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RESPONSE TO NRC QUESTION 221.18

NON-PROPRIETARY VERSION
CPC/CEAC SOFTWARE
MODIFICATIONS FOR
SAN ONOFRE UNIT 2

AUGUST, 1980

COMBUSTION ENGINEERING, INC.
NUCLEAR POWER SYSTEMS
POWER SYSTEMS GROUP
WINDSOR, CONNECTICUT 06095

8009050308

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J. M. Christens

Instrumentation and Controls Engineering

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1.0 INTRODUCTION

1.1 Report Scope

The Core Protection Calculator (CPC) System developed by Combustion Engineering is a digital system which calculates the minimum departure from Nucleate Boiling Ratio (DNBR) and the peak local power density (LPD) on-line and generates a reactor trip if either the minimum DNBR or the peak LPD approaches the specified Acceptable Fuel Design Limit. Arkansas Nuclear One (ANO) Unit 2, which incorporates the CPC's, received its operating license in 1978 after a substantial review of the CPC System by the NRC. After ANO-2 received its operating license and during its first fuel cycle, two sets of software changes were made to the CPC System in accordance with the NRC-approved CPC software change procedure (References 1 and 2) and implemented at ANO-2. The CPC software for San Onofre Nuclear Generating Station (SONGS) Unit 2 contains additional functional design changes. This report describes these changes to the ANO-2 Cycle 1 CPC software. At this time, the SONGS Unit 2 CPC System functional design is also planned for use in SONGS Unit 3 and ANO-2 Cycle 2.

1.2 Report Summary

The basis for modifications made to the CPC/CEAC software fall into three general categories, (1) those due to the implementation of an improved DNBR calculation, (2) those resulting from operating experience gained during ANO-2 Cycle 1, and (3) those providing improved diagnostic capabilities to the operator. Changes in the first category consist of implementation of the new DNBR calculation and a revision of the DNBR update calculation designed to provide consistency. Changes in the second category consist of increasing the number of addressable constants and of applying the pump-dependent uncertainty on LPD in the UPDATE program rather than the Trip Sequence program. Changes in the third category include modification of the CEAC snapshot buffer in order to increase the flexibility to retain the cause of a trip condition.

The general format used in describing each software modification contained in this report is a statement of the change, the reason for the change, and a detailed description of the change including algorithm descriptions in symbolic algebra. In addition to this, an appendix is included to provide a detailed functional description of the new DNBR algorithm. A second appendix describes the revised DNBR update calculation based on the new DNBR calculation.

This description of the CPC changes is provided in response to NRC Question 221.18 on the SONGS docket.

1.3 References for Section 1.0

1. CEN-39(A)-P, Revision 02, The CPC Protection Algorithm Software Change Procedure, December 21, 1978.

2. CEN-39(A)-P, Supplement 1-P, Revision 01, January 5, 1979.

2.0 SOFTWARE MODIFICATIONS

2.1 Compensated Local Power Density (LPD) Calculation Changes

1.) Change: The pump-dependent uncertainty on LPD is applied in the DNBR and LPD Update (UPDATE) program instead of the Trip Sequence program.

Reason: In the previous design, the pump-dependent uncertainty on LPD was applied in the Trip Sequence program. As a result, the LPD margin provided to the CPC operator's module and to the analog margin meter had not included this uncertainty. The uncertainty was used, however, in the trip decision logic. This change in the present design will include the uncertainty in the LPD margin to the CPC operator's module and the analog meters with less than four pumps running.

Description: The LPD value to be used in the trip decision is multiplied by the pump-dependent uncertainty factor in the UPDATE rather than the Trip Sequence program. This factor is based upon the number of pumps operating above a pre-specified speed as determined in the Primary Coolant Mass Flow (FLOW) program.

In the previous design, the local power density margin is calculated in the UPDATE program as:

$$L_{PDT} = L_{PDO} \cdot B_{ERR3}$$

$$L_{PDMAR} = K_{DA3}(L_{PDSP} - L_{PDT})$$

where L_{PDO} = the maximum compensated local power density

B_{ERR3} = an addressable local power density uncertainty factor

L_{PDT} = the LPD used in the trip decision

L_{PDSP} = the LPD trip setpoint

K_{DA3} = a factor scaling LPD for D/A conversion

L_{PDMAR} = the local power density margin for output to a D/A converter

In the Trip Sequence Program, the LPD trip contact output is set if

$$F_2 \cdot L_{PDT} \geq L_{PDSP}$$

and the LPD pre-trip contact output is set if

$$F_2 \cdot L_{PDT} \geq C_2$$

where F_2 = A pump-dependent uncertainty factor
C_2 = LPD pre-trip setpoint

Thus, the value of F_2 was not factored into the calculation of local power density margin. Since F_2 equals 1.0 with four reactor coolant pumps running, L_{PDMAR} was correct with four pumps running. With less than four pumps running, the value of F_2 may not equal 1 and therefore the indicated margin to trip may be incorrect.

In the new CPC design the pump-dependent uncertainty factor F_2 is applied in the UPDATE program. The value of L_{PDT} is calculated as

$$L_{PDT} = L_{PDO} \cdot B_{ERR1} \cdot F_2$$

In the Trip Sequence program the LPD trip contact is set if

$$L_{PDT} \geq L_{PDSP}$$

and the LPD pretrip contact is set if

$$L_{PDT} \geq C_2$$

2.2 Power Distribution (POWER) Calculation Changes

1.) Change: Addressable constants have been added for:

a) CEA shadowing factor adjustments,
b) planar radial peaking factor adjustments, and
c) boundary point power correlation coefficients (B_{PPCC}'s)

Reason: As a result of experience gained during the ANO-2 Cycle 1 startup tests, addressable constants have been added to adjust CPC power distributions based on startup measurement tests. The additional addressable constants used to adjust the CEA shadowing and planar radial peaking factors provide more accurate modelling for CEA configurations which may occur at higher power levels. This change results in improved accuracy in the calculations of core power and power distribution. The addressable boundary point power correlation coefficients allow the CPC power distribution to be adjusted based on boundary point power values determined during startup tests.

Description: Three additional addressable consants have been added to both the planar radial peaking factor and the CEA shadowing factor determination at each core axial node (total of six additional constants). Four B_{PPCC}'s located in the Data Base have been made addressable. The appropriate sections of the POWER program have been modified to accommodate this change.

Figure 1 indicates the table partition to be used for determination of the addressable multipliers to the planar radials and rod shadowing factors. The following logic is used to select the correct multipliers based on CEA configuration.

If $I_n = 1$ and if $J = 1$

then $A_{Sn} = 1.0$

and $A_{Rn} = \alpha_{R1}$

If $I_n = 1$ and if $2 \leq J \leq I_{col}$

then $A_{Sn} = \alpha_{S2}$

and $A_{Rn} = \alpha_{R2}$

If $I_n = 2$ and if $J = 1$

then $A_{Sn} = \alpha_{S3}$

and $A_{Rn} = \alpha_{R3}$

If $I_n = 2$ and if $2 \leq J \leq I_{col}$

then $A_{Sn} = \alpha_{S4}$

and $A_{Rn} = \alpha_{R4}$

If $3 \leq I_n \leq I_{row}$ and if $J=1$

then $A_{Sn} = \alpha_{S5}$

and $A_{Rn} = \alpha_{R5}$

If $3 \leq I_n \leq I_{row}$ and if $2 \leq J \leq I_{col}$

then $A_{Sn} = \alpha_{S6}$

and $A_{Rn} = \alpha_{R6}$

If $I_n > I_{row}$ or if $J > I_{col}$

then $A_{Sn} = \alpha_{S7}$

and $A_{Rn} = \alpha_{R7}$

where: I_n = row index based on CEA Regulating Group positions (see Figure 1).

J = column index based on part-length rod (PLR) and Shutdown Bank positions (see Figure 1).

A_{sn} = multiplier on CEA shadowing factor at axial node n

A_{Rn} = multiplier on planar radial peaking factor at axial node n

I_{col}, I_{row} = constants that define partition of table in Figure 1.

(N_{col} = number of columns in the planar radial and shadowing factor table)

The addressable multipliers B_{PPCC1} through B_{PPCC4} replaced the Data Base constants α_1 through α_8. A description of changes to the boundary point power correlation calculation is described in Change B.4).

2.) Change: Some fixed numbers in the POWER calculation have been changed to Data Base constants.

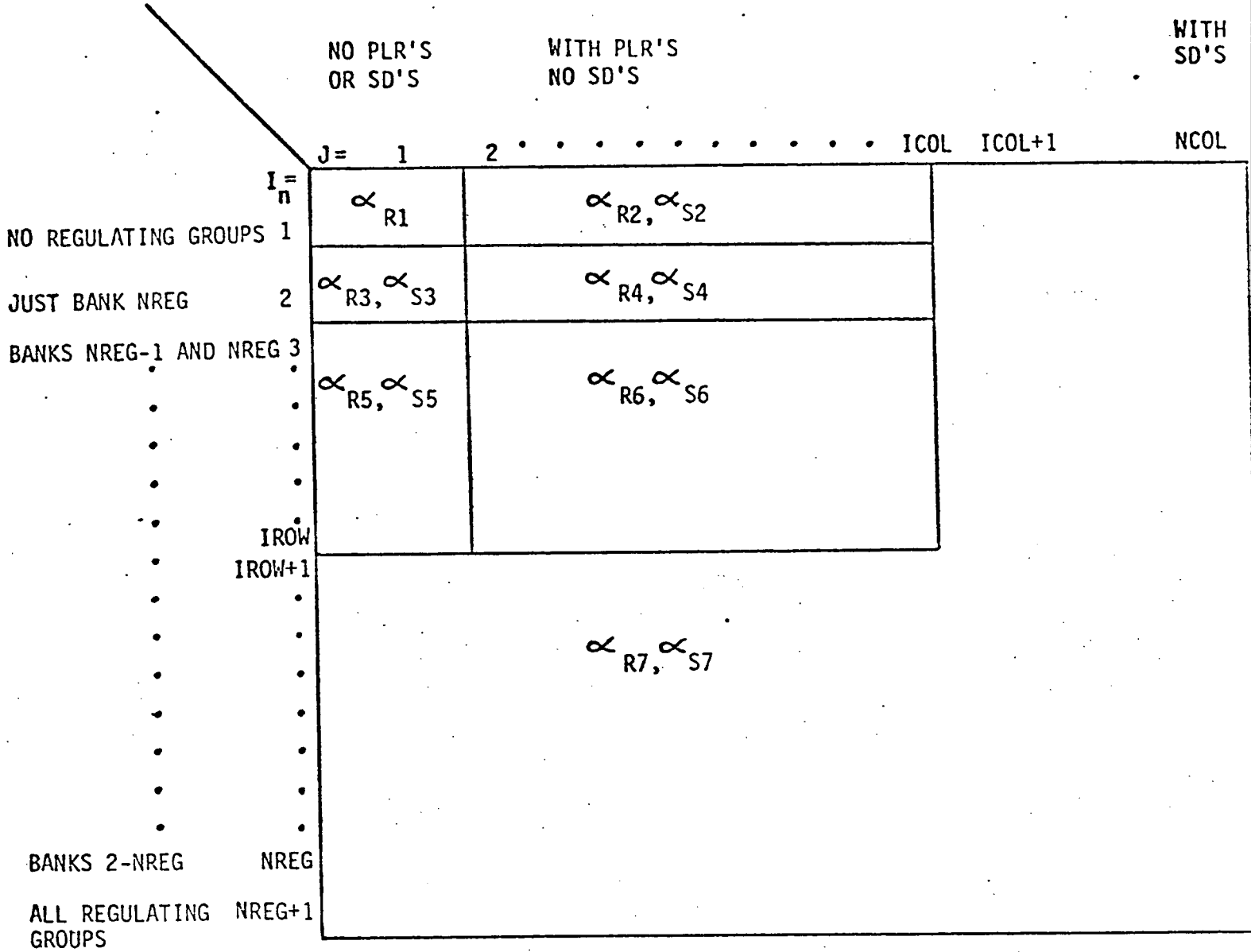

FIGURE 2-1 PARTITION FOR APPLICATION OF ADDRESSABLE MULTIPLIERS FOR PLANAR RADIALS (α_{Ri}) AND ROD SHADOWING (α_{Si}) FACTORS

Reason: Several fixed numbers in the POWER calculation were based upon ANO-2 design and Cycle 1 conditions. Making these numbers Data Base constants provides the flexibility to change these values due to plant-specific designs without changing the CPC Functional Specification.

Description: The fixed numbers which have been changed to data base constants are:

a) [redacted]

b) [redacted]

Three data base constants have also been added to the determination of the final corrected ex-core detector values to correct for the fractional amplitude of each detector signal.

Following is a list of new Data Base constants, their previous values and their definitions:

Data Base Constant	Previous Value	Definition
P_{MINU}	[redacted]	
P_{MINL}		
A_{mpm}		
A_{mpl}		
A_{mpu}		
PWR_m		
PWR_{U1}		
PWR_{U2}		
PWR_{L1}		
PWR_{L2}		

3.) Change: Planar radial peaking factors are now adjusted by a [ ]

Reason: The planar radial peaking factors are dependent on the [ ]

Description: [ ]

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FIGURES 2-2, 2-3a, 2-3b, 2-3c, 2-3d

PAGES 2-10, 2-11

4.) Change: The boundary point power correlation has

Reason:

Description:

[

]

5.) Change: A pre-selected axial power distribution is used during low power operation.

Reason: This change provides a core average axial shape for use

[

]

] The pre-selected shape ensures a conservative axial power distribution at low power[ ]

Description: [ ]

2.3 General Changes

1.) Change: The Core Element Assembly Calculator (CEAC) logic has been modified to allow for a two (2) CEA subgroup.

Reason: The CEA's in the 2-CEA subgroup are not assigned to a specific core quadrant. A CEA core quadrant deviation counter is incremented for each CEA deviation in a core quadrant, and if this number exceeds a pre-specified number of deviations, the CEAC failed sensor flag is set. The CEAC logic is modified to bypass the core quadrant deviation counter for a CEA deviation in the 2-CEA subgroup.

Description: For a CEA deviation within the 2- CEA subgroup the CEA at the more withdrawn position is arbitrarily considered to be the deviating CEA. The CEA at the lower position defines the subgroup position. The existing logic results in a CASE=+1 type deviation in the 2-CEA subgroup. But the CEA's in the 2-CEA subgroup are not assigned to any quadrant and deviating CEA's within this subgroup should not be in the core quadrant deviation counts. Thus, the present design is such that the CEA deviation quadrant counter is incremented when CASE=+1 only in $N_{CEA} \neq 2$. (where N_{CEA} = number of CEA's in subgroup).

2.) Change: The DNBR and LPD pre-trip setpoints have been made addressable constants.

Reason: This change adds flexibility in setting pre-trip alarm setpoints and allows for adjustment of the setpoints without a revision to the Data Base.

Description: The DNBR pre-trip setpoint (A_2, dimensionless) and the LPD pre-trip setpoint (in KW/FT) have been added to the list of addressable constants which may be changed from the operator's module.

This change does not require a change to the DNBR pre-trip logic. However, since the LPD pre-trip setpoint has units of KW/FT and the LPD has units of percent of core average, the following change is made.

If Local Power Density pre-trip limit is violated, issue a Local Power Density Trip or pre-trip signal:

$$C_2 = \text{LPDPTS} \cdot C_{LPD}$$

If $Z \geqslant C_2$

then LPD pre-trip C.O. = 1

otherwise reset the LPD pre-trip C.O.,

LPD Pre-Trip C.O. = 0

wher Z = dynamically compensated Local Power Density computed in DNBR and Power Density Update Program, (%)

LPDPTS = Addressable Local Power Density pre-trip Setpoint (KW/FT)

C_{LPD} = Conversion Factor (%/(KW/FT))

C_2 = Local Power Density pre-trip setpoint (%)

LPD Pre-Trip C.O. = Local Power Density pre-trip Signal

A_2 = Addressable DNBR pre-trip setpoint

The functional design group will provide the default values of A_2 and LPDPTS.

3.) Change: The update period for the CEAC CRT display has been changed to 3.0 seconds.

Reason: Previously, the update period for the CEAC CRT display was 2.0 seconds. Based upon the increased number of CEA's in post-ANO-2 CPC plants this period is changed to a value of no greater than 3.0 seconds.

Description: This update consists of a fixed algorithm scheduling rate, which will be no greater than 3.0 seconds.

4.) Change: New curve fits have been made for core coolant enthalpy/ temperature and specific volume determinations.

Reason: The hot and cold leg specific volumes are computed as part of the flow resistance calculation in the FLOW program. Previously, these values were based on temperature values. The new curve fits provide for a pressure adjustment to the temperature dependent curve fit coefficients. The curve fit is further improved by having a higher order in temperature. The primary pressure values used are computed from raw input values sampled in UPDATE.

Description: Several curve fits to specific volume were attempted and a "best" overall fit was defined as that which yielded the smallest maximum absolute error. This case was identified as being:

[ ] order in temperature
[ ] order in pressure

with polynomial coefficients of 4 significant figures.

The ranges on temperature and pressure corresponding to this case were

[ ] ≤ Temperature ≤ [ ]

[ ] psia ≤ Pressure(P) ≤ [ ]

the curves fits for specific volume versus temperature and pressure are given as:

V_c = [ ]

V_{c1} = [ ]

*If the hot leg temperature is within [ ] of the saturated temperature, the CPC will initiate the currently implemented hot leg saturation trip.

V_{c2} = [

V_h =

V_{h1} =

V_{h2} =]

where: [ ]

and where:

V_c = normalized average cold leg specific volume

V_{c1} = normalized specific volume in cold leg 1A or 1B

V_{c2} = normalized specific volume in cold leg 2B or 2A

V_h = normalized average hot leg specific volume

V_{h1} = normalized specific volume in hot leg 1

V_{h2} = normalized specific volume in hot leg 2

T_c = average cold leg coolant temperature, ^oF

T_{c1} = coolant temperature in cold leg 1A or 1B, ^oF

T_{c2} = coolant temperature in cold leg 2B or 2A, ^oF

T_h = average hot leg coolant temperature, ^oF

T_{h1} = coolant temperature in hot leg 1, °F

T_{h2} = coolant temperature in hot leg 2, °F

P = primary pressure, psia

[ ]

(see Figure 4 for coolant leg designations)

The values of curve fit coefficients are given below:

SV_{00} = [ ]
SV_{10} =
SV_{20} =
SV_{30} =
SV_{40} =
SV_{01} =
SV_{11} =
SV_{21} =
SV_{31} =
SV_{41} = [ ]

Maximum absolute error of curve fit = [ ]

Maximum percent error of curve fit = [ ]

The hot and cold leg enthalpy-temperature ratio computations are performed in the Static Thermal Power Calcualtion. The new curve fits are based upon improved curve fit coefficient values.

In the previous design, the curve fits were performed for enthalpy rather than the enthalpy temperature (H/T) ratio and the H/T ratio was obtained by dividing the calculated enthalpy by the temperature. A "best" curve fit for the H/T ratio was arrived at in a manner similar to that for the specific volume curve fits. The best case is defined as:

[ ] order in temperature
[ ] order in pressure

with polynomial coefficients of 6 significant figures

and the same temperature and pressure ranges as those for specific volume.

the curve fits for H/T ratios versus temperature and pressure are given as:

C_{IN1} = [ ]

C_{IN2} = [ ]

C_{OUT1} = [ ]

C_{OUT2} = [ ]

where: [ ]

and where: P_{ST} = static value of pressurizer pressure, psia

T_{h1}, T_{h2} = hot leg temperatures in hot legs 1 and 2, respectively, ^{o}F

C_{IN1} = enthalpy-temperature ratio of water in cold legs 1A and 1B, Btu/lbm - ^{o}F

C_{IN2} = enthalpy-temperature ratio of water in cold legs 2A and 2B, BTU/lbm - ^{o}F

C_{OUT1} = enthalpy-temperature ratio of water in hot leg 1, BTU/lbm-^{o}F

C_{OUT2} = enthalpy-temperature ratio of water in hot leg 2, BTU/lbm-^{o}F

HTR_{ij} = pressure dependent coefficients used to determine enthalpy temperature ratios [ ]

The values of curve fit coefficients are given below:

HTR_{00} =
HTR_{10} =
HTR_{20} =
HTR_{30} =
HTR_{01} =
HTR_{11} =
HTR_{21} =
HTR_{31} =

[ ]

Maximum absolute error of curve fit = [ ] BTU/lbm - ^{o}F

Maximum percent error of curve fit = [ ]

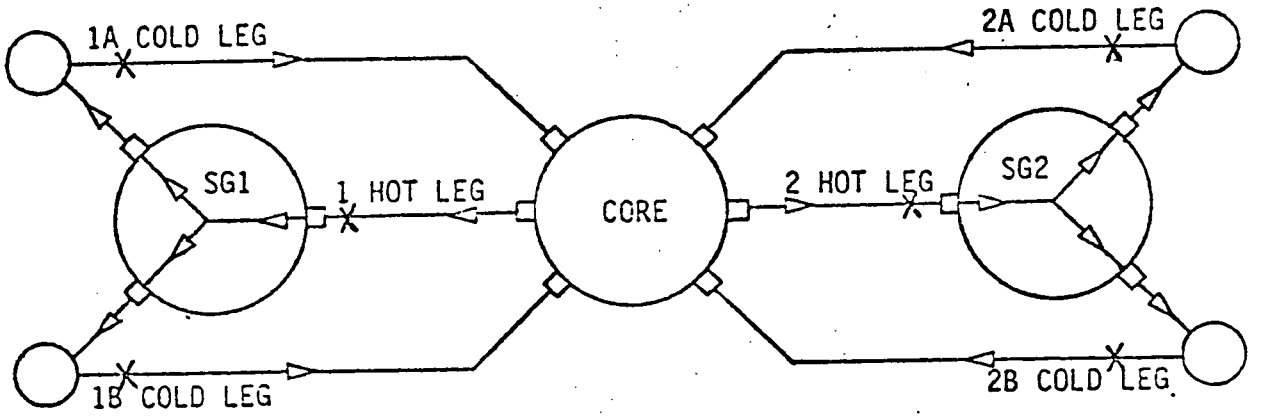


FIGURE 2-4

Schematic of Primary System Showing
Approximate Location of Temperature Sensors

5.) Change: The slope of the coolant temperature shadowing factor (C_{t1}) has been made an addressable constant.

Reason: The temperature shadowing factor correction factor is used in the neutron flux power and the power distribution calculations. The shadowing factor is verified during startup testing. As an addressable constant, the slope of the shadowing factor can be adjusted based on test measurements, resulting in a more accurate CPC calculation.

Description: The constant C_{t1} was previously a non-addressable Data Base value in UPDATE. It is now an addressable constant which can be updated at the operator's module based on startup test measurements.

2.4 Diagnostic Changes

1.) Change: The CEAC snapshot buffer is changed to be similar to that for the CPC's.

Reason: In the previous CEAC design, a buffer was filled with a snapshot of CEAC input and output data if a CEAC penalty was calculated. This buffer was then updated every 5 seconds for as long as the penalty existed. Based on ANO-2 operating experience, more useful diagnostic information may be obtained if the CEAC snapshot is recorded for the first penalty factor calculated by the CEAC and is not overwritten unless plant personnel manually clear the buffer. This change makes the CEAC snapshot diagnostic similar to the CPC trip snapshot diagnostic.

Description: A snapshot of CEA positions is initiated by 1) a CEAC PF greater than 1.0, 2) the large PF flag, 3) a CEAC failure caused by either an excessive number of sensor failures or an excessive number of deviating CEA's in a core quadrant. The CEA positions are stored in a buffer and cannot be overwritten until that snapshot is printed out at a teletype or the buffer is cleared by plant personnel through an addressable constant which is added to the CEAC Point ID table. The addressable constant shall also be a flag indicating the status of the buffer ; filled or clear. As an example the constant could be zero (0) for a cleared buffer and one (1) for a filled buffer. Changing the constant from 1 to 0 could be used to clear the buffer.

2.) Change: The failed sensor ID numbers used to indicate large differences in the CPC PF's have been changed.

Reason: In the previous design, the failed sensor ID number for a given sensor was generally the same as the Point ID number for that sensor. However, the CPC failed sensor ID's for the maximum allowable differences between the DNBR and LPD penalty factors were ID's 038 and 039, which did not correspond to the information in CPC Point ID's 038 and 039. The CPC failed sensor ID's are thus changed for the present design.

Description: The CPC failed sensor ID numbers used to indicate large differences in the DNBR and LPD PF's have been changed from locations 038 and 039 to locations 998 and 999, respectively.

i.e., if $|PF_1 - PF_2| \geq E_D$,

or if $|PF_{L1} - PF_{L2}| \geq E_L$

then sensor ID's 998 on 999 are entered into the failed sensor stack

where: PF_1, PF_2 = CEA deviation penalty factor for DNBR from CEAC1, CEAC2 respectively.

PF_{L1}, PF_{L2} = CEA deviation penalty factor for LPD from CEAC1, CEAC2, respectively.

E_D, E_L = maximum allowable differences between the DNBR and LPD penalty factors, respectively

3.) Change: An addressable constant has been added to the CEAC to rewrite the entire CEAC display.

Reason: In the previous design, the entire CEAC display was rewritten only during CEAC initialization after a restart. Spurious electronic noise may interfere with those portions of the CEAC CRT display which are not periodically updated. The new software provides a means to clear the entire CEAC CRT display without restarting the calculator.

Description: An addressable constant is added to the CEAC Point ID table to allow the operator to rewrite the entire CEAC CRT display

2.5 DNBR Calculation Changes

1.) Change: Replace the W-3 DNBR calculation with the CE-1 DNBR calculation.

Reason: The accuracy of the DNBR calculation is increased.

Description: (See Appendix A, enclosed)

2.) Change: Replace the DNBR update calculation in the UPDATE program with a DNBR update calculation which is based on the CE-1 DNBR calculation implemented in the STATIC program.

Reason: This change makes the DNBR update calculation consistent with the CE-1 DNBR correlation calculation being implemented in the STATIC program.

Description: (See Appendix B, enclosed)

APPENDIX A

PART 1: CETOP2 FUNCTIONAL DESCRIPTION

1.0 INTRODUCTION

This document provides a functional description of the CETOP2 algorithm, which is intended to be used to perform the DNBR computations in the Core Protection Calculators (CPCs). The methodology of this algorithm applies to a general C-E PWR core and is to be incorporated into the generic CPC design.

The prediction-correction numerical scheme and the lumped channel technique (Ref. 1) in CETOP2 are used to solve the conservation equations for a three dimensional representation of the open-lattice core. The hot channel critical heat flux is calculated using the CE-1 correlation. Several simplified correlations for calculating the fluid properties are employed to shorten the running time. This results in more accurate DNBR prediction than the previous CPCTH approach, yet the required execution time constraints are met.

CETOP2 divides the core into four modeling channels: Core Region Channel, Hot Assembly Channel, Buffer Channel and Hot Channel (See below). Based on the mass, momentum and energy interactions between these modeling channels, the local coolant conditions are determined at several axial locations (nodes) for each of the four channels. Ultimately, the hot channel conditions are used for the DNBR calculation.

Channel 1	Channel 2	Channel 3	Channel 4
Core Region	Hot Assembly	Buffer Channel	Hot Channel

THE FOUR MODELING CHANNELS USED BY CETOP2

The local coolant conditions are computed at [ ] axial nodes, for each of the four channels. When the hot-channel conditions are known, [ ] The DNBR is then calculated at each node and the minimum selected for output. The major steps are:

1. Calculation of the general operating conditions (inlet enthalpy, saturation properties, etc.);

2. Calculation of the core and hot assembly local coolant conditions using [ ] nodes each;

3. Calculation of the buffer and hot channel local coolant conditions using [ ] axial nodes;

4. [ ]

5. Calculation of DNBR.

A flow diagram for the CETOP2 algorithm is given in Figure 1.1.

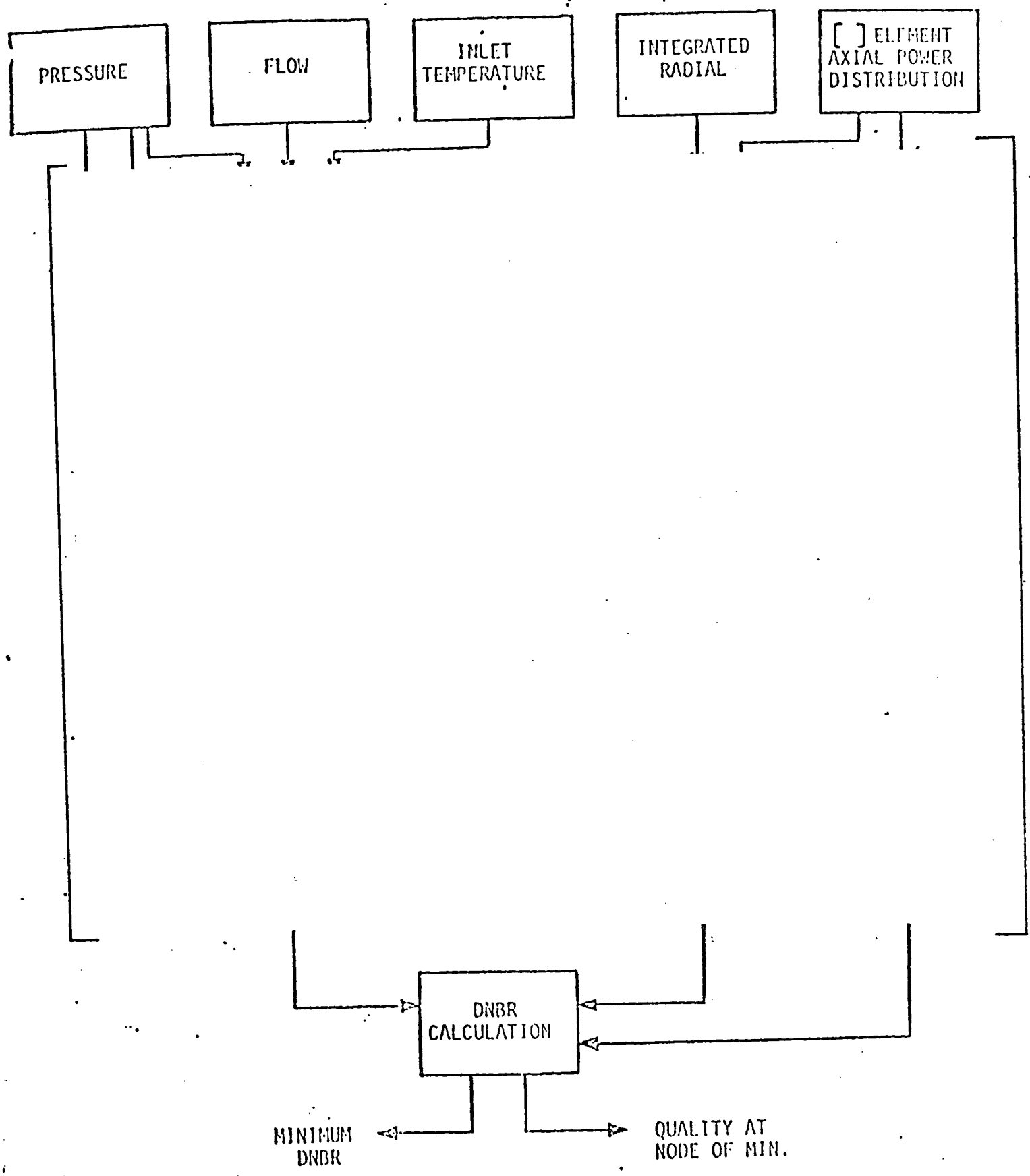
The notation used herein is employed to allow for maximum flexibility in implementation, and clarity of specification. Many quantities are expressed as two-dimensional arrays, in the interest of clarity, but it is not a functional requirement to implement them in this way. Additionally, it may be possible in some cases to combine constants into composite terms.

Unless indicated otherwise the following convention will be employed, (using enthalpy as an example).

$h_i(j)$ = Specific enthalpy at node j, channel i.

The generic constants and the plant specific constants for SONGS are included herein. The associated accuracy of the algorithm when compared to the design code is also addressed.

FIGURE 1.1 CETOP2 ALGORITHM FLOW



2.0 ALGORITHM SPECIFICATION

This section defines the specific techniques for calculating the DNBR from the known process variables. The inputs and outputs are defined in Section 2.1. Sections 2.2 through 2.11 comprise the body of the algorithm. Sections 2.12 and 2.13 define two required mathematical functions.

2.1 INTERFACE REQUIREMENTS

2.1.1 Inputs

The algorithm requires the following process parameters:

- P - Primary coolant system pressure (psia).
- T_{cmax} - Maximum compensated cold leg temperature (°F).
- M_c - Calibrated, normalized core coolant mass flow rate.
- ϕ_{CALC} - Core average heat flux (% of nominal heat flux)
- TR - Azimuthal tilt allowance (addressable constant)
- PF - CEA deviation penalty factor for DNBR
- PD_i - Pseudo hot pin power distribution calculated in the Power Distribution program, i=1,[ ]
- P_{1EPC} - Integrated one pin radial peak.
- ASI - Hot channel axial shape index.

2.1.2 Outputs

The primary outputs of this algorithm are listed below. Additional information is available if required, for example the saturation enthalpy or the hot-channel exit quality.

- $DNBR_{st}$ - Minimum hot-channel DNBR.
- X_{st} - Hot channel quality at node of minimum DNBR.

The following outputs are required by the [ ]

[ ]

2.1.3 Constants

Defined in Section 3.

2.2 SATURATION PROPERTIES

The saturated fluid properties are obtained from the following polynomials.

$$T_f = \sum_{i=1}^{[\,]} ATF_i \cdot p^{(i-1)}$$

$$h_f = \sum_{i=1}^{[\,]} AHF_i \cdot p^{(i-1)}$$

$$h_{fg} = \sum_{i=1}^{[\,]} AHFG_i \cdot p^{(i-1)}$$

$$v_f = \sum_{i=1}^{[\,]} AVF_i \cdot p^{(i-1)}$$

$$v_g = \sum_{i=1}^{[\,]} AVG_i \cdot p^{(i-1)}$$

$$\mu_f = \sum_{i=1}^{[\,]} AVIF_i \cdot p^{(i-1)}$$

Where

P = Primary coolant system pressure (psia)
T_f = Saturation temperature (°F)
h_f = Saturated liquid specific enthalpy (Btu/lb_m)
h_{fg} = Latent heat of vaporization (Btu/lb_m)
v_f = Saturated liquid specific volume (ft^3/lb_m)
v_g = Saturated vapor specific volume (ft^3/lb_m)
μ_f = Saturated liquid viscosity ($lb_m/ft/sec$)
ATF,AHF,AHFG,AVF,AVG,AVIF = polynomial coefficients, constant.

[ ]

2.3 CALCULATION OF PRESSURE DEPENDENT TERMS

The VOLUME and FRICFAC functions, defined in Sections 2.11 and 2.12, involve a number of terms which depend only on pressure.

[

]

The following are used by the VOLUME function:

$$BALPL_i = \sum_{j=1}^{[\,]} ALL_{ij} \cdot p^{(j-1)}, \qquad [\quad]$$

$$BALPH_i = \sum_{j=1}^{[\,]} ALH_{ij} \cdot p^{(j-1)}, \qquad [\quad]$$

Where

BALPL = Coefficients for void fraction vs. quality polynomial (low quality)

BALPH = Coefficients for void fraction vs. quality polynomial (high quality)

ALL = [ ] array of void fraction vs. quality and pressure coefficients (Reference 2) - Quality < [ ] constant.

ALH = same as above except for quality ≥ [ ] constant.

The following terms are used in the friction factor calculation.

[ ]

FF_i = [ ]

where

FF = Intermediate results used by the FRICFAC function.

CF = Various constants (array of [ ]).

2.4 CALCULATION OF INLET CONDITIONS

The core and hot assembly inlet conditions are calculated as follows.

$$h_{in} = \sum_{i=1}^{[\,]} B_i [T_{cmax}]^{(i-1)}, \qquad \text{where } B_i = \sum_{j=1}^{[\,]} AEN_{ij} \cdot p^{(j-1)}$$

$$v_{in} = \sum_{i=1}^{[\,]} BSVOL_i \, [h_{in}]^{(i-1)}$$

$$G_{in} = (M_c + M_{ERR}) \cdot G_{AVG}$$

If $P_{1B2} \leq P_{1EPC} < P_{1B3}$

and $ASI_{B2} \leq ASI < ASI_{B3}$

and $T_{B2} \leq T_{CMAX} < T_{B3}$

and $PP_{B2} \leq P < PP_{B3}$

Then FSPLIT = FSPLIT1

and E = E1

and $J_{TRP} = 0$

Otherwise FSPLIT = FSPLIT2

and E = E2

and J_{TRP} is determined as follows:

if $P_{1B1} \leq P_{1EPC} < P_{1B4}$

and $ASI_{B1} \leq ASI < ASI_{B4}$

and $T_{B1} \leq T_{CMAX} < T_{B4}$

and $PP_{B1} \leq P < PP_{B4}$

then $J_{TRP} = 0$

otherwise $J_{TRP} = 1$

[ ]

$$M_{cs} = M_c$$

Where:

h_{in} = Inlet core coolant specific enthalpy (Btu/lb_m)
v_{in} = Inlet core coolant specific volume (ft^3/lb_m)
G_{in} = Coolant mass flux at core inlet ($lb_m/ft^2/sec$)
ASI = Hot channel axial shape index.
FSPLIT = Hot assembly flow starvation factor.
T_{cmax} = Maximum cold leg temperature (°F)
M_c = Normalized core average mass flow rate.
AEN = [ ]array of coefficients for enthalpy vs. pressure and temperature correlation.
BSVOL = Array of coefficients for specific volume vs. enthalpy correlation.
FSPLIT1,FSPLIT2 = Region-dependent flow splits, constants.
M_{ERR} = Flow measurement uncertainty adjustment term.
G_{AVG} = Design core average mass flux ($lb_m/ft^2/sec$).
P_{1Bi} = Integrated one pin radial break points for selection of regions[ ].

P_{1EPC} = Integrated one pin radial
P = Primary Pressure (psia)
T_{Bi} = Maximum cold leg temperature break points for selection of regions ($i = 1,[\ ]$ (^oF)
PP_{Bi} = System pressure break points for selection of regions ($i=1,[\ ]$ (psi
$E_{1,2}$ = Region-dependent algorithm uncertainty allowances
E = Multiplicative power uncertainty factor for DNBR calculation (region-dependent)
ASI_{Bi} = Constant, ASI break point for selection of region ($i = 1,[\ ]$
J_{TRP} = DNBR region trip flag

2.5 CALCULATION OF LINEAR HEAT DISTRIBUTIONS

The hot pin axial heat flux distributions are calculated as follows:

$$\phi_c(i) = \phi_{CALC} \cdot TR \cdot PF \cdot PD_i \quad [\quad]$$

Four[ ]linear heat distributions are computed for the four modeling channels. The[ ]hot pin axial heat flux distribution is combined with the integrated one pin radial peak, and collapsed to[ ]distributions, as follows:

For $j = [\quad]$

$$q_1'(j) = \left[\quad\right] \cdot Q_{AVG} \cdot \pi \cdot D_{H1} \cdot B_{ERR1} \cdot E$$

$$q_2'(j) = \left[\quad\right] \cdot \left(\frac{P_2}{P_4}\right) \cdot Q_{AVG} \cdot \pi \cdot D_{H2} \cdot B_{ERR1} \cdot E$$

$$q_3'(j) = \left[\quad\right] \cdot \left(\frac{P_3}{P_4}\right) \cdot Q_{AVG} \cdot \pi \cdot D_{H3} \cdot B_{ERR1} \cdot E$$

$$q_4'(j) = \left[\quad\right] \cdot Q_{AVG} \cdot \pi \cdot D_{H4} \cdot B_{ERR1} \cdot E$$

where

q_1' = [ ]element core-region linear heat distribution (Btu/ft/sec)

q_2' = [ ] element hot-assembly linear heat distribution (Btu/ft/sec)

q_3' = [ ] element buffer channel linear heat distribution (Btu/ft/sec)

q_4' = [ ] element hot channel linear heat distribution (Btu/ft/sec)

ϕ_c = [ ] element hot pin relative axial power distribution ($\phi_c(i)$ = relative power in axial segment i of the hot pin).

$P1_{EPC}$ = Integrated one pin radial peak.

Q_{AVG} = core average heat flux at full power ($Btu/ft^2/sec$) constant.

π = 3.14159... constant.

P_2 = [

P_3 = [

P_4 = [ ]

D_{H1}-D_{H4} = Heated diameter of respective channel (ft), constant.

BERR1 = Addressable DNBR uncertainty factor.

[ ]

2.6 COMPUTATION OF CORE/HOT-ASSEMBLY FLUID PROPERTIES

The calculations described in this section result in the enthalpy, mass flux, cross-flow and pressure drop axial distributions, for both the core region and hot-assembly channels. The hot-assembly distributions will be used in subsequent calculations. (Section 2.7)

The properties at each node depend on the properties of the upstream and downstream nodes. The method of solution is a prediction/correction scheme. The technique is summarized below:

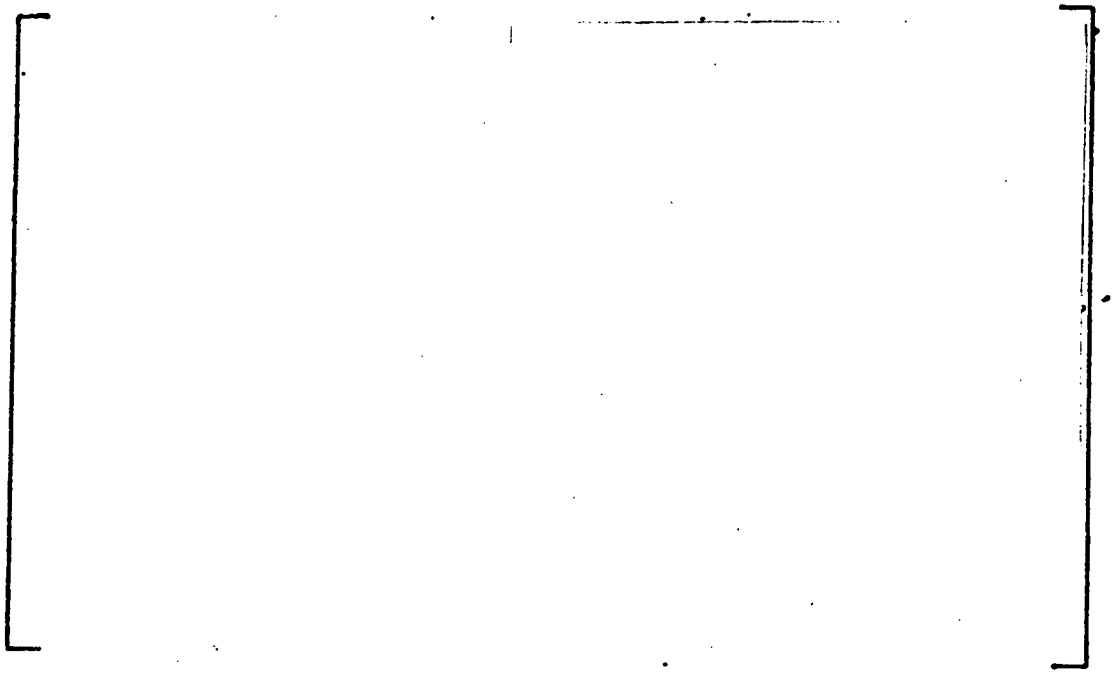
At each of the [ ] the following calculations are performed:

- Prediction of mass fluxes at node j.
- Prediction of enthalpies at node j+1.
- Prediction of specific volumes and friction factors at node j+1.
- Prediction of cross-flow at node j+1.
- [ ]
- Calculation of corrected mass-fluxes at node j.
- [ ]
- Calculation of cross-flow resistance at node j+1.
- [ ]

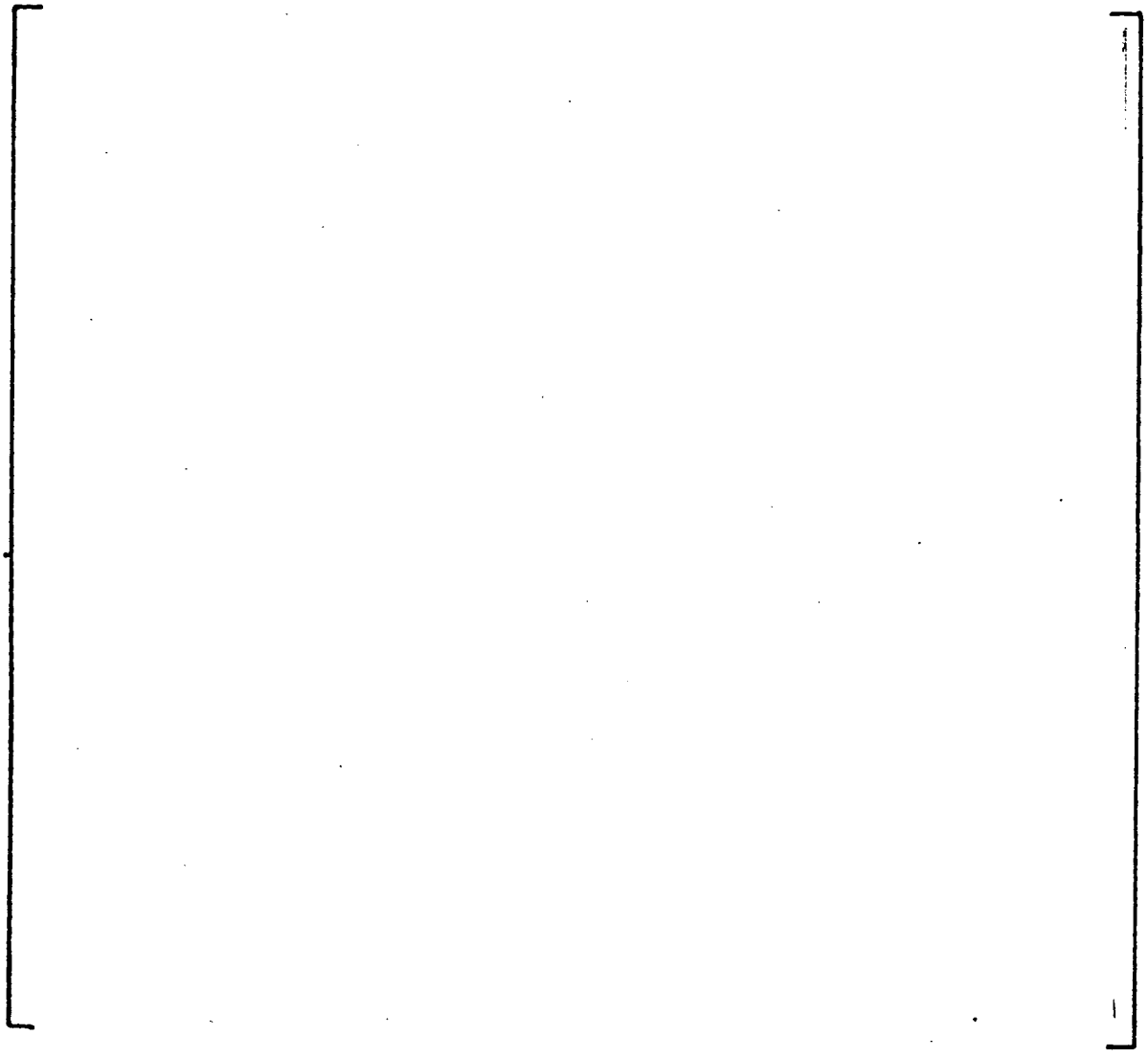
The calculations involved in each of the above steps are defined in the following sub-sections.

2.6.1 Initialization of State Variables

[ ]



2.6.2 Nodal Loop



PAGES A-13, A-14

[

]

2.6.3 Calculations at [ ] Node

[

]

[redacted]

2.7 CALCULATION OF BUFFER/HOT-CHANNEL FLUID PROFILES

The calculations described in this section result in the enthalpy and mass flux distributions for the buffer and the hot channels. The hot channel distributions will be used subsequently in the critical heat flux calculations.

[redacted]

2.7.1 Initialization of State Variables

[redacted]

2.7.2 Nodal Loop

[redacted]

PAGES A-18, A-19

[redacted]

2.8 COMPUTE HOT CHANNEL QUALITY AND FLOW PROFILES

[redacted]

[redacted]

2.9 HOT CHANNEL HEAT FLUX DISTRIBUTIONS

The calculations described in this section result in the hot-channel critical heat flux and actual local heat flux distributions.

2.9.1 Local Heat Flux Distribution

[redacted]

[redacted]

2.9.2 Hot Channel Critical Heat Flux

[redacted]

[redacted]

2.10 CORRECTION FOR NON-UNIFORM HEATING

The correction factors for non-uniform heating are calculated from:

[redacted]

[

]

2.11 CALCULATION OF STATIC DNBR

The DNB ratio at each hot-channel node is given by

For $F(K) \leq 0.0$ or $q''_{LOCAL}(K) \leq 0.0$

$$DNBR_K = 0.0$$

Otherwise,

$$DNBR_K = \frac{q''_{DNB}(K)}{F_K \cdot q''_{LOCAL}(K)} \qquad K=2,3..[\ ]$$

The minimum is selected and adjustment terms applied.

$$DNBR_{MIN} = MIN\ [\ DNBR_2,\ DNBR_3 \ldots\ DNBR_{[21]}]$$

$$DNBR_{ST} = E_{DNB1} \cdot [DNBR_{MIN} + E_{DNB2}]$$

and

[

]

[redacted]

DNBR = Array of DNB ratios in hot-channel

$DNBR_{ST}$ = Minimum STATIC DNBR.

E_{DNB1}, E_{DNB2} = DNBR adjustment terms, constant

2.12 DEFINITION OF VOLUME FUNCTIONS

The preceeding calculations make use of the VOLUME functions* defined in this section. The independent variables in these functions are pressure (P) and local specific enthalpy (h). The three specific volumes resulting from these calculations are:

V(P,h) = Specific volume at pressure P and enthalpy h

VP(P,h) = Specific volume to be used in momentum pressure drop.

VFRIC(P,h) = Specific volume to be used in friction pressure drop.

*VP, VFRIC and V will be collectively referred to as "VOLUME".

First the local quality, X, is calculated

$$X = (h-h_f)/h_{fg}$$

Then,

$$\text{If } X \leq 0 \qquad V = VP = VFRIC = \sum_{i=1}^{[\,]} ASVOL_i \cdot [h]^{(i-1)},$$

otherwise the void fraction is calculated:

$$\alpha = \begin{cases} \sum_{i=1}^{[\,]} BALPL_i \cdot X^{(i-1)} & \text{if } P \leq P_{BRK1} \text{ and } X_{BRK1} \leq X < X_{BRK3} \\ \sum_{i=1}^{[\,]} BALPH_i \cdot X^{(i-1)} & \text{if } P \leq P_{BRK1} \text{ and } X \geq X_{BRK3} \\ \dfrac{X \cdot \upsilon_g}{X \cdot \upsilon_g + (1-X)\upsilon_f} & \text{if } P > P_{BRK1} \text{ or } X < X_{BRK1} \end{cases}$$

Then,

$$V = \frac{\upsilon_f \cdot \upsilon_g}{\alpha \cdot \upsilon_f + (1-\alpha) \cdot \upsilon_g}$$

$$VP = \upsilon_f \frac{(1-X)^2}{(1-\alpha)^2} + \upsilon_g \frac{X^2}{\alpha^2}$$

$$VFRIC = \upsilon_f$$

Where:

BALPL, BALPH = Void fraction vs. quality coefficients defined in Sec. 2.2.

v_f, v_g, h_f, h_{fg} = Saturation conditions calculated in Section 2.2

ASVOL = Subcooled specific volume vs. enthalpy polynomial coefficients, constant.

X_{BRK1}, X_{BRK3} = Quality break points.

P_{BRK1} = Pressure break point.

2.13 DEFINITION OF FRICFAC FUNCTION

The preceeding calculations make use of the FRICFAC function defined in this section. This is a function of [ ] variables and is defined as

FRICFAC[ ] = local channel friction factor

where the dummy arguments are defined as

[ ]

Specifically the calculation proceeds as follows:

[ ]

PAGES A-28, A-29, A-30, A-31 and A-32

3.0 CONSTANTS

3.1 GENERIC CONSTANTS

The generic constants, i.e. those not expected to change from plant to plant, are summarized in Table 3.1. The numerical values of the constants are included.

3.2 PLANT SPECIFIC CONSTANTS

Constants in this category may be different from plant to plant. Additionally some constants may even differ from fuel cycle to fuel cycle for a given plant. These constants are summarized in Table 3.2.

TABLE 3.1

GENERIC CONSTANTS

NAME	VALUE(S)[a]	DESCRIPTION
ATF		
AHF		
AHFG		
AVF		
AVG		
AVIF		
AEN		

TABLE 3.1 (Continued)

GENERIC CONSTANTS

NAME	VALUE(S)	DESCRIPTION
ALL		
ALH		

TABLE 3.1 (Continued)

GENERIC CONSTANTS

NAME	VALUE(S)	DESCRIPTION
ASVOL		
BVISC		
BTEMP		
BKPRD		
BMPT2		
BFRTH		
FSPCON		
DBCON		
KPRDF		
π		
g_c		
$XBRK_1$		
X_{BRK2}		
X_{BRK3}		
X_{BRK4}		

TABLE 3.1 (Continued)

GENERIC CONSTANTS

NAME	VALUE(S)	DESCRIPTION
P_{BRK1}		
P_{BRK2}		
P_{BRK3}		
CF		

TABLE 3.1 (Continued)

GENERIC CONSTANTS

NAME	VALUE(S)	DESCRIPTION
C		
α_3		
α_4		
α_5		
α_6		
α_7		
α_8		

TABLE 3.1 (Continued)

GENERIC CONSTANTS

NAME	VALUE(S)	DESCRIPTION
EX1, EX2	[	]
K_1		

[ ]

TABLE 3.2

PLANT-SPECIFIC CONSTANTS FOR SONGS (TYPICAL)

NAME	VALUE(S)	DESCRIPTION
Q_{AVG}		
Q_{HOT}		
Q_{FUEL}		
SKECDK		
P_2		
P_3		
P_4		
A_1		
A_2		
A_3		
A_4		
D_{H1}		
D_{H2}		
D_{H3}		
D_{H4}		
D_{E1}		
D_{E2}		
D_{E4}		
H_{PERIM1}		
H_{PERIM2}		
H_{PERIM4}		
ΔX		
F_{SPLIT1}		
F_{SPLIT2}		
ASI_{B1}		
ASI_{B2}		
ASI_{B3}		
ASI_{B4}		
T_{B1}		
T_{B2}		
T_{B3}		
T_{B4}		

TABLE 3.2 (Continued)

PLANT-SPECIFIC CONSTANTS FOR SONGS (TYPICAL)

NAME	VALUE(S)	DESCRIPTION
PP_{B1}	[redacted]	
PP_{B2}		
PP_{B3}		
PP_{B4}		
P_{1B1}		
P_{1B2}		
P_{1B3}		
P_{1B4}		
C_H		
C_N		
α_o		
WP1CON		
E_1		
E_2		

TABLE 3.2 (Continued)

PLANT-SPECIFIC CONSTANTS FOR SONGS (TYPICAL)

NAME	DESCRIPTION
WP2CON	[ ]
[ ]	
CIJCON	[ ]
[ ]	
E_{DNB1}	[ ]
E_{DNB2}	
M_{ERR}	

(a) Channel 1 - Core Region, 2 - Hot Assembly, 3 - Buffer Channel, 4 - Hot Channel.

4.0 REFERENCES

1. C. Chiu, J. F. Church, Three-Dimensional Lumped Subchannel Model and Prediction - Correction Numerical method for Thermal Margin Analysis of PWR Cores, TIS-6191, June, 1979.

2. Combustion Engineering, Inc., TORC CODE: A Computer Code for Determining the Thermal Margin of a Reactor Core, CENPD-161-NP, July, 1975

PART 2: ACCURACY ASSESSMENT OF CETOP 2 ALGORITHM

1.0 Analytical Technique

1.1 General Strategy

The accuracy assessment of the CETOP2 algorithm is performed by comparing its calculated overpower margin to that calculated by CETOP-D for the same reactor core and coolant conditions. The reactor core simulated is typical of those plants that will use the CPC. A large data base is used in the CETOP2 accuracy assessment to provide a sufficient statistical data base from which a comparison can be made. It is not essential to the validity of the analysis that the simulators generate exact distributions for any given CEA configuration or time in life, but only to generate a large number of diverse distributions.

The final result of the analysis described above is an uncertainty factor which, when applied as a multiplicative adjustment to the core power level input to the CETOP2 algorithm, results in a calculated DNBR that is conservative with respect to a CETOP-D evaluation of the actual core power distribution to at least the 95/95 probability/confidence level.

1.2 CPC Constants

Calculations are performed using CETOP2 and the design code CETOP-D. Each code is initialized with input derived from the same source. For the geometric constants (core active length, hydraulic diamter, etc.) the data source is constructed from print specifications of the core; for design variables such as engineering factors, the input values are taken from data typically reported in Section 4.0 of Safety Analysis Reports. The remaining input items are the process variables of core inlet temperature, reactor coolant system pressure, core flow rate, radial peaking factor, the normalized axial power distribution, and the specification of constants related solely to the CETOP2 and CETOP-D models.

Calculations are performed with identical process variable input. In this manner, the errors in the CETOP2 results are isolated to those modeling features that generate errors in predicting the DNBR and quality at the node of minimum DNBR.

1.3 Thermal Margin Method

1.3.1 Overpower Comparison

The 95/95 uncertainty factors for CETOP2 are quantified in terms of overpower margin by comparing results with those from CETOP-D over a range of process variables wide enough to include conditions possible during some abnormal event, such as an Anticipated Operational Occurrence (AOO). Therefore, CETOP2/CETOP-D comparisons described result in a conservative estimate of the error for both normal and abnormal operating conditions.

The uncertainty of CETOP2 will be quantified in terms of overpower margin. In order for this technique to be justified, the resultant overpower margin penalty must lead to DNBR comparisons that achieve 95/95 statistical levels, regardless of the core power level.

1.3.2 Effect of the Overpower Uncertainty Factor on DNBR

The CETOP2 uncertainty is quantified in terms of overpower margin. Since the CPC computes DNBR, the uncertainty assessment is valid only if the uncertainty factor when applied to the core power input to CETOP2 produces DNBR errors that meet the 95% probability level at any core power.

To demonstrate that the method employed in the analysis satisfies this condition, CETOP2 and CETOP-D are rerun at 100% and 50% of rated power with the uncertainty factor applied to CETOP2. In both the 100% and 50% cases, 95% of the CETOP2 computed DNBRs must be conservative with respect

to the CETOP-D calculated values. This will ensure that the use of an overpower margin uncertainty is a sufficient and conservative measure for accommodating the DNBR uncertainty in the CPC.

References:

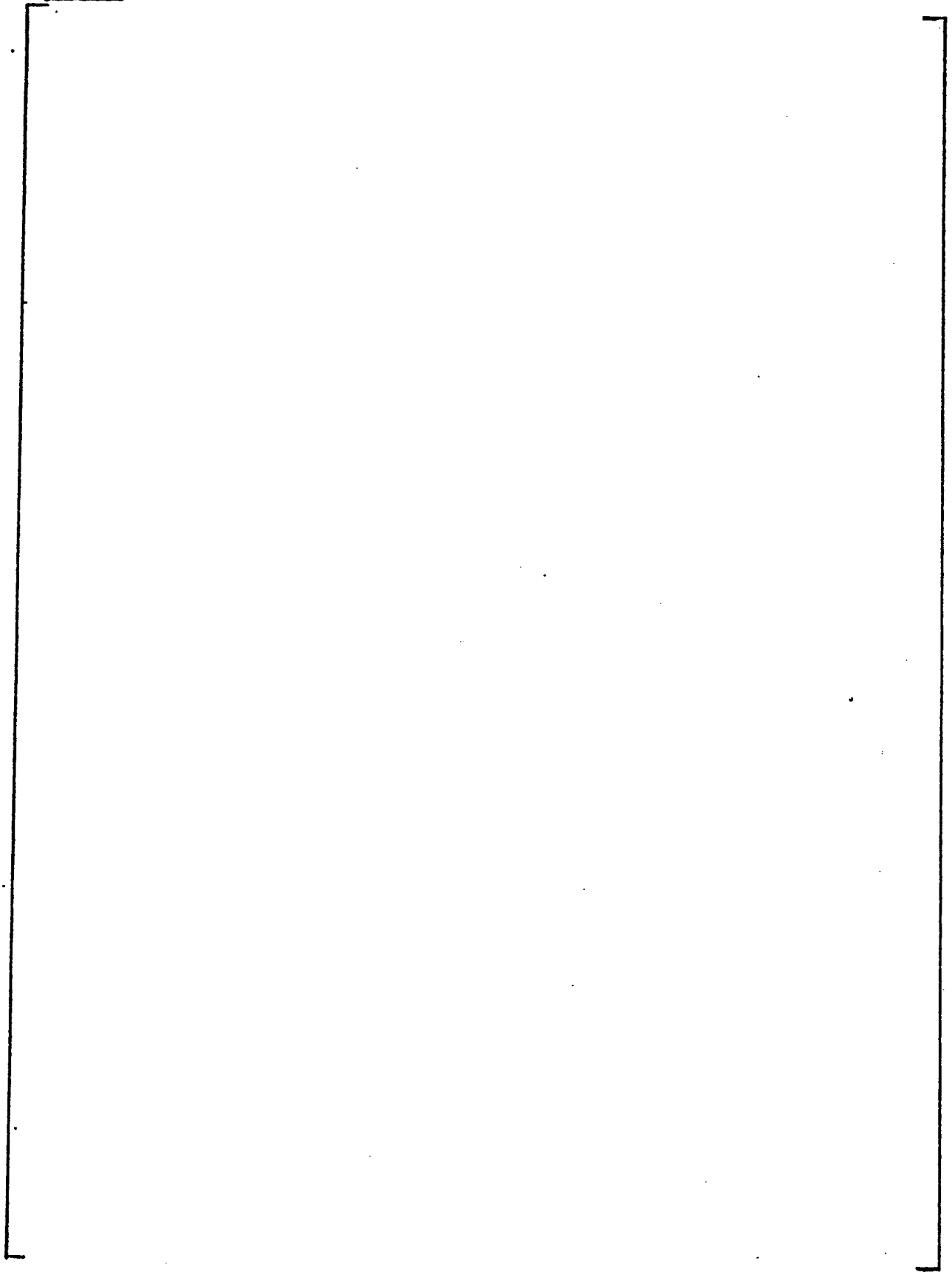
1. "CPC: Assessment of the Accuracy of PWR Safety System Actuation as Performed by the Core Protection Calculators," CENPD-170, Supplement 1, Combustion Engineering, Inc., November, 1975.

2. "CPC: Assessment of the Accuracy of PWR Safety System Actuation as Performed by the Core Protection Calculators," CENPD-170, Combustion Engineering, Inc., November, 1975.

APPENDIX B

CPC
DNBR and Quality Update Program

1. Inputs:



2. Outputs:

2.1 DNBR is the current updated minimum DNB ratio.

2.2 X is the current updated quality.

3. Calculations:

3.1 The following fluid properties are determined with the same functions specified in STATIC.

$$h_{in} = \sum_{i=1}^{[\,]} B_i \; T_{cmax}^{(i-1)}, \text{ where } B_i = \sum_{j=1}^{[\,]} AEN_{ij} \cdot p^{(j-1)}$$

$$h_f = \sum_{i=1}^{[\,]} AHF_i \cdot p^{(i-1)}$$

$$h_{fg} = \sum_{i=1}^{[\,]} AHFG_i \cdot p^{(i-1)}$$

where,

h_{in}: Core inlet enthalpy (BTU/LBM)

h_f : Liquid enthalpy at saturation (BTU/LBM)

h_{fg}: Latent heat of vaporization (BTU/LBM)

AEN: 4x4 array of coefficients for enthalpy vs. pressure and temperature correlation

AHF: polynomial coefficients, constant

AHFG: polynomial coefficients, constant

3.2 The current quality at the node of minimum DNBR is calculated as follows:

[
]

3.3 The current F-correction factor is calculated as:

[ ]

3.4 The current hot channel critical heat flux is calculated as follows:

[ ]

3.5 The current minimum DNBR is calculated as follows:

[ ]

4. Data Base Constants (Typical):

[redacted]