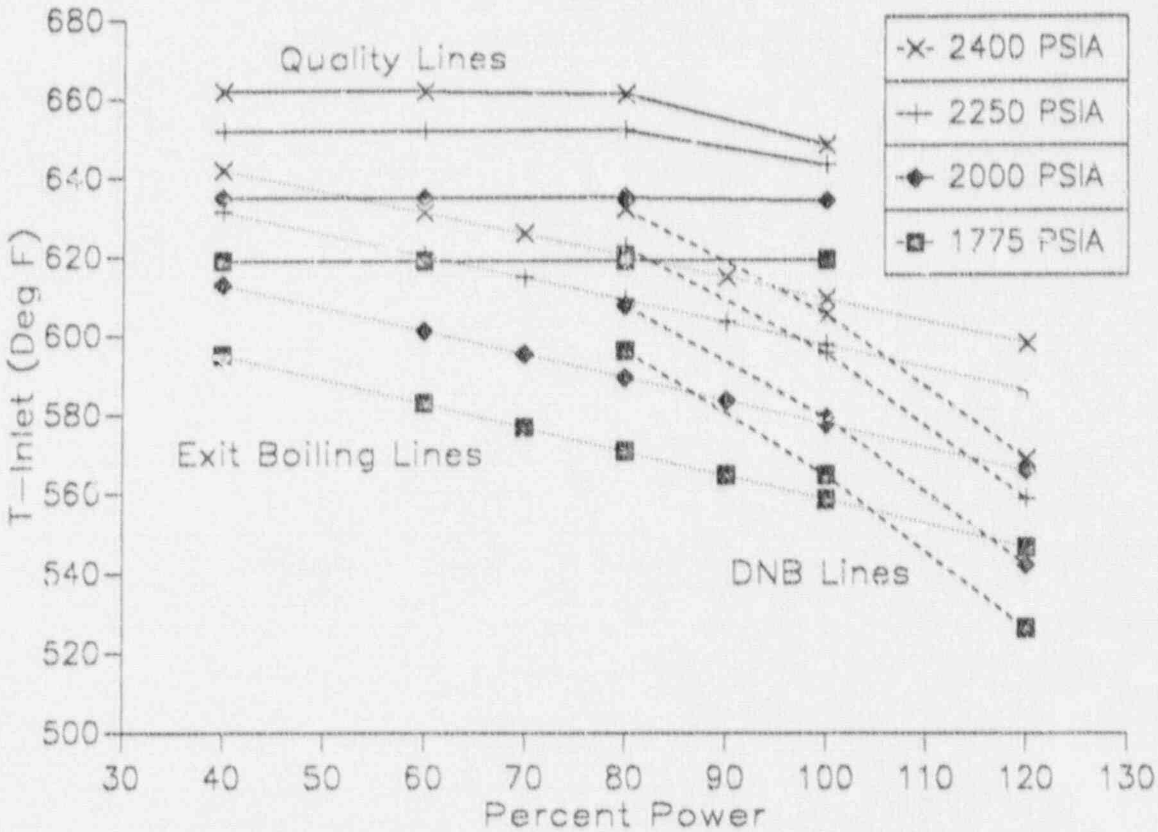

Figure 3. Core Exit Quality, Exit Boiling, and DNB Limit Lines

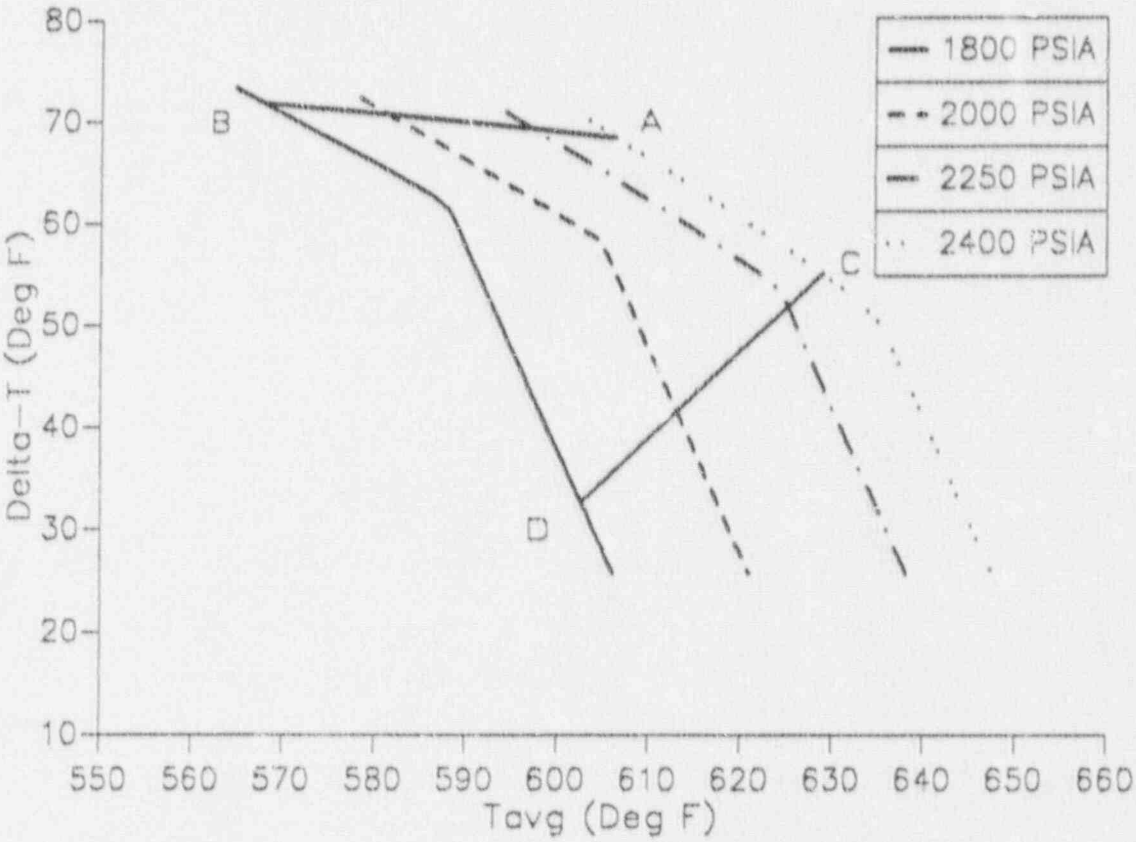

Figure 4. Core Thermal Limit Lines

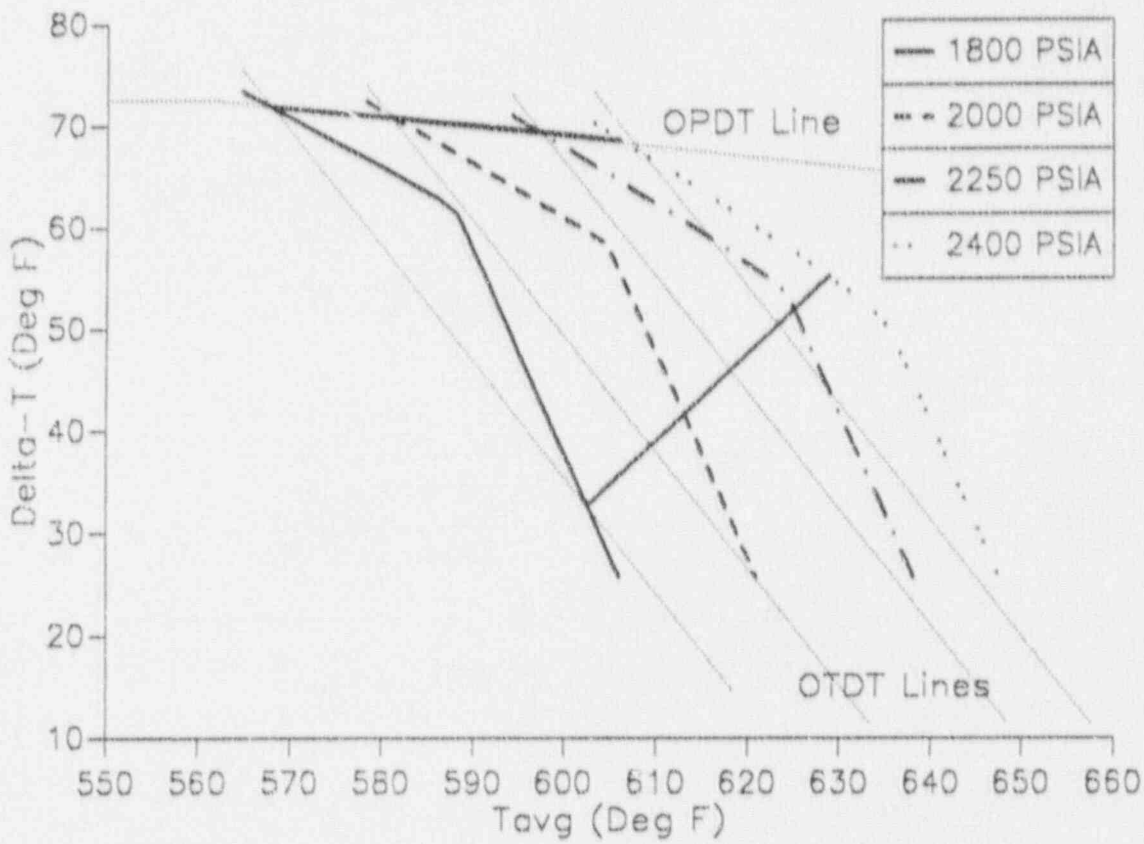

Figure 5. Overtemperature and Overpower Limits

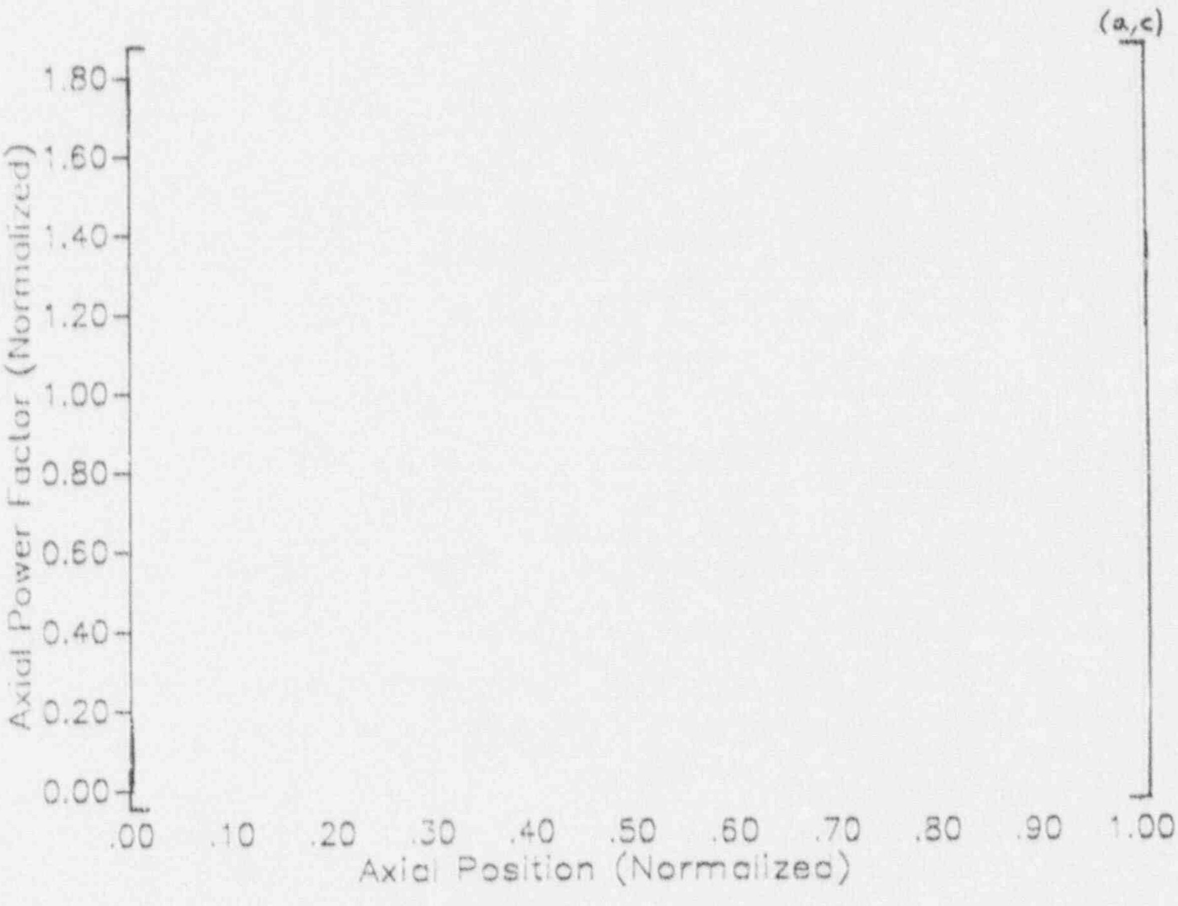

Figure 6. Axial Offset DNB Envelopes Axial Shapes

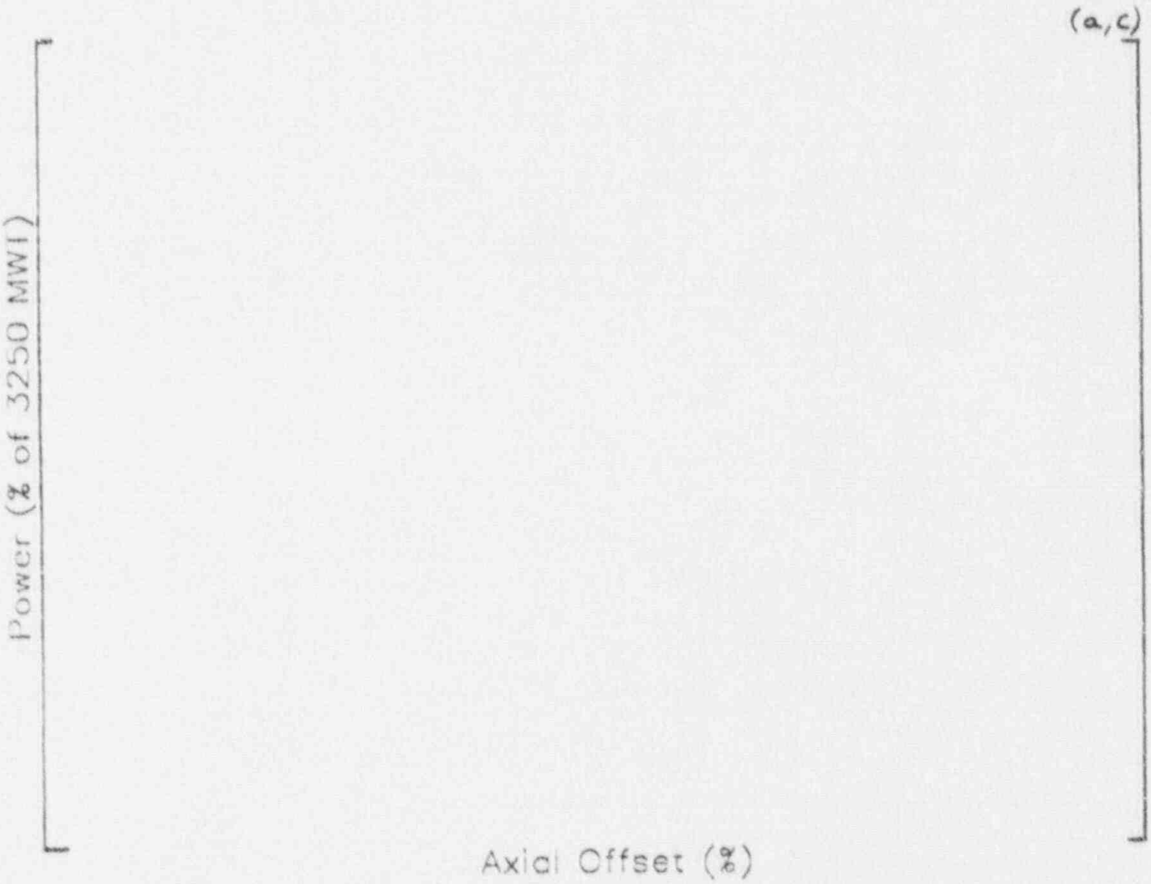

Figure 7. Axial Offset DNB Envelopes

Figure 8. f(Delta-I) Reset Function

4.0 Conclusions

As stated in the Introduction, the purpose of this report is to document the changes in the methods described in the original CECo transient topical report to incorporate the RTDP for DNB limiting transients and the inclusion of the calculations for the OTΔT and OPΔT protection setpoints. The calculational basis for these methods has been previously established by Westinghouse. This report presents the CECo application of these methods.

For the RTDP, the calculational procedure for determining a Design Limit DNBR and a Safety Analysis Limit DNBR was described, and a sample calculation was presented. As a check of the Safety Analysis Limit, Locked Rotor and Loss of Flow transients were analyzed to demonstrate that margin to the Safety Analysis Limit DNBR is maintained.

For the OTΔT and OPΔT setpoint calculations, the calculational procedure for determining the setpoint equations was presented, and sample calculations were performed to determine the constants for the setpoint equations. If these calculations were to be applied to an actual plant analysis, the setpoint constants generated would have to verified to show that the setpoints still provide DNB margin. This is normally accomplished by analyzing the RCCA Withdrawal at Power and Loss of Load transients with the new setpoint constants. This verification will be performed when finalized OTΔT and OPΔT setpoints are generated for the stations.

Also, plant values for the constants K_1 and K_4 would have to be calculated based on appropriate allowances for plant instrumentation uncertainties and measurement errors.

In summary, this report demonstrates that CECo is capable of applying the Westinghouse methods referred to and described in this report to the performance of reload safety analysis for CECo PWRs.

5.0 References

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