Sandia Laboratories

STATISTICAL ANALYSIS OF THE BLOWDOWN PHASE OF A LOSS-OF-COOLANT ACCIDENT IN A PRESSURIZED WATER REACTOR AS CALCULATED BY RELAP4/MOD 6

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coefficients; churn-turbulent slip correlation (as implemented in RELAP4/MOD6); two-phase friction and form loss factors; containment pressure; ECC system temperature; two-phase pump degradation and accumulator pressure.

Approximately 200 RELAP blowdown calculations were performed during the study. The response surfaces and PCT distributions, however, were based on 134 runs, the others being dropped primarily because they employed different gap conductance models. Twelve different response surfaces were produced based on different underlying statistical assumptions. Since these assumptions are completely arbitrary, it is encouraging and gratifying that these different surfaces yielded similar results.

The study indicated that 7 of the input variables dominated the prediction of peak clad temperature. The three most important parameters were gap width, total peaking factor and fuel (UO_2) thermal conductivity. The PCT sensitivities at nominal (or mid-range) were roughly $\pm 80^{\circ}$, $\pm 60^{\circ}$ and $\pm 40^{\circ}$F, respectively, for a change of approximately $\pm 1\sigma$ (1/6 of the total range). Four additional variables were also found to have appreciable influence on PCT, although less than that of the fuel parameters. In order, they are Condie-Bengston film boiling heat transfer, two-phase friction, slip coefficient and power level. Critical heat flux and subcooled discharge coefficient did not seem as important as these seven. Evidence was produced, however, which implied that subcooled critical flow was more important for low values of PCT than for high. Since our sample was intentionally biased toward higher temperatures, the reduced significance of subcooled discharge might, in part, be due to the smaller number of calculations at low temperatures.

The metal-water reaction is significant only at temperatures above about 2000°F. Because of this and the small number of calculations in which it was varied, it was not included in the response surface.

The fact that peaking factor (PF) was more important than power level is probably due to the much larger range assigned to PF. It varied from 24% to 132% above core average power, while a ±3σ range for power level was ±6%. Since PF varied approximately ±30% about its midrange, it could be expected to be about 5 times as important as power level. This assumption was supported by the data. The sensitivities of the PCT distributions to changes in the means and sigmas of the input distributions were, in general, quite small. Also, changing sigmas of the input distributions has little effect on the mean of the PCT distribution and changing the means has little effect on the sigma of the PCT distribution.

Future work will involve the calculation of the entire accident sequence through the end of reflood using the TRAC code.[3] In addition, the blowdown data will be employed in continuing statistical investigations of surfaces other than PCT.

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STATISTICAL LOCA

GOAL - DETERMINE PCT PROBABILITY DISTRIBUTION AND ITS SENSITIVITY TO INPUT VARIABLES BASED ON STATISTICAL ANALYSES OF COMPUTER CALCULATIONS OF A LOCA.

APPLICATIONS:

1. QUANTIFY THE CONSERVATISM OF THE REQUIREMENTS OF 10 CFR 50 APPENDIX K.

2. PROVIDE INFORMATION FOR RESEARCH EVALUATION AND REQUIREMENTS.

STATISTICAL LOCA

THREE MAJOR PHASES

I. THERMAL HYDRAULIC COMPUTER CALCULATIONS

II. GENERATION OF RESPONSE SURFACE

III. STATISTICAL ANALYSIS OF RESPONSE SURFACE

I. THERMAL HYDRAULIC CALCULATIONS
   - THIS PHASE IS DETERMINISTIC

   A. DETERMINE INPUT VARIABLES AND DISTRIBUTIONS

   B. PRODUCE A BEST ESTIMATE MODEL OF THE REACTOR

   C. ADDRESS ACCURACY, APPLICABILITY, ADAPTABILITY AND LIMITATIONS OF PHYSICAL MODELS

   D. MODIFY CODE AS NECESSARY: E.G., DIALS, PRE-PROCESSOR ROUTINES

   E. PERFORM A SUFFICIENT NUMBER OF COMPUTER CALCULATIONS, BASED ON SOME VARIABLE SELECTION SCHEME

II. GENERATION OF RESPONSE SURFACE

- THIS PHASE IS ESSENTIALLY NONSTOCHASTIC.
- INPUT VARIABLE RANGES ARE REQUIRED, BUT NOT DISTRIBUTIONS.

A. SELECT POINTS AT WHICH CALCULATIONS WILL BE PERFORMED -- DEFINE SAMPLE SPACE.

SELECTION SCHEMES - LATIN HYPERCUBE SAMPLING AND/OR
- FRACTIONAL FACTORIAL SAMPLING

B. DETERMINE BASIS FUNCTIONS AND ASSUMPTION - LINEAR, LOG, STANDARDIZED, ETC.

C. DETERMINE FIT CRITERIA - WHEN TO STOP

D. DETERMINE SENSITIVITIES OF PCT SURFACE TO VARIATION OF INPUTS ABOUT NOMINAL
   - NON-RANDOM
   - PARTIAL DERIVATIVES

III. STATISTICAL ANALYSIS

- THIS PHASE IS STOCHASTIC
- INPUT VARIABLE DISTRIBUTIONS ARE REQUIRED
- ASSUMPTION OF "GOOD" APPROXIMATING SURFACE

PERFORM MONTE CARLO ANALYSES ON PCT SURFACES TO GET

A. PCT PROBABILITY DISTRIBUTION - MEDIAN, VARIANCE, 90TH AND 99TH PERCENTILES

B. SENSITIVITIES OF PCT DISTRIBUTION TO CHANGES IN INPUT DISTRIBUTIONS
   - CHANGES IN MEAN AND SIGMA OF PCT DISTRIBUTION FOR CHANGES IN
     1. MEAN OF INPUT VARIABLE FROM NOMINAL TO NOMINAL + 1/5 UPPER RANGE

     2. SIGMA OF INPUT VARIABLE FROM NOMINAL TO 1/2 NOMINAL

THIS STUDY ADDRESSED

1. A SINGLE ACCIDENT (DBA) - BLOWDOWN PHASE OF A DECLG BREAK IN THE ZION PWR

2. THE SELECTION OF VARIABLES IMPORTANT TO BLOWDOWN BEHAVIOR DURING THIS DBA

3. THE DETERMINATION OF UNCERTAINTY RANGES AND PROBABILITY DISTRIBUTIONS FOR THOSE VARIABLES.

4. THE PRODUCTION OF A REASONABLE BEST ESTIMATE OF THE REACTOR

5. THE GENERATION OF A RESPONSE SURFACE TO APPROXIMATE RELAP OVER THE RANGE OF INTEREST

6. THE DETERMINATION OF THE RELATIVE IMPORTANCE OF THE VARIABLES PRESENT IN THE RESPONSE SURFACE

7. THE DETERMINATION OF THE PCT PROBABILITY DISTRIBUTION AND ITS SENSITIVITY

THIS STUDY DID NOT ADDRESS

1. OTHER ACCIDENTS, REACTORS OR CODES

2. THE ACCURACY OF RELAP OR ITS CONSTITUENT MODELS IN PREDICTING LOCA BEHAVIOR (GAP CONDUCTANCE MODELS WERE INVESTIGATED SERENDIPITOUSLY)

3. THE RESOLUTION OF ARGUMENTS CONCERNING THE MERITS OF PARTICULAR STATISTICAL SAMPLING TECHNIQUES

MAJOR CONCLUSIONS - RELAP PHASE

- MOST IMPORTANT PARAMETERS ARE FUEL RELATED WITH APPROXIMATE RELATIVE IMPORTANCES OF

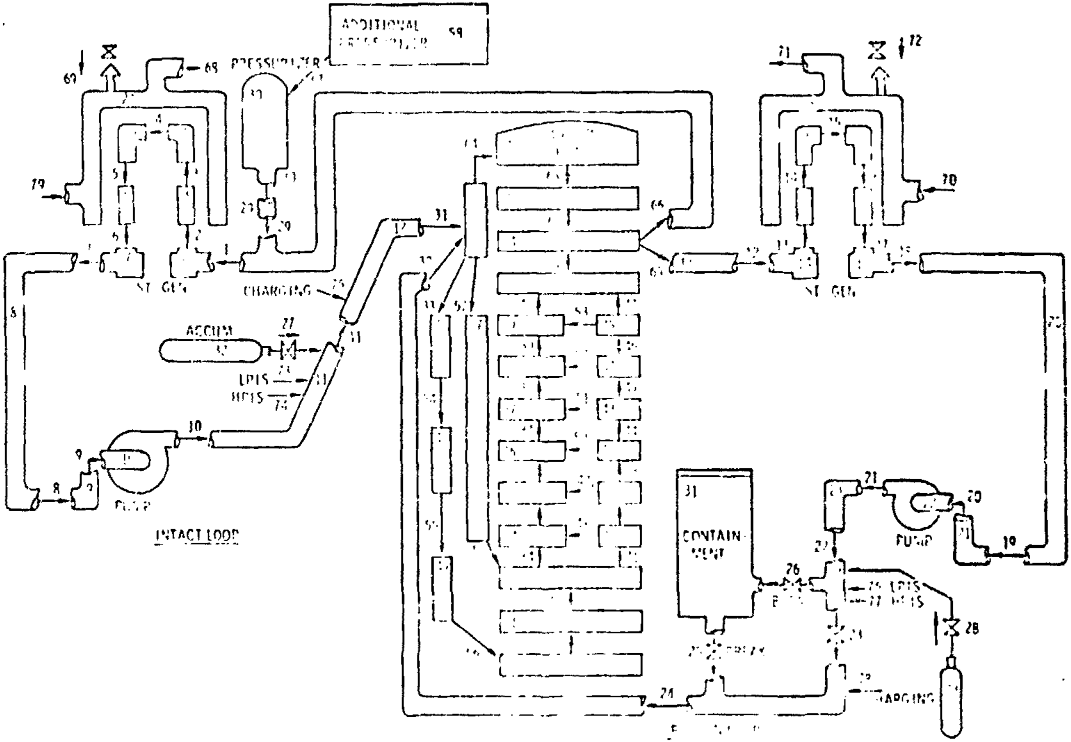
  $\pm$ 80°/σ FOR GAP WIDTH
  $\pm$ 60°/σ FOR TOTAL PEAKING FACTOR
  $\pm$ 40°/σ FOR FUEL THERMAL CONDUCTIVITY

- OTHER IMPORTANT PARAMETERS ARE FILM BOILING HEAT TRANSFER, TWO-PHASE FRICTION, SLIP AND POWER LEVEL.

- CRITICAL FLOW AND DNB WERE NOT AS IMPORTANT AS THE ABOVE PARAMETERS.

- SENSITIVITY OF PCT DISTRIBUTION TO CHANGES IN MEANS & SIGMAS OF INPUT DISTRIBUTIONS VARY FROM ABOUT 0 TO 8°F PER 1% CHANGE IN NOMINAL.

- RESULTS ARE STRONGLY DEPENDENT ON SOME PHYSICAL MODELS IN RELAP.



RELAP4 Nodalization for Statistical Study

Preprocessor Input Parameters - Summary

	Parameter	Range	Nominal Value
1.	DLEBRY = subcooled discharge coefficient	0.7 - 1.2	0.9
2.	DLBEN = saturated discharge coefficient	-0.25 - 1.0	0.
3.	SLIP = slip correlation dial	-1. - 1.	0.
4.	DLTF = 2-phase form loss dial DLTFFN = 2-phase Fanning friction loss dial These dials are assumed to be equal, and a single variable	0.4 - 1.6	1.0
5.	DCHF = critical heat flux dial	0.3 - 3.0	1.0
6.	DHTC6 = Condie-Bengston dial	0.5 - 2.0	1.0
7.	DHTC7 = free convection and radiation dial	0.6 - 1.5	1.0
8.	DHTC8 = Dittus-Boelter dial	0.5 - 2.0	1.0
9.	DHTC9 = Hsu and Bromley-Pomeranz dial	0.5 - 2.0	1.0
10.	DLBLK = flow blockage dia. multiplier	0.4 - 1.6	1.0
11.	DLMWR = multiplier of Metal-Water reaction rates[†]	0.85 - 1.15	1.0
12.	DLPWR = power level multiplier	0.94 - 1.06	1.0
13.	DLCPR = increment to be added to containment pressure table	-5. - 10. psia	0.
14.	DLPUMP = dial for 2-phase pump head multiplier	-1. - 1.	0.
15.	ECCTMP = temperature of accumulator and safety injection system water	40. - 140°F	90°F
16.	DLACC = accumulator pressure	593.2 - 693.2 psia	643.2 psia
17.	TLF = time in life[††]	0 - 440 months	220 months
18.	PFUNC = peaking factor uncertainty multiplier[†††]	.84 - 1.16	1.0
19.	DLECON = UO_2 thermal conductivity* multiplier	.6 - 1.3	1.0
20.	DLGAP = additive uncertainty** in radial gap size NOB = 0 → fresh fuel = 1 → once burned fuel	± 1.5 mils	0.
21.	DLDEC = decay heat multiplier	-.06 - 1.0	0.

[†]Not implemented because of coding error.

[††]This parameter affects only peaking factors, gap widths, and decay heat rates. Those effects are otherwise accounted for, and TLF is not used in generating the response surface (although it is still required for probabilistic PCT calculations).

[†††]This parameter multiplies the result of peaking factor modelling depending on TLF. The quantity used in the response surface modelling was total peaking factor (midrange 1.78; range 1.24 - 2.32). The sensitivity studies in Chapter 6 used ± 16%.

* *The reciprocal of this quantity is used in the response surface.*

** This quantity modifies the cold gap width resulting from TLF and NOB values. For response modeling, the final value of gap width is used. (nominal 2.28×10^{-4} ft; range 2.9×10^{-5} - 4.42×10^{-4} ft). The sensitivity studies in Chapter 6 used ± 1.5 mils.

SEVEN MOST IMPORTANT VARIABLES

VARIABLE K	NAME	TYPE	NOMINAL	BASE CASE	MIDRANGE	RANGE	STD. COEFF. A(K)	B(K)
3	SLIP	A	0.	1.0*	1.0*	.3→3.0*	.00033	.66234
4	FRICTION	M	1.0	1.0	1.0	.4→1.6	.98985	.41653
6	CB-HT	M	1.0	1.0	1.0	.5→2.0	1.04941	.41261
12	POWER	M	1.0	1.0	1.0	.94→1.06	1.00635	.04159
18	PF	M	F(T)+	1.575	1.782	1.24→2.32+	1.68059	.26314
19	1/K	M	1.0	1.0	1.0	.77→1.67	1.16475	.31304
20	GAP	A	F(T)++	2.736 MILS	2.825 MILS	.35→5.3++	.25007	.09994

*RANGE AND BASE CASE FOR DV = 1 + D * SLIP FOR $\alpha < 0.8$

+PF: $1.48 \leq F(T) \leq 2.0$, $\pm 3\sigma = \pm 16\%$

++GAP: $1.85 \leq F(T) \leq 3.8$ MILS, $\pm 3\sigma = \pm 1.5$ MILS

STATISTICAL TERMS

- A "RESPONSE SURFACE" IS A FUNCTION (OFTEN A POLYNOMIAL) THAT APPROXIMATES THE CODE CALCULATIONS OVER A GIVEN REGION.

- A "RESIDUAL" IS THE DIFFERENCE BETWEEN THE RESPONSE SURFACE EQUATION AND THE CODE CALCULATION AT A DATA POINT.

- "STANDARDIZING" IS A TRANSFORMATION Z(K) = [X(K) - A(K)]/B(K), WHERE A's AND B's ARE MEANS AND SIGMAS OF THE VALUES OF THE INPUT VARIABLES USED IN THE MODELLING.

- "R^2" IS THE PROPORTION OF THE TOTAL VARIATION IN THE DEPENDENT VARIABLE ACCOUNTED FOR BY THE MODEL.

RMS RESIDUALS FOR THE MODELS USED IN THE SENSITIVITY STUDIES

MODEL CODE	NUMBER OF TERMS IN MODEL	NUMBER OF BASIC VARIABLES IN MODEL	MODEL TYPE		RMS RESIDUALS °F
FE-9	9	11	NON LIN	L′	70.4
CY-9	9	13	NON LIN(C)	L′	71.3
B3-9	9	9	NON LOG	L′	66.0
C2-9	9	13	NON LOG(C)	L′	76.6
B8-9	9	9	STD LIN	L″	76.5
B8-11	11	10	STD LIN	L″	71.3
B8-13	13	10	STD LIN	L″	66.3
CA-9	9	7	STD LOG	L′	69.0
CA-11	11	7	STD LOG	L′	62.7
CG-9	9	7	STD LOG	L″	68.1
CG-11	11	7	STD LOG	L″	62.5
CG-13	13	8	STD LOG	L″	58.0

"STD" DENOTES STANDARDIZED

"LIN" DENOTES LINEAR

"NON" DENOTES NON-STANDARDIZED

"LOG" DENOTES NATURAL LOGARITHM

ROOT MEAN SQUARE PREDICTION ERRORS
FOR VARIOUS PHILOSOPHIES OF MODEL CONSTRUCTION

Model Code*	Model Type		RMSPE (°F)	Model Size
FE	NON LIN	L'	42	12
CY	NON LIN (C)	L'	44	12
B3	NON LOG	L'	46	11
C2	NON LOG (C)	L'	61	10
B8	STD LIN	L'	49	12
CA	STD LOG	L'	46	6
CF	STD LIN	L''	51	9, 10
CG	STD LOG	L''	47	11, 12
CV	STD LOG (C)	L'	46 , 45	6, 14

RESPONSE SURFACE CG-11

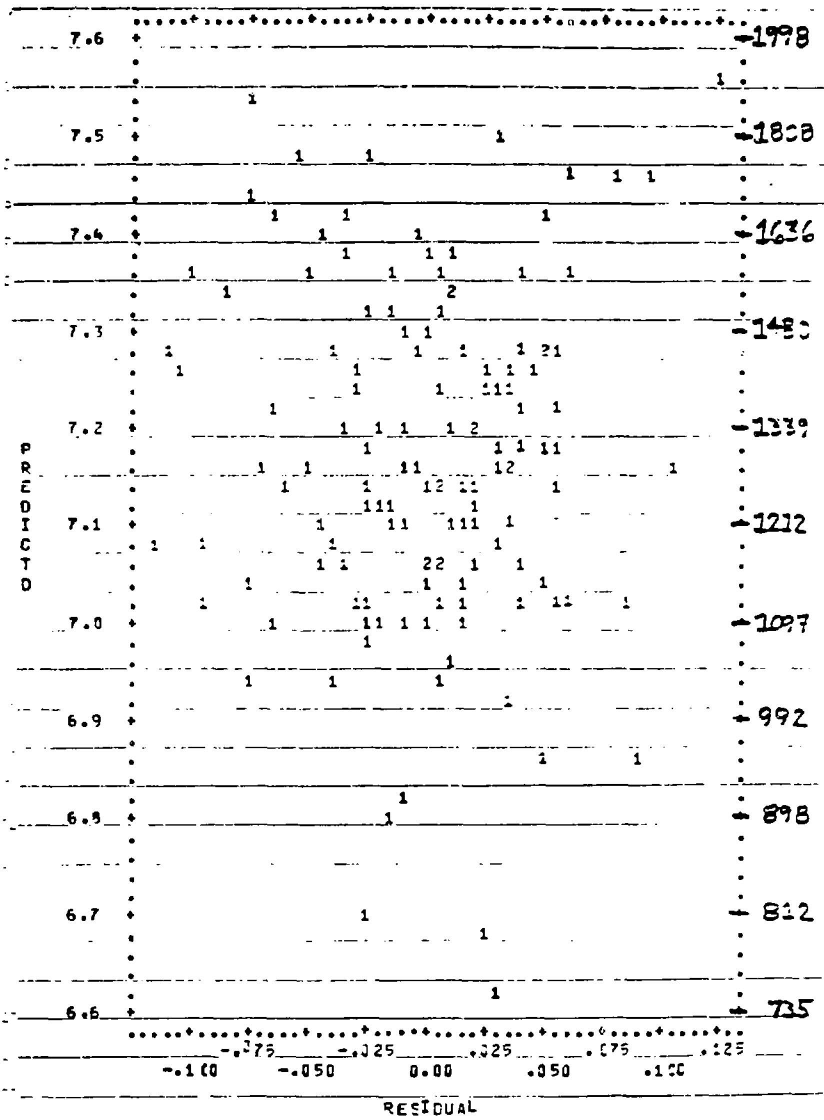
$$
\begin{aligned}
\text{LOG (PCT)} = {} & 7.183 - .02314 * Z(3) + .03041 * Z(4) \\
& - .03324 * Z(6) + .02465 * Z(12) \\
& + .08017 * Z(18) + .07163 * Z(19) \\
& + .09211 * Z(20) - .02244 * Z(18)^2 \\
& - .02811 * Z(19) * Z(20) + .01691 * Z(18)^2 * Z(20) \\
& - .01459 * Z(20)^3
\end{aligned}
$$

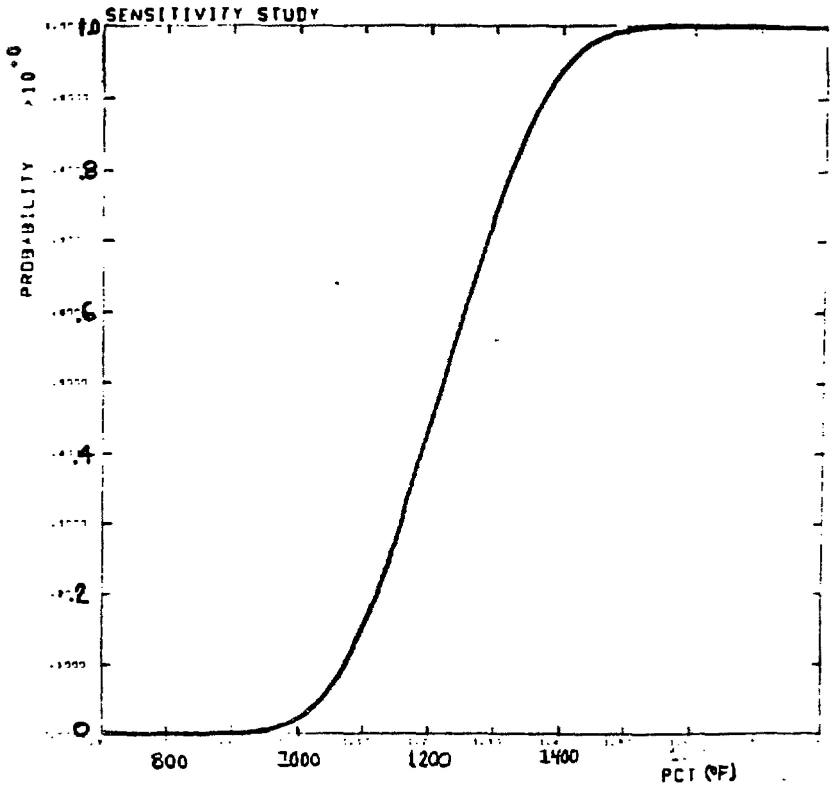
STANDARDIZED, LOG, L" (LINEAR TERMS FIRST)
R^2 = .9350, RMSR = 4.8% (62.5°F)

$Z(K) = [X(K) - A(K)]/B(K)$

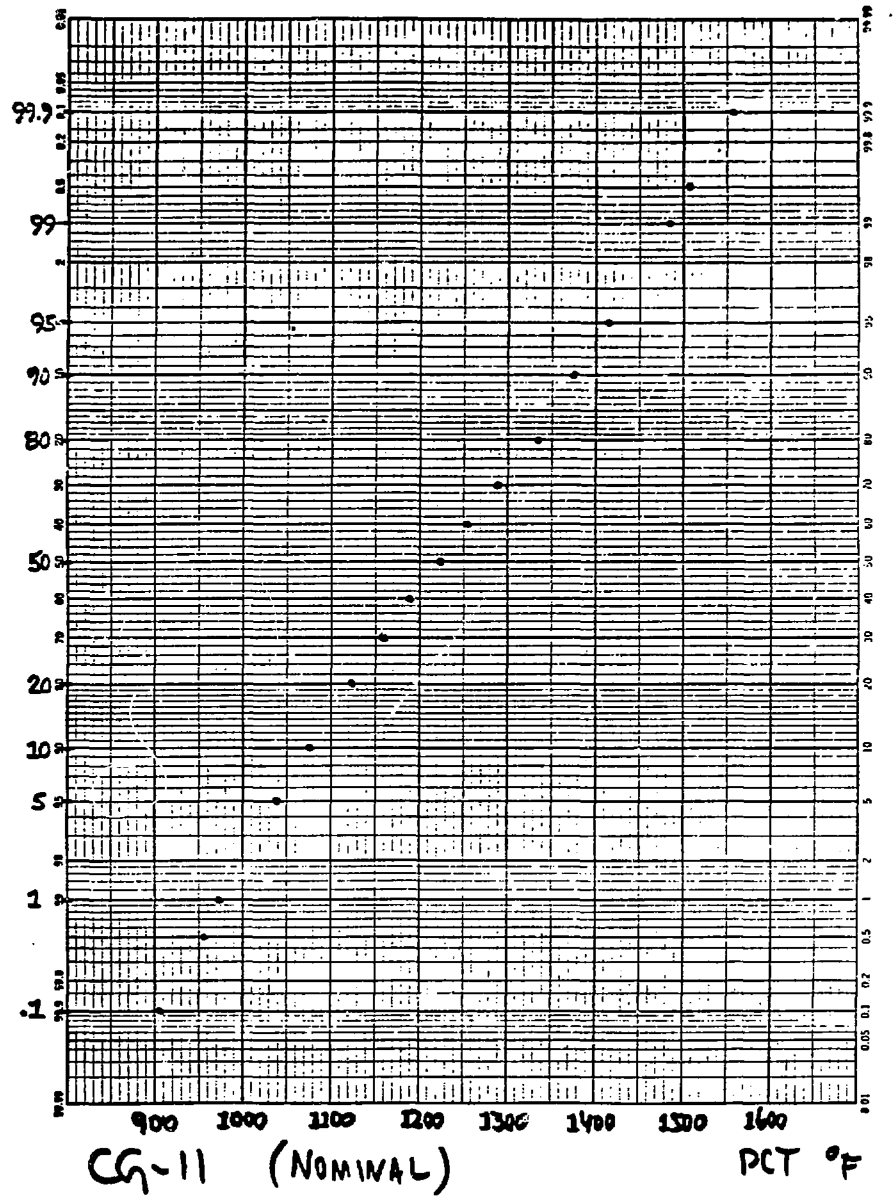
"NOMINAL" = 1290°F
MEDIAN OF PCT DISTRIBUTION = 1227 (1237)
90TH PERCENTILE OF PCT DISTRIBUTION = 1376 (1376)
99TH PERCENT = 1493 (1466)

NUMBERS IN PARENTHESES ARE INTERCEPTS OF REGRESSION EQUATIONS (a_0) IN CH. 6. THEY MAY BE CONSIDERED AS ESTIMATES OF THE MEAN, 90TH AND 99TH PERCENTILES.


PREDICTD
7.6
7.5
7.4
7.3
7.2
7.1
7.0
6.9
6.8
6.7
6.6
-.100
-.050
0.00
.050
.100
RESIDUAL
1998
1636
992
898
812
735


SENSITIVITY STUDY
PROBABILITY ×10^0
1.0
.8
.6
.4
.2
0
800
1000
1200
1400
PCT (°F)

MODEL CG-11


99.9
99
95
90
80
50
20
10
5
1
.1
900
1000
1100
1200
1300
1400
1500
1600
CG-11 (NOMINAL)
PCT °F

RELATIVE IMPORTANCE OF INPUT VARIABLES TO PCT SURFACE FOR CG-11 MODEL

VARIABLE		°F/σ AT X^-	°F/σ AT X^+	°F/1% AT .99 N	°F/1% AT 1.01 N	°F/1% BASED ON Δ Δ^-	°F/1% BASED ON Δ Δ^+
3	SLIP	15	-15	0.6*	-0.2*	0.5*	-0.2*
4	FRICTION	-25	16	-0.9	0.9	-1.0	0.9
6	CB-HT	22	-27	1.0	-1.0	1.1	-1.0
12	POWER	-16	15	-7.6	7.7	-7.8	7.7
18	PF	-77	37	-5.5	5.2	-6.8	4.0
19	1/K	-26	59	-3.1	3.1	-3.1	3.2
20	GAP	-83	98	-3.3	3.3	-2.8 (100)	3.4 (119)+

Δ ≡ STANDARDIZED CHANGE

N ≡ MIDRANGE

*A + 1 σ CHANGE OF SLIP YIELDS A 67% CHANGE IN DV

A - 1 σ CHANGE OF SLIP YIELDS A 33% CHANGE IN DV

+°F/MIL

"STAR POINT" SENSITIVITIES

VARIABLE	$T_{HI}-T_{LO}$	SENSITIVITY $^oF/\sigma$*	$^oF/\%$**
20 - GAP WIDTH	1747-1618	71 (86)+	3.2 OR 4.5
	1618-1514	57 (69)+	1.6 OR 2.6
18 - TOTAL PEAKING FACTOR	1747-1578	48	4.4 OR 6.1
	1271-1183	63	5.5 OR 6.4
19 - RECIPROCAL UO_2 THERMAL CONDUCTIVITY	1389-1165	37	1.9 OR 4.2
6 - CONDIE-BENGSTON FILM BOILING	1183-1258	-25	-.8 OR -1.5
4 - TWO-PHASE FRICTION	1225-1183	14	.7 OR 1.1
3 - SLIP CORRELATION	1127-1183	-19	-.3 OR -.8++
12 - POWER	1618-1563	18	9.2 OR 9.7
5 - CHF	1183-1223	-13	-.2 OR -.6
14 - TWO-PHASE PUMP HEAD MULTIPLIER	1215-1183	11	?
1 - SUBCOOLED DISCHARGE	1196-1183	4	.4 OR .5
COEFFICIENT	1183-1104	26	2.8 OR 3.6
2 - SATURATED DISCHARGE	1183-1184	-0.3	.03 OR .04++
COEFFICIENT	1195-1183	4	?

*$\sigma \equiv 1/6$ * TOTAL RANGE

+^oF/MIL

**% BASED ON HIGH AND LOW VALUES OF VARIABLE

++A CHANGE FROM 0. TO 1. ON THE SLIP DIAL IS A CHANGE FROM 1.0 TO 3.0 ON THE SLIP MULTIPLIER. SIMILARLY, SATURATED DISCHARGE GOES FROM .75 TO 1.0.

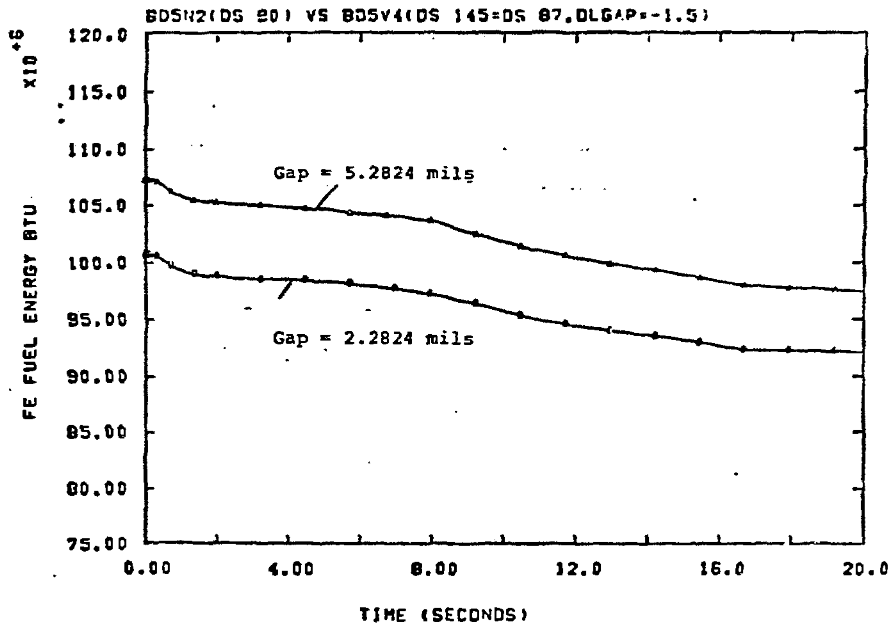


Fig. 5.3.1 Effect of Gap width on Total Stored Energy

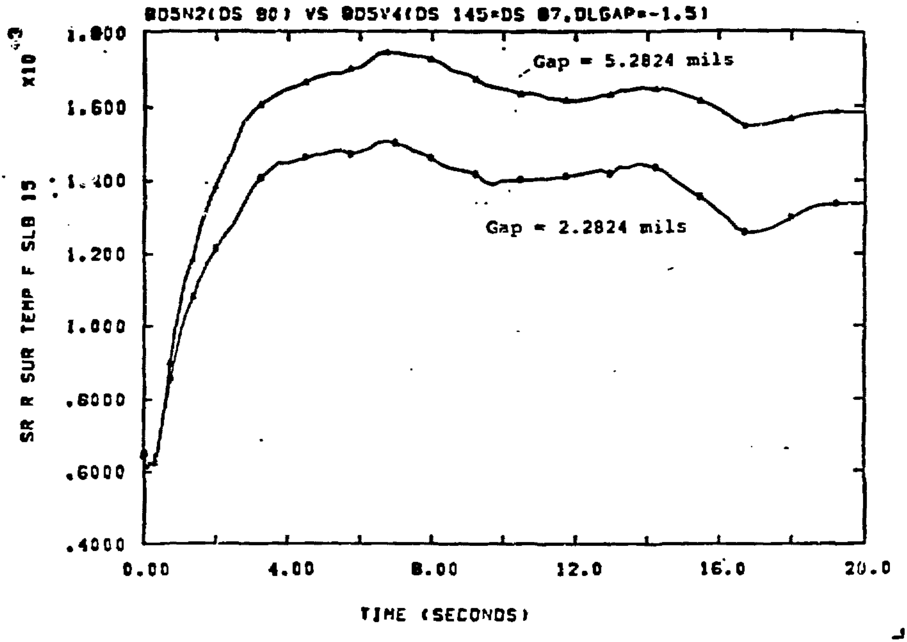


Fig. 5.3.2 Effect of Gap width on PCT

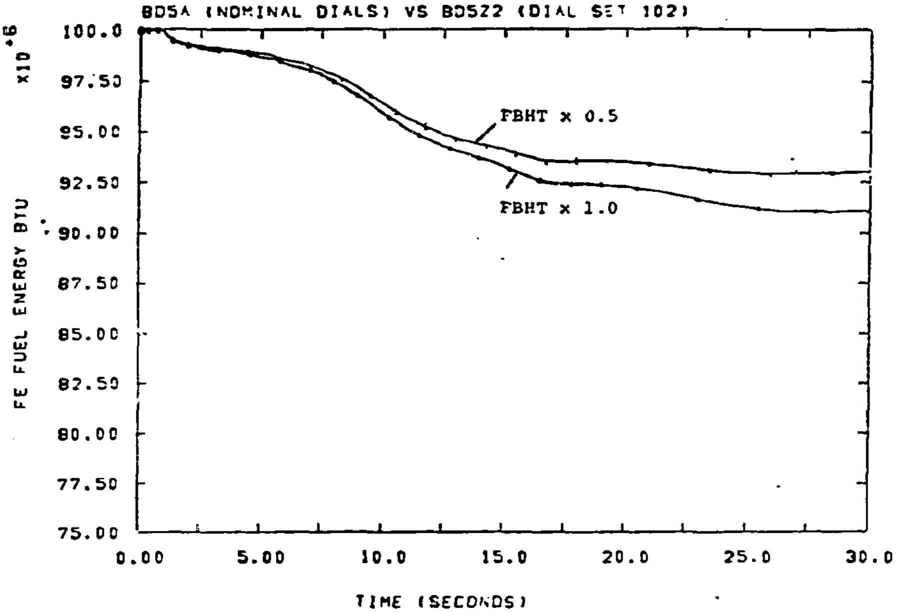


Fig. 5.3.7 Effect of C-B Film Boiling HT Coefficient Multiplier on Total Stored Energy

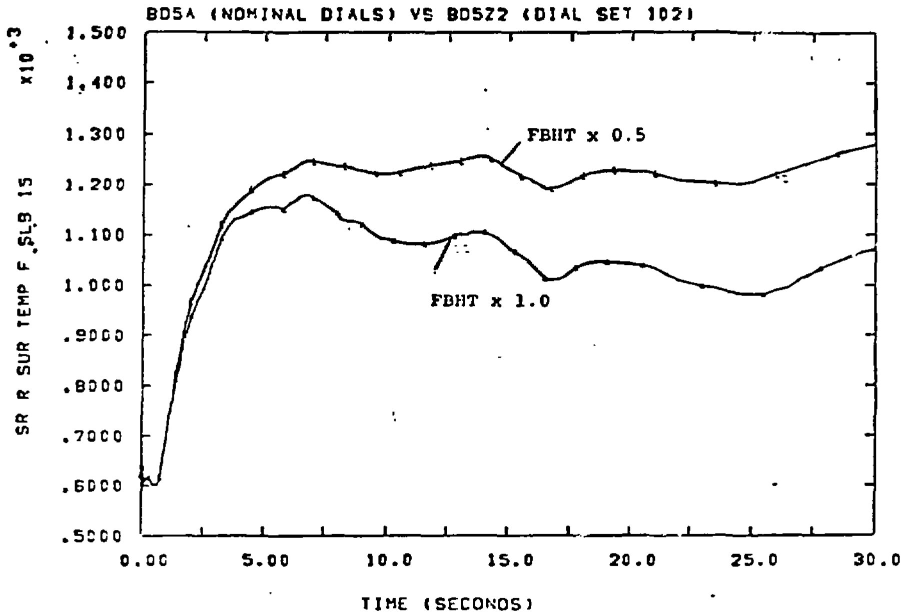


Fig. 5.3.8 Effects of C-B Film Boiling HT Coefficient Multiplier on PCT

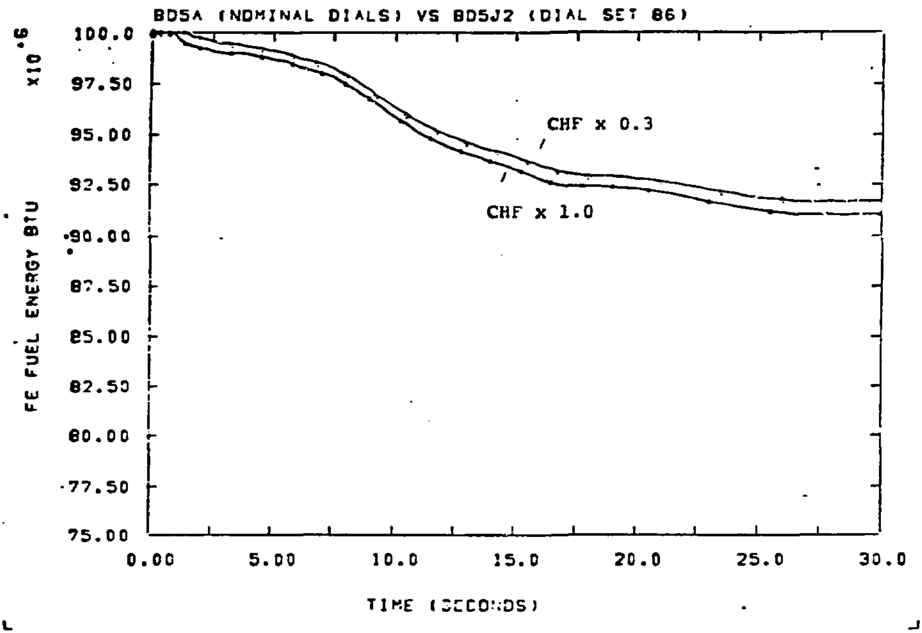


Fig. 5.3.17 Effect of CHF Multiplier on Total Stored Energy

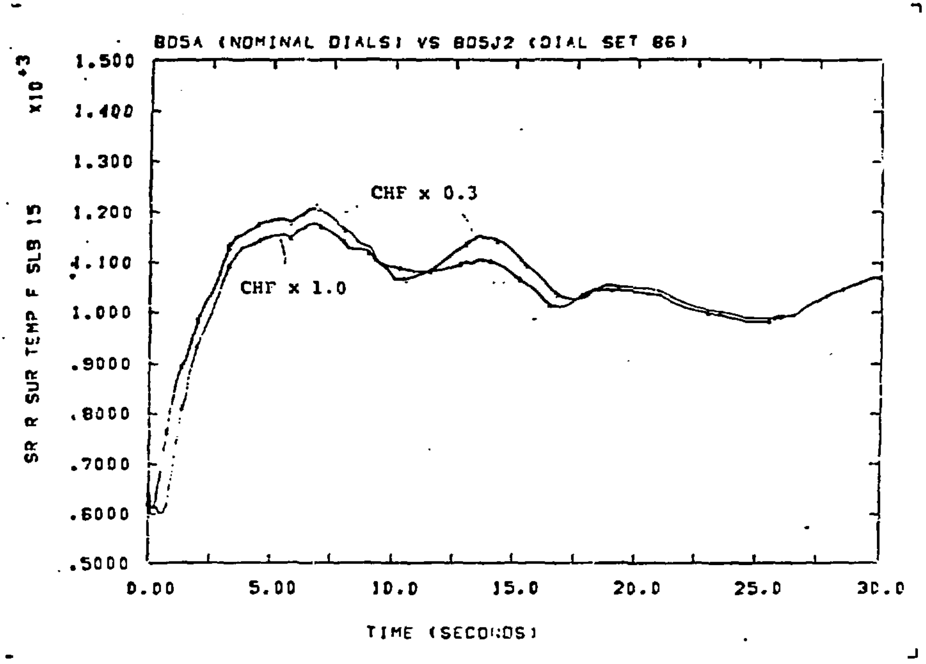


Fig. 5.3.18 Effect of CHF Multiplier on PCT

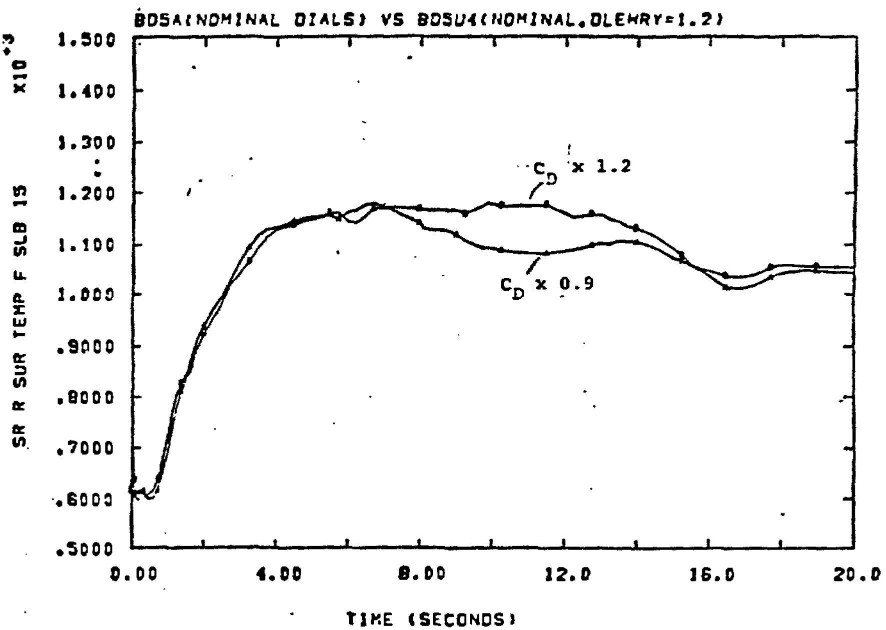


Fig. 5.3.20 Effect of High Subcooled Discharge Coefficient on PCT

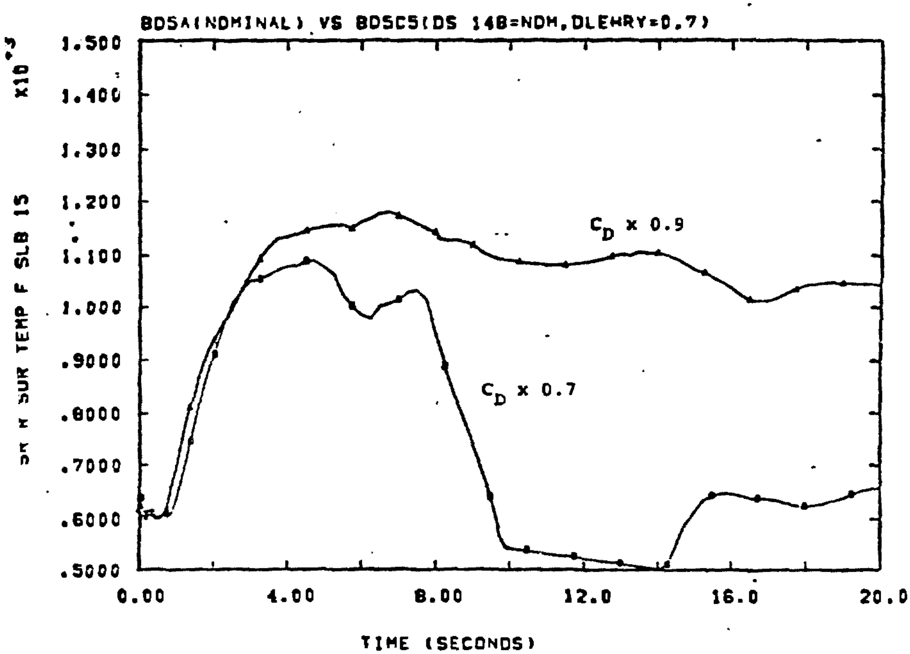


Fig. 5.3.26 Effect of Low Subcooled Discharge Coefficient on PCT

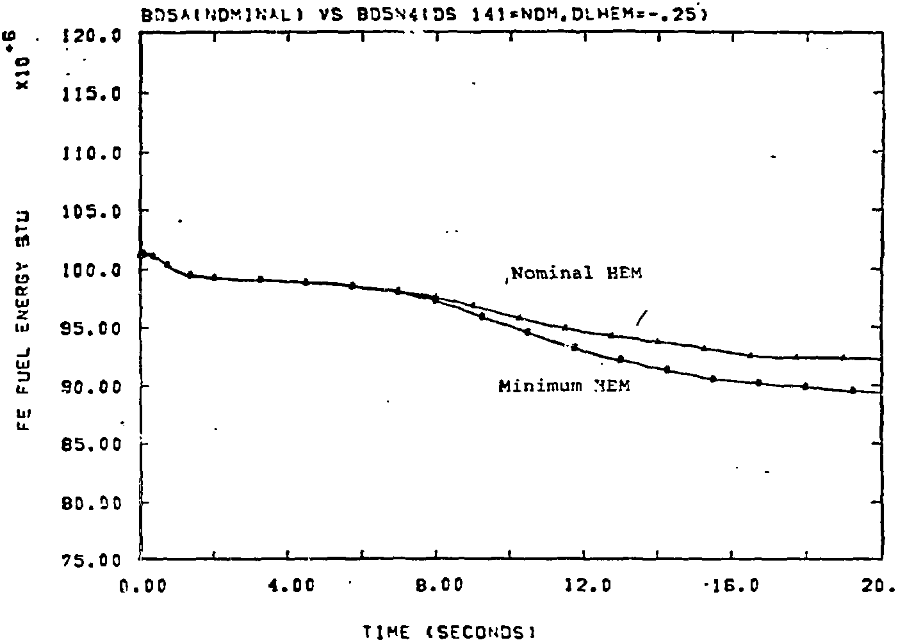


Fig. 5.3.27 Effect of Saturated Discharge Coefficient on Total Stored Energy

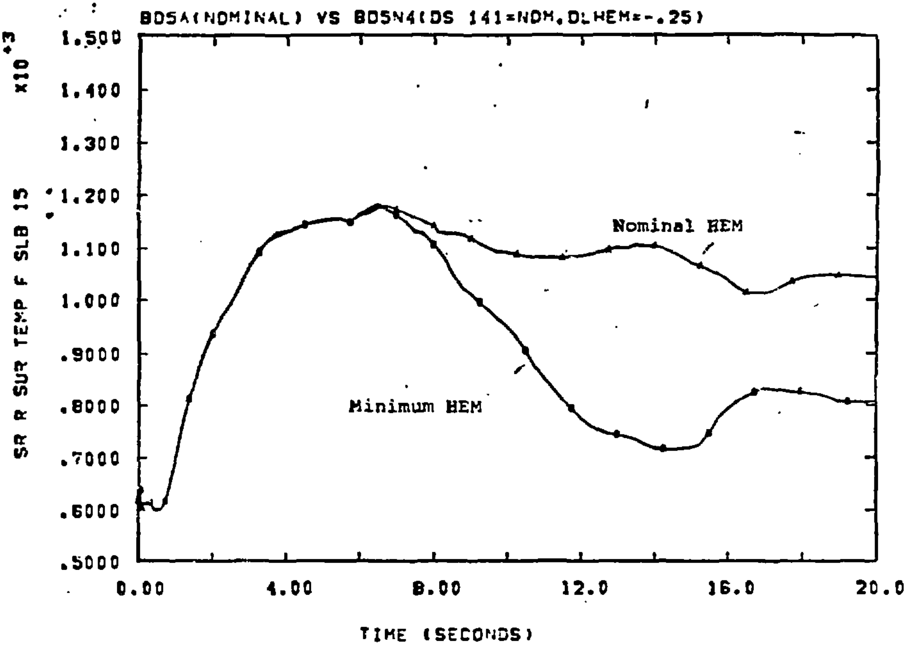


Fig. 5.3.28 Effect of Saturated Discharge Coefficient On PCT

11 - METAL WATER REACTION - "STAR POINTS"

T_{HIGH}	T_{LOW}	SENSITIVITY - °F/σ
1850	1857	- 2°/σ
1878	1852	9°/σ
1890	1883	2°/σ
2151	2077	12°/σ
2151	2105	15°/σ
2267	2185	27°/σ

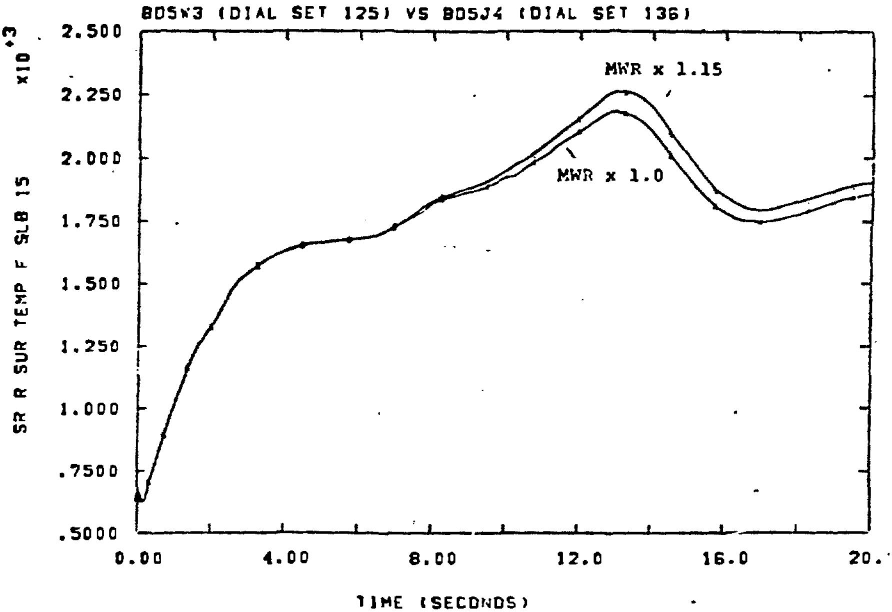


Fig. 5.3.29 Effect of Metal-Water Reaction Dial on PCT

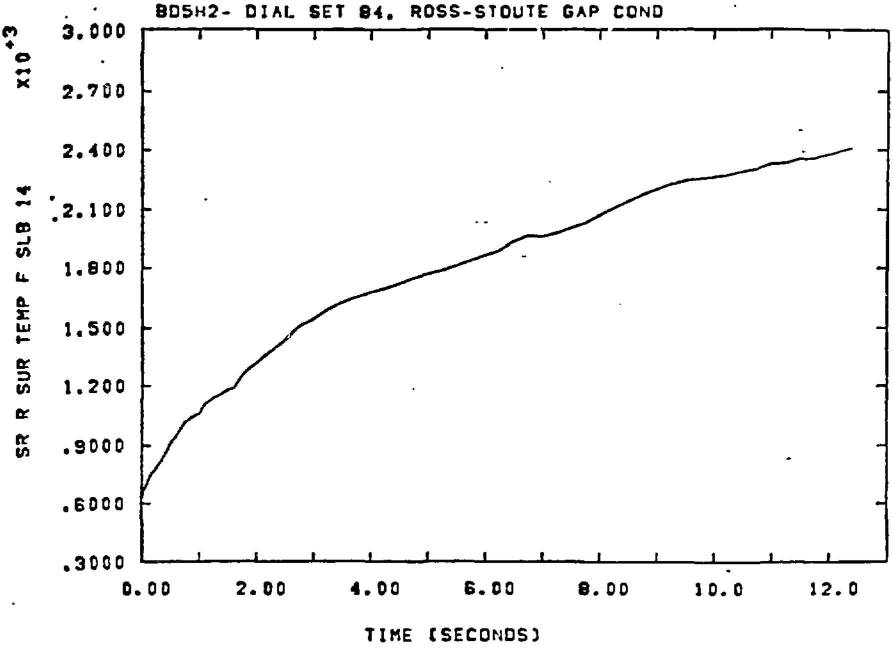


Fig. 5.3.30 Clad Temperature, DS 84, Slab 14

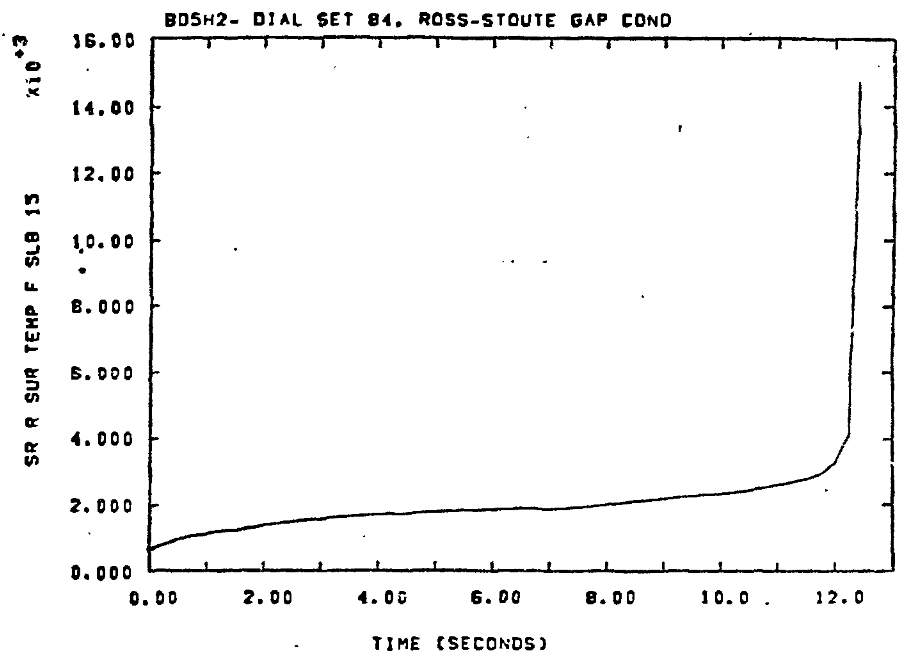


Fig. 5.3.31 Clad Temperature, DS 84, Slab 15

SENSITIVITIES OF PCT DISTRIBUTION TO CHANGES IN INPUT MEANS

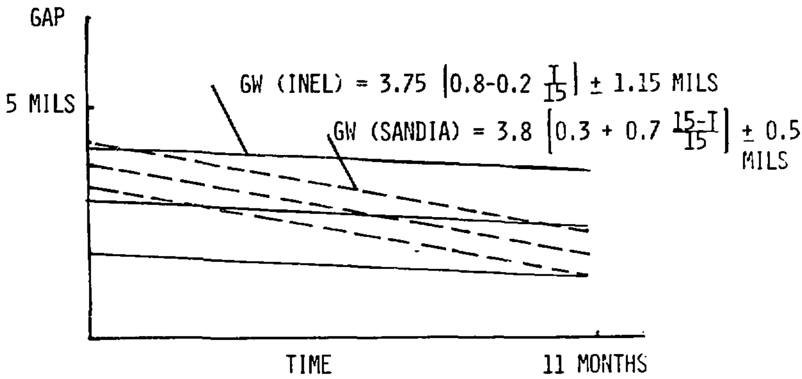
VARIABLE		$^oF/\sigma_U$			^oF/% NOMINAL		
		$\sigma_U \equiv$ 1/3 UPPER 1/2 RANGE					
		ΔPCT_M	ΔPCT_{90}	ΔPCT_{99}	ΔPCT_M	ΔPCT_{90}	ΔPCT_{99}
3	SLIP	-15	-17	-17	-.2	-.3	-.3
4	FRICTION	15	17	19	0.9	1.0	1.1
6	CB-HT	-26	-28	-28	-1.0	-1.1	-1.1
12	POWER	15	15	17	7.7	7.7	8.5
18'	PF	35	34	35	7.0	6.6	7.0
19'	K	-26	-22	-22	-2.8	-2.4	-2.4
20'	GAP	48	47	38	2.7(96)*	2.6	2.2

ALL BASED ON CG-11 MODEL
*NUMBER IN PARENTHESIS IS ^oF/MIL

PEAKING FACTOR (POWER) SENSITIVITIES - $^{o}F/1\%$

	MODEL CG-11	MODEL B8-9
AT .99 N	-5.5 (-7.6)	-7.3 (-7.3)
AT 1.01 N	5.2 (7.7)	7.3 (7.3)
AT Δ^-	-6.8 (-7.8)	-7.3 (-7.5)
AT Δ^+	4.0 (7.7)	7.3 (7.0)
FROM ΔPCT	7.0 (7.7)	7.0 (6.8)
FROM Δ90TH	6.6 (7.7)	7.3 (7.7)
FROM Δ99TH	7.0 (8.5)	7.6 (7.7)
STAR POINTS	4.4 TO 6.4 (9.2 TO 9.7)	

RADIAL GAP WIDTH - MILS



	NOMINAL	σ	σ_{EFF}	RANGE	MIDRANGE
INEL	2.45-3.00	± 1.15	± 1.16	0-6.45	3.225
SANDIA	1.85-3.80	± 0.5	± 0.75	.35-5.3	2.825

STATISTICAL LOCA

TRAC PHASE IN PROGRESS

ADVANTAGES:

- PERMITS FULL ACCIDENT ANALYSIS FROM BLOWDOWN THROUGH END OF REFLOOD
- MULTIDIMENSIONAL AND TWO-FLUID CORE ANALYSIS
- IMPROVED MODELS

DISADVANTAGES:

- TRAC IN EARLY STAGE OF DEVELOPMENT AND ASSESSMENT IS INCOMPLETE
- ADDITIONAL MODEL DEVELOPMENT MAY BE REQUIRED