80051202 36

NUREG/CR-0940
SAND79-1206
R4

Uncertainty Analysis for a PWR Loss-of-Coolant Accident: I. Blowdown Phase Employing the RELAP4/MOD6 Computer Code

George P. Steck, Marshall Berman, Rupert K. Byers

Printed January 1980

Sandia Laboratories

SF 2900 Q(7-73)

Prepared for
U. S. Nuclear Regulatory Commission

NOTICE

Available from
National Technical Information Service
Springfield, VA 22161

NUREG/CR-0940
SAND79-1206
R4

UNCERTAINTY ANALYSIS FOR A PWR LOSS-OF-COOLANT ACCIDENT: I. BLOWDOWN PHASE EMPLOYING THE RELAP4/MOD6 COMPUTER CODE

George P. Steck
Marshall Berman
Rupert K. Byers

Date Published: January 1980

Sandia Laboratories
Albuquerque, NM 87185
Operated by
Sandia Corporation
for the
U.S. Department of Energy

Prepared for
Division of Systems Safety
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555
Under Interagency Agreement DOE 40-550-75
NRC FIN No. A-1014

ABSTRACT

The feasibility of performing an uncertainty analysis of a reactor accident by using a large computer code and a comparatively small number of calculations is demonstrated. With fewer than 200 blowdown runs, 21 variables are investigated for their impact on peak clad temperature (PCT) models. Seven of the 21 input variables dominate in predicting PCT and, of these, the 3 most important are fuel-related parameters: gap width, total peaking factor, and UO_2 thermal conductivity. Less important are Condie-Bengston film boiling heat transfer, two-phase friction multiplier, slip correlation multiplier, and power level. Critical heat flux and the subcooled discharge coefficient were less important than the preceding variables. The sensitivities of the PCT distributions to changes in the means and variance of the input distributions are in general quite small.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (cont)

ILLUSTRATIONS (cont)

ILLUSTRATIONS (cont)

TABLES

TABLES (cont)

SUMMARY

This study has demonstrated the feasibility of performing an uncertainty analysis of a reactor accident using a large computer code and a comparatively small number of calculations. With a data base of fewer than 200 blowdown runs, we have produced an acceptable plant model, investigated 21 input variables and their distributions, produced peak clad temperature (PCT) models and determined their sensitivities to input assumptions.

It is assumed that the reader is well acquainted with both the reactor thermal hydraulics and the statistical methodology employed in the uncertainty analysis. For further background information, consult the References at the end of this report.

The major conclusion of this work is that 7 of the 21 input variables dominate the prediction of peak clad temperature. The three most important parameters are gap width, total peaking factor, and UO_2 thermal conductivity. The PCT sensitivities near nominal (or midrange) input values are roughly $\pm 80°$, $\pm 60°$, and $\mp 40°$ F, respectively, for a change of about $\pm 1\ \sigma$(1/6 of the total range). Four additional variables are 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 multiplier, slip or phase relative velocity coefficient, and power level.

Critical heat flux and subcooled discharge coefficient, C_D, did not seem as important as the above-mentioned variables. Evidence is presented that C_D has a much greater influence for low values of PCT than for high. Since our sample was intentionally biased toward higher temperatures, the reduced significance of C_D may, in part, be due to the smaller number of calculations at low temperatures. The metal-water reaction is significant

only at temperatures above ~2000°F. Because of this and the small number of calculations in which it was varied, it is discussed separately and is not included in the statistical data base.

The sensitivities of the PCT distributions to changes in the means and sigmas of the input distributions are, 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.

Earlier work had produced a rule-of-thumb which indicated that about $2n^2$ calculations would be required to produce a reliable response surface if there were n important variables. This study implies that the RELAP-generated surface is sufficiently complex that $2(n+1)^2$ or more calculations would probably provide a better estimate of the minimum sample size.

UNCERTAINTY ANALYSIS FOR A PWR LOSS-OF-COOLANT ACCIDENT: I. BLOWDOWN PHASE EMPLOYING THE RELAP4/MOD6 COMPUTER CODE

1. Introduction

The statistical Loss-of-Coolant Accident (LOCA) program at Sandia Laboratories, Albuquerque, has addressed the development and application of statistical methods for predicting peak clad temperature (PCT) in pressurized water reactors (PWRs) during a LOCA. The method employed uses a response surface approach. A large computer code, RELAP4/MOD6,[1 2] is used to perform a limited number of calculations based on inputs selected according to statistical sampling techniques. The parameter of interest in the code output, e.g., PCT, is then statistically correlated with the input, usually by means of a generalized polynomial or "response surface." Under the assumption that the polynomial is a good approximation for the computer code over the region of investigation, probabilistic statements concerning PCT can be based on Monte Carlo runs using the response surface. The statistical evaluation also yields information concerning the relative importance of the various input parameters in the determination of PCT and can provide estimates of the effects of changes in means and distributions of the input variables on the mean and distribution of PCT.

This report summarizes the results of using the RELAP code to study the blowdown phase of a LOCA. Various response surfaces are generated based on 134 code evaluations of PCT, and their accuracy in predicting various PCT subsets is evaluated. The relative importances of the various input parameters are considered based on the complete data set as well as various "star point" calculations (results of varying only a single parameter at a time). The effects of employing certain modelling options are also discussed. Future work will address the complete accident sequence from blowdown through reflood using the TRAC code.[3]

1.1 Plant Model and Accident Definition

The accident postulated as the basis of this study is a double-ended guillotine piping break in one of the main coolant loops of a PWR. Calculations of the thermal-hydraulic response of the reactor system, subsequent to the break, yield predictions of maximum temperature experienced by the fuel rod cladding.

The model chosen for use in the program is based on Westinghouse design and operating information for the Zion I plant. Idaho National Engineering Laboratory (INEL) supplied Sandia with RELAP input data for use in the blowdown portion of the analysis. The data were developed as a part of the BE/EM project.[4] During the course of the program, a number of changes were made in the input and in Sandia's version of RELAP. Test calculations were also performed to investigate some aspects of the methods being used. This section will deal briefly with the results of that portion of the study. The reader interested in a more detailed treatment should see the periodic reports issued during the study.[5-13]

Changes to the original input deck included tests with finer zoning in the lower plenum region and corrections to inertias specified for junctions at the breaks and in the primary coolant loops downstream of the pumps. The effect on PCT of these alterations was virtually nil. Other tests were made to study the consequences of selecting the enthalpy transport option and of various decay heat models, which also had fairly insignificant effects on calculated PCT.

One of the parameters to be varied for the statistical analysis was specified to be reactor power level. Because this could require a very time-consuming readjustment of initial conditions for every calculation, we investigated whether RELAP calculations would "relax" from unbalanced initial conditions to a steady state in a reasonable amount of computer time. If this attempt proved successful, we could avoid rebalancing the input by initiating the break after a suitable delay. During that investigation, a number of difficulties with unrealistic oscillations and unacceptable changes in the state of the reactor were encountered. The oscillations were eliminated by a correction to the estimate used for the choked inertial flow calculation, and by the addition of a large volume connected to the pressurizer, to act as a "buffer" during long delays before break initiation (see the nodalization in Figure 1-1). This additional volume is isolated from the system at the end of the delay period, and has no effect on calculated PCT. An example of the improvement in RELAP's steady state capability appears in Figure 1-2, showing flows through the cooling jets to the upper head.

The results of calculations of transient behavior following different delay periods did not show sufficient convergence for our study. Therefore, we performed calculations at the limits of the power level range, ±6%, after balancing the model for the off-nominal initial conditions. When we compared results of the balanced calculations (e.g., the temperature histories in Figure 1-3), we observed good agreement for different delay periods. There was also good agreement in PCTs for calculations with and without balancing for off-nominal initial conditions (Figure 1-4). The latter result enabled us to proceed without the need to balance a very large number of input conditions.

Results of calculations using RELAP4/MOD5 heat transfer routines (HTRC) in MOD6 were compared with those using the MOD6 blowdown routine (HTS2). The MOD6 version produced lower PCT than a standard MOD5 run in both cases.

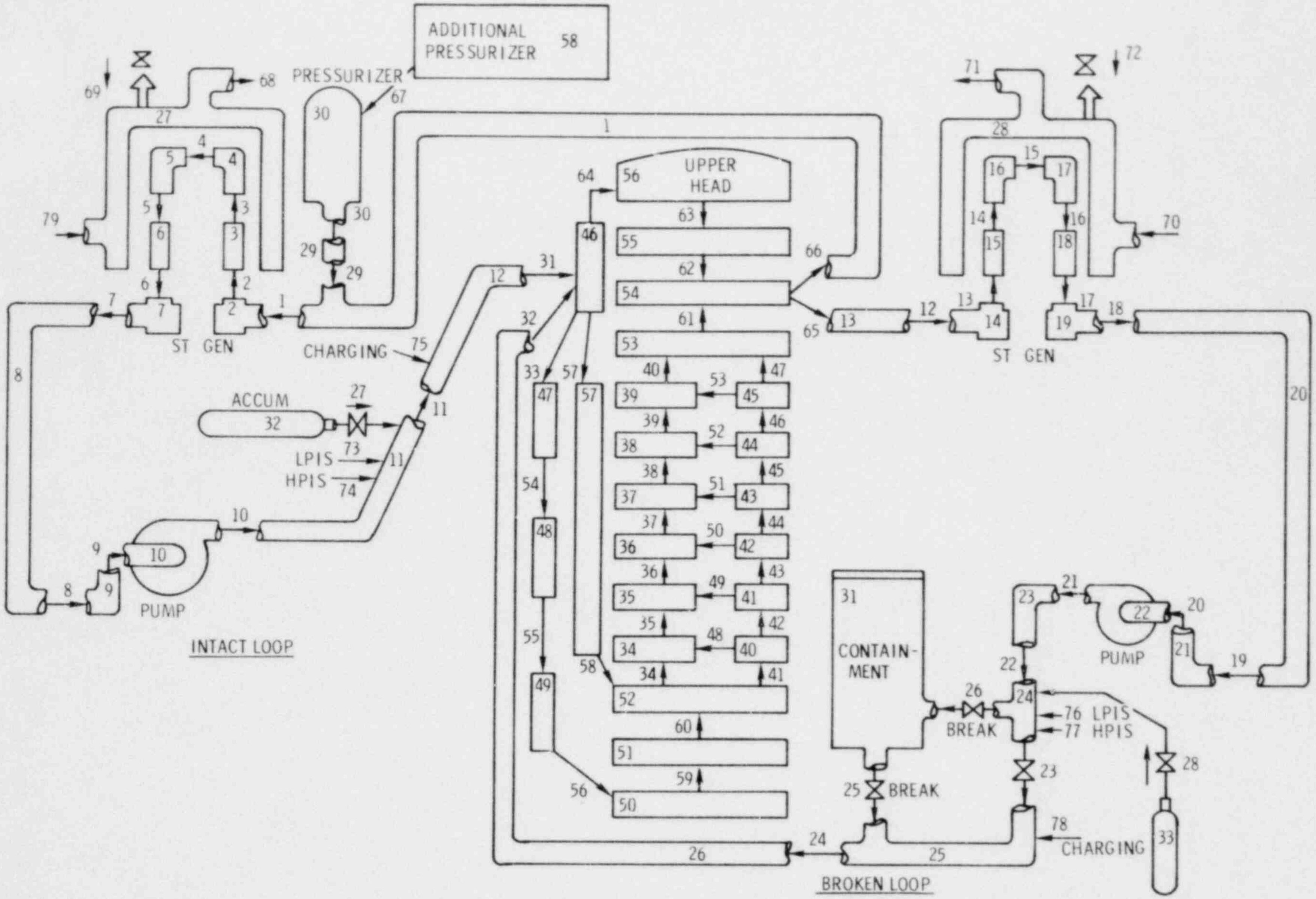


Figure 1-1 RELAP4 Nodalization for Statistical Study

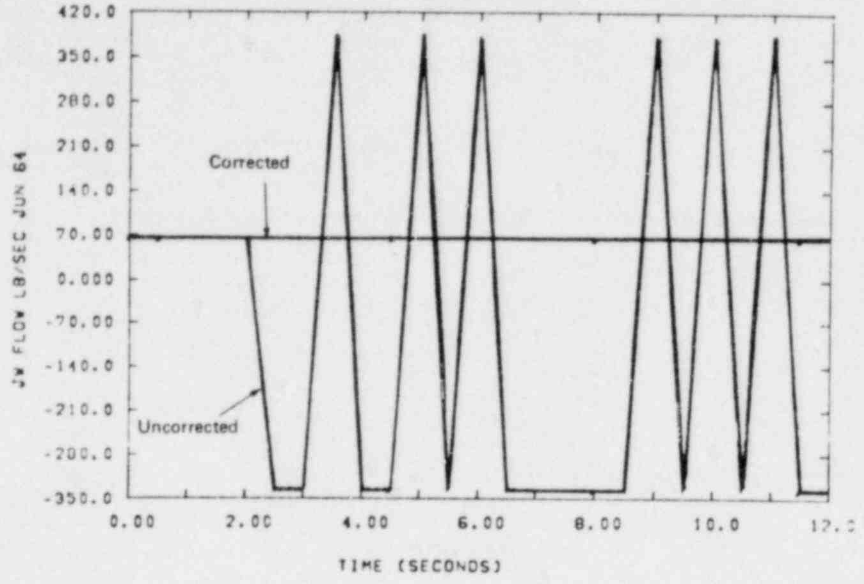


Figure 1-2 Flow From Inlet Annulus to Upper Head, Uncorrected vs Corrected Inertial Estimator (100% Power)

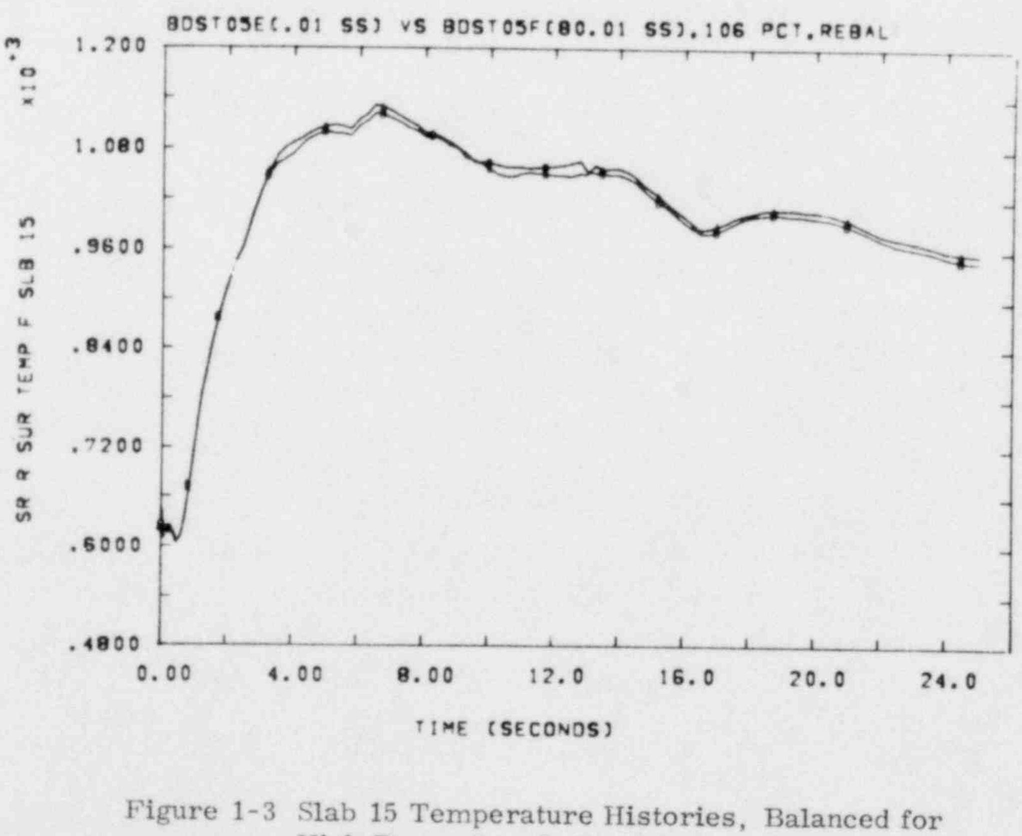


Figure 1-3 Slab 15 Temperature Histories, Balanced for High Power Level, No Delay and 80-Second Delay

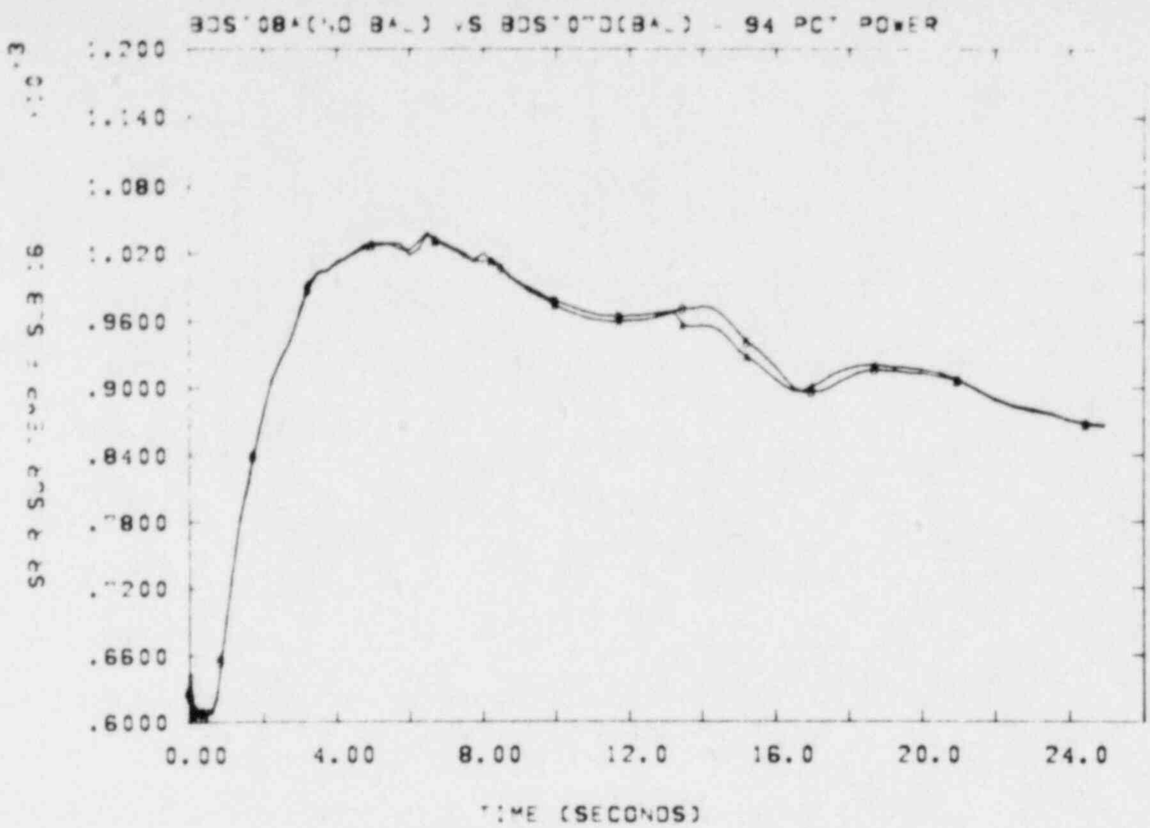


Figure 1-4 Slab 16 Temperature Histories, Balanced for Low Power Level and Not Balanced

One of the topics included in the scope of this program was the effect of describing the fuel as fresh or once-burned, with the description yielding the higher PCT to be used in the main part of the study. This effect was seen to be highly dependent on which model, MacDonald-Broughton (M-B) or Ross-Stoute (R-S), was used for thermal conductance of the fuel-to-clad gap. This question is addressed in more detail in Section 1.3.

In the calculations performed for the comparisons mentioned above, no clearly unphysical results were seen after the oscillations referred to were removed. Table 1-1 summarizes the effects of the various modifications to the input and to RELAP.

Table 1-1

Modifications to Original Model

Variation	Effect
Finer lower plenum zoning	None on PCT
Junction inertias	None on PCT
Enthalpy transport off*	PCT down ~50°F (compared with E.T. on)
Pressurizer buffer	"Quieter" pressurizer in steady state. None on PCT
Decay Heat Standard	Insignificant
Fresh* or c[illegible]-burned fuel	Insignificant for M-B gap model
	Fresh ~80°F higher for R-S
Heat transfer modelling:	(Compared to MOD5/HTRC)
MOD6/HTRC	PCT ~20°F lower
MOD6/HTS2*	PCT ~70°F lower
Choked flow estimator*	Good steady-state results None on PCT
Initial thermal balancing	Small effect on PCT

*Indicates used in runs for statistical analysis.

Late in the program, we discovered (1) that a pre-existing coding error had prevented us from altering one of the statistical variables (the metal-water oxidation parameter), and (2) that the combination of RELAP and our computer system would not always produce identical results from identical input. These discoveries were sources of some concern; their consequences are discussed in Section 5.3.3 and the Appendix, respectively.

1.2 Blowdown Variables and Ranges

As a result of consultations between members of NRC, INEL, and Sandia staff, a set of 21 RELAP input quantities was selected as being of possible importance to PCT during blowdown. This number of variables was felt to be a reasonable compromise between including all possibly influential parameters and confining the program to a feasible number of computer runs. The nominal values and ranges for the parameters were based on a combination of operating data and engineering judgment.[14-17]

The method chosen to achieve variations in RELAP input sets is based on an extension of the use of "dials," which is standard input practice for the code. Input variables for statistical analysis are assigned values over their ranges by several sampling techniques. The techniques employed were Latin hypercube sampling (LHS), with both uniform and biased variable distributions; fractional factorial sampling (FFS) with full factorial on a subset of the input variables; and variations in selected input values designed to show output sensitivities or achieve high temperatures. References 18 through 20 provide information on some of these techniques.

A number of the variables are controlled by multiplicative "dials" provided in the standard version of RELAP4/MOD6. The majority, however, required changes to values on a large number of RELAP input cards. This fact led to the development of a preprocessor code. The preprocessor performs all calculations necessary to convert the sampled statistical variables to suitable RELAP input. The following is a description of the input variations performed and their implementation. The "†" symbol indicates that the variable is treated in the standard RELAP4/MOD6 way.

1. Subcooled Break Flow† -- This dial (nominal 0.9; range 0.7 -1.2) multiplies the subcooled (extended) critical flow rate yielded by the Henry-Fauske model.

2. Saturated Break Flow -- The critical flow rate given by the homogeneous equilibrium model (HEM) is multiplied by a quantity calculated in the following way:

$$D_f = \begin{cases} 1 + D_I \ , \ D_I \leq 0 \\ 1 + D_I \ (1.5 \ e^{-10.986X}), \ D_I > 0 \ , \end{cases}$$

where, D_f is the flow multiplier, D_I the value input to RELAP, and X the donor volume quality. D_I has a nominal value of 0.0, and ranges from -0.25 to 1.0.

3. Slip Correlation -- This parameter multiplies the calculated relative velocity for the churn-turbulent flow regime. The multiplier, D_v, is calculated from the input dial value, D_{sc}, and is a function of junction void fraction, α, as follows:

$$1.0 + 0.7\ D_{sc},\ D_{sc} \le 0.0$$
$$D_v = 1.0 + 2.0\ D_{sc},\ D_{sc} > 0 \text{ and } \alpha \le 0.8$$
$$D_v = 3.0\ (1.0 + (\alpha - 0.8)/0.195,\ D_{sc} > 0 \text{ and } \alpha > 0.8.$$

D_{sc} has a nominal value of 0.0 and ranges from -1.0 to 1.0. The preprocessor prepares a table of values of D_v, for insertion into the RELAP deck.

4. Form Loss and Friction Loss for Two-Phase Flow -- Frictional pressure drops are multiplied by a quantity having the range 0.4 to 1.6 and a nominal value of 1.0. The two-phase Fanning friction loss multiplier is available in the generic version of RELAP; the junction form loss term was added to RELAP for this study.

5. DNB Correlation† -- All critical heat fluxes are multiplied by a dial with nominal value 1.0 and range 0.3 to 3.0.

6. High Flow Film Boiling Heat Transfer† -- Mode 6 heat transfer fluxes are multiplied by a dial whose nominal value is 1.0 and range is 0.5 to 2.0.

7. Low Flow, High Void Fraction, Free Convection, and Radiation† -- Mode 7 heat transfer fluxes are multiplied by a dial ranging from 0.6 to 1.5, with nominal value 1.0.

8. Reverse Forced Convection to Vapor[†] -- Dittus-Boelter (Mode 8) heat transfer fluxes are multiplied by a value, nominally 1.0, ranging from 0.5 to 2.0.

9. Low Flow, Low Void Fraction[†] -- This dial has a nominal value of 1.0 and ranges from 0.5 to 2.0. It multiplies only the Bromley-Pomeranz film boiling contribution to fluxes in Mode 9 heat transfer.

10. Flow Blockage -- This multiplier, added to RELAP for our study, has a nominal value of 1.0 and a range of 0.4 to 1.6.

11. Clad Oxidation[†] -- This multiplier was intended to operate on the energy production rate from the $Zr-H_2O$ reaction, with a nominal value of 1.0 and range 0.85 to 1.15. A coding error, discussed elsewhere in this report, resulted in bypassing this dial for the statistical analysis.

12. Power Level -- Initial total power level is multiplied in the preprocessor by a value ranging from 0.94 to 1.06, with nominal equal to 1.0.

13. Containment Pressure -- In our calculations, containment pressure is specified as a tabular function of time. For the statistical study, an additive quantity (range -5.0 to 10.0 psi) modifies all but the initial pressure values for the table. Saturation temperatures for the resulting pressures are obtained from the steam tables, and the necessary cards inserted in the RELAP input deck.

14. Pump Degradation -- RELAP provides the option of modelling changes in pump performance due to cavitation effects. A void-fraction-dependent interpolation between single-phase and two-phase performance curves is used to model this phenomenon. For the statistical study, this model is varied by specifying low, nominal, and high functions of void fraction which multiply

pump performance curves. A dial (nominal value 0.0, range -1.0 to 1.0) is used by the preprocessor to interpolate between the nominal curve and one of the limiting curves, depending on the dial's sign.

15. Emergency Core Cooling System Temperature -- This variable controls the temperature in the accumulators, high and low pressure injection systems, and charging systems. Its value ranges from 40° to 140°F, with a nominal of 90°F.

16. Accumulator Pressure -- This parameter has a nominal value of 643.2 psia and a range of 593.2 to 693.2 psia.

17. Fuel Time-In-Life -- This variable affects three of the other statistical variables (see 18, 20, and 21 below). Its value (nominal 226 mos, range 0 to 440 mos) is not a RELAP input variable; its consequences on the statistical analysis appear only implicitly through those variables, and it is not considered in the response surface modelling (but is required for the Monte Carlo PCT probability estimates).

18. Peaking Factors and Normalized Power -- Based on operating data from the Surry plant units 1 and 2, Sheron has recommended a procedure for defining power distributions and axial, radial, and total peaking factors as functions of fuel cycle number (first, second, or equilibrium) and time into the cycle.[16] To avoid an inordinate amount of complexity, all fuel assemblies are assumed to be in the same state (as opposed to 1/3 fresh, 1/3 once-burned, etc). Fuel cycles are assumed to be 12 mos in duration, including a 1-mo shutdown for refueling. Sheron's work was based on an assumption of six equal axial nodes through the core; in our model, the top node is only about 1/2 the height of the others. This fact was accounted for by altering the axial power distributions.

The procedure for obtaining power fractions for the core heat slabs begins by obtaining the total peaking factor given by time-in-life, and multiplying it by the uncertainty dial (variable 18, nominal value 1.0, range 0.84 to 1.16). The method may thus be thought of as yielding a "pseudonominal" total peaking factor (i.e., nominal for a given fuel age), which is further altered by the uncertainty multiplier. Axial peaking factors for each core node are also defined by time-in-life, and, in turn, define normalized power values. Radial peaking factors result from the ratio of total to axial peaking factors for each core level. Separate normalizing factors for the average core, hot pin, and hot channel then give power fractions for each of the 18 core nodes. The actual value of the total peaking factor, and not its uncertainty dial, is used as input for the response surface modelling.* The results of the procedure outlined above give it a range of 1.24 to 2.32 and a nominal value of 1.57.

19. Fuel Thermal Conductivity -- This quantity is multiplied by a dial whose nominal value is 1.0 and which ranges from 0.6 to 1.3. For the response surface, the reciprocal of the resulting conductivity is used.*

20. Fuel-to-Clad Cold Gap Width -- The value of this quantity also depends on time-in-life, and whether the fuel is treated as fresh or once-burned. First, the expression

$$w = 3.16667 \left(0.3 + 0.7 \left(\frac{15 - T}{15} \right) \right) \times 10^{-4} \text{ (ft)}$$

is evaluated. T is time-in-life (TLF) in months (Modulo 11) for fresh fuel; for once-burned fuel, T is Min [15,11 + TLF (Modulo 11)].

---

*Except for the probabilistic analyses.

Initial cold gap width is then obtained with an additive uncertainty parameter whose nominal value is 0.0 and limiting values are $\pm 1.25 \times 10^{-4}$ ft (± 1.5 mil). With the assumption that the sum of gap width and fuel radius is constant at 1.55625×10^{-2} ft, the preprocessor generates geometry definition cards for the core slab regions, and inserts them in the RELAP input set.

Again, the value analyzed for the response surface modelling is not the uncertainty dial, but the end result for gap width.* Its midrange value is 2.335×10^{-4} ft, and its range is 2.9×10^{-5} to 4.42×10^{-4} ft (fresh fuel).

21. Decay Heat -- INEL supplied Sandia with RELAP modifications which convert old ANS standard decay heat rates to the revised rates.[21 22] This is accomplished with a table of rate multipliers (A(t), say), whose values depend on time after shutdown. For this study, NRC desired that fission product decay power also depend on TLF, in months, and be modified by an uncertainty parameter. We achieve this in the following way:

Let t be time (in seconds) after shutdown, and F(t) be the decay power after infinite irradiation time. Further, let S be the number of seconds in a month (assumed to be 2.628×10^6), and T be time into the cycle; i.e., T = S * TLF (Modulo 11).

We begin by generating a set of normalized factors

$$\varphi(t) = \Big\{ F(t) - F(t + T) + B\big[F(t + T + S) - F(t + T + 12S)\big] \Big\} / F(t),$$

*Except for the probabilistic analyses.

where B is 0 for fresh fuel and 1 for once-burned fuel. The values, φ, are then altered by the uncertainty dial, D, by the operation

$$\tilde{\varphi}(t) = \begin{cases} (1 + D)\,\varphi(t), & D \leq 0 \\ (1 - D)\,\varphi(t) + 1.2D, & D > 0. \end{cases}$$

D is specified to be on the interval [- 0.06, 1.0], and has a nominal value of 0.0. The set of values $\tilde{\varphi}(t)$ multiply the conversion factors A(t), giving the final decay heat description.

Note that as a consequence of the input variations described above, the original model from the BE/EM study has been considerably altered. In particular, containment pressure, peaking factors, gap widths, and decay heat modelling are quite different.

Table 1-2 summarizes the values used by the preprocessor to produce RELAP input for the statistical study. Nominal values and ranges are also listed, with appropriate notations when the response surface model treats something other than the dial used by the preprocesscr.

We wish to emphasize that many of the dials, by their specified ranges and nominal values, may appear to have simply multiplicative or additive effects. This view can be misleading in some cases, because of the complex nature of the dials' results on RELAP input and modelling. Naturally, the PCT response models are not affected by this question; however, slight ambiguities in the sensitivity results may sometimes occur.

Table 1-2

Preprocessor Input Parameters: Summary

Parameter	Range	Nominal Value
1. DLEHRY = subcooled discharge coefficient	0.7 ⟶ 1.2	0.9
2. DLHEM = saturated discharge coefficient	-0.25 ⟶ 1.0	0
3. SLIP = slip correlation dial	-1 ⟶ 1	0
4. DLTF = 2-phase form loss dial DLTFFM = 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 dial multiplier	0.4 ⟶ 1.6	1.0
11. DLMWR = multiplier of metal-water reaction rates*	0.85 ⟶ 1.15	1.0
12. DLPWR = power vel 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°
16. DLACC = accumulator pressure	593.2 ⟶ 693.2 psia	643.2 psia
17. TLF = time in life**	0 ⟶ 440 mo	226 mo
18. PFUNC = peaking factor uncertainty multiplier†	0.84 ⟶ 1.16	1.0
19. DLECON = UO_2 thermal conductivity multiplier‡	0.6 ⟶ 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	-0.06 ⟶ 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 to 2.32). The sensitivity studies in Section 6 used ±16%.

‡The reciprical of this quantity is used in the response surface.

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

Consider, for example, the pump degradation variable (DLPUMP, Item 14 in Table 1-2). Its nominal value and range might lead to the conclusion that this parameter is merely an additive variation on a single quantity. However, recall that the effect of the pump degradation parameter is an interpolation between functions of void fraction (see Figure 1-5). Furthermore, the curve that results is then used to interpolate between pump performance curves. DLPUMP is treated in the statistical analysis as an additive variable, for lack of a better approach, but this is clearly a very simplistic view.

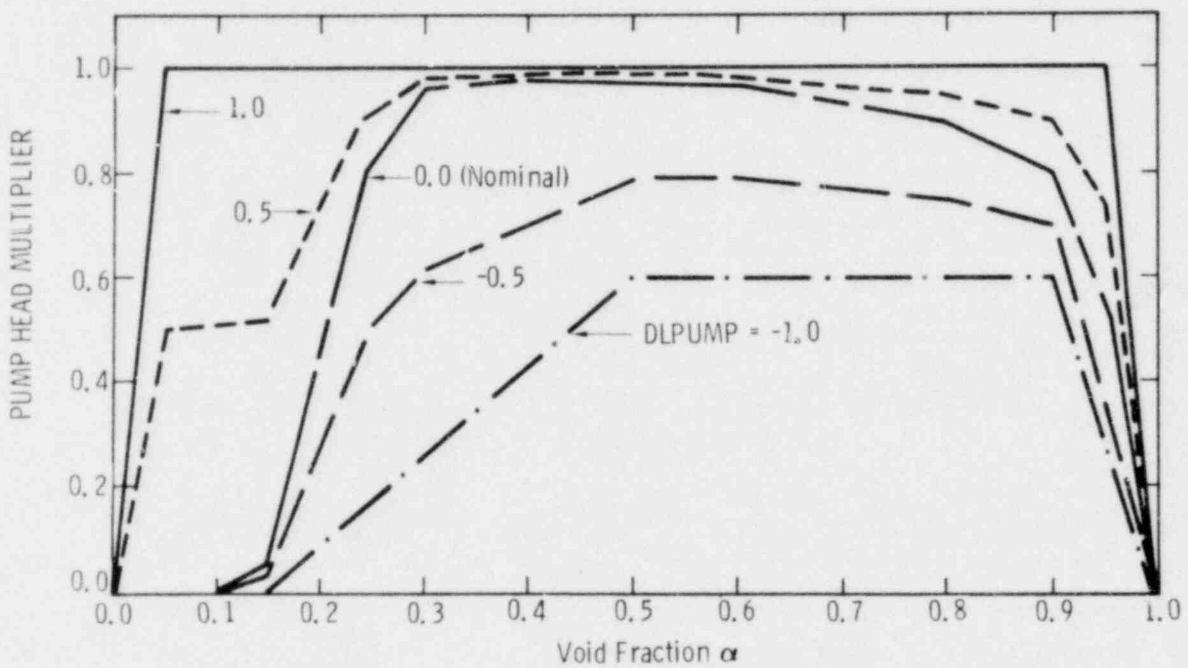


Figure 1-5 Effect of Pump Degradation Dial on Head Multiplier Curves

1.3 Effect of Gap Conductance Models on PCT

One of the options in the RELAP input deck received from INEL was the selection of the MacDonald-Broughton model for the thermal conductance of the fuel-to-clad gap. The other gap conductance option available in RELAP is a modification of the Ross-Stoute model. Table 1-3 contains the salient features of these two models. In the following the models will be denoted by the forms M-B and R-S.

Table 1-3

Gap Conductance Models

Modified Ross-Stoute	MacDonald-Broughton
1. BE in MOD 6 (EM in MOD 5)*	1. BE** in MOD 6 only
2. No burnup dependence, i.e., fresh fuel	2. Functional dependence on burnup (but not implemented in MOD 6)
3. Axisymmetric expansion	3. Cracked fuel model (30% of fuel assumed to be in contact with clad at 0% burnup)
4. INEL recommends for pressurized fuel	4. INEL recommends for unpressurized fuel

*BE/EM used 10X multiplier in MOD 5 to make R-S into a BE model.

**Sandia version multiplied by 6.

One of the first questions to be addressed in this study was the effect of describing the fuel as fresh or once-burned. The description yielding the higher value for PCT was then to be used in the remainder of the study. The comparison using the M-B model showed a very slightly lower (~2°F out of ~1100°F) PCT for the once-burned fuel. We concluded that the choice was unimportant, and a set of 26 calculations was performed for statistical analysis, using fresh fuel.

About this time we discovered that, in our version of RELAP4/MOD6, the effective gap conductance was the result of multiplication of the M-B value by a factor of 6. Conversations with INEL revealed that this was done in an attempt to match the fuel stored energy results from a FRAP-S calculation. We also learned that an error was present in the radiative heat transfer term in the M-B model coding, and that the R-S model is now the recommended one for describing pressurized fuel rods. For these reasons, comparisons of the relative effects of the gap conductance models were made.

Table 1-4 compares surface temperatures, fuel centerline temperatures, gap temperature differences, and fuel stored energies in nominal-case calculations for the R-S, M-B, and M-B-without-multiplication models. The very high gap conductance produced with the M-B model (including the factor of 6) yielded much lower temperature drops across the gap, hence lower centerline temperatures and more rapid energy removal from the fuel rod.

Table 1-4

Comparison of Fuel Gap Conductance Models for Statistical LOCA, Base Case

MODEL

1--MacDonald-Broughton MOD 6 - Sandia

2--Modified Ross-Stoute MOD 6

3--Model 1 without the 6X multiplier

4--Model 1 without the 6X multiplier, with HT error fix

	MODEL		
	1	2	3 & 4*
INITIAL CONDITIONS			
$T_{SURFACE}$	~700°**	~700°	~700°
ΔT_{GAP}	10-15°	150-170°	70-90°
T_C	~2190°	230-250° HIGHER THAN No. 1	80-100° HIGHER THAN No. 1
PCT CONDITIONS (6.5 s)			
PCT	~1120°	100° HIGHER THAN No. 1	40° HIGHER THAN NO. 1
ΔT_{GAP}	2-5°	20-40°	10-25°
T_C	~1240°	180-200° HIGHER THAN NO. 1	100-110° HIGHER THAN No. 1
FUEL ENERGY	~98 x 10^6 Btu	3% HIGHER THAN No. 1	1% HIGHER THAN No. 1

*The HT error fix made negligible difference.

**All temperatures in °F.

Another difference between the two models is the effect of treating the fuel as fresh or once-burned. As noted above, the M-B model yielded almost no difference for the two fuel treatments. This occurs because the gap temperature drop is so small that a change in gap width (which depends on whether or not the fuel is fresh) can have no significant effect. The R-S model, however, yields a thermal conductance sufficiently low that the effect of the fuel description can be important. The fuel stored energy and temperature history at the hot spot (Figures 1-6 and 1-7, respectively) demonstrate this result. Note that, since gap width is one of the statistical variables, its influence on PCT is highly dependent on the gap conductance model used.

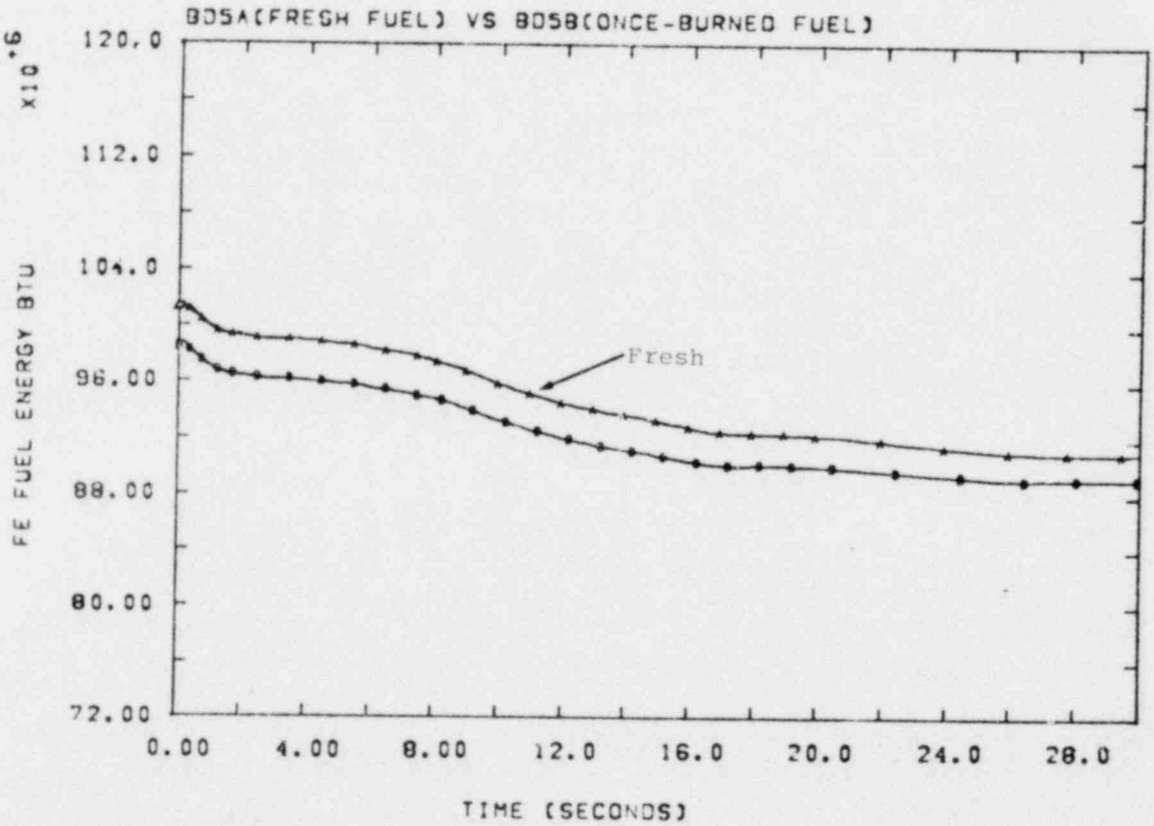


Figure 1-6 Fuel Stored Energy in R-S Calculations, Fresh vs Once-Burned Fuel

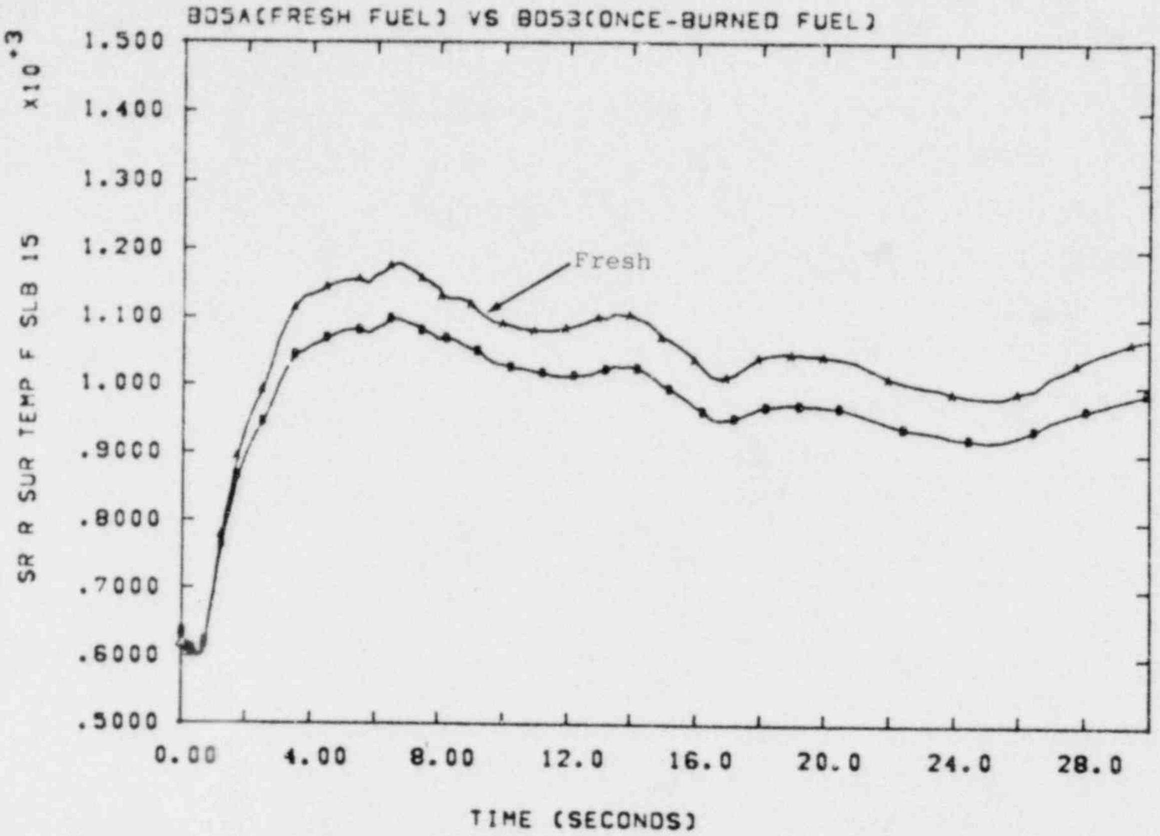


Figure 1-7 Slab 15 Temperature in R-S Calculations, Fresh vs Once-Burned Fuel

This last point is demonstrated by the results of the relative importance analyses (see Section 5) and response surfaces generated for two groups of calculations. The groups were runs for the first 26 statistical input sets, using M-B for one group and R-S for the other. (Because of the pressurized rods and gap width effect, R-S was used in the full study.) The M-B set showed fuel thermal conductivity, peaking factor, and Condie-Bengston heat transfer were of dominant importance to the PCT results. Gap width did not appear with any significance in the response surfaces. Examination of various details of the calculations and of input variable ranges indicated that the model results were physically reasonable, at least for the high-significance variables.

Additional analyses of the M-B set, using a variety of surface modelling techniques like those in the full statistical study (see Section 3), did not change the relative importance of highly ranked variables. However, probably because of the small sample size, only 2 variables (fuel conductivity and peaking factor) were seen to be significant in as many as 6 of the 11 response surfaces generated.

When a similar analysis was carried out on the 26-run R-S set, a different pattern was observed. Gap width became the dominant variable in 12 different models, with reasonably good agreement as to relative importance. This is consistent with the results of the main study. Variable 1 (subcooled discharge coefficient) was second in importance in 9 of the 12 models; in the full set it did not appear with any significance. Peaking factor and fuel thermal conductivity did not appear for the 26-run analysis, in contrast to the full study results. Another difference is that, when "star-point" sensitivities were calculated for variable 1, its influence was greater for temperatures below the RELAP nominal. (See Section 5.3.2.) Here, the preponderance of PCTs is above that value. This discrepancy is again probably caused by small sample sizes, as well as by the complexity of interactions between the various phenomena.

Table 1-5 presents a brief summary of the relative importance values given by averaging the response surfaces for the two 26-run sets. Notice that there is very little agreement between results for the two sets. Also, for both sets, most of the terms do not appear in even a majority of the surfaces calculated.

These analyses of the M-B and R-S 26-run sets, and comparison with the study results, emphasize three important points: different physical models can have very important, and not always obvious, consequences on the statistical results; as more response surfaces are employed, and as agreement among the results improves, confidence in those results grows; finally, the use of small data bases for the statistical analysis can be extremely misleading.

Table 1-5

Average* Relative Importance for 26-Run M-B and R-S Response Surfaces

M-B (11 Surfaces)			R-S (12 Surfaces)		
Term	Importance (°F)	Frequency**	Term	Importance (°F)	Frequency**
19	43	6	20	80	12
19 x 20 x 20	31	5	1	30	9
18	28	6	1 x 19	16	5
6	-18	5	4	13	5
3 x 16	16	4	3 x 16	4	2
3 x 15	-14	4	6	-3	1
13	5	1	19	3	1
4	4	1	13 x 19	-2	1
12 x 18	4	1			

*Linear average from all surface model results

**Number of surface models in which the term appears

2. The Data

The data* were gathered in stages as indicated in Table 2-1. The data themselves are listed in Tables 2-2a and b. Table 2-2a lists the value of each of the input variables used for a particular run under an appropriate code. In two cases, though, a value of both a variable and a transform of it are given. These are PFUNC and PKTOT (variable 18) and DLGAP and GAPWID (variable 20). In each of these cases the first value is transformed into the second, which is also affected by time-in-life (variable 17). Time-in-life is then dropped as an input variable, and PKTOT and GAPWID are distinct variables in the response surface. Also, the table value shown under DLECON is the original 19, i.e., the reciprocal of variable $\overline{19}$. From this point on, the numbers $\overline{18}$, $\overline{19}$, and $\overline{20}$ will refer only to the transformed variables and all the analyses are done on them.

The second listing, Table 2-2b, gives the maximum temperature, time of maximum temperature, and the temperature at 20 seconds for the central slabs 14, 15, and 16. The accumulator turn-on time is also given. The PCT is the largest of the temperatures given in columns 3, 6, and 9, and is not listed separately.

Only the results of runs 0 to 134 (less run 84) are used in this study.

---

*For the purpose of this study, "data" refers to PCTs occurring no later than 20 reactor seconds.

Table 2-1

Summary of Data Collection

Dial Set	Type*	No.	Comments**
0	Nominal	1	Base case
1 - 25	LHS	25	Each variable uniform over its entire range.
26 - 40	LHS	15	Variables 12 and $\overline{19}$ uniform above nominal; other variables uniform over entire range.
41	Try for high	1	Variables 4, 18, $\overline{19}$ and 20 at their upper limits, variable 6 at its lower limit.
42 - 73	FFS†	32	Fractional factorial with all variables (except 17 and hence 18 and 20) at either upper or lower limit. Full factorial on variables 1, 5, 12, 18, $\overline{19}$. Variable 17 uniform over entire range.
74 - 83	OAAT	10	One-at-a-time on variables 1, 5, 12, 18, 19. Variable 17 uniform over entire range.
84 - 86	Try for high	3	84: 1, 4, 10, 12, 18, $\overline{19}$, 20, 21 at upper limit; 5, 13, 17 at lower limit 85: 4, 18, $\overline{19}$, 20 at upper limit; 5, 6 at lower limit 86: 5 at lower limit.
87 - 90	OAAT	4	X_{17} = 0.1, 12, 18, and 20 varied between nominal and high.
91 - 100	LHS	10	17 uniform 0-6 months, 6 uniform below nominal, 12,18,$\overline{19}$,20 uniform above nominal.
101 - 102	OAAT	2	4 and 6 varied
103 - 134	FFS	32	Similar to dial sets 42 - 73 except variable ranges are reduced by a factor of $1/\sqrt{2}$ and 17 is 1.6 or 9.4 months.

Table 2-1 (cont)

Summary of Data Collection

Dial Set	Type*	No.	Comments**
135 - 140	X_{11}	6	11 finally varied‡
141 - 151	OAAT	11	Additional star point runs

*LHS denotes Latin Hypercube Sampling; see page 64.
FFS denotes Fractional Factorial Sampling; see page 64.
OAAT denotes One-at-a-Time Sampling.

**When not otherwise specified, a variable is set to nominal. Variable $\overline{19}$ is reciprocal UO_2 thermal conductivity = 1/19.

†Note added in proof. For some as yet unexplained reason, the desired fractional factorial was only partially implemented on variables 6, 7, 8, and 9. As a result, estimates of their effect are degraded. However, when the observations are taken in total it is felt that this degradation is not serious.

‡Because of a coding error in the version of RELAP being used, variable 11 was never changed until runs 135 through 140.

Table 2-2a

Statistical Study - Dial Sets

04/24/79

SET	DLEHRY	DLHEM	SLIP	DLTF	DCHF	DHTC6	DHTC7	DHTC8	DHTC9	DLBLK	DLMWR	DLPHR	DLCPR	DLPUMP	ECCTP	DLACC	TLF	PFUNC	PKTOT	DLECON	DLGAP	GAPWID	DLDEC
**** BASE CASE ****																							
0	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000
**** MCKAY - CONOVER SAMPLING ****																							
1	.816	-.106	.525	.623	1.002	1.616	.624	1.823	.910	.974	1.000	.965	1.103	-.697	84.4	634.6	178.3	.979	1.60229	.782	-1.104	.0001907	.476
2	1.157	.459	.252	1.313	1.284	1.068	.980	.912	.880	1.215	1.000	1.031	6.726	.411	113.6	657.5	108.8	1.091	1.64919	.884	-.690	.0001143	-.030
3	1.059	.192	.191	.834	.463	.998	1.080	1.335	.991	1.069	1.000	1.018	3.474	-.285	78.6	655.9	102.2	1.096	1.77733	1.076	-1.329	.0001586	-.025
4	.832	.133	.145	1.271	.339	.604	1.005	1.041	1.330	.652	1.000	1.034	4.747	-.185	59.3	601.2	289.2	.998	1.61841	1.232	-.499	.0002278	.456
5	.844	.678	.018	.586	.938	1.512	.875	1.309	.717	1.016	1.000	1.036	2.878	-.377	123.5	651.8	396.3	.985	1.64495	.828	-.741	.0002505	.142
6	.898	-.039	.409	.480	1.463	.897	.752	.622	1.224	.571	1.000	1.008	-.337	-.657	120.4	608.1	37.5	.922	1.47519	1.133	-.123	.0002399	-.041
7	.886	-.123	-.279	1.011	.424	1.033	.820	.814	1.429	.748	1.000	.999	-2.352	-.417	62.8	621.9	350.3	.893	1.35733	1.021	-.923	.0001023	-.046
8	1.003	.019	-.113	1.046	2.448	.658	.909	1.381	1.151	1.288	1.000	.947	2.302	.317	90.8	682.2	71.7	.940	1.48518	.806	.482	.0002726	.056
9	.964	-.050	.787	1.030	.495	.910	1.177	.889	1.036	1.171	1.000	1.025	-1.063	-.091	54.2	647.0	198.2	1.052	1.75859	.755	-.170	.0002995	-.011
10	.874	.068	.697	1.095	1.572	1.445	1.234	.677	1.122	1.205	1.000	.984	-3.648	.468	75.6	630.5	238.2	1.022	1.58919	1.167	.753	.0002730	-.024
11	1.078	.621	-.694	1.151	2.138	.680	1.261	.743	.857	1.122	1.000	.972	-1.330	.200	98.5	616.2	309.6	1.065	1.75547	.722	.657	.0003478	.550
12	.740	-.015	-.575	.713	1.692	1.304	1.284	.826	.825	.599	1.000	.995	1.996	-.803	49.7	673.0	67.6	.876	1.44394	.940	-.546	.0002475	-.015
13	.943	.252	-.234	1.517	1.871	.966	1.366	1.155	.800	1.093	1.000	1.012	-1.943	-.024	93.5	660.9	317.9	.964	1.45561	.942	.946	.0002492	.029
14	1.038	-.057	.060	.782	.614	.851	.783	.520	1.067	.727	1.000	.957	-2.998	.221	119.5	672.3	359.8	1.073	1.65776	1.113	.046	.0002052	-.007
15	.998	.555	.651	1.364	.817	1.377	.708	.640	.775	1.248	1.000	1.043	4.324	.150	87.9	611.7	432.5	1.040	1.68132	.668	1.020	.0003499	-.019

Table 2-2a (Cont)

04/24/79

SET	DLFHRY	DLHSH	SLIP	CLTF	CCHF	DHTC6	DHTC7	DHTC8	DHTC9	DLBLK	DLMWR	DLPWR	DLCPH	DLPUMP	ECCTP	DLACC	TLF	FFUNC	PKTOT	DLICON	DLGAP	GAPHIF	DLDEC
16	.749	.335	.361	.907	1.123	.778	1.143	1.016	.941	.681	1.000	.947	-3.938	.374	137.6	669.0	12.3	.959	1.61155	1.194	.181	.0003125	-.035
17	.803	-.212	-.370	.744	.673	.532	1.027	1.229	1.042	.951	1.000	.977	-2.643	.543	64.7	641.1	278.6	.951	1.39050	1.055	1.299	.0003717	-.037
18	.795	-.154	-.794	1.200	1.984	.743	.792	1.457	.886	.890	1.000	1.050	8.816	-.255	67.9	635.7	216.7	.927	1.43374	.980	.582	.0002514	.617
19	1.103	-.396	-.065	1.232	.635	.797	.859	.711	.957	1.388	1.000	.980	-2.076	-.130	112.1	619.9	142.3	1.009	1.51683	1.104	.880	.0002378	.796
20	1.031	-.186	-.422	.513	1.438	1.187	1.056	1.673	1.268	.794	1.000	1.004	.361	-.528	130.6	642.1	174.6	1.111	1.68313	1.190	-.271	.0001522	.387
21	.915	-.070	-.603	1.403	.570	1.217	1.118	1.547	1.094	1.451	1.000	.993	5.937	.822	95.9	648.6	382.8	1.055	1.61236	1.037	-.355	.0001570	.280
22	.781	.510	-.194	.921	1.238	.700	.932	.788	.985	.919	1.000	.961	5.705	.055	101.6	663.8	255.5	.911	1.48796	.923	.300	.0003047	-.005
23	.766	.878	.326	.564	1.044	1.121	1.186	.958	.942	.432	1.000	.970	-.646	.760	79.3	623.1	410.9	1.122	1.80641	1.085	-.857	.0001876	.686
24	.947	-.137	-.486	.679	.722	1.408	.713	1.185	1.304	1.342	1.000	1.021	-1.642	.608	105.0	626.7	133.0	1.027	1.70310	.984	.086	.0003091	.223
25	.865	.399	.551	1.138	.883	1.722	1.349	1.083	1.703	.525	1.000	1.013	.150	-.524	72.9	678.3	29.2	.951	1.47878	.678	.333	.0002380	.235

Table 2-2a (Cont)

04/24/79

**** MCKAY - CONOVER SAMPLING - BIASED TO HIGHER TEMPERATURES ****

SET	DLCHRY	DLHEM	SLIP	DLTF	CCHF	DHTC6	CHTC7	DHTC8	DHTC3	DLBLK	DLMHR	DLPHP	DLCPP	DLPUMP	ECCTP	DLACC	TLF	PFUNC	PKTOT	DLECON	DLGAP	GAPHID	DLDFC
26	1.003	.601	.411	1.104	.643	.568	.722	1.957	1.349	1.010	1.000	1.043	6.129	-.161	117.0	675.8	313.2	.959	1.52320	.694	.963	.0003201	-.007
27	.753	-.029	-.249	.604	.525	.655	1.081	.839	1.001	1.422	1.000	1.047	1.777	.185	51.5	611.5	340.2	.903	1.35898	.879	-.064	.0001656	.373
28	.942	.492	.042	.742	.381	1.534	1.192	1.007	.951	1.104	1.000	1.007	2.662	-.105	101.2	644.2	397.3	1.003	1.65829	.661	-1.095	.0002062	.246
29	1.029	-.152	.551	1.180	1.354	.769	.845	.922	1.128	.614	1.003	1.041	-.604	-.287	103.7	657.6	267.7	1.085	1.75045	.825	1.067	.0003509	-.023
30	.912	-.008	.602	.477	2.948	1.196	1.034	1.224	1.209	.871	1.000	1.031	-4.223	-.465	64.3	648.4	353.5	1.098	1.81169	.853	-.682	.0002377	.960
31	.794	-.094	.721	.703	.437	1.053	.896	1.102	1.275	1.208	1.000	1.055	-1.185	.544	56.6	664.3	94.1	.872	1.37193	.776	.576	.0002745	0.000
32	1.059	-.059	-.544	1.447	.772	.693	1.117	1.449	.938	1.257	1.000	1.034	-1.463	-.025	94.4	670.3	416.3	1.029	1.56405	.747	-.876	.0001062	-.040
33	.887	.321	.320	1.337	1.500	1.346	.780	.778	.791	1.340	1.000	1.022	5.361	.405	129.1	626.3	51.5	.937	1.45233	.840	-.744	.0001472	.281
34	1.113	-.093	-.278	1.205	.681	.948	1.218	1.530	.901	.473	1.000	1.051	-.175	.090	70.7	618.3	136.5	.906	1.44959	.778	-.323	.0002233	.519
35	.822	-.121	.256	.872	.925	1.406	.653	.733	.838	1.026	1.000	1.035	8.279	.575	77.9	679.5	201.4	1.120	1.81252	.912	-.079	.0002598	-.014
36	.959	.438	.090	.992	.968	1.218	1.315	.631	1.047	.532	1.000	1.016	-2.471	-.575	74.0	638.6	59.2	.993	1.58894	.717	.698	.0003128	-.051
37	.835	.730	-.082	.551	2.097	.836	.977	.711	.777	1.155	1.000	1.027	.853	.800	120.6	624.2	255.3	1.017	1.66448	.697	.295	.0003073	.133
38	1.077	.110	-.580	1.070	1.679	1.779	.815	1.177	.865	.910	1.000	1.024	-1.984	.326	112.0	654.5	8.9	.943	1.48362	.812	-.529	.0001411	.627
39	.763	.173	-.810	1.278	1.247	1.028	.930	1.378	1.179	.690	1.000	1.013	3.885	-.785	83.6	607.1	224.0	1.053	1.69356	.892	.438	.0002941	-.016
40	.858	-.179	-.457	.802	1.128	.840	1.349	.577	1.093	.788	1.000	1.010	-1.183	-.427	90.9	633.1	156.1	1.070	1.75479	.636	.082	.0002925	-.031
41	.900	1.000	0.000	1.600	1.000	.500	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.160	1.82698	.600	1.500	.0003530	0.000

Table 2-2a (Cont)

04/24/79

**** FRACTIONAL FACTORIAL SAMPLING ****

SET	DLFHRY	DLHEM	SLIP	DLTF	CCHF	DHTC6	DHTC7	DHTC8	DHTC9	DLBLK	DLMHR	DLPWF	DLCPW	DLPUMP	ECCTP	DLACC	TLF	PFUNC	PKLF	DLECON	DLGAP	GAPWIC	DLDEC
42	.700	-.250	-1.000	.400	.300	1.000	1.000	1.000	1.000	.400	1.000	.940	-5.000	-1.000	40.0	593.2	354.7	.840	1.36916	.600	-1.500	.0001517	-.060
43	.700	1.000	1.000	.400	.300	1.000	1.000	1.000	1.000	1.600	1.000	.940	10.000	1.000	40.0	693.2	219.4	.840	1.26153	1.300	1.500	.0002891	1.000
44	.700	-.250	-1.000	1.600	.300	1.000	1.000	1.000	1.000	1.600	1.000	.940	10.000	1.000	140.0	593.2	78.9	1.160	1.82797	.600	1.500	.0003538	1.000
45	.700	1.000	1.000	1.600	.300	1.000	1.000	1.000	1.000	.400	1.000	.940	-5.000	-1.000	140.0	693.2	43.4	1.160	1.74121	1.300	-1.500	.0000375	-.060
46	.700	1.000	1.000	.400	.300	1.000	1.000	1.000	1.000	1.600	1.000	1.060	10.000	1.000	140.0	593.2	168.4	.840	1.36005	.600	-1.500	.0001471	-.060
47	.700	-.250	-1.000	.400	.300	1.000	1.000	1.000	1.000	.400	1.000	1.060	-5.000	-1.000	140.0	693.2	281.0	.840	1.32289	1.300	1.500	.0003529	1.000
48	.700	1.000	1.000	1.600	.300	1.000	1.000	1.000	1.000	.400	1.000	1.060	-5.000	-1.000	40.0	593.2	367.5	1.160	1.85640	.600	1.500	.0003755	1.000
49	.700	-.250	-1.000	1.600	.300	1.000	1.000	1.000	1.000	1.600	1.000	1.060	10.000	1.000	40.0	693.2	74.1	1.160	1.78563	1.300	-1.500	.0000714	-.060
50	.700	-.250	1.000	1.600	3.000	1.000	1.000	1.000	1.000	1.600	1.000	.940	-5.000	1.000	40.0	693.2	163.2	.840	1.27805	.600	-1.500	.0000556	1.000
51	.700	1.000	-1.000	1.600	3.000	1.000	1.000	1.000	1.000	.400	1.000	.940	10.000	-1.000	40.0	593.2	329.8	.840	1.25618	1.300	1.500	.0002825	-.060
52	.700	-.250	1.000	.400	3.000	1.000	1.000	1.000	1.000	.400	1.000	.940	10.000	-1.000	140.0	693.2	94.7	1.160	1.81325	.600	1.500	.0003425	-.060
53	.700	1.000	-1.000	.400	3.000	1.000	1.000	1.000	1.000	1.600	1.000	.940	-5.000	1.000	140.0	593.2	62.7	1.160	1.79377	1.300	-1.500	.0000776	1.000
54	.700	1.000	-1.000	1.600	3.000	1.000	1.000	1.000	1.000	.400	1.000	1.060	10.000	-1.000	140.0	693.2	398.5	.840	1.37200	.600	-1.500	.0001547	1.000
55	.700	-.250	1.000	1.600	3.000	1.000	1.000	1.000	1.000	1.600	1.000	1.060	-5.000	1.000	140.0	593.2	85.1	.840	1.29419	1.300	1.500	.0003226	-.060
56	.700	1.000	-1.000	.400	3.000	2.000	1.500	.500	.500	1.600	1.000	1.060	-5.000	1.000	40.0	693.2	5.8	1.160	1.99866	.600	1.500	.0003560	-.060
57	.700	-.250	1.000	.400	3.000	1.000	1.000	1.000	1.000	.400	1.000	1.060	10.000	-1.000	40.0	593.2	259.4	1.160	1.81922	1.300	-1.500	.0000371	1.000
58	1.200	1.000	-1.000	1.600	.300	1.000	1.000	1.000	1.000	1.600	1.000	.940	10.000	-1.000	140.0	693.2	17.1	.840	1.43130	.600	1.500	.0004103	1.000

Table 2-2a (Cont)

04/24/79

SET	DLSHRY	DLHEM	SLIP	DLTF	DCHF	DHTC6	DHTC7	DHTC8	DHTC9	DLBLK	DLHWR	DLPWP	DLCPR	DLPLHP	ECCTP	DLACC	TLF	FFUNC	PKTOT	DLFCON	DLGAP	GAPWID	DLETC
59	1.200	-.250	1.000	1.500	.300	1.000	1.600	1.000	1.000	.400	1.000	.940	-5.000	1.000	140.0	593.2	381.9	.840	1.29570	1.300	-1.500	.0000742	-.060
60	1.200	1.000	-1.000	.400	.300	1.000	1.000	1.000	1.200	.400	1.000	.940	-5.000	1.000	40.0	693.2	291.5	1.160	1.83658	.600	-1.500	[illegible]	-.060
61	1.200	-.250	1.000	.400	.300	1.000	1.600	1.000	1.000	1.600	1.000	.940	10.000	-1.000	40.0	593.2	183.7	1.160	1.79484	1.300	1.500	.0003284	1.000
62	1.200	-.250	1.000	1.600	.300	1.000	1.000	1.000	1.000	.400	1.000	1.060	-5.000	1.000	40.0	693.2	409.8	.840	1.36768	.600	1.500	.0004002	1.000
63	1.200	1.000	-1.000	1.600	.300	1.000	1.000	1.000	1.000	1.600	1.000	1.060	10.000	-1.000	40.0	593.2	421.3	.840	1.36060	1.300	-1.500	.0001427	-.060
64	1.200	-.250	1.000	.400	.300	2.000	.600	.500	.500	1.600	1.000	1.060	10.000	-1.000	140.0	693.2	232.1	1.160	1.92150	.600	-1.500	.0001752	-.060
65	1.200	1.000	-1.000	.400	.300	2.000	.600	2.000	.500	.400	1.000	1.060	-5.000	1.000	140.0	593.2	26.9	1.160	1.84893	1.300	1.500	.0003698	1.000
66	1.200	1.000	1.000	.400	3.000	.500	1.500	.500	.500	.400	1.000	.940	10.000	1.000	140.0	593.2	394.4	.840	1.27487	.600	1.500	.0003022	-.060
67	1.200	-.250	-1.000	.400	3.000	.500	1.500	2.000	.500	1.600	1.000	.940	-5.000	-1.000	140.0	693.2	69.8	.840	1.35419	1.300	-1.500	.0001359	1.000
68	1.200	1.000	1.000	1.600	3.000	2.000	.600	.500	.500	1.600	1.000	.940	-5.000	-1.000	40.0	593.2	135.3	1.160	1.87976	.600	-1.500	.0001433	1.000
69	1.200	-.250	-1.000	1.600	3.000	2.000	.600	2.000	.500	.400	1.000	.940	10.000	1.000	40.0	693.2	200.1	1.160	1.90259	1.300	1.500	.0004108	-.060
70	1.200	-.250	-1.000	.400	3.000	2.000	.600	2.000	2.000	1.600	1.000	1.060	-5.000	-1.000	40.0	593.2	297.8	.840	1.39619	.600	1.500	.0004303	-.060
71	1.200	1.000	1.000	.400	3.000	2.000	.600	.500	2.000	.400	1.000	1.060	10.000	1.000	40.0	693.2	106.2	.840	1.30665	1.300	-1.500	.0000858	1.000
72	1.200	-.250	-1.000	1.600	3.000	.500	1.500	2.000	2.000	.400	1.000	1.060	10.000	1.000	140.0	593.2	431.7	1.160	1.88998	.600	-1.500	.0001511	1.000
73	1.200	1.000	1.000	1.600	3.000	.500	1.500	.500	2.000	1.600	1.000	1.060	-5.000	-1.000	140.0	693.2	356.7	1.160	1.85130	1.300	1.500	.0003716	-.060
74	.700	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	152.5	1.000	1.51743	1.000	0.000	.0001770	0.000

Table 2-2a (Cont)

04/24/79

SET	DLEHRY	DLHEM	SLIP	DLTF	DCHF	DHTC6	DHTC7	DHTC8	DHTC9	DLBLK	DLMWR	DLPHP	DLCPR	DLPUMP	ECCTP	DLACC	TLF	PFUNC	PKTOT	DLEGON	DLGAP	GAPWID	DLOIC
75	1.200	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	230.1	1.000	1.56692	1.000	0.000	.0001677	0.000
76	.900	0.000	0.000	1.000	.300	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	196.6	1.000	1.51504	1.000	0.000	.0001749	0.000
77	.900	0.000	0.000	1.000	0.300	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	249.5	1.000	1.54383	1.000	0.000	.0002057	0.000
78	.900	0.000	0.000	1.000	1.300	1.000	1.000	1.000	1.000	1.000	1.000	.940	0.000	0.000	90.0	643.2	145.3	1.000	1.63626	1.000	0.000	.0002823	0.000
79	.900	0.000	0.000	1.100	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.060	0.000	0.000	90.0	643.2	264.4	1.000	1.66790	1.000	0.000	.0003104	0.000
80	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	322.9	.840	1.35217	1.000	0.000	.0002588	0.000
81	.900	0.000	0.000	1.000	1.300	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	125.5	1.160	1.85677	1.000	0.000	.0002508	0.000
82	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	345.5	1.000	1.59972	.600	0.000	.0002499	0.000
83	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	304.6	1.000	1.54830	1.300	0.000	.0002343	0.000

Table 2-2a (Cont)

04/24/79

SET

**** SENSITIVITY STUDIES ****

SET	DLEHRY	DLHEM	SLIP	DLTF	CCHF	DHTC6	CHTC7	DHTC8	DHTC9	CL ILK	DLHHR	DLPWR	DLCPR	DLPUMP	ECCTP	DLACC	TLF	PFUNC	PKTOT	DLECON	DLGAP	GAPWID	DLDEC
84	1.200	0.000	0.000	1.600	.300	1.000	1.000	1.000	1.300	1.600	1.000	1.060	-5.000	0.000	90.0	643.3	.1	1.16[illegible]	2.31613	.600	1.500	.0004402	1.000
85	.900	0.000	0.000	1.600	.300	.500	1.000	1.000	1.000	1.000	1.000	1.030	0.000	0.000	90.0	643.2	226.0	1.160	1.82698	.600	1.500	.0003530	1.000
86	.900	0.000	0.000	1.000	.300	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000
87	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.060	0.000	0.000	90.0	643.2	.1	1.160	2.31613	1.000	0.000	.0003152	0.000
88	.900	0.000	0.000	1.000	1.300	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	.1	1.160	2.31613	1.000	0.000	.0003152	0.000
89	.900	0.000	0.000	1.000	1.300	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	.1	1.000	1.99667	1.000	1.500	.0004402	0.000
90	.900	0.000	0.000	1.300	1.000	1.000	1.000	1.000	1.000	1.060	1.000	1.060	0.000	0.000	90.0	643.2	.1	1.160	2.31613	1.000	1.500	.0004402	0.000
91	1.103	.391	.750	1.235	.405	.511	.933	1.347	1.330	.744	1.000	1.008	-.843	-.530	85.4	631.6	3.9	1.122	2.06785	.871	.366	.0002895	-.038
92	.833	-.108	-.322	.625	1.122	.534	1.197	.556	.999	1.082	1.060	1.052	-4.099	-.727	61.2	635.9	.4	1.031	2.04825	.637	1.306	.0004196	.063
93	.932	.517	-.094	.835	.372	.646	.802	.804	1.371	.463	1.000	1.042	7.171	.479	103.9	654.1	5.6	1.065	1.34813	.751	.853	.0003050	-.016
94	1.070	.124	.356	.937	.607	.782	.707	1.210	1.236	1.160	1.000	1.036	4.405	.027	67.6	606.7	2.1	1.053	2.03229	.674	.459	.0003239	.714
95	.849	-.050	-.289	.683	.493	.849	.737	.867	.809	1.050	1.000	1.016	5.819	-.004	81.5	669.3	2.7	1.027	1.96157	.936	1.121	.0003702	-.030
96	.794	-.159	.165	.538	.776	.735	1.248	.703	.599	1.275	1.000	1.019	2.212	.211	93.8	674.9	1.2	1.090	2.13640	.797	.271	.0003215	-.026
97	.876	.179	.077	1.009	1.765	.704	.856	1.824	.681	.649	1.000	1.047	-.337	.343	110.5	615.1	.7	1.108	2.19015	.833	1.096	.0003977	.220
98	.751	.677	-.712	1.122	1.594	.879	1.106	1.443	1.386	1.409	1.000	1.037	-2.277	-.213	49.0	643.3	5.3	1.069	1.87538	.709	.590	.0002875	-.044
99	1.005	-.014	.511	1.281	1.219	.680	1.031	1.021	.738	.970	1.000	1.023	-2.964	-.401	117.7	659.2	4.3	1.141	2.07396	.862	.878	.0003263	.327
100	.984	-.136	-.545	1.413	2.019	.586	1.404	.959	1.840	.793	1.000	1.028	1.328	.769	128.6	626.4	3.1	1.099	2.09114	.770	.721	.0003309	.560

Table 2-2a (Cont)

04/24/79

SET	DLEHRY	DLHEM	SLIP	DLTF	CCHF	DHTC6	DHTC7	DHTC8	DHTC9	DLBLK	DLMHR	DLPWF	DLCFL	DLPUMP	FCCTP	DLACC	TLF	PFUNC	PKTOT	DLTCON	DLGAP	GAPWID	DLDFC
101	.900	0.000	0.000	1.600	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57493	1.000	0.000	.0002280	0.000
102	.900	0.000	0.000	1.100	1.000	.500	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000

Table 2-2a (Cont)

04/24/79

**** SECOND FRACTIONAL FACTORIAL SAMPLING ****

SET	DLEHRY	DLHFH	SLIP	DLTF	DCHF	DHTC6	CHTC7	DHTC8	DHTC9	DLBLK	DLAHR	DLPWR	DLCPR	DLPUMP	ECCTP	DLACC	TLF	FFUNC	PKTCT	DLECON	DLGAP	GAPHID	DLOEC
103	.754	-.177	-.707	.523	.427	.613	.697	.613	.613	.523	1.000	.957	-3.536	-.707	54.6	607.8	1.6	.884	1.72053	.697	-1.061	.0002045	-.042
104	1.103	.707	.707	.523	.427	.613	1.332	1.633	.613	.523	1.000	1.042	7.071	.707	125.4	678.6	1.6	.884	1.72053	1.204	-1.061	.0002045	.707
105	1.103	-.177	.707	.523	2.175	.613	.697	1.633	1.633	1.394	1.000	.957	-3.536	.707	125.4	678.6	1.6	.884	1.72053	.697	1.061	.0003812	.707
106	.754	.707	-.707	.523	2.175	.613	1.332	.613	1.633	1.394	1.000	1.042	7.071	-.707	54.6	607.8	1.6	.884	1.72053	1.204	1.061	.0003812	-.042
107	.754	.707	.707	.523	.427	.613	1.332	.613	1.633	1.394	1.000	.957	7.071	.707	125.4	607.8	9.4	1.111	1.72117	.697	-1.061	.0000895	.707
108	1.103	-.177	-.707	.523	.427	.613	.697	1.633	1.633	1.394	1.000	1.042	-3.536	-.707	54.6	678.6	9.4	1.111	1.72117	1.204	-1.061	.0000895	-.042
109	1.103	.707	-.707	.523	2.175	.613	1.332	1.633	.613	.523	1.000	.957	7.071	-.707	54.6	678.6	9.4	1.111	1.72117	.697	1.061	.0002663	-.042
110	.754	-.177	.707	.523	2.175	.613	.697	.613	.613	.523	1.000	1.042	-3.536	.707	125.4	607.8	9.4	1.111	1.72117	1.204	1.061	.0002663	.707
111	.754	.707	-.707	.523	2.175	1.633	.697	1.633	.613	1.394	1.000	1.042	7.071	.707	54.6	678.6	9.4	.884	1.36987	.697	-1.061	.0000895	.707
112	1.103	-.177	.707	.523	2.175	1.633	1.332	.613	.613	1.394	1.000	.957	-3.536	-.707	125.4	607.8	9.4	.884	1.36987	1.204	-1.061	.0000895	-.042
113	1.103	.707	.707	.523	.427	1.633	.697	.613	1.633	.523	1.000	1.042	7.071	-.707	125.4	607.8	9.4	.884	1.36987	.697	1.061	.0002663	-.042
114	.754	-.177	-.707	.523	.427	1.633	1.332	1.633	1.633	.523	1.000	.957	-3.536	.707	54.6	678.6	9.4	.884	1.36987	1.204	1.061	.0002663	.707
115	.754	-.177	.707	.523	2.175	1.633	1.332	1.633	1.633	.523	1.000	1.042	-3.536	-.707	125.4	678.6	1.6	1.111	2.16176	.697	-1.061	.0002045	-.042
116	1.103	.707	-.707	.523	2.175	1.633	.697	.613	1.633	.523	1.000	.957	7.071	.707	54.6	607.8	1.6	1.111	2.16176	1.204	-1.061	.0002045	.707
117	1.103	-.177	-.707	.523	.427	1.633	1.332	.613	.613	1.394	1.000	1.042	-3.536	.707	54.6	607.8	1.6	1.111	2.16176	.697	1.061	.0003812	.707
118	.754	.707	.707	.523	.427	1.633	.697	1.633	.613	1.394	1.000	.957	7.071	-.707	125.4	678.6	1.6	1.111	2.16176	1.204	1.061	.0003812	-.042
119	1.103	-.177	-.707	1.394	2.175	.613	1.332	.613	1.633	.523	1.000	1.042	7.071	-.707	125.4	678.6	9.4	.884	1.36987	.697	-1.061	.0000895	.707

Table 2-2a (Cont)

04/24/79

SET	DLFHRY	DLHEM	SLIP	DLTF	DCHF	DHTC6	DHTC7	DHTC8	DHTC9	DLBLK	DLHHR	DLPHP	DLCPP	DLPLMP	ECCTP	DLACC	TLF	FFUNC	PKTOT	DLECON	DLGAP	GAPHIO	DLDEC
120	.754	.707	.707	1.394	2.175	.613	.697	1.633	1.633	.523	1.000	.957	-3.536	.707	54.6	607.8	9.4	.884	1.36987	1.204	-1.061	.0000895	-.042
121	.754	-.177	.707	1.394	.427	.613	1.332	1.633	.613	1.394	1.000	1.042	7.071	.707	54.6	607.8	9.4	.884	1.36987	.697	1.061	.0002663	-.042
122	1.103	.707	-.707	1.394	.427	.613	.697	.613	.613	1.394	1.000	.957	-3.536	-.707	125.4	678.6	9.4	.884	1.36987	1.204	1.061	.0002663	.707
123	1.103	.707	.707	1.394	2.175	.613	.697	.613	.613	1.394	1.000	1.042	-3.536	.707	54.6	678.6	1.6	1.111	2.16176	.697	-1.061	.0002045	-.042
124	.754	-.177	-.707	1.394	2.175	.613	1.332	1.633	.613	1.394	1.000	.957	7.071	-.707	125.4	607.8	1.6	1.111	2.16176	1.204	-1.061	.0002045	.707
125	.754	.707	-.707	1.394	.427	.613	.697	1.633	1.633	.523	1.000	1.042	-3.536	-.707	125.4	607.8	1.6	1.111	2.16176	.697	1.061	.0003812	.707
126	1.103	-.177	.707	1.394	.427	.613	1.332	.613	1.633	.523	1.000	.957	7.071	.707	54.6	678.6	1.6	1.111	2.16176	1.204	1.061	.0003812	-.042
127	1.103	.707	-.707	1.394	.427	1.633	1.332	1.633	1.633	1.394	1.000	.957	-3.536	.707	125.4	607.8	1.6	.884	1.72053	.697	-1.061	.0002045	-.042
128	.754	-.177	.707	1.394	.427	1.633	.697	.613	1.633	1.394	1.000	1.042	7.071	-.707	54.6	678.6	1.6	.884	1.72053	1.204	-1.061	.0002045	.707
129	.754	.707	.707	1.394	2.175	1.633	1.332	.613	.613	.523	1.000	.957	-3.536	-.707	54.6	678.6	1.6	.884	1.72053	.697	1.061	.0003812	.707
130	1.103	-.177	-.707	1.394	2.175	1.633	.697	1.633	.613	.523	1.000	1.042	7.071	.707	125.4	607.8	1.6	.884	1.72053	1.204	1.061	.0003812	-.042
131	1.103	-.177	.707	1.394	.427	1.633	.697	1.633	.613	.523	1.000	.957	7.071	-.707	54.6	607.8	9.4	1.111	1.72117	.697	-1.061	.0000895	.707
132	.754	.707	-.707	1.394	.427	1.633	1.332	.613	.613	.523	1.000	1.042	-3.536	.707	125.4	678.6	9.4	1.111	1.72117	1.204	-1.061	.0000895	-.042
133	.754	-.177	-.707	1.394	2.175	1.633	.697	.613	1.633	1.394	1.000	.957	7.071	.707	125.4	678.6	9.4	1.111	1.72117	.697	1.061	.0002663	-.042
134	1.103	.707	.707	1.394	2.175	1.633	1.332	1.633	1.633	1.394	1.000	1.042	-3.536	-.707	54.6	607.8	9.4	1.111	1.72117	1.204	1.061	.0002663	.707

Table 2-2a (Cont)

04/24/79

SET	DLFHRY	DLHEM	SLIP	DLTF	DCHF	DHTC6	CHTC7	DHTC8	DHTC9	DLBLK	DLMWR	DLPWF	DLCPW	DLPUMP	ECCTP	DLACC	TLF	PFUNC	PKTOT	DLECON	DLGAP	GAPHID	DLD-C
**** METAL-WATER REACTION SENSITIVITY STUDIES ****																							
135	1.200	-.250	-1.000	1.600	3.000	.500	1.500	2.000	2.000	.400	1.150	1.060	10.000	1.000	140.0	593.2	431.7	1.160	1.88398	.600	-1.500	.0001511	1.000
136	.754	.707	-.707	1.394	.427	.613	.697	1.633	1.633	.523	1.150	1.042	-3.536	-.707	125.4	607.5	1.6	1.111	2.16176	.697	1.061	.0003812	.707
137	.900	3.000	0.008	1.600	.300	.500	1.000	1.000	1.000	1.000	1.150	1.000	0.000	0.000	90.0	643.2	226.0	1.160	1.82698	.600	1.500	.0003530	0.000
138	.876	.179	.077	1.009	1.769	.704	.856	1.824	.681	.640	1.150	1.047	-.337	.343	110.5	615.3	.7	1.108	2.19015	.833	1.096	.0003977	.220
139	.900	0.000	0.000	1.600	1.000	.500	1.000	1.000	1.000	1.000	1.150	1.000	0.000	0.000	90.0	643.2	226.0	1.160	1.82696	.600	1.500	.0003530	0.000
140	1.202	-.250	-1.000	1.600	3.000	.500	1.500	2.000	2.000	.400	.850	1.060	10.000	1.000	140.0	593.2	431.7	1.160	1.88998	.500	-1.500	.0001511	1.000

Table 2-2a (Cont)

04/24/79

**** SENSITIVITY STUDIES ****

SET	DLEHRY	DLHEM	SLIP	DLTF	DCHF	DHTC6	DHTC7	DHTC8	DHTC9	DLBLK	DLMHR	DLPHR	DLCPR	DLPUMP	ECCTP	DLACC	TLF	PFUNC	PKTOT	DLECON	DLGAP	GAPWID	DLDEC
141	.900	-.250	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000
142	.900	0.000	1.000	1.000	1.000	1.000	1.600	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000
143	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	1.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000
144	1.200	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000
145	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.060	0.000	0.000	90.0	643.2	.1	1.160	2.31613	1.000	-1.500	.0001902	0.000
146	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.060	0.000	0.000	90.0	643.2	.1	.840	1.67720	1.000	1.500	.0004402	0.000
147	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	345.5	1.000	1.59972	1.300	0.000	.0002499	0.000
148	.700	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000
149	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.160	1.82698	1.000	0.000	.0002280	0.000
150	.900	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.130	1.78000	1.000	.090	.0002355	0.000
151	.900	1.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	90.0	643.2	226.0	1.000	1.57498	1.000	0.000	.0002280	0.000

Table 2-2b

Statistical Study Results - BD5 Series

04/24/79

DIAL SET	SLAB 14 TIME(MAX)	SLAB 14 MAX TEMP	SLAB 14 TEMP(20)	SLAB 15 TIME(MAX)	SLAB 15 MAX TEMP	SLAB 15 TEMP(20)	SLAB 16 TIME(MAX)	SLAB 16 MAX TEMP	SLAB 16 TEMP(20)	ACCUMULATOR TURN ON TIME
0	6.75	1179.	921.	6.63	1183.	1043.	6.52	1179.	1043.	12.50
1	5.00	1251.	599.	4.28	1082.	626.	4.28	1100.	641.	13.25
2	5.50	1146.	926.	5.40	1170.	945.	5.39	1203.	970.	10.75
3	7.44	1164.	967.	7.08	1189.	978.	7.08	1178.	967.	10.75
4	8.25	1257.	1116.	7.46	1271.	1156.	7.30	1273.	1154.	13.00
5	4.00	1134.	663.	3.47	1162.	664.	3.41	1184.	832.	10.75
6	5.00	1051.	611.	4.34	1068.	640.	4.22	1090.	668.	12.75
7	6.25	[illegible]64.	596.	6.26	988.	751.	6.13	1013.	804.	14.00
8	11.62	1333.	1230.	11.62	1328.	1235.	11.62	1321.	1236.	11.25
9	7.25	1427.	1197.	7.23	1443.	1235.	7.23	1442.	1223.	12.25
10	5.75	1130.	824.	5.66	1133.	815.	5.66	1163.	821.	12.25
11	8.99	1552.	1418.	9.15	1555.	1432.	9.19	1553.	1425.	11.50
12	4.50	1049.	608.	4.53	10[illegible]2.	651.	4.75	1047.	700.	13.25
13	11.69	1255.	1054.	11.67	1262.	1066.	11.73	1281.	1086.	11.50
14	6.75	1127.	756.	6.33	1129.	952.	5.90	1154.	981.	11.75
15	5.83	1425.	1050.	5.82	1445.	1068.	5.73	1457.	1066.	12.00
16	7.25	1221.	818.	7.33	1293.	1086.	7.33	1328.	1113.	11.50
17	6.22	1348.	1145.	6.21	1351.	1174.	6.21	1337.	1169.	14.50
18	7.00	1197.	697.	6.84	1200.	1010.	6.85	1215.	1060.	14.75
19	7.47	1194.	1139.	7.30	1200.	1136.	6.14	1224.	1161.	13.00
20	5.00	1036.	571.	4.53	1020.	600.	4.66	1045.	746.	13.25
21	7.44	1123.	1005.	7.04	1137.	1009.	7.17	1160.	1026.	13.25
22	11.50	1308.	1130.	11.47	1327.	1147.	11.47	1312.	1138.	11.00
23	4.28	1008.	671.	9.62	1062.	818.	9.23	1089.	831.	10.75
24	6.36	1355.	1035.	5.75	1330.	1065.	5.39	1308.	1046.	13.50
25	8.47	1211.	838.	8.44	1194.	840.	8.36	1208.	847.	10.75

Table 2-2b (Cont)

04/24/79

DIAL SET	SLAB 14 TIME(MAX)	SLAB 14 MAX TEMP	SLAB 14 TEMP(20)	SLAB 15 TIME(MAX)	SLAB 15 MAX TEMP	SLAB 15 TEMP(20)	SLAB 16 TIME(MAX)	SLAB 16 MAX TEMP	SLAB 16 TEMP(20)	ACCUMULATOR TURN ON TIME
26	10.00	1431.	1330.	5.90	1442.	1338.	5.89	1461.	1354.	10.[illegible]5
27	4.00	973.	598.	4.81	1044.	809.	5.04	1071.	950.	13.75
28	11.55	1383.	957.	8.31	1358.	969.	8.31	1275.	934.	10.75
29	7.50	1532.	1348.	7.36	1536.	1357.	6.81	1543.	1351.	12.75
30	5.00	1170.	703.	4.36	1130.	757.	4.36	1197.	852.	12.00
31	6.25	1212.	757.	6.62	1255.	933.	6.61	1255.	999.	13.00
32	12.25	1394.	1279.	12.45	1404.	1297.	12.45	1416.	1310.	12.00
33	10.75	1127.	834.	10.82	1155.	854.	10.69	1184.	872.	11.75
34	13.28	1283.	1158.	13.28	1270.	1160.	7.51	1264.	1175.	12.75
35	6.53	1292.	756.	6.49	1279.	828.	6.48	1275.	984.	13.00
36	10.07	1438.	1081.	10.07	1415.	1084.	10.07	1380.	1082.	11.00
37	10.50	1460.	1196.	10.53	1486.	1214.	10.81	1515.	1206.	11.00
38	11.75	1196.	930.	12.47	1220.	956.	12.34	1214.	958.	11.25
39	4.38	1294.	1112.	6.92	1280.	1152.	6.92	1272.	1141.	13.50
40	5.97	1425.	1240.	5.96	1425.	1285.	5.98	1405.	1244.	14.50
41	13.27	1852.	1629.	13.26	1828.	1721.	13.26	1833.	1719.	12.50
42	3.56	1048.	637.	3.55	1075.	786.	3.58	1049.	784.	16.75
43	2.40	750.	577.	3.85	1011.	661.	2.98	1047.	721.	10.00
44	7.84	1569.	1393.	7.94	1553.	1360.	7.94	1531.	1334.	18.00
45	2.83	883.	555.	4.20	1011.	610.	4.31	1061.	805.	11.00
46	3.51	946.	755.	4.20	1174.	893.	4.49	1175.	907.	11.50
47	3.14	1213.	754.	3.12	1211.	881.	2.75	1197.	890.	14.75
48	9.30	1489.	1338.	8.24	1559.	1372.	8.69	1562.	1363.	12.50
49	7.59	1119.	890.	7.42	1146.	938.	7.41	1151.	960.	15.00
50	3.91	928.	601.	6.01	1055.	666.	6.31	1061.	714.	14.00
51	3.96	958.	710.	10.21	1010.	848.	10.32	1036.	873.	12.75

Table 2-2b (Cont)

04/24/79

DIAL SET	SLAB 14 TIME(MAX)	SLAB 14 MAX TEMP	SLAB 14 TEMP(20)	SLAB 15 TIME(MAX)	SLAB 15 MAX TEMP	SLAB 15 TEMP(20)	SLAB 16 TIME(MAX)	SLAB 16 MAX TEMP	SLAB 16 TEMP(20)	ACCUMULATOR TURN ON TIME
52	3.60	1074.	719.	3.65	1225.	764.	3.60	1278.	807.	13.50
53	3.29	848.	609.	3.63	930.	658.	3.66	950.	768.	11.75
54	10.56	1326.	1168.	10.25	1349.	1193.	11.33	1311.	1168.	11.25
55	4.40	1111.	600.	4.46	1132.	637.	4.46	1150.	683.	15.75
56	10.67	1330.	1009.	10.82	1533.	931.	11.05	1469.	923.	10.50
57	3.61	735.	532.	4.28	998.	535.	4.16	1038.	548.	15.00
58	7.20	1531.	1309.	7.11	1539.	1327.	6.80	1538.	1344.	10.50
59	3.91	752.	513.	3.90	772.	525.	3.89	791.	538.	14.25
60	7.42	1451.	1206.	7.07	1480.	1217.	7.05	1456.	1207.	9.25
61	5.37	1226.	800.	5.37	1227.	917.	5.46	1243.	979.	13.25
62	17.82	1436.	1323.	17.36	1520.	1366.	17.36	1511.	1357.	12.75
63	6.50	973.	787.	6.75	987.	801.	6.63	984.	804.	12.00
64	5.11	1304.	906.	4.39	1292.	940.	3.89	1260.	923.	11.75
65	7.61	1314.	934.	6.83	1366.	828.	6.45	1448.	834.	11.00
66	5.80	1158.	1110.	5.80	1194.	1133.	5.80	1220.	1155.	10.00
67	4.38	890.	585.	4.38	887.	599.	4.38	873.	614.	12.50
68	5.92	1280.	871.	5.92	1293.	892.	5.91	1276.	873.	11.75
69	7.38	1403.	1302.	8.44	1495.	1323.	9.74	1519.	1397.	13.50
70	4.21	1245.	939.	4.65	1316.	957.	5.01	1353.	902.	14.75
71	4.62	755.	514.	4.61	764.	516.	3.80	770.	518.	9.00
72	19.49	2019.	2079.	19.71	2105.	2102.	19.53	2026.	2020.	15.50
73	5.62	1406.	1325.	5.60	1417.	1335.	5.59	1426.	1338.	9.75
74	4.15	949.	566.	4.54	987.	600.	4.35	1015.	693.	13.75
75	11.69	1365.	947.	9.80	1061.	952.	9.64	1074.	969.	11.50
76	6.81	1389.	892.	6.66	1095.	945.	6.53	1117.	975.	12.50
77	6.78	1122.	[illegible]66.	6.63	1120.	1000.	6.51	1122.	1008.	12.50

Table 2-2b (Cont)

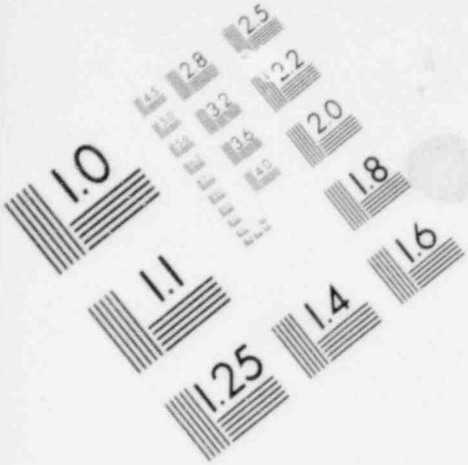
04/24/79

DIAL SET	SLAB 14 TIME(MAX)	SLAB 14 MAX TEMP	SLAB 14 TEMP(20)	SLAB 15 TIME(MAX)	SLAB 15 MAX TEMP	SLAB 15 TEMP(20)	SLAB 16 TIME(MAX)	SLAB 16 MAX TEMP	SLAB 16 TEMP(20)	ACCUMULATOR TURN ON TIME
78	6.93	1256.	1005.	6.65	1258.	1102.	6.54	1239.	1087.	12.50
79	6.81	1408.	1202.	6.65	1407.	1224.	6.65	1378.	1204.	12.50
80	6.96	1147.	924.	6.66	1145.	998.	6.63	1133.	990.	12.50
81	6.64	1312.	1113.	6.65	1320.	1174.	6.52	1316.	1172.	12.50
82	6.91	1386.	1270.	6.67	1389.	1289.	6.64	1365.	1272.	12.50
83	6.79	1062.	709.	6.64	1067.	940.	6.52	1076.	949.	12.50
84	12.40	2408.	0.	12.40	14713.	0.	12.40	2053.	0.	12.25
85	10.84	1318.	1657.	14.89	1883.	1775.	14.90	1883.	1772.	12.75
86	6.85	1206.	1010.	6.67	1214.	1051.	6.53	1223.	1058.	12.50
87	7.11	1618.	1406.	6.70	1611.	1428.	6.49	1508.	1324.	12.50
88	6.89	1563.	1350.	6.66	1561.	1373.	6.63	1478.	1289.	12.50
89	7.14	1640.	1419.	6.87	1636.	1436.	6.48	1554.	1348.	12.50
90	7.12	1747.	1576.	6.73	1746.	1582.	6.72	1668.	1513.	12.50
91	5.72	1399.	1222.	5.69	1480.	1303.	5.57	1453.	1269.	11.25
92	5.43	1657.	1640.	5.47	1683.	1582.	5.47	1627.	1592.	13.50
93	10.88	1620.	1352.	10.91	1665.	1389.	10.92	1662.	1386.	10.50
94	12.40	1683.	1442.	12.33	1741.	1240.	12.47	1661.	1438.	11.75
95	6.01	1534.	1244.	5.97	1576.	1345.	5.97	1531.	1299.	12.50
96	4.93	1495.	0.	4.58	1501.	0.	4.58	1471.	0.	0.00
97	12.18	1857.	1573.	12.18	1791.	1444.	12.18	1742.	1577.	12.00
98	11.92	1525.	1316.	11.98	1613.	1385.	12.08	1579.	1363.	11.50
99	7.65	1562.	0.	7.62	1616.	0.	7.62	1606.	0.	0.00
100	16.60	1701.	1682.	9.94	1713.	1677.	17.32	1720.	1715.	13.75
101	8.31	1210.	1047.	8.31	1215.	1053.	8.17	1225.	1063.	12.50
102	7.09	1244.	1198.	13.90	1258.	1228.	6.62	1257.	1227.	12.50
103	4.59	1180.	944.	4.59	1290.	1145.	4.60	1182.	1036.	15.25

Table 2-2b (Cont)

04/24/79

DIAL SET	SLAB 14 TIME(MAX)	SLAB 14 MAX TEMP	SLAB 14 TEMP(20)	SLAB 15 TIME(MAX)	SLAB 15 MAX TEMP	SLAB 15 TEMP(20)	SLAB 16 TIME(MAX)	SLAB 16 MAX TEMP	SLAB 16 TEMP(20)	ACCUMULATOR TURN ON TIME
78	6.93	1256.	1005.	65	1258.	1102.	6.54	1239.	1087.	12.50
79	6.81	1408.	1202.	6.65	1407.	1224.	6.65	1378.	1204.	12.50
80	6.96	1147.	924.	6.66	1145.	998.	6.63	1133.	990.	12.50
81	6.64	1312.	1113.	6.65	1320.	1174.	6.52	1316.	1172.	12.50
82	6.91	1386	1270.	6.67	1389.	1289.	6.64	1365.	1272.	12.50
83	6.79	1062.	709.	6.64	1067.	940.	6.52	1076.	949.	12.50
84	12.40	2408.	0.	12.40	14713.	0.	12.40	2053.	0.	12.25
85	10.84	1318.	1657.	14.89	1883.	1775.	14.90	1883.	1772.	12.75
86	6.85	1206.	1010.	6.67	1214.	1051.	6.53	1223.	1058.	12.50
87	7.11	1618.	1406.	6.70	1611.	1428.	6.49	1508.	1324.	12.50
88	6.89	1563.	1350.	6.66	1561.	1373.	6.63	1478.	1289.	12.50
89	7.14	1640.	1419.	6.87	1636.	1436.	6.48	1554.	1348.	12.50
90	7.12	1747.	1576.	6.73	1746.	1582.	6.72	1668.	1513.	12.50
91	5.72	1399.	1222.	5.69	1480.	1303.	5.57	1453.	1269.	11.25
92	5.43	1657.	1640.	5.47	1683.	1582.	5.47	1627.	1592.	13.50
93	10.88	1620.	1352.	10.91	1665.	1389.	10.92	1662.	1386.	10.50
94	12.40	1583.	1442.	12.33	1741.	1240.	12.47	1661.	1438.	11.75
95	6.01	1534.	1244.	5.97	1576.	1345.	5.97	1531.	1299.	12.50
96	4.93	1495.	0.	4.58	1501.	0.	4.58	1471.	0.	0.00
97	12.18	1857.	1573.	12.18	1791.	1444.	12.18	1742.	1577.	12.00
98	11.92	1525.	1316.	11.98	1613.	1385.	12.08	1579.	1363.	11.50
99	7.65	1562.	0.	7.62	1616.	0.	7.62	1606.	0.	0.00
100	16.60	1701.	1682.	9.94	1713.	1677.	17.32	1720.	1715.	13.75
101	8.31	1210.	1047.	8.31	5.	1053.	8.17	1225.	1063.	12.50
102	7.09	1244.	1198.	13.90	1258.	1228.	6.62	1257.	1227.	12.50
103	4.59	1180.	944.	4.59	1290.	1145.	4.60	1182.	1036.	15.25



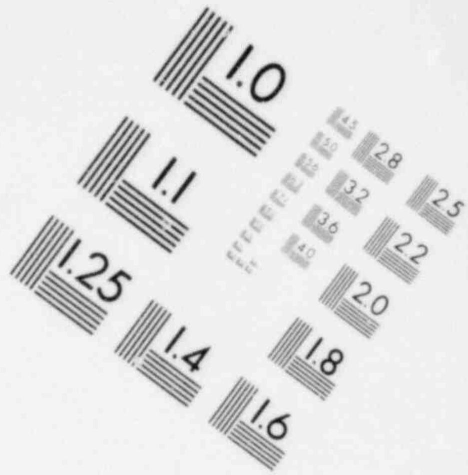
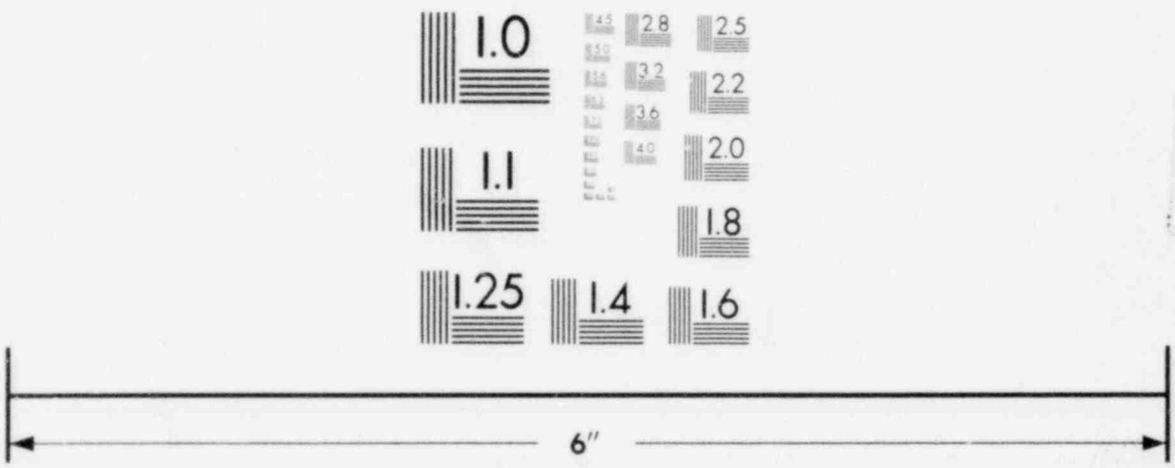
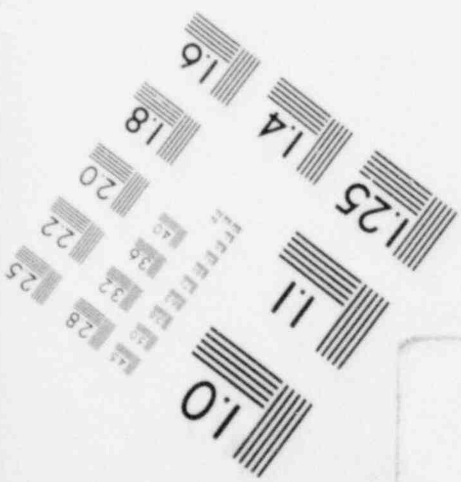


IMAGE EVALUATION
TEST TARGET (MT-3)





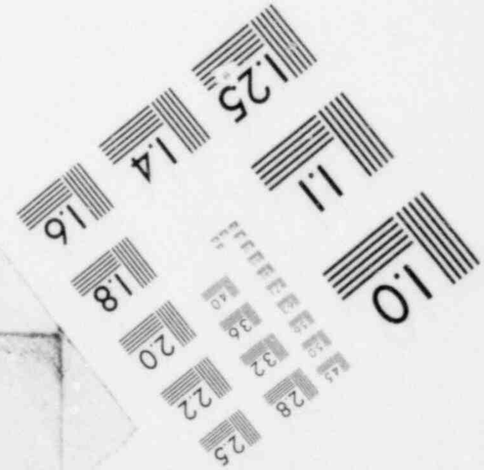


Table 2-2b (Cont)

04/24/79

DIAL SET	SLAB 14 TIME(MAX)	SLAB 14 MAX TEMP	SLAB 14 TEMP(20)	SLAB 15 TIME(MAX)	SLAB 15 MAX TEMP	SLAB 15 TEMP(20)	SLAB 16 TIME(MAX)	SLAB 16 MAX TEMP	SLAB 16 TEMP(20)	ACCUMULATOR TURN ON TIME
130	8.08	1447.	1215.	7.04	1473.	1246.	14.37	1414.	1269.	14.00
131	6.47	1250.	920.	6.42	1319.	1009.	6.41	1335.	1006.	13.75
132	10.75	1117.	836.	10.82	1165.	874.	11.04	1174.	888.	11.25
133	7.53	1282.	0.	7.53	1269.	0.	8.03	1368.	0.	0.00
134	5.67	1176.	809.	5.70	1190.	824.	5.69	1211.	835.	11.75
135	19.48	2101.	2091.	19.74	2151.	2151.	19.60	2036.	2031.	15.50
136	12.72	2138.	1897.	13.17	2267.	1906.	12.79	1993.	1853.	12.25
137	14.91	1835.	1670.	14.91	1890.	1761.	14.95	1889.	1784.	12.75
138	12.16	1850.	1574.	12.16	1797.	1451.	12.16	1733.	1579.	12.00
139	13.22	1878.	1643.	13.22	1830.	1724.	13.22	1836.	1722.	12.50
140	19.48	2077.	2067.	19.68	2070.	2066.	19.52	2017.	2011.	15.50
141	6.65	1181.	627.	6.51	1184.	866.	6.36	1184.	927.	14.75
142	5.69	1101.	675.	5.71	1106.	877.	5.71	1127.	942.	12.25
143	6.67	1153.	1045.	6.55	1203.	1052.	6.43	1215.	1057.	12.50
144	11.72	1196.	1052.	9.91	1182.	1052.	9.92	1178.	1056.	11.50
145	6.96	1300.	1305.	6.56	1514.	1334.	6.51	1352.	1203.	12.50
146	7.11	1578.	1381.	6.89	1569.	1378.	6.49	1464.	1276.	12.50
147	6.80	1162.	887.	6.65	1165.	1025.	6.51	1163.	1020.	12.50
148	4.04	1051.	596.	4.60	1091.	659.	4.43	1104.	858.	13.75
149	6.77	1265.	1044.	6.64	1268.	1130.	6.55	1271.	1133.	12.50
150	6.92	1257.	1039.	6.63	1265.	1125.	6.54	1268.	1128.	12.50
151	6.84	1167.	906.	6.94	1185.	920.	6.94	1195.	931.	10.75

Table 2-2b (Cont)

04/24/79

DIAL SET	SLAB 14 TIME(MAX)	SLAB 14 MAX TEMP	SLAB 14 TEMP(20)	SLAB 15 TIME(MAX)	SLAB 15 MAX TEMP	SLAB 15 TEMP(20)	SLAB 16 TIME(MAX)	SLAB 16 MAX TEMP	SLAB 16 TEMP(20)	ACCUMULATOR TURN ON TIME
104	5.41	1126.	988.	5.40	1178.	1034.	5.39	1135.	983.	9.50
105	6.61	1472.	1076.	6.34	1498.	1396.	6.22	1433.	1317.	12.00
106	11.93	1534.	1222.	11.74	1478.	1264.	11.98	1378.	1197.	11.50
107	9.87	1171.	946.	9.73	1387.	1221.	9.85	1428.	1241.	11.00
108	4.83	1134.	936.	4.66	1174.	1024.	4.67	1192.	1056.	11.25
109	9.81	1430.	1261.	9.86	1439.	1280.	10.00	1471.	1299.	9.50
110	4.30	1171.	0.	4.67	1232.	0.	4.66	1269.	0.	0.00
111	4.64	1034.	742.	10.40	1118.	798.	10.44	1104.	801.	10.50
112	4.45	789.	537.	4.45	806.	547.	4.05	815.	562.	12.75
113	4.99	1086.	759.	6.02	1084.	770.	6.00	1106.	779.	10.75
114	3.54	1022.	585.	3.51	1039.	642.	2.78	1051.	699.	13.75
115	5.03	1322.	709.	3.89	1381.	821.	3.83	1276.	761.	13.00
116	7.02	1144.	789.	6.58	1161.	820.	6.21	1148.	798.	11.25
117	6.16	1525.	1359.	6.14	1547.	1364.	6.28	1602.	1296.	13.75
118	3.75	1372.	705.	3.74	1442.	807.	3.71	1368.	783.	10.75
119	7.70	1277.	1263.	6.82	1292.	1292.	7.94	1292.	1297.	13.00
120	3.75	796.	570.	5.20	891.	791.	5.12	908.	829.	11.75
121	8.00	1307.	1032.	8.22	1337.	1197.	7.93	1366.	1234.	14.75
122	6.42	1192.	1062.	6.39	1204.	1082.	6.38	1222.	1101.	10.50
123	5.75	1471.	1464.	5.74	1528.	1530.	5.73	1440.	1415.	10.25
124	5.49	1215.	601.	5.80	1275.	1157.	5.83	1219.	1092.	16.00
125	12.75	2125.	1888.	13.00	2185.	1861.	12.83	1992.	1851.	12.25
126	6.42	1513.	0.	6.43	1560.	0.	6.42	1501.	0.	0.00
127	6.41	1278.	904.	6.29	1367.	969.	6.05	1231.	888.	12.25
128	5.45	1081.	604.	5.76	1151.	657.	5.76	1099.	723.	13.75
129	9.68	1437.	1046.	9.89	1450.	1080.	10.10	1414.	1042.	11.00

In regression studies where there is experimental error present, it is important for the independent variables to be as nearly uncorrelated as possible and fractional factorial sampling guarantees this. In a case such as ours, where there is assumed to be no experimental error, this absence of correlation is not as important. Nevertheless, the correlations among the 20 variables observed in the first 135 di . sets (omitting dial set 84) were computed and found to be small. (Variable 11 was constant for these runs.) When the 190 possible correlations are sorted on the first digit after the decimal point, there are 169 with first digit 0; 17 with first digit 1; 2 with first digit 2; and 2 with first digit 3. These last four are $\rho(6,7) = -.24$, $\rho(3,8) = -.23$, $\rho(17,18) = -.38$, and $\rho(18,20) = .35$.

The conclusion is that all the correlations among the basic variables are small enough so that no problems in interpreting the results can arise from that source.

As a ma' er of interest, we plot PCT vs $time_{PCT}$ in Figure 2-1. As can be seen, there is a definite trend toward higher temperatures at later times. There was an effort to model $time_{PCT}$ and use it as an independent variable in developing a model for PCT, but it was not instructive.

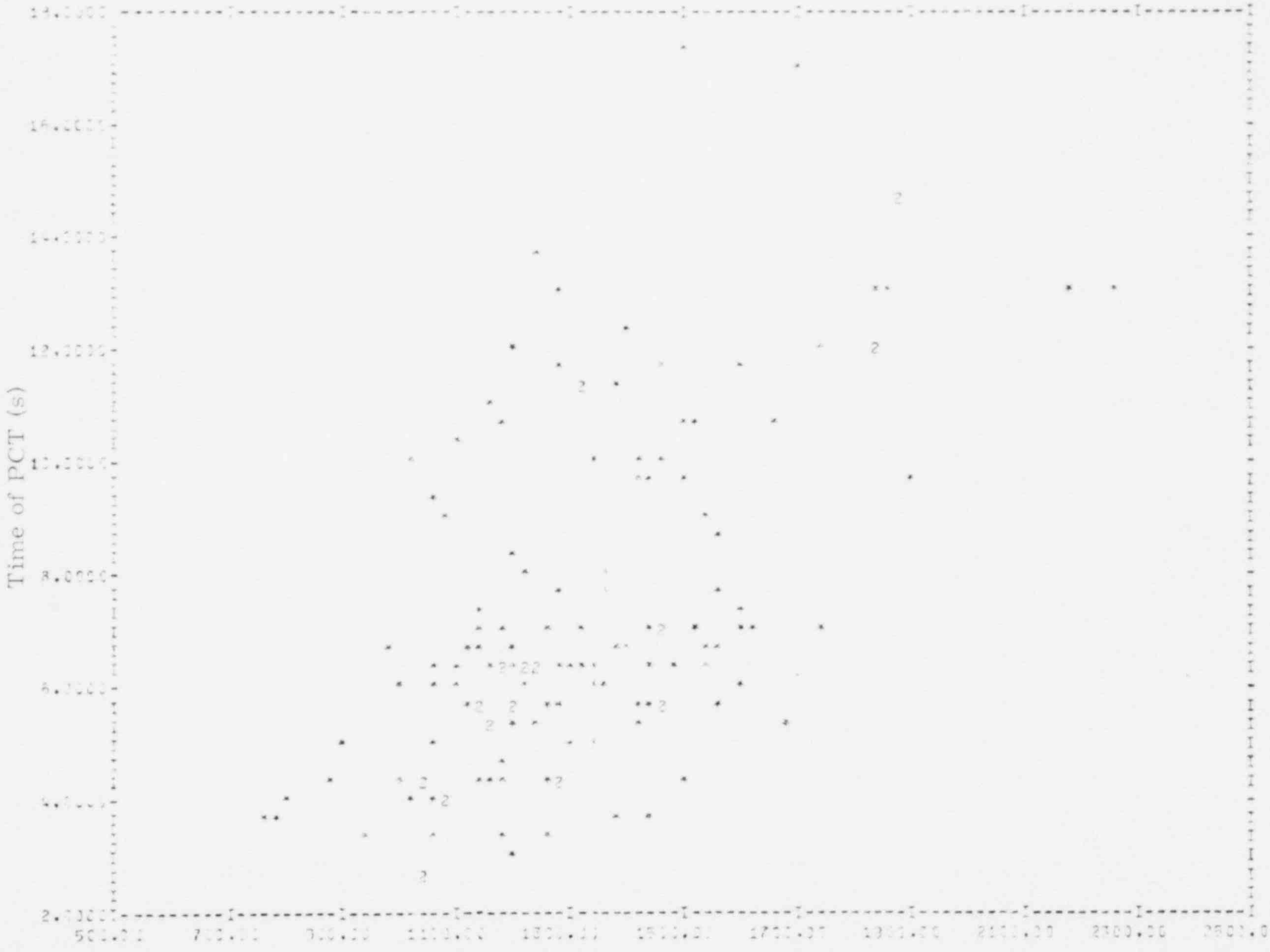


Figure 2-1. Plot of PCT vs Time of PCT for the Dial Sets of Table 2-2.
(a "2" denotes two points which overlapped)

Because of problems in interpreting the models and the sensitivity studies based on data involving the variation of X_{11}(Zr/H_2O reaction), it was decided to base this report only on those dial sets for which X_{11} was set at nominal, i.e., dial sets 0 to 134 (less set 84).

For those unfamiliar with the terms "Latin Hypercube Sampling" and "Fractional Factorial Sampling," the salient features of these two methods of sampling are described here.

Latin Hypercube Sampling -- This is a method of sampling an input space that spreads the points out as much as possible. It was developed by M. D. McKay at Los Alamos Scientific Laboratory. Let there be K inputs X_1, X_2, ..., X_K, each with its own probability distribution. If n observations are desired, the range of X_i is divided into n equiprobable segments (if the distribution of X_i is uniform, then the segments will be of equal length) and a value of X is chosen randomly from each segment. This is done for each of the K inputs and the results arranged in matrix form with K rows and n columns. The rows are then independently rearranged by a random permutation. The n observations are now the n columns of this matrix. There is a very slight change of multiple colinearities among the observations, and it is a good idea to check for this.

Fractional Factorial Sampling -- If a high and low value are chosen for each of the K variables and zero and one associated with the low and high values, respectively, then a complete factorial consists of the 2^K observations obtained by allowing each of the K variables to take each of its two values. A fractional factorial consists of a subset of these observations carefully chosen so that estimates formed from them have desirable statistical properties.

The principal difference, for our purposes, between these two schemes is that the LHS scheme spreads points out all over the space (as best it can) and the FFS scheme takes them on the vertices of a K-dimensional cube.

3. Statistical Modelling Considerations

3.1 Introduction

In this chapter we present response surfaces for PCT constructed from a variety of points of view and, although it may seem that we create unnecessary confusion by so doing, in fact the opposite is true for the following reason: If response surfaces which are created from many points of view and which are grossly different in structure all lead to the same conclusions, both qualitative and quantitative, then one's confidence in those conclusions is greatly strengthened. Similarly, one's confidence in conclusions that are reached by some points of view and not others is weakened.

It will be seen that all points of view lead to the conclusion that variables 3, 4, 6, 12, $\overline{18}$, $\overline{19}$ and $\overline{20}$ are the most important variables and that there is good agreement, also, on the magnitudes of their sensitivities (3 $\equiv$ slip; 4 $\equiv$ 2-phase friction loss; 6 $\equiv$ Condie-Bengston dial; 12 $\equiv$ power level multiplier; $\overline{18}$ $\equiv$ total peaking factor; $\overline{19}$ $\equiv$ reciprocal of fuel thermal conductivity multiplier; $\overline{20}$ $\equiv$ gap width).

3.2 Possible Modelling Philosophies

Approximating surfaces can be formed for a particular set of data in a variety of ways. The Biomed Stepwise Regression package (BMDP-77-2R, available from the UCLA Medical School) which was used for the analyses in this chapter, requires that some "philosophical" questions be answered:

- How statistically significant must a term be before it is allowed in the model, and how much can the significance of a term decrease as other terms are added before it is dropped from the model?

- In what order are terms considered for entry into the model?

- Whether to model the maximum temperatures (over time) of slabs 14, 15, and 16 separately and let PCT be the largest of these three individual predictions, or to model PCT directly, independently of which slab yields the maximum?

- Whether to model PCT, log(PCT), or other transformations?

- Whether or not to standardize the input variables?

- Whether to do regressions with the ranks* of the inputs or the inputs themselves?

The following choices were made:

- After some experimentation we decided to use as lower bounds $F_{in} = F_{out} = 6$. In Table 5-2(a) actual results for these parameters are given for the 12 models studied. This means, for a particular model, that the actual Fs** for all terms entering the model exceeded the tabulated F_{in} value and that at no time did any F drop below the tabulated F_{out} value.

---

*In a rank regression, each value of a variable, say gap width, is replaced by its place position (1 for smallest, 2 for next smallest, etc) in the ordered sequence of all such values (i.e., all gap widths). Similarly, each PCT is replaced by its place position in the ordered sequence of all PCTs.

**These Fs are the values of the F-statistic used for testing the statistical significance of a model term.

- Two orders of admission of terms to a model are used. The first, L', allows all terms -- linear, quadratic or cubic -- to be available together. The other, L", allows linear terms in first and only when the best linear model has been found are quadratic and cubic terms considered.

- The decision to model PCT directly is based on the fact that that approach predicted PCT for new data points better than its competitor.

- The log model predicts better in the cases studied but both approaches are used in the sensitivity studies.

- Standardizing the input variables is (almost universally) considered to be a good idea in the usual regression context. However, in our context its utility is not obvious because nonstandardized models predict very well (see Section 4). Consequently, both kinds of models are considered.

- The fact that a predominately linear model can fit the data fairly well would seem to imply that a rank regression ought to do as well or better than a regular regression. In actual fact, R^2s from rank regressions were generally 10 to 20% lower than their non-rank counterparts. Consequently, rank regression was not used.

There is reason to believe from physical considerations that terms like 12 x 18 x 19, 12 x 18 x 20 and 12 x 18 x 21 might contain all the information about their constituent variables that is needed. Therefore, special surfaces were made with this idea in mind under two sets of conditions:

1. One cubic term considered at a time and its constituent variables not allowed in linear or quadratic terms.

2. All three cubic terms allowed and their constituent variables allowed in linear and quadratic terms.

The second set of conditions resulted in better predictions than the first so was considered the better of the two approaches. In what follows, these models are coded "(C)".

3.3 Specific Models

Information about the models used in the sensitivity studies is summarized in Table 3-1.

Table 3-1

Information About the Models Used in the Sensitivity Studies

Model Code	Number of Terms in Model	Number of Basic Variables in Model	Model Type*	
FE-9	9	11	Non Lin	L'
CY-9	9	13	Non Lin(C)	L'
B3-9	9	9	Non Log	L'
C2-9	9	13	Non Log(C)	L'
B8-9	9	9	Std Lin	L"
B8-11	11	10	Std Lin	L"
B8-13	13	10	Std Lin	L"
CA-9	9	7	Std Log	L'
CA-11	11	7	Std Log	L'
CG-9	9	7	Std Log	L"
CG-11	11	7	Std Log	L"
CG-13	13	8	Std Log	L"
CF-9**	9	9	Std Lin	L'
CF-11**	11	10	Std Lin	L'
CF-13**	13	10	Std Lin	L'
CX-9**	9	9	Std Lin(C)	L'
CV-9**	9	7	Std Log(C)	L'

*"Std" denotes standardized "Non" denotes non-standardized

"Lin" denotes linear "Log" denotes natural logarithm

**The CF models are identical to their B8 counterparts, CX-9 is identical to B8-9, and CV-9 is identical to CG-9; so these models will no longer be considered separately.

As will be seen, the nonstandardized (C) models each have two of the special cubic terms in them. This apparently results from the variables not being standardized because when they are, as in models CX-9 and CV-9, these terms disappear.

The word "standardized" and its code "Std" mean that the input variables have been changed from Xs to Zs through the equation $Z(k) = [X(k) - A(k)]/B(k)$, where the coefficients $\{A(k)\}$ and $\{B(k)\}$ are the means and standard deviations, respectively, of the values of the input variables used in the modelling. Note that they are <u>not</u> the means and standard deviations of the input distributions postulated for these variables. The standardizing coefficients are given in Table 3-2. Also given in this table is a symbol denoting whether a variable is additive (A) or multiplicative (M).

Table 3-2

Coefficients for Standardizing the Input Variables by the Equation $Z(k) = [X(k) - A(k)]/B(k)$

Variable	Type	Normalizing Coefficient A	Normalizing Coefficient B
1	M	.92605	.16897
2	A	.20821	.43526
3	A	.00033	.66234
4	M	.98985	.41653
5	M	1.27179	.92282
6	M	1.04941	.41261
7	M	1.00395	.24046
8	M	1.06720	.39985
9	M	1.04544	.35791
10	M	.97420	.40423
12	M	1.00635	.04159
13	A	1.37719 psia	5.07030 psia
14	A	.00004	.65231
15	A	89.97463°F	33.24230°F
16	A	643.07840	33.05323 psia
18	M	1.68059	.26314
19	M	1.16475	.31304
20	A	$.25007 \times 10^{-3}$ ft	$.09994 \times 10^{-3}$ ft
21	A	.26120	.39157

A detailed description of the first 12 models listed in Table 3-1 is given in Tables 3-3, 3-4 and 3-5, where R^2 denotes the proportion of total variation in the dependent variable accounted for by the model and RMSR is an abbreviation for root mean square of the residuals.

Table 3-3 is to be read as follows: Under model FE-9 we find

$$PCT = 515.2 + 74.93*X(3)*X(10) - 115.7*X(6)*X(12) \pm \cdots$$

$$+ 203.5*X(12)*X(12)*X(\overline{18}).$$

For standardized models we find, for example, for model B8-9 in Table 3-4

$$PCT = 1318. - 31.49*Z(3) + 40.91*Z(4) \pm \cdots + 23.13*Z(8)*Z(\overline{18})$$

$$= 1318 - 31.49* \frac{X(3) - .00033}{.66234} + 40.91* \frac{X(4) - .98985}{.41653}$$

$$\pm \cdots + 23.13* \frac{X(8) - 1.06720}{.39985} * \frac{X(\overline{18}) - 1.68059}{.26314},$$

where the standardizing coefficients are from Table 3-2.

Table 3-3

Response Surfaces With Nonstandardized Input Variables

Model Type	Linear		Linear		Log		Log	
Model Code	FE-9(L')		CY-9(C)(L')		B3-9(L')		C2-9(C)(L')	
	PCT = 515.2		PCT = 625.7		LOG(PCT) = 6.180		LOG(PCT) = 6.434	
	+74.93	3x10	+73.67	1x4	+.4390	$\overline{19}$	-.07507	6
	-115.7	6x12	-66.88	2x4	+1.285	$\overline{20}$	+.0004644	16
	+23.92	8x14	+41.80	4x8	-.03948	1x3	-.08345	2x2
	-.1718	3x16	-75.68	3x9	-.01871	4x5	+.05327	4x8
	+54.40	4x$\overline{18}$	+44.29	3x10	-.08200	6x6	-.06636	3x9
	+46.11	8x$\overline{19}$	+1.014	2x15	-.2681	6x12	+.04508	3x10
	+146.5	$\overline{18}$x$\overline{19}$	-89.92	6x$\overline{19}$	+.06177	4x$\overline{18}$	+.0008921	2x15
	+1976.	$\overline{20}$x$\overline{20}$	+222.2	12x$\overline{18}$x$\overline{19}$	+.2290	12x12x$\overline{18}$	+.1313	12x$\overline{18}$x$\overline{19}$
	+203.5	12x12x$\overline{18}$	+565.7	12x$\overline{18}$x$\overline{20}$	-.3640	$\overline{19}$x$\overline{19}$x$\overline{20}$	+.4620	12x$\overline{18}$x$\overline{20}$
R^2	.9188		.9167		.9262		.9011	
RMSR	70.4°F		71.3°F		5.1% (66.0°F)*		5.9% (76.6°F)	

*For models based on the logarithm of PCT the RMSR can be interpreted as a percent of some average temperature. We have used 1300°F which is very near the mean of the PCTs used in the analyses.

Table 3-4

Response Surfaces with Standardized Input Variables

Model Type	Linear		Linear		Linear		Log		Log		Log	
Model Code	B8-9(L")		B8-11(L")		B8-13(L")		CG-9(L")		CG-11(L")		CG-13(L")	
	PCT = 1318.		PCT = 1299.		PCT = 1302.		LOG(PCT) = 7.188		LOG(PCT) = 7.188		LOG(PCT) = 7.174	
	-31.49	3	-30.85		-29.94	3	-.02167	3	-.02314	3	-.01980	3
	+40.91	4	+38.11	4	+38.03	4	+.03136	4	+.03041	4	+.03136	4
	-48.33	6	-50.41	6	-59.82	6	-.03565	6	-.03324	6	-.04240	6
	+30.30	12	+30.75	12	+27.08	12	+.02432	12	+.02465	12	+.02406	12
			+19.71	14	+18.29	14						
	+111.8	$\overline{18}$	+109.1	$\overline{18}$	+103.7	$\overline{18}$	+.08764	$\overline{18}$	+.08017	$\overline{18}$	+.07815	$\overline{18}$
	+92.84	$\overline{19}$	+92.98	$\overline{19}$	+92.77	$\overline{19}$	+.06853	$\overline{19}$	+.07163	$\overline{19}$	+.07088 +.09016	$\overline{19}$ $\overline{20}$
	+95.08	$\overline{20}$	+99.65	$\overline{20}$	+97.53 +19.63	$\overline{20}$ 6x6	+.07781 -.01629	$\overline{20}$ $\overline{18}$x$\overline{18}$	+.09211 -.02244	$\overline{20}$ $\overline{18}$x$\overline{18}$	+.01317 -.02267	6x6 $\overline{18}$x$\overline{18}$
	+17.35	3x10	+20.24	3x10	+20.48 -29.11	3x10 14x14	-.02572	$\overline{19}$x$\overline{20}$	-.02811	$\overline{19}$x$\overline{20}$	-.01299 -.02768	7x$\overline{20}$ $\overline{19}$x$\overline{20}$
	+23.13	8x$\overline{18}$	+24.45 +19.12	8x$\overline{18}$ $\overline{20}$x$\overline{20}$	+26.06 +25.50	8x$\overline{18}$ $\overline{20}$x$\overline{20}$			+.01691 -.01459	$\overline{18}$x$\overline{18}$x$\overline{20}$ $\overline{20}$x$\overline{20}$x$\overline{20}$	+.01922 -.01589	$\overline{18}$x$\overline{18}$x$\overline{20}$ $\overline{20}$x$\overline{20}$x$\overline{20}$
R^2	.9041		.9180		.9302		.9217		.9350		.9450	
RMSR	76.5°F		71.3°F		66.3°F		5.2%(68.1°F)*		4.8%(62.5°F)		4.5%(58.0°F)	

*For models based on the logarithm of PCT the RMSR can be interpreted as a percent of some average temperature. We use 1300°F which is very near the mean of the PCTs used in the analysis.

Table 3-5

Response Surfaces With Standardized Input Variables

Model Type	Log		Log	
Model Code	CA-9(L')		CA-11(L')	
	LOG(PCT) = 7.187		LOG(PCT) = 7.187	
	-.02150	3	-.02321	3
	+.03159	4	+.03049	4
	-.03647	6	-.03398	6
	+.08814	$\overline{18}$	+.08019	$\overline{18}$
	+.06981	$\overline{19}$	+.07315	$\overline{19}$
	+.07749	$\overline{20}$	+.09411	$\overline{20}$
	-.01434	$\overline{18}\times\overline{18}$	-.02069	$\overline{18}\times\overline{18}$
	-.02626	$\overline{19}\times\overline{20}$	-.02899	$\overline{19}\times\overline{20}$
	+.01402	$12\times\overline{19}\times\overline{19}$	+.01521	$12\times\overline{19}\times\overline{19}$
			+.01780	$\overline{18}\times\overline{18}\times\overline{20}$
			-.01619	$\overline{20}\times\overline{20}\times\overline{20}$
R^2	.9195		.9348	
RMSR	5.3% (69.0°F)*		4.8% (62.7°F)	

*For models based on the logarithm of PCT the RMSR can be interpreted as a percent of some average temperature. We have used 1300°F which is very near the mean of the PCTs used in the analyses.

Plots of the estimated density function and estimated cumulative distribution function as determined by 10 000 samples of each of the 12 different response surfaces with the nominal mean and standard deviation 1/6 the range* are given in Figures 3-1 through 3-13. In generating these data, nominal values of peaking factor (18) and gap width (20) were calculated using time-in-life (17). Therefore, variables 18, 19, and 20 were statistically sampled, not $\overline{18}$, $\overline{19}$ and $\overline{20}$. A comparison of Figures 3-10 and 3-13 gives a measure of the sampling error because the plots for response surfaces B8-9 and CX-9 were both obtained before it was realized the surfaces were the same. The horizontal scale of all plots is from 700° to 1800°F with tics every 100°F. The vertical scale is from 0 to 0.005 for the density plots and from 0 to 1 for the distribution plots.

On those occasions when it becomes necessary to settle on one model for some reason, we recommend CG-11. This is a standardized model for the logarithm of PCT that emphasizes linear terms; that is, a STD LOG (L") model.

There is no compelling reason for picking this particular model. However, there is a general preference among statisticians for standardized models, and there is a specific preference on our part for logarithm models for PCT because they have consistently performed better throughout this study. These considerations lead us, therefore, to either a CG or a CA model.

The choice between them is based principally on their treatment of variable 12. It appears linearly in the CG models and as an interaction with the square of variable $\overline{19}$ in the CA models. The presence of the multiplicative constant, $\overline{19}^2$ (whose standardized value was very nearly zero), falsely decreases the relative importance of 12 in the vicinity of nominal (see Table 5-2).

---

*Actually, the standard deviation used is 1/3 the upper half range if the value of the variable is above nominal and 1/3 the lower half range if the value of the variable is below nominal.

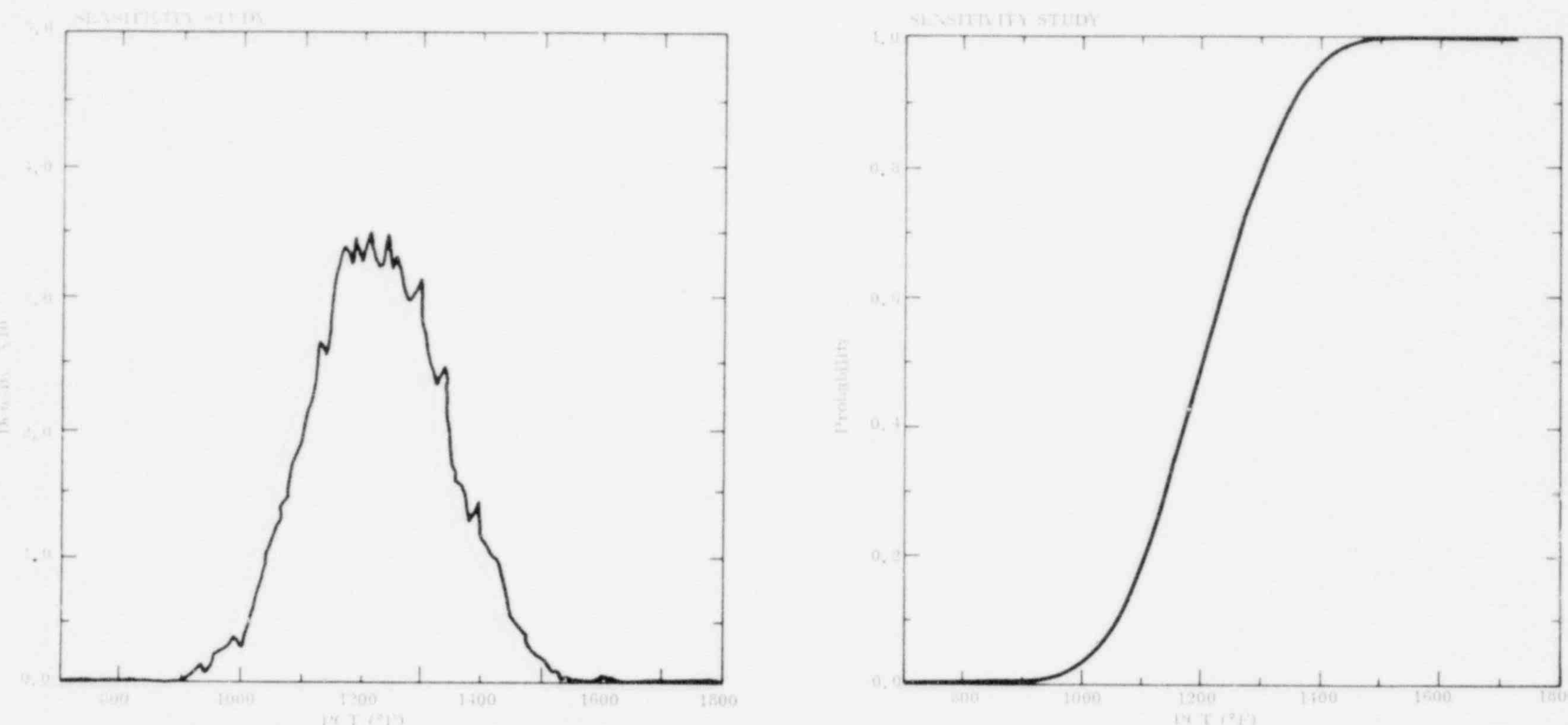


Figure 3-1. Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface CG-9 as Determined by 10 000 Samples. (The input distributions all have means equal to nomin.l and standard deviations equal to 1/6 the range.)

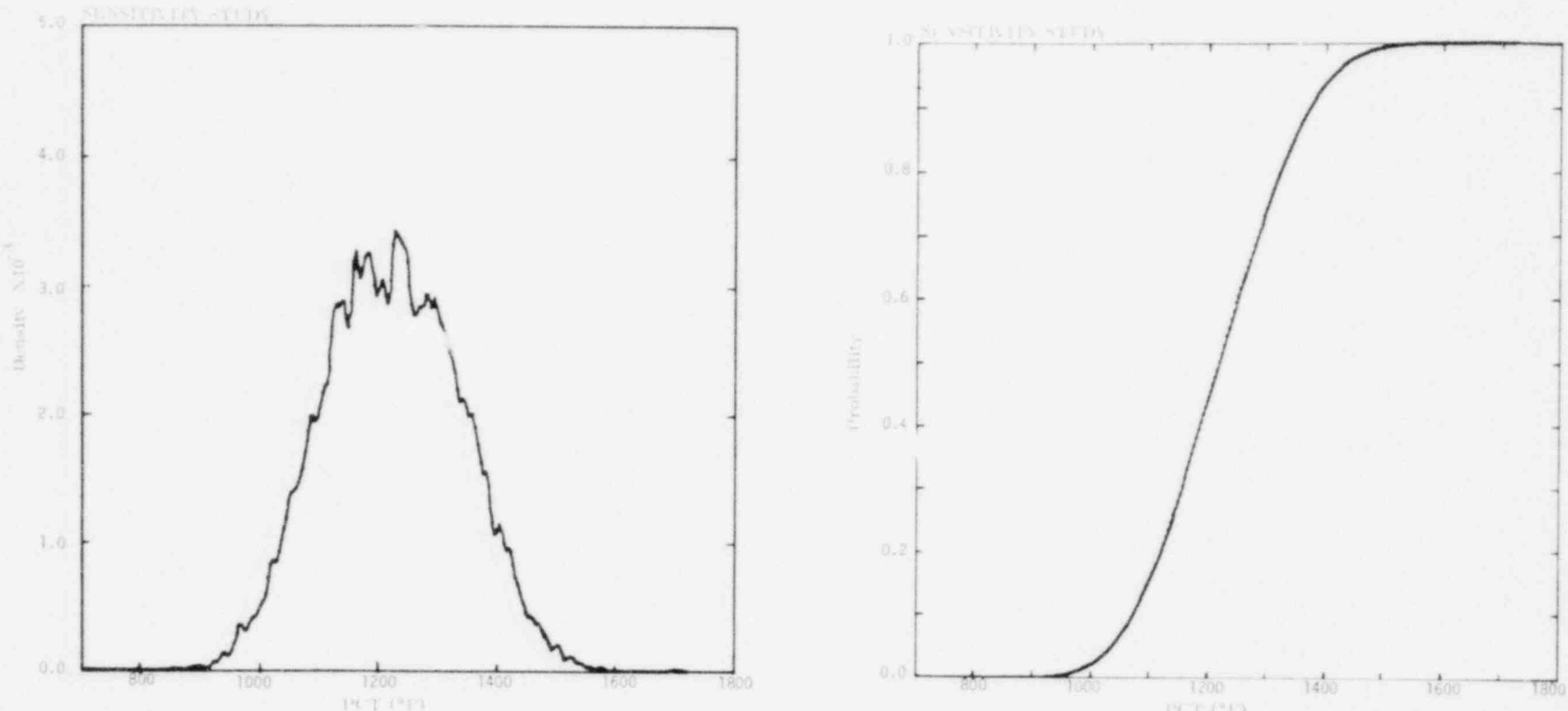


Figure 3-2 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface CG-11 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

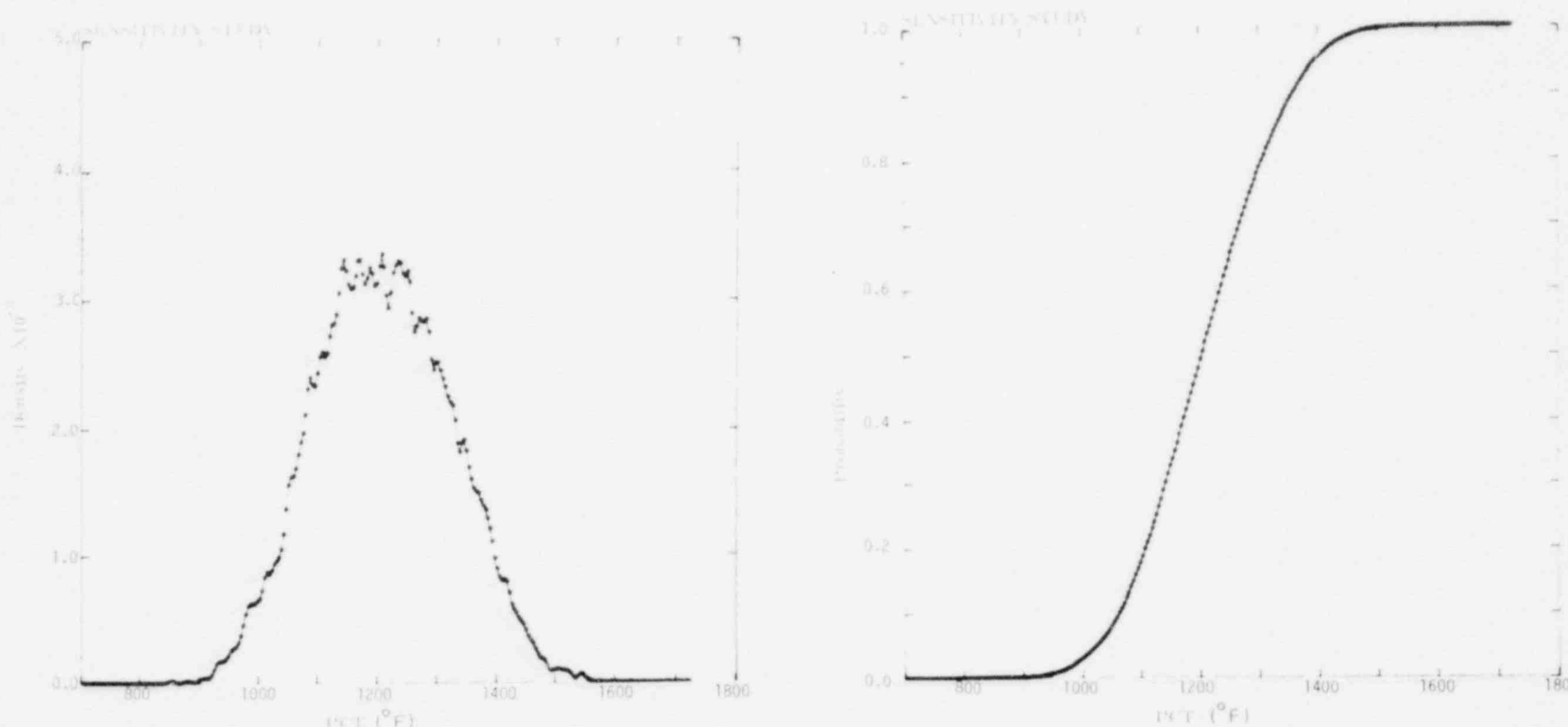


Figure 3-3 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface CG-13 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

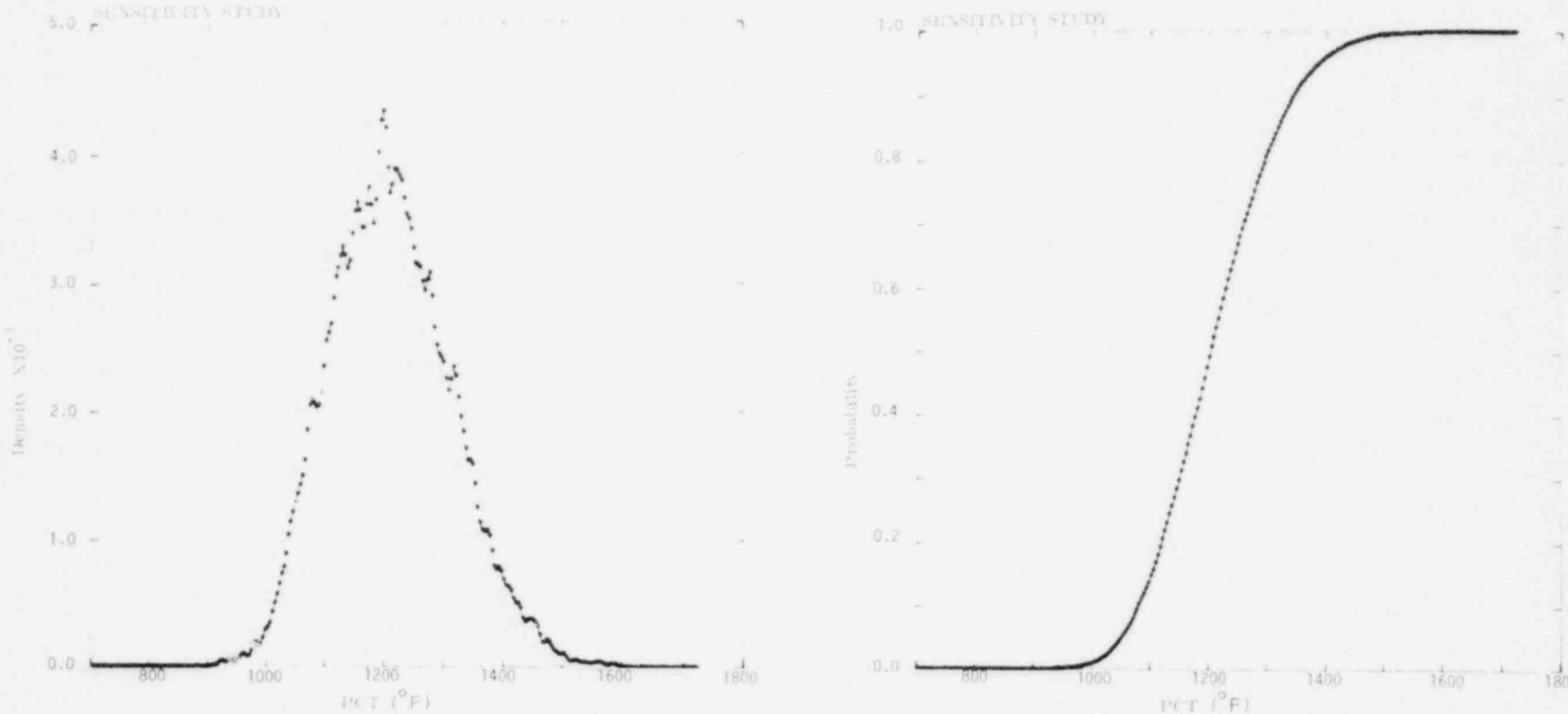


Figure 3-4 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface FE-9 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

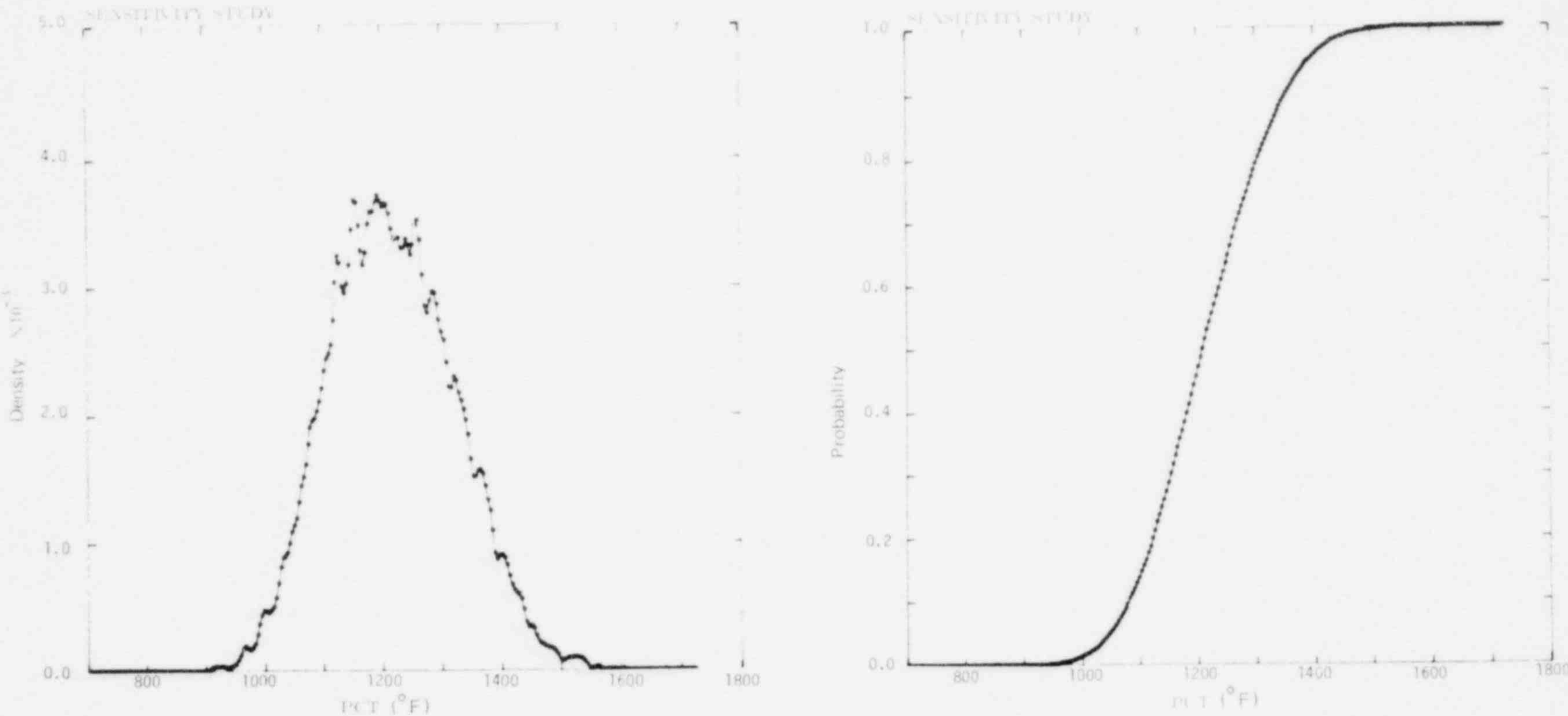


Figure 3-5 Plocs of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface B3-9 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

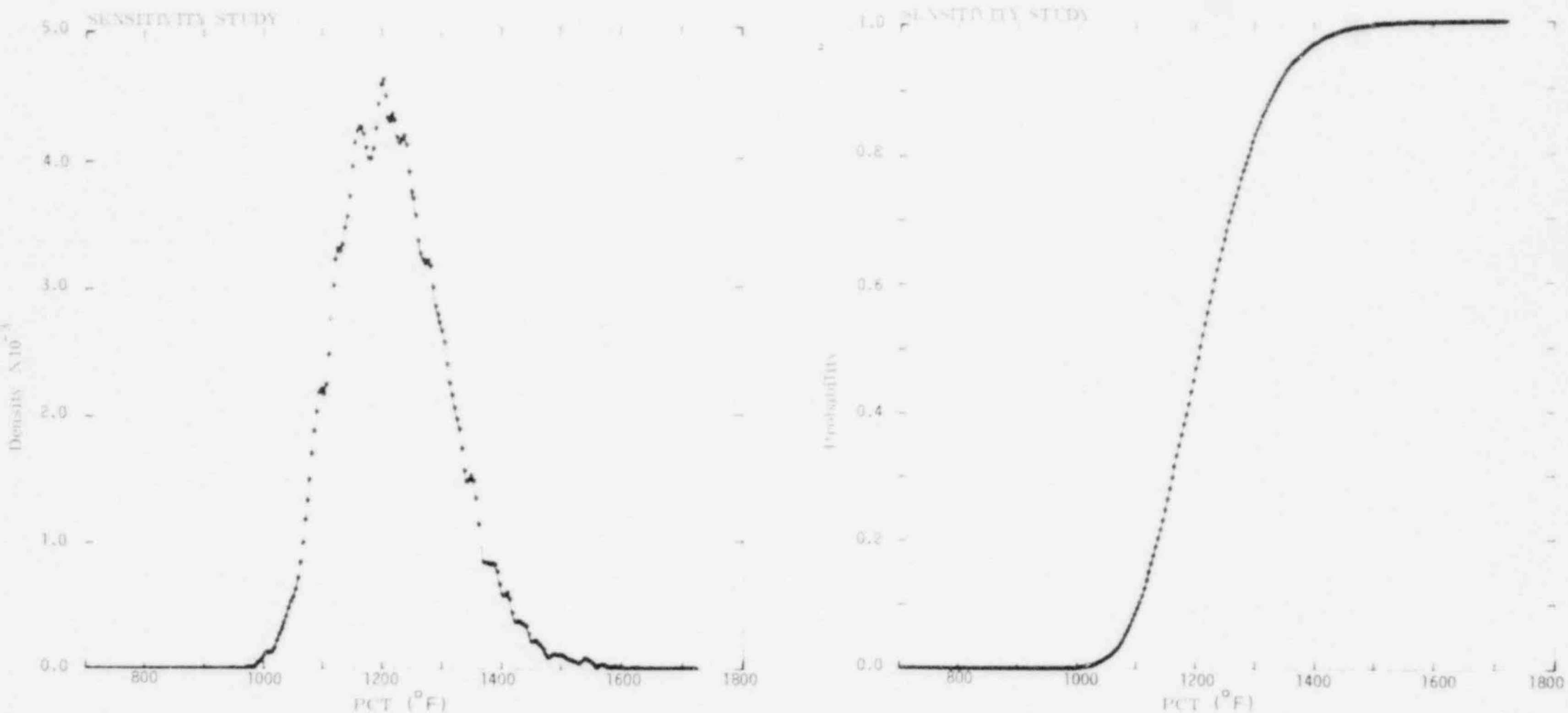


Figure 3-6 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface C2-9 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

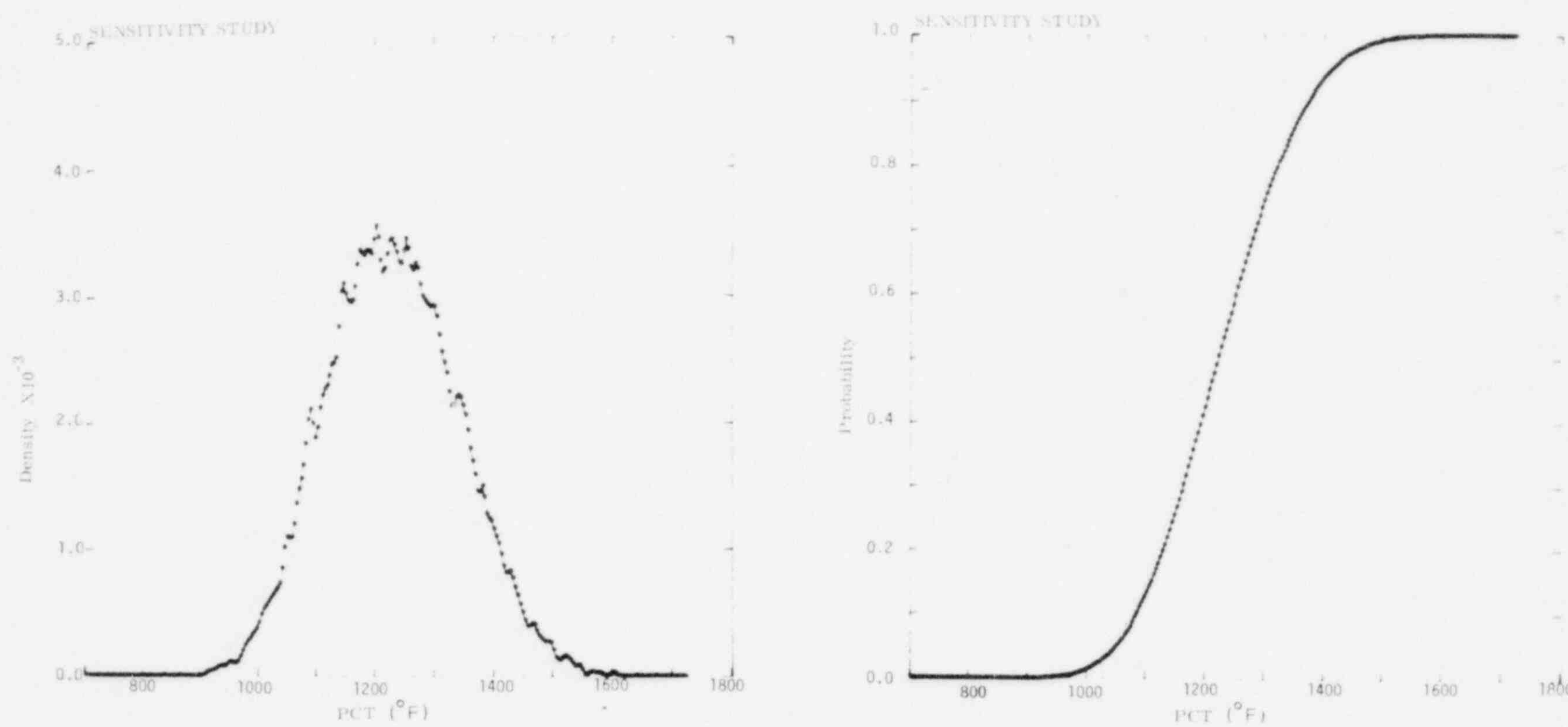


Figure 3-7 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface CA-9 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

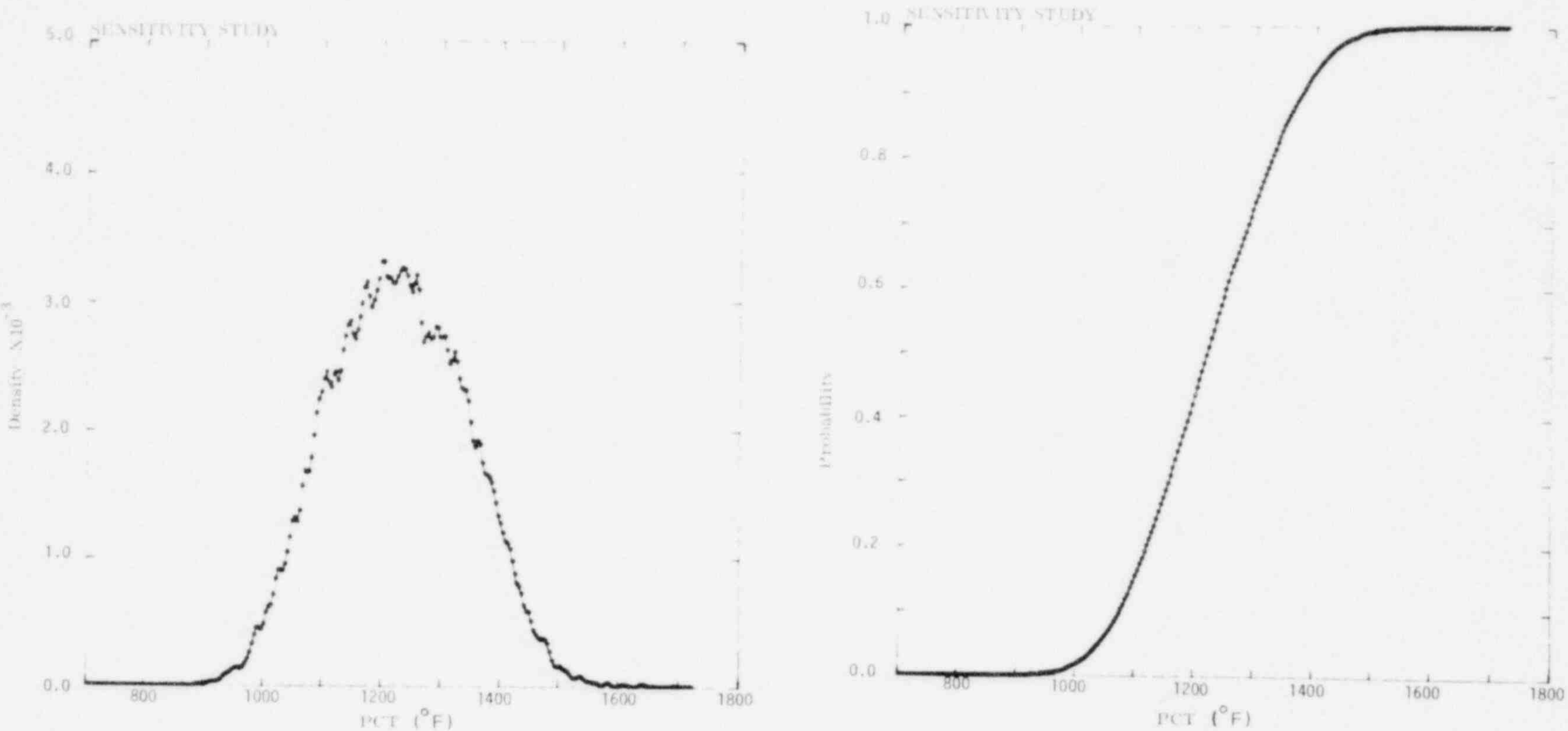


Figure 3-8 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface CA-11 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

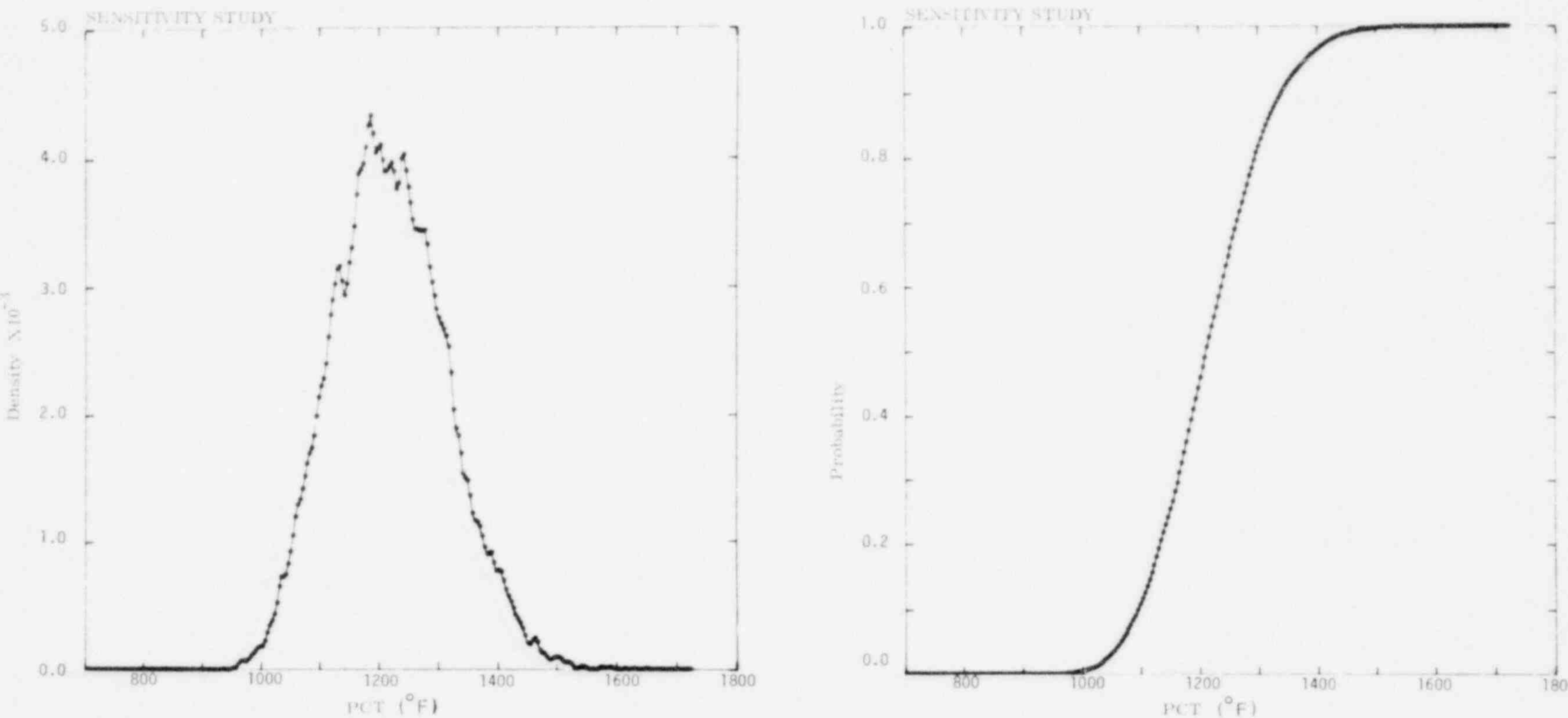


Figure 3-9 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface CY-9 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

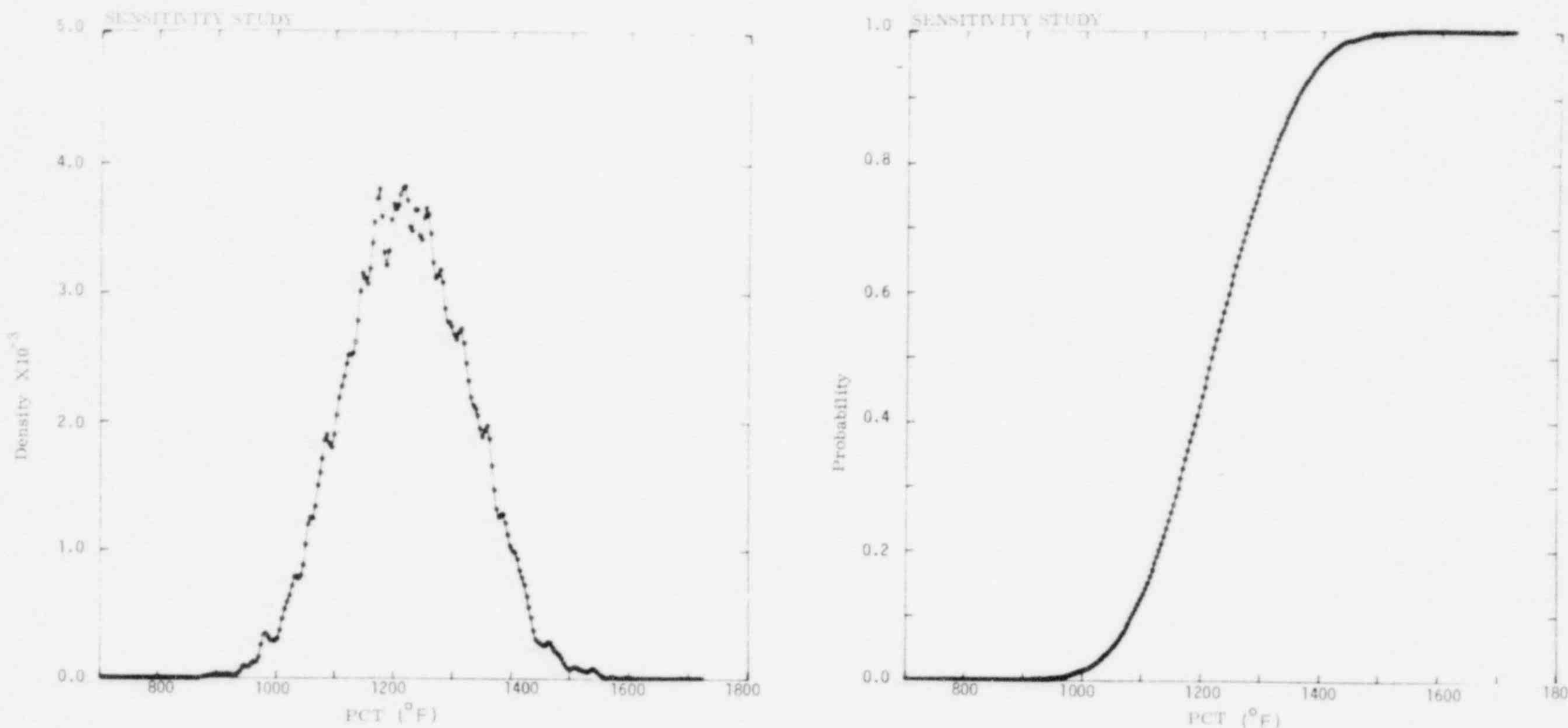


Figure 3-10 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface B8-9 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

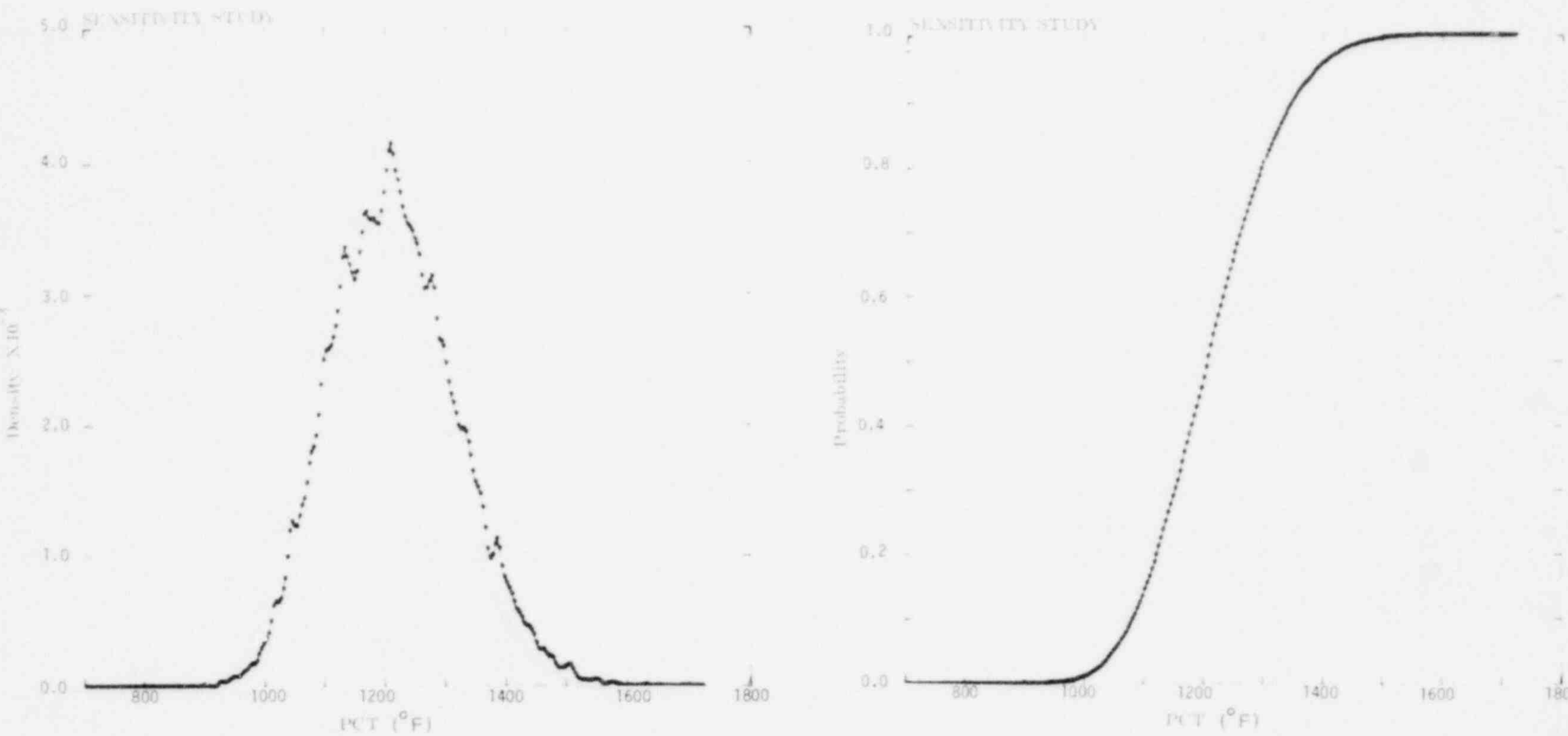


Figure 3-11 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface B8-11 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

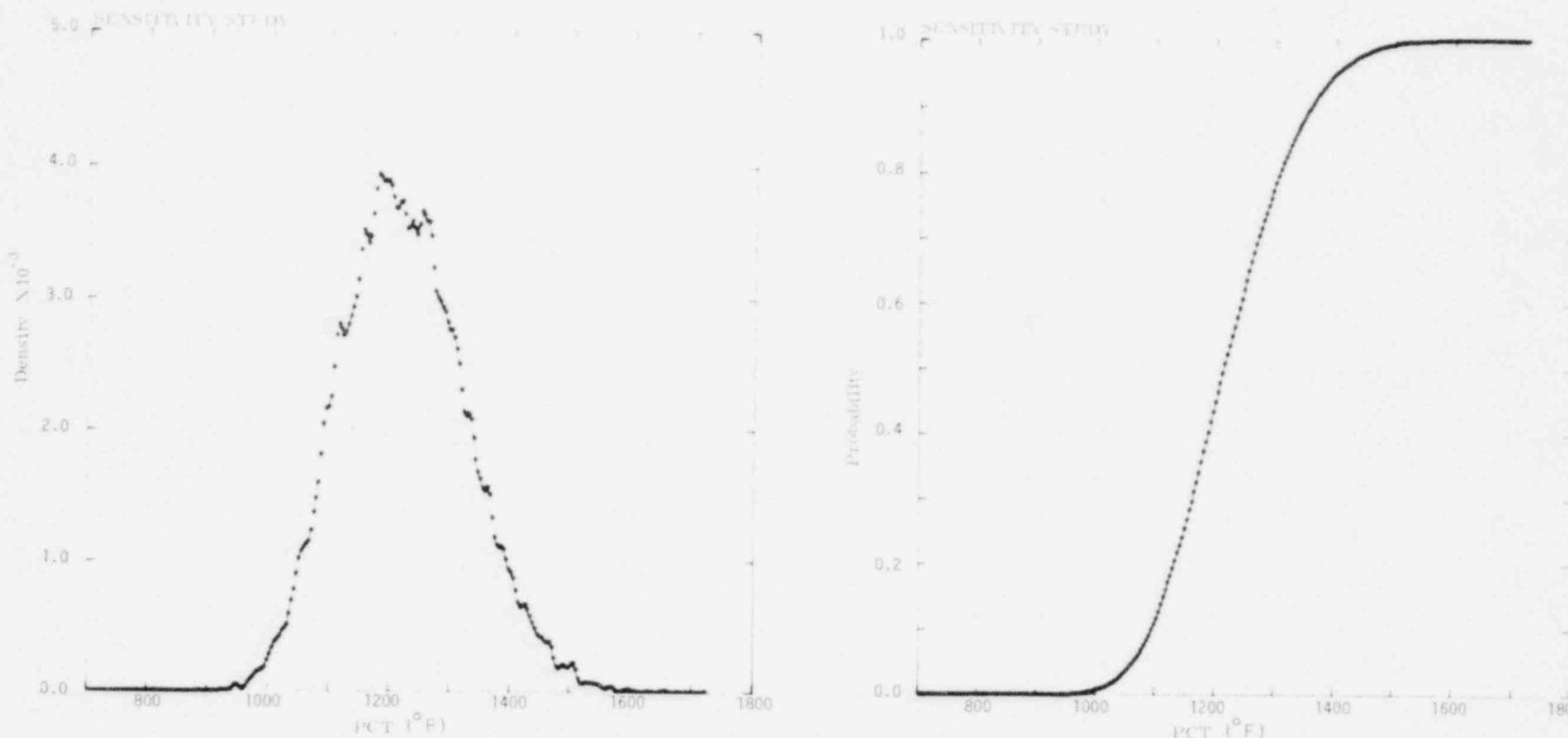


Figure 3-12 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface B8-13 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

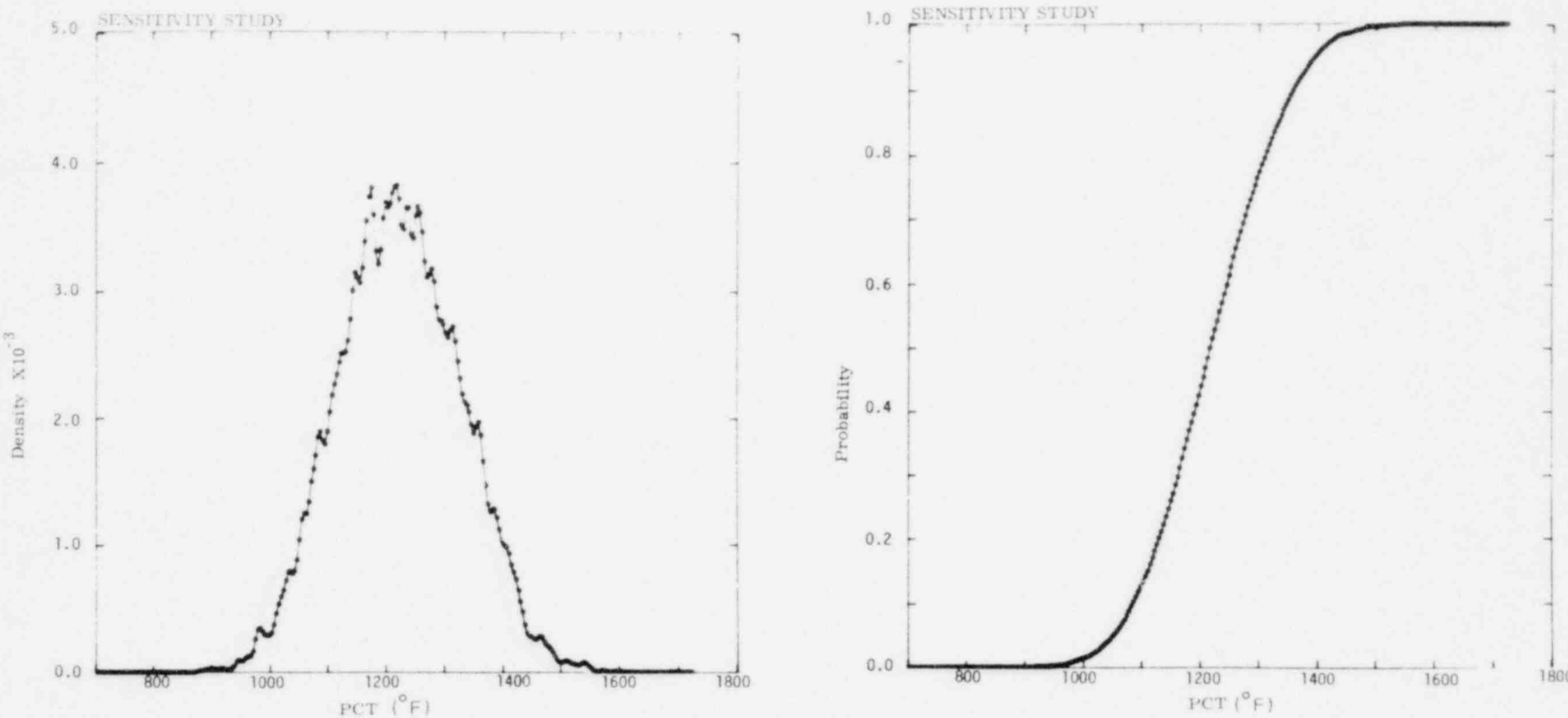


Figure 3-13 Plots of the Estimated Density Function and Estimated Cumulative Distribution Function for PCT Response Surface CX-9 as Determined by 10 000 Samples. (The input distributions all have means equal to nominal and standard deviations equal to 1/6 the range.)

The choice is now among the sizes of the CG models. The choice of CG-11 is a compromise -- a tradeoff between model complexity and model fit. The data justify a model with more than 9 terms but 13 seems excessive. The appearance of the 7 x $\overline{20}$ interaction in the 13-term model might suggest that overfit is occurring. Therefore, the 11-term model is chosen and CG-11 is the recommended model.

The analysis of variance table for model CG-11 produced by the BMDP-2R stepwise regression program is given in Table 3-6. Variables denoted as 3, 4, 6, ..., 20 in this table refer to the corresponding basic variable, and variables denoted as 160, 194, 227, and 234 refer, respectively, to $\overline{18}$ x $\overline{18}$, $\overline{19}$ x $\overline{20}$, $\overline{18}$ x $\overline{18}$ x $\overline{20}$, and $\overline{20}$ x $\overline{20}$ x $\overline{20}$.

TABLE 3-6

Analysis of Variance Table for Model CG-11

Multiple R-Square	.9350
Std Error of Est.	.0481

Analysis of Variance

	Sum of Squares	DF	Mean Square	F Ratio
Regression	4.0629851	11	.3693623	159.669
Residual	.28222228	122	.2313297E-02	

Y-Intercept is 7.18764531

Variable		Coefficient	Std. Error of Coeff	Std. Reg Coeff	F to Remove
X(3)	3	-.2313551045E-01	.00426586	-.1279969555	29.4
X(4)	4	.3041360079E-01	.00423883	.1682628950	51.5
X(6)	6	-.3324204469E-01	.00427816	-.1839112559	60.4
X(12)	12	.2465080924E-01	.00428142	.1363803314	33.2
X(18)	18	.8016991135E-01	.00502234	.4435392116	254.8
X(19)	19	.7163364930E-01	.00428662	.3963123293	279.3
X(20)	20	.9211464234E-01	.00996320	.5096232511	85.5
X(160)	160	-.2243862863E-01	.00398961	-.1530583217	31.6
X(194)	194	-.2810961482E-01	.00383494	-.1725175887	53.7
X(227)	227	.1691352224E-01	.00399222	.1644738395	17.9
X(234)	234	-.1459395380E-01	.00424642	-.1890573102	11.8

4. Prediction Analyses

4.1 Summary

The best PCT model (or response surface) for sensitivity studies is one that predicts new data points best. One more-or-less standard way of "predicting" with a complete data set to which new points cannot be added is to drop the data points one at a time and predict them with models based on the remaining points. By summing the squared prediction errors, one gets what is called a prediction error sum of squares (PRESS) value. This PRESS value is a guide in deciding when to stop adding terms. Often, as terms are added to a model, these PRESS values will decrease as the fit improves and then increase as "overfit" takes over. The minimum PRESS value then dictates an appropriate model size. In our case, however, the PRESS values steadily decreased and the only minimum was the last value computed. They did, however, level off (for large data sets) at a model size of about 10% of the sample size and, in general, we use models of this approximate size.

4.2 Predicting the LHS Dial Sets 1 to 25

When large data sets are available, it is instructive to use one block of data to predict another. Here we discuss the results of using dial sets 0 and 26 through 134 (less dial set 84) to predict the LHS dial sets 1 to 25. The LHS dial sets were chosen as the "predictees" because they were intentionally scattered over the whole input parameter space.

By this sort of prediction it is possible to compare various modelling philosophies. Table 4-1 shows the results when philosophies corresponding to those used in the sensitivity studies are used. The root mean square prediction errors (RMSPE) range from 42°F for the best model to 61°F for the worst.

Table 4-1

Root Mean Square Prediction Errors and Model Size for Which They are Attained 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

*Model Code refers to response surfaces used for the sensitivity studies that have the same model philosophy as listed under the Model Type column.

There are three principal conclusions to be drawn from Table 4-1:

1. The two best models from this prediction point of view are nonstandardized.

2. The root mean square prediction errors are considerably smaller than the residual mean squares for the final models given in Tables 3-3, 3-4, and 3-5.

3. After ignoring the worst model, there is not too much difference among the various philosophies.

A conclusion of lesser import is:

4. For most of the listed models, which are all based on 109 observations, the root mean square prediction error is minimized for a model size of about 10% of the sample size, i.e., 10, 11, or 12 terms.

Conclusion (2) that a model can predict new data better than it "predicts" the data on which it is based, is at first surprising. The reason for it is probably the fact that the 25 LHS dial sets being predicted are points interior to those doing the predicting. The true surface is complex and hard to fit on the edges though an approximating surface can fit well in the center. This same argument may also account for the fact that models based on the first 42 fractional factorial runs predicted the PCTs for 40 LHS dial sets with half the prediction error that was observed when the roles of predictor and predictee were reversed.

Since the input distributions will concentrate the sampled input points even closer to the center of the input space than these 40 LHS dial sets were, and since the final models are based on 134 dial sets rather than 109, we expect an RMS error of sampled PCTs of about 30° to 35°F.

5. Relative Importance of Input Variables to the PCT Response Surface

5.1 Introduction

There are two kinds of sensitivity to be considered. One is the sensitivity of a response surface to the individual basic variables and this sensitivity can be measured by the change in PCT occasioned by some standardized change in a particular variable. This type of sensitivity will be called "relative importance." The other kind is the sensitivity of the PCT distribution to changes in the input distributions. It is discussed in Section 6. In both cases we use the 12 surfaces described earlier in Section 3.

5.2 Quantification of Relative Importance of Input Variables

Before we can describe how relative importance is determined, we need to make a distinction between the usage of additive variables (A) and multiplicative variables (M). Table 5-1 lists type, normalizing coefficients, lower limit, nominal, and upper limit for each variable. It also lists upper and lower standardized changes for each variable. These are described below.

Since it is sometimes the case for additive variables that the upper and lower limits are not equidistant from nominal and for multiplicative variables that the ratio of upper limit to nominal is not the same as the ratio of nominal to lower limit, we define a "standardized change" to an input variable separately above and below nominal.

If X_k is an additive variable, we define

$$X_k^+ = \text{nominal}(X_k) + 1/3[\text{upper limit}(X_k) - \text{nominal}(X_k)]$$

$$X_k^- = \text{nominal}(X_k) - 1/3[\text{nominal}(X_k) - \text{lower limit}(X_k)].$$

Similarly, if X_k is a multiplicative variable, we define

$$X_k^+ = \text{nominal}(X_k) \times [\text{upper limit}(X_k)/\text{nominal}(X_k)]^{1/3}$$

$$X_k^- = \text{nominal}(X_k) \times [\text{nominal}(X_k)/\text{lower limit}(X_k)]^{-1/3}.$$

It is seen that the definitions of $X_k^{\pm}$ for additive and multiplicative variables are similar; in fact, we treat a multiplicative variable as if its logarithm were an additive variable.

We now define standardized changes, $\Delta_k^{\pm}$, above and below nominal for each variable by the formulae:

$$\Delta_k^+ = X_k^+ - \text{nominal } (X_k)$$

$$\Delta_k^- = X_k^- - \text{nominal } (X_k) \quad .$$

We can now define response surface sensitivity to the input variable X_k. First, obtain PCT_{nom} by evaluating the surface with all variables at nominal or midrange. (We consider surfaces for log(PCT) to have been exponentiated.) Then evaluate the surface with all variables at nominal except X_k which is first set equal to X_k^+ (getting PCT_k^+) and second set equal to X_k^- (getting PCT_k^-). The two differences, $PCT_k^{\pm} - PCT_{nom}$, are the sensitivities to X_k above and below nominal. Remember, though, that if a surface is in terms of standardized variables, then the equations $Z(k) = [X(k) - A(k)]/B(k)$ must be used.

Table 5-1

Values of Type, Normalizing Coefficients, Lower Limit, Nominal, Upper Limit and Standardized Changes Above and Below Nominal for Each Input Variable

VAR	TYPE	NORM.* COEFF. A	NORM.* COEFF. B	LOWER LIMIT	NOMINAL OR MIDRANGE	UPPER LIMIT	STANDARD. CHANGE BELOW NOMINAL	STANDARD. CHANGE ABOVE NOMINAL
1	M	.92605	.16897	.700	.9000	1.200	-.07232	.09058
2	A	.20821	.43526	-.250	0.0000	1.000	-.08333	.33333
3	A	.00033	.66234	-1.000	0.0000	1.000	-.33333	.33333
4	M	.98985	.41653	.400	1.0000	1.600	-.26319	.16961
5	M	1.27179	.92282	.300	1.0000	3.000	-.33057	.44225
6	M	1.04941	.41261	.500	1.0000	2.000	-.20630	.25992
7	M	1.00395	.24046	.600	1.0000	1.500	-.15657	.14471
8	M	1.06720	.39985	.500	1.0000	2.000	-.20630	.25992
9	M	1.04544	.35791	.500	1.0000	2.000	-.20630	.25992
10	M	.97420	.40423	.400	1.0000	1.600	-.26319	.16961
12	M	1.00635	.04159	.940	1.0000	1.060	-.02041	.01961
13	A	1.37719	5.07030	-5.000	0.0000	10.000	-1.66667	3.33333
14	A	.00004	.66231	-1.000	0.0000	1.000	-.33333	.33333
15	A	89.97463	33.24230	40.000	90.0000	140.000	-16.66667	16.66667
16	A	643.07840	33.05323	593.200	643.2000	693.200	-16.66667	16.66667
$\overline{18}$	M	1.68059	.26314	1.240	1.7800	2.320	-.20207	.16436
$\overline{19}$	M	1.16475	.31304	.769	1.0000	1.670	-.08383	.18642
$\overline{20}$†	A	.25007	.09994	.029	.2355	.442	-.06883	.06883
21	A	.26120	.39157	-.060	0.0000	1.000	-.12000	.33333

*Note that the normalizing coefficients A(k) and B(k) are used when a surface is based on standardized input variables $Z(k) = [X(k) - A(k)]/B(k)$.

†For variable $\overline{20}$ in ft x 10^{-3}.

Collectively, Tables 5-2(a), (b), and (c) show the separate sensitivities above and below nominal for each of the 12 response surfaces being considered. The numbers given below the variable number are the standardized changes above and below nominal, $\Delta_k^{\pm}$.

Table 5-2a

Relative Importances (°F) of Variables 1 through 6 Above and Below Nominal for Each of Twelve Models*

Model			F_{in}/F_{out}**	PCT_{nom} (°F)	Variable 1 -.072	1 +.091	2 -.083	2 +.333	3 -.333	3 +.333	4 -.263	4 +.170	5 -.331	5 +.442	6 -.206	6 +.260
FE-9	Non Lin	L'	10/8	1275					+12	-12	-25	+16			+24	-30
CY-9	Non Lin(C)	L'	6/6	1277	- 5	+ 6	- 2	+ 8	+10	-10	-28	+18			+19	-23
B3-9	Non Log	L'	10/10	1273					+15	-15	-30	+20	+ 8	-10	+32	-27
C2-9	Non Log(C)	L'	8/8	1259			- 9	+22	+ 9	- 9	-18	+11			+20	-24
B8-9	Std Lin	L"	10/10	1298					+15	-15	-26	+17			+24	-30
B8-11	Std Lin	L"	9/9	1278					+15	-15	-24	+16			+25	-32
B8-13	Std Lin	L"	9/9	1282					+14	-14	-24	+15			+37	-33
CA-9	Std Log	L'	12/12	1304					+14	-14	-26	+17			+24	-30
CA-11	Std Log	L'	12/12	1292					+15	-15	-25	+16			+22	-27
CG-9	Std Log	L"	14/14	1301					+14	-14	-26	+17			+23	-29
CG-11	Std Log	L"	11/11	1290					+15	-15	-25	+16			+22	-27
CG-13	Std Log	L"	9/9	1274					+13	-13	-25	+16			+34	-30

*Nominal for variables 18 and 20 are midranges.

**F_{in}/F_{out} denote, respectively, lower bounds for the maximum and minimum values of the F-statistic for testing the significance of terms in the indicated model.

PCT_{nom} computed using midranges for variables 18 and 20 should be compared with the RELAP value of 1268°F computed under the same conditions.

Table 5-2b

Relative Importances (°F) of Variables 7 through 14 Above and Below Nominal for Each of Twelve Models

Model	Variable 7		8		9		10		12		13		14	
	-.157	+.145	-.206	+.260	-.206	+.260	-.263	+.170	-.020	+.020	-1.67	+3.33	-.333	+.333
FE-9 Non Lin L'			-10	+12			*	*	-12	+12			- 8	+ 8
CY-9 Non Lin(C) L'			- 9	+11	*	*	*	*	-13	+12				
B3-9 Non Log L'									-14	+14				
C2-9 Non Log(C) L'			-14	+18			*	*	-11	+11				
B8-9 Std Lin L"			- 5	+ 6			*	*	-15	+14				
B8-11 Std Lin L"			- 5	+ 6			*	*	-15	+15			-10	+10
B8-13 Std Lin L"			- 5	+ 6			*	*	-13	+13			-17	+ 2
CA-9 Std Log L'									- 2	+ 2				
CA-11 Std Log L'									- 3	+ 3				
CG-9 Std Log L"									-15	+15				
CG-11 Std Log L"									-16	+15				
CG-13 Std Log L"	- 2	+ 1							-15	+15				

*Indicates a sensitivity less than 0.5.

Table 5-2c

Relative Importances (°F) of Variables 15 through 21 Above and Below Nominal for Each of Twelve Models

Model	Variable 15		Variable 16		Variable 18		Variable 19		Variable 20		Variable 21	
	-16.7	+16.7	-16.7	+16.7	-.202	+.164	-.083	+.186	-.069	.069	-.020	+.333
FE-9 Non Lin L'			*	*	-82	+66	-26	+57	-55	73		
CY-9 Non Lin(C) L'	*	*			-72	+58	-26	+57	-69	+ 69		
B3-9 Non Log L'					-73	+62	-29	+61	-78	+ 83		
C2-9 Non Log(C) L'	*	*	-10	+10	-60	+51	-24	+56	-69	+ 73		
B8-9 Std Lin L"					-83	+67	-25	+55	-65	+ 65		
B8-11 Std Lin L"					-81	+66	-25	+55	-56	+ 74		
B8-13 Std Lin L"					-76	+62	-25	+55	-50	+ 74		
CA-9 Std Log L'					-85	+57	-26	+59	-79	+ 85		
CA-11 Std Log L'					-77	+39	-28	+62	-85	+100		
CG-9 Std Log L"					-85	+54	-25	+57	-79	+ 84		
CG-11 Std Log L"					-77	+37	-26	+59	-83	+ 98		
CG-13 Std Log L"					-74	+35	-25	+58	-80	+ 95		

*Indicates a sensivity less than 0.5.

To illustrate the construction of Table 5-2, suppose a surface is entirely linear and given by

$$PCT = \sum_{r} b_r X_r \quad .$$

Then,

$$PCT_{nom} = \sum_{r} b_r \cdot \text{nominal}(X_r)$$

and, for example,

$$PCT_k^+ = \sum_{r,r\neq k} b_r \cdot \text{nominal}(X_r) + b_k X_k^+ \ ,$$

so that

$$\Delta PCT_k^+ \equiv PCT_k^+ - PCT_{nom}$$

$$= b_k[X_k^+ - \text{nominal}(X_k)]$$

$$= b_k \Delta_k^+ \quad .$$

If the surface is expressed in terms of normalized variables the only difference in the above example is that the last formula becomes

$$\Delta PCT_k^+ = b_k \Delta_k^+ / B_k \ ,$$

where B_k is the normalizing coefficient for X_k from Table 5-1.

Matters become a little more complicated for nonlinear surfaces but the determined reader can unravel the algebra. The result is, for example, that for each cross-product term, $b_{ik}X_iX_k(i\neq k)$, in the response surface equation one adds

$$b_{ik} \cdot \text{nominal}(X_i) \cdot \Delta_k^+$$

or

$$b_{ik} \cdot [\{\text{nominal}(X_i) - A_i\}/B_i] \cdot (\Delta_k^+/B_k) \quad ,$$

to

$$b_k \Delta_k^+ \text{ or } b_k \Delta_k^+/B_k$$

as the case may be.

Table 5-3 summarizes the information in Table 5-2 for the seven most important variables as determined by response surface model CG-11. The data are presented first in terms of °F change in PCT for a standardized change Δ (i.e., °F/σ) as in Table 5-2, then with Δ converted to a percentage in the last two columns. The central columns labelled °F/1% were computed by substitution directly into the CG-11 response surface equation at 0.99 and 1.01 times nominal.

Table 5-3

Relative Importance of Input Variables to PCT Surface for CG-11 Model

	°F/σ		°F/1%		°F/1% Based on Δ	
Variable	at X^-	at X^+	at 0.99 N	at 1.01 N	for Δ^-	for 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 (-101)**	3.4 (118)**

Δ ≡ Standardized Change

N ≡ Midrange

*a + 1σ change of slip yields a 67% change in DV

a - 1σ change of slip yields a 33% change in DV

**°F/mil

5.3 Discussion of Results

Referring to Table 5-2, there are seven variables which appear in all 12 models. Furthermore, despite the gross differences in the points of view under which the models were constructed, there is remarkable agreement on the magnitude of the sensitivities. In terms of relative importance, the seven variables can be divided into three separate groups. The most important variables are $\overline{20}$, $\overline{18}$ and $\overline{19}$; i.e., gap width, total peaking factor, and UO_2 thermal conductivity, in roughly that order. These fuel-related parameters clearly dominated the response surfaces. The next most important were 6 and 4, the Condie-Bengston film boiling heat transfer coefficient multiplier and the two-phase friction and form loss multiplier. The response surfaces were roughly 1/2 to 1/3 as sensitive to these variables as to those in the first group, $\overline{20}$, $\overline{18}$, and $\overline{19}$. The final pair of variables are 3 and 12, the slip correlation multiplier and the power level. These parameters are only about half as important as those in the second group. Since all points of view in model building led to the same important seven variables, we are confident that the sensitivities are really in the data and are not by-products of a particular modelling philosophy. Also, since roughly 140 calculations were required to distinguish seven variables, we might propose a rule of thumb from this study; namely, that about 20 calculations are required for each important variable. It is also possible that $2(n + 1)^2$ calculations might represent the minimum sample size for n important variables, if no subset of n (e.g., $n \sim 1$) is considered.

5.3.1 The Seven Most Important Variables

In physical terms, PCT is a function of the power generated within the fuel, its transport from the fuel to the cladding, and the rate at which heat is lost from the clad to the fluid. Total peaking factor, power level, and fission product decay determine heat production. In this study, the fact that peaking factor was more important than power level is probably due to the much larger range assigned to it. PKTOT varies from 24 to 132% above core average power, while a $\pm 3\sigma$ range for power level is $\pm 6\%$. If we consider the fact that PKTOT varies approximately $\pm 30\%$ about its midrange, we could postulate that PKTOT would b~, at most, five times as important as power level. This assumption is clearly supported by the data in Table 5-2. Decay heat was not an important variable for blowdown. It must be retained for future TRAC studies, however, since its importance to reflood PCT is expected to be significant.

Resistance to the flow of heat from the fuel to the clad is proportional to the reciprocal of UO_2 thermal conductivity and to the gap width (or reciprocal of gap conductance). The influence of these variables, however, is derived from their effect on initial fuel stored energy, not on transport rates during the transient. Figures 5-1 and 5-3 illustrate the differences in total energy stored in the core for the full 6σ range on gap width and UO_2 thermal conductivity, respectively. The difference in stored energy at the start of the transient is maintained almost unchanged throughout the blowdown. Peak clad temperatures mirror these stored energy differences, as shown in Figures 5-2 and 5-4. Total peaking factor affects only the power in the hot channel, and therefore has a negligible effect on total stored energy (Figure 5-5). The difference in PCT (Figure 5-6) is due to the difference in stored energy in the hot assembly only.

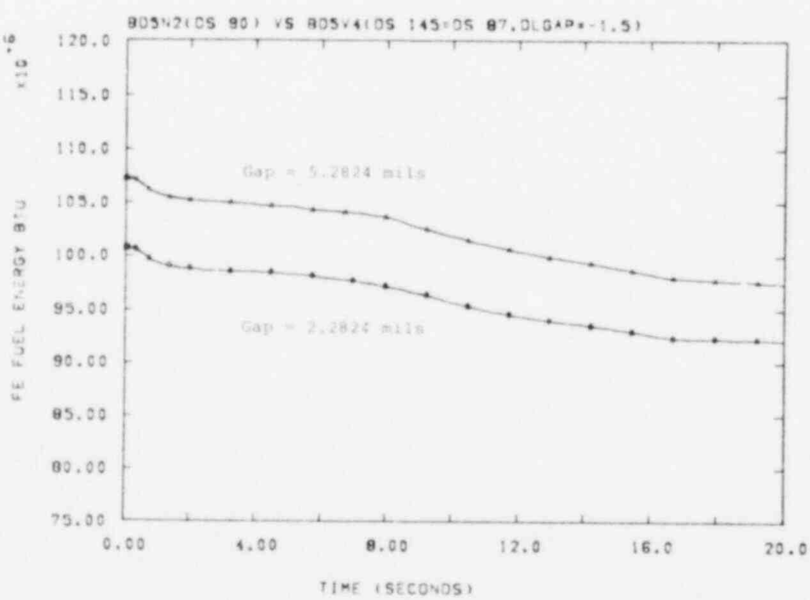


Figure 5-1 Effect of Gap Width on Total Stored Energy

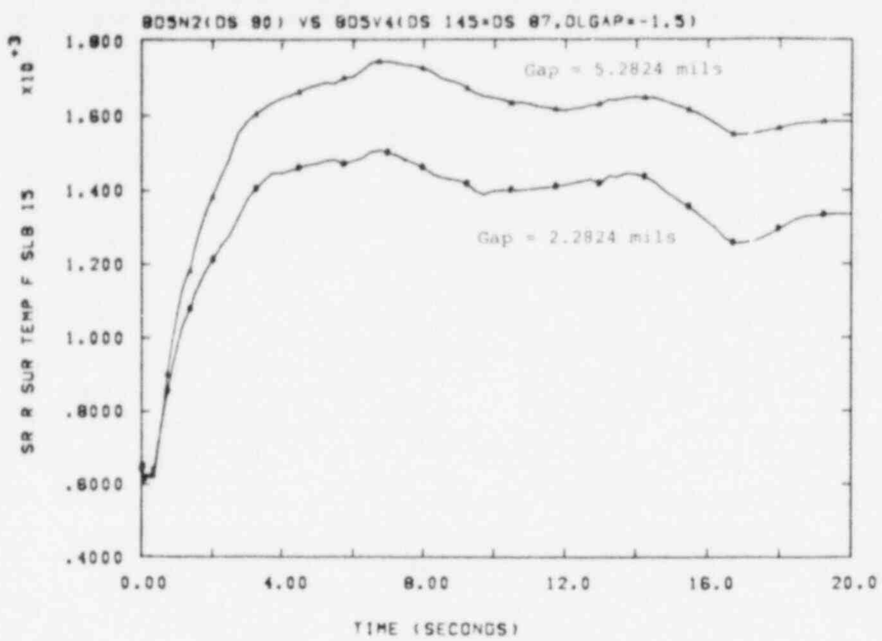


Figure 5-2 Effect of Gap Width on PCT

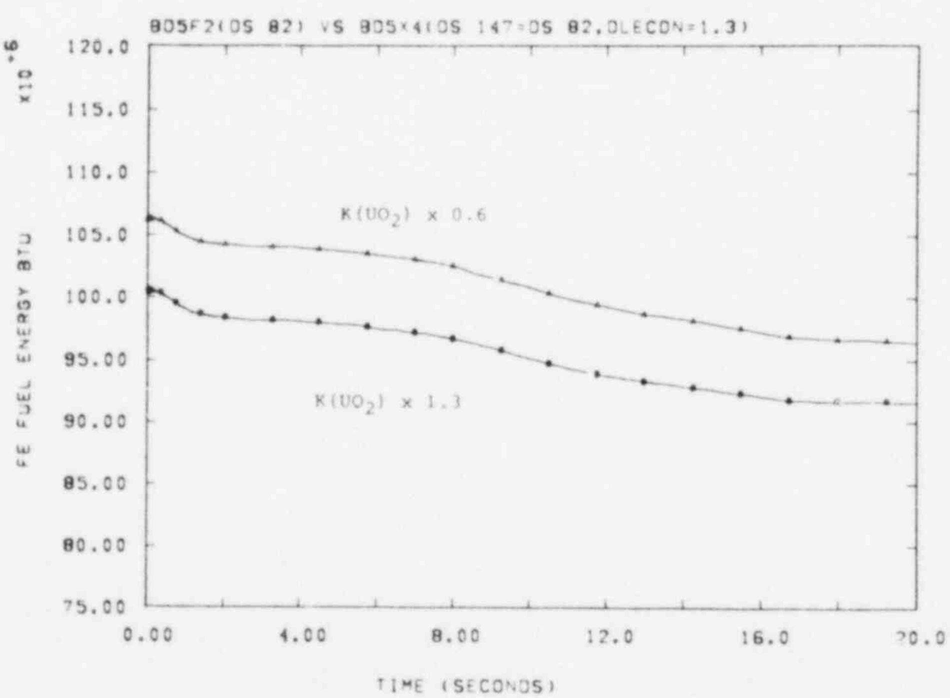


Figure 5-3 Effect of UO_2 Thermal Conductivity on Total Stored Energy

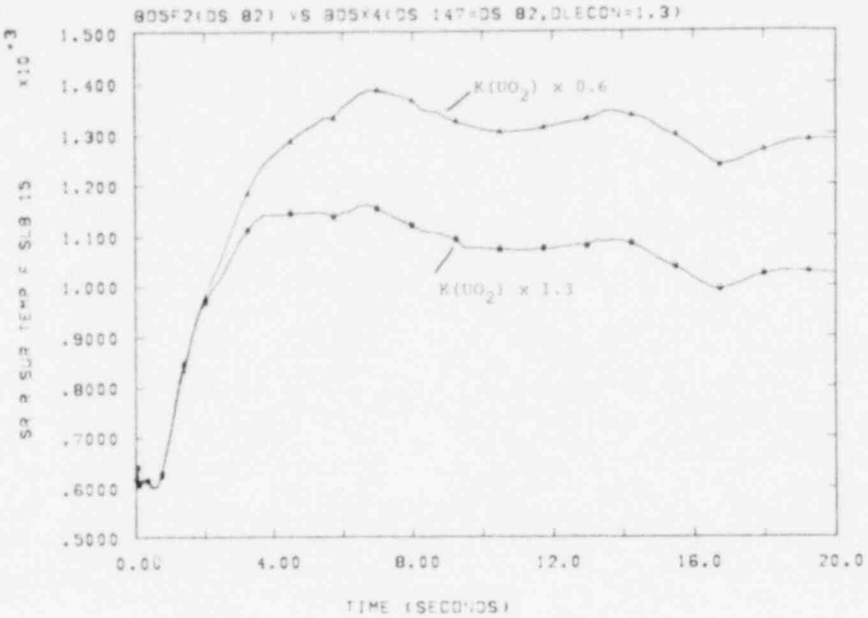


Figure 5-4 Effect of UO_2 Thermal Conductivity on PCT

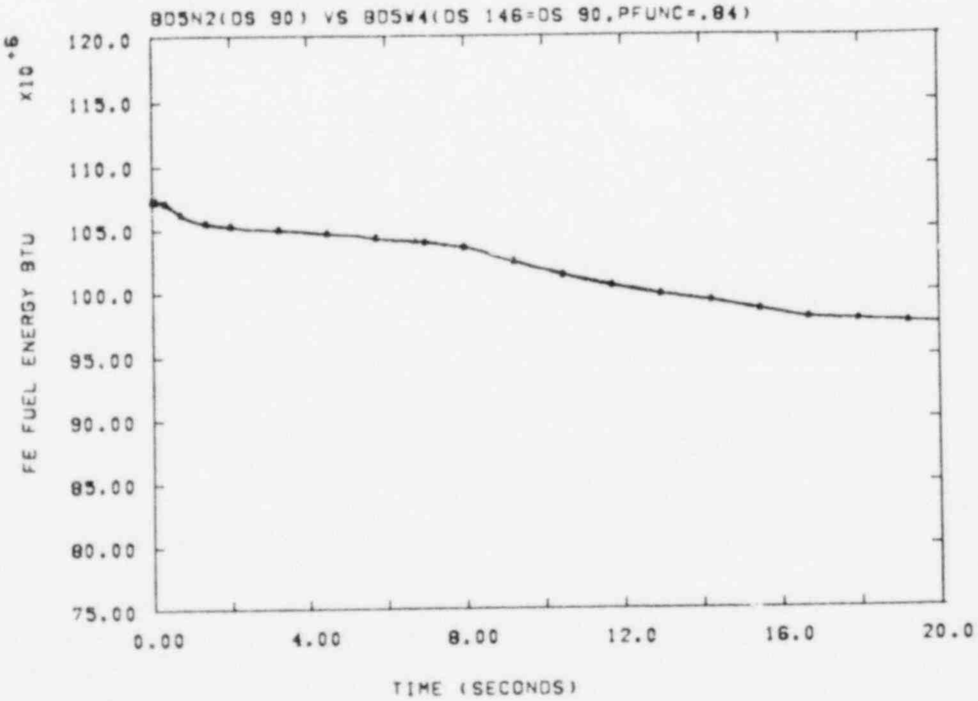


Figure 5-5 Effect of Total Peaking Factor
on Total Stored Energy

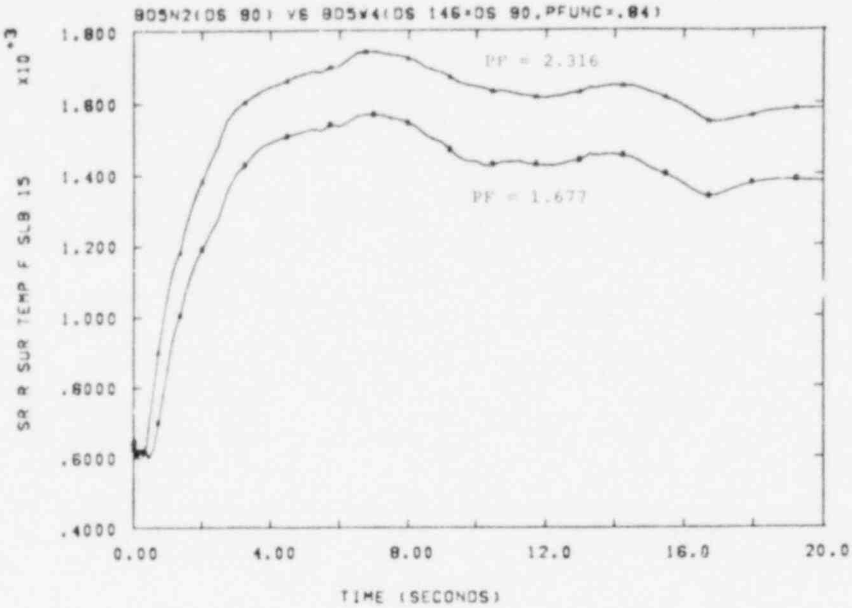


Figure 5-6 Effect of Total Peaking Factor on PCT

The rate at which heat is removed from the clad is determined by the heat transfer coefficient, h, and the difference between the wall and fluid temperatures, ΔT:

$$q = h\Delta T ,$$

where h can be a function of mass flux, quality, pressure, thermal conductivity, specific heat, viscosity, surface tension, density, temperature, emissivity, or geometry. In this study, only the Condie-Bengston high flow film boiling heat transfer mode appears to have had a significant effect on PCT. Free convection and radiation (Mode 7), reverse forced convection to vapor (Mode 8), and low flow, low void fraction heat transfer (Mode 9) played much smaller roles during blowdown. (Note, however, that reverse Dittus-Boelter (Mode 8) did appear in 6 of the 12 models in Table 5-2. Additional calculations might demonstrate that it could be the eighth most important variable.)

The effects of film boiling heat transfer on core stored energy and clad temperature are illustrated in Figures 5-7 and 5-8, respectively.

Obviously, the more efficiently heat is removed, the more quickly does the stored energy decrease. Figure 5-7 demonstrates that the difference continues to increase, even at 30 s after the break. This might result in a significant effect of blowdown heat transfer on the ultimate clad temperatures during reflood. (While the difference in peak clad temperature is 75°F, as shown in Figure 5-8, the separation has grown to 185°F by 20 s.)

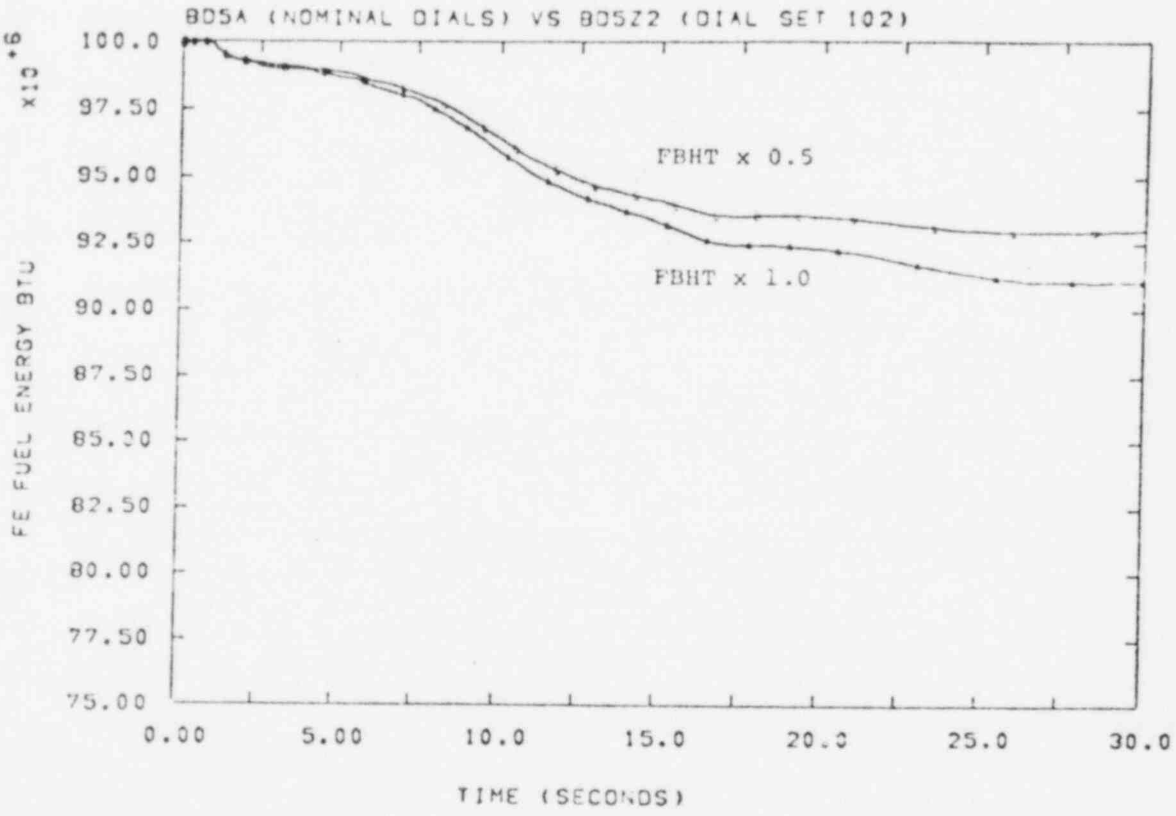


Figure 5-7 Effect of C-B Film Boiling HT Coefficient Multiplier on Total Stored Energy

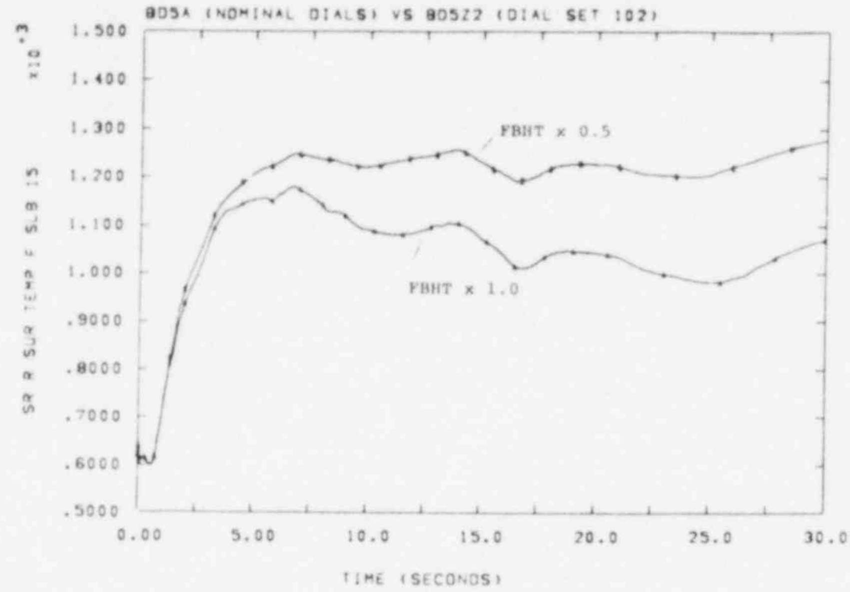


Figure 5-8 Effect of C-B Film Boiling HT Coefficient Multiplier on PCT

Since clad temperature is completely governed by the difference between heat added and removed from the zircalloy, the hydraulic variables cannot directly affect PCT. They must act indirectly, with some heat transfer coefficient, h, employed as an intermediary. Consequently, the effects of hydraulic conditions on PCT are extremely complex and difficult to assess. In the statistical study, interactions are permitted; i.e., cross-product terms combining a hydraulic variable with a heat transfer variable can occur in the polynomial representation of the PCT response surface. The two hydraulic variables shown to be important in this study were two-phase friction (4) and slip (3). Referring to Table 3-3, we do note occasional synergistic effects such as 4 x 5, 4 x 8, and 3 x 9. No statistical significance, however, should be ascribed to these occasional combinations, since variables 3 and 4 are often coupled to wholly unrelated ones in a nonphysical way (e.g., 3 x 16, 4 x $\overline{18}$). Variables 3 and 4 demonstrate behavior similar to that of an enhanced or degraded heat transfer coefficient during the early phase of blowdown. Figures 5-9 and 5-11 show a faster decrease in core stored energy as two-phase friction decreases or slip increases. This effect reaches a maximum, however, and does not continue to grow as it did for film boiling heat transfer. Slip and friction would then be less important during reflood. Clad temperatures in the same two situations are shown in Figures 5-10 and 5-12. A straightforward attempt to correlate these two-phase variables with core flow, and then core flow with heat transfer is not fruitful. Figure 5-13 shows that core flow was nearly identical for the two extreme friction cases for the first 6 s of the transient. From about 6 to 13 s, more friction led to slightly reduced core upflow, which appears to have coincided with higher slab temperatures. During this same time frame, however, increased slip yielded negative core flow to about 7 s and random flows thereafter (Figure 5-14). These flows are essentially uncorrelated with the temperature behavior in Figure 5-12; the earlier figure indicates that larger slip produced a lower temperature very early in the transient, which persevered throughout the blowdown. Temperatures in the two-phase friction comparison, Figure 5-10, were nearly identical for the first 3 s and then followed erratic paths through the remainder of the blowdown.

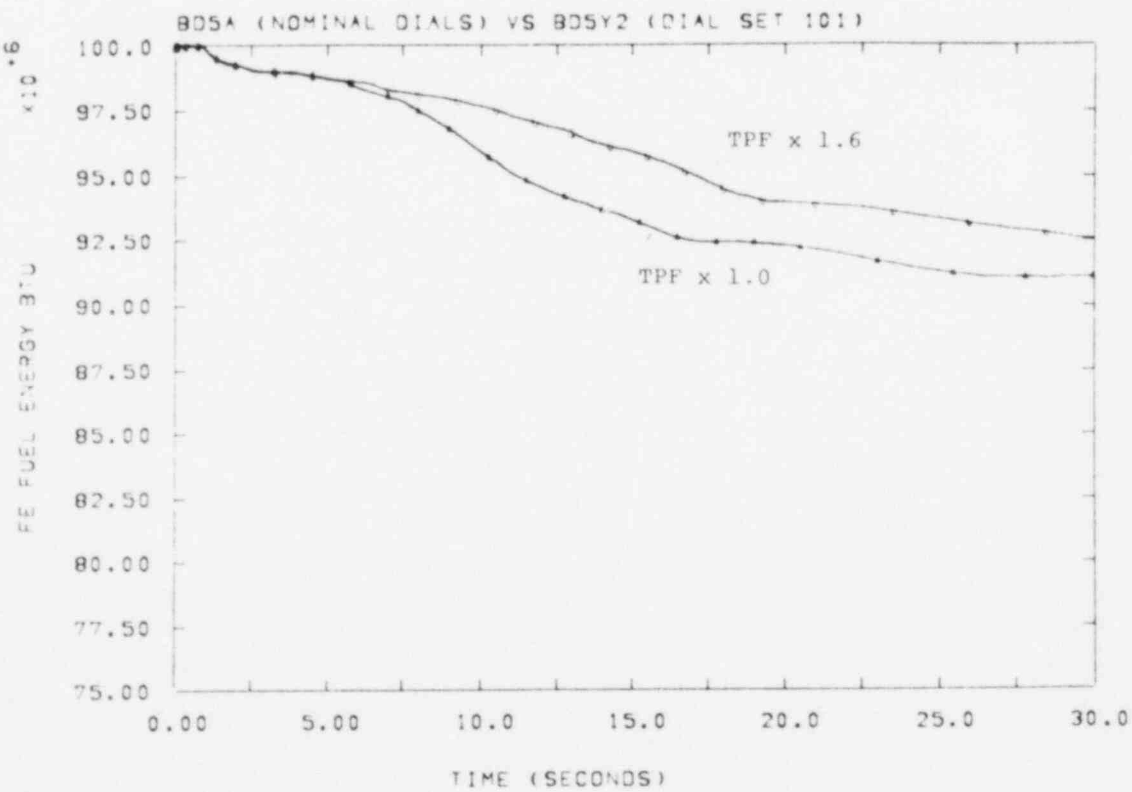


Figure 5-9 Effect of Two-Phase Friction Multiplier on Total Stored Energy

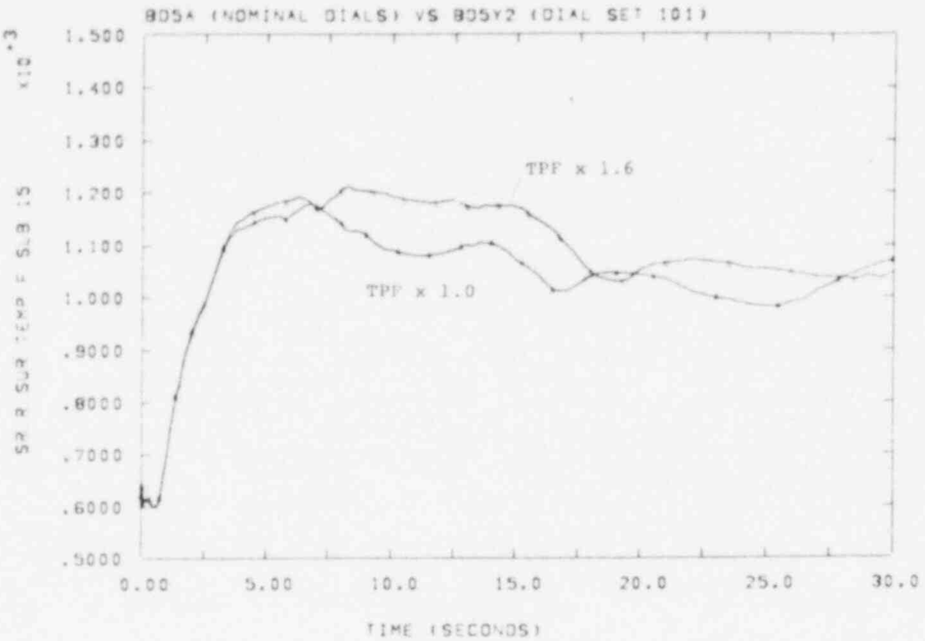


Figure 5-10 Effect of Two-Phase Friction Multiplier on PCT

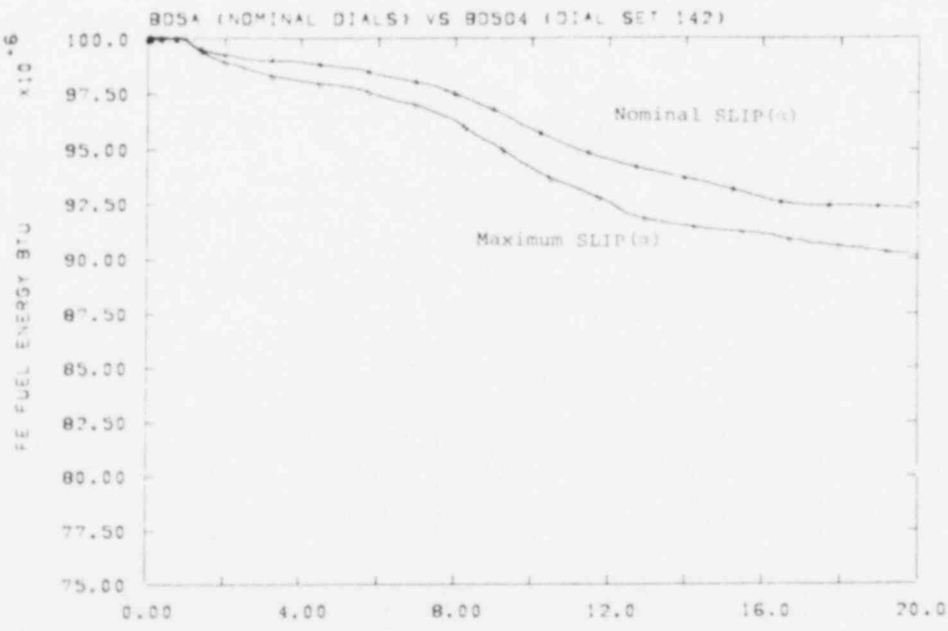


Figure 5-11 Effect of Slip Multiplier on Total Stored Energy

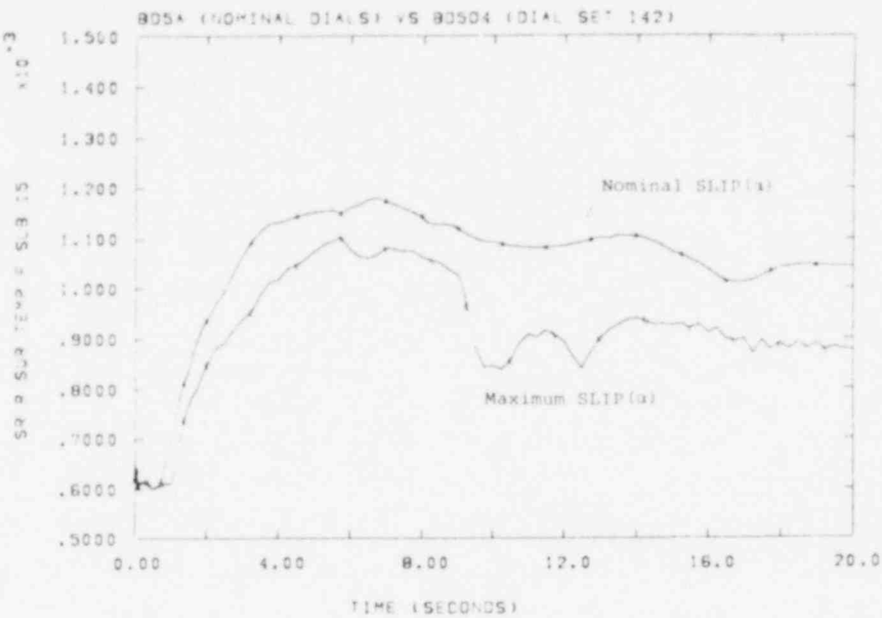


Figure 5-12 Effect of Slip Multiplier on PCT

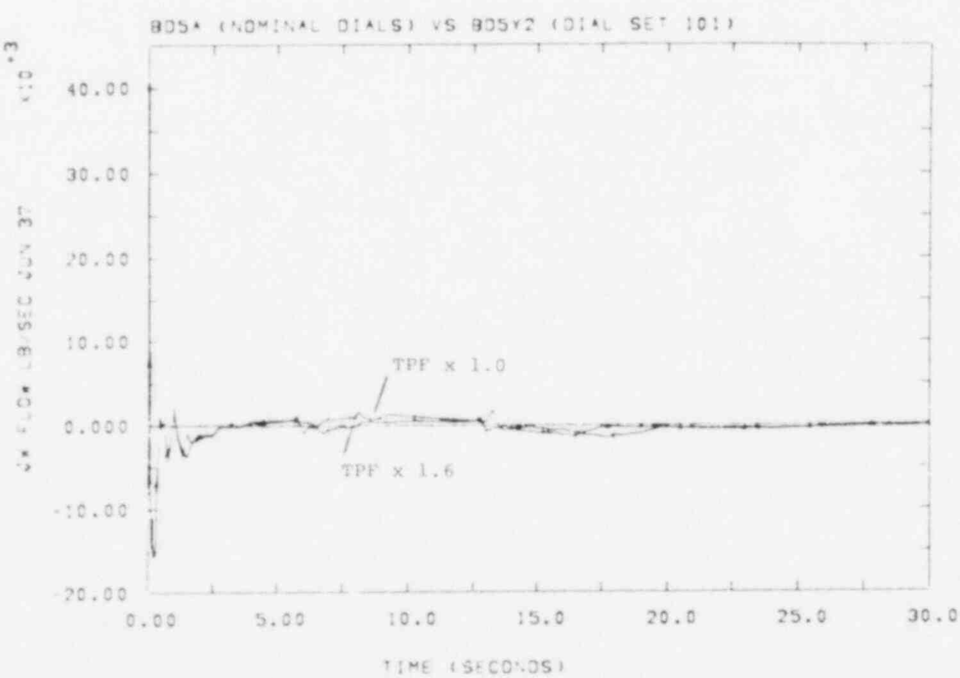


Figure 5-13 Effect of Two-Phase Friction Multiplier on Core Flow

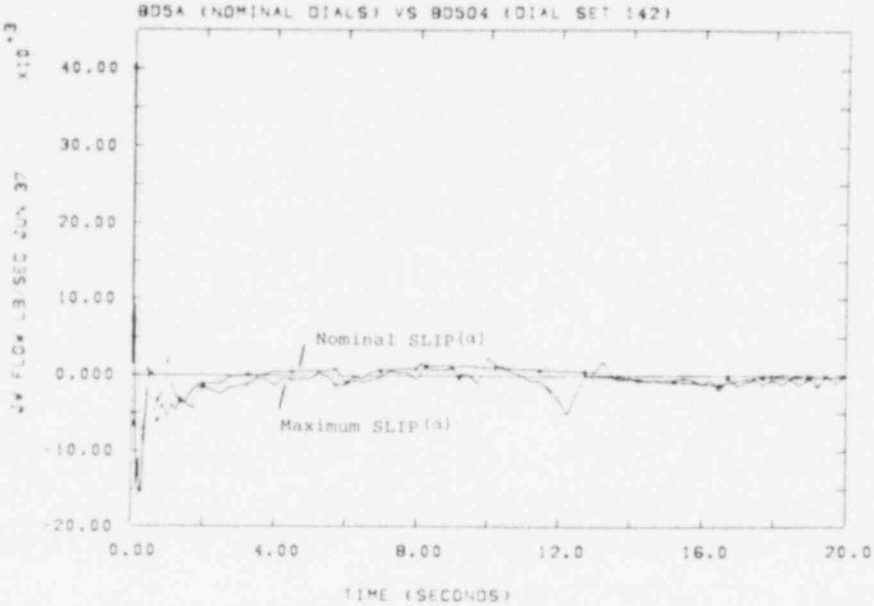


Figure 5-14 Effect of Slip Multiplier on Core Flow

This study has demonstrated that, of the hydraulic variables considered, the most important dealt with two-phase flow, namely friction and slip. To more precisely elucidate the physical connection between these variables and the heat transfer coefficients which directly influence PCT would require significantly more runs and a deeper analysis than the superficial discussion presented here.

5.3.2 Variables of Lesser Importance

In conjunction with the statistical program, several calculations were performed in which only one variable at a time was changed. Several of these "star points" are listed in Table 5-4. In some cases, there are two entries for a variable. These were attempts to investigate the variable behavior both above and below nominal, or at medium and high temperatures. Note the excellent agreement in both rank and estimates of absolute sensitivity between the first seven entries in the table and the conclusions of the entire statistical study. The last four entries, however, did not appear to be important. They will be discussed here in terms of the star point results.

Table 5-4

Selected "Star Point" Sensitivities

Variable	$T_{hi}-T_{lo}$ (°F)	Sensitivity °F/σ*	Sensitivity °F/%**
$\overline{20}$ - Gap width	1747-1618	71 (86)†	3.3 or 4.5
	1618-1514	57 (69)†	1.6 or 2.6
$\overline{18}$ - Total peaking factor	1747-1578	48	4.4 or 6.1
	1271-1183	63	5.5 or 6.4
$\overline{19}$ - 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
	1170-1183	- 4	-.07 or -.2
14 - Two-phase pump head multiplier	1215-1183	11	?
1 - Subcooled discharge coefficient	1196-1183	4	.4 or .5
	1183-1104	26	2.8 or 3.6
2 - Saturated discharge coefficient	1183-1184	-.3	.03 or .04≠
	1195-1183	4	?

*σ ≡ 1/6 * total range

**% based on high and low values of variable

†°F/mil

≠A change from 0 to 1 on the slip dial is a change from 1 to 3 on the slip multiplier. Similarly, saturated discharge goes from 0.75 to 1.

The two-phase pump head multiplier seemed to be almost as important as the other two-phase variables (3 and 4) already discussed. Indeed, as shown in Figures 5-15 and 5-16, its effect on fuel energy and clad temperature was very similar to that observed for slip and friction, i.e., gradual, enhanced core cooling with increasing pump head two-phase degradation, the effect being confined to blowdown, and diminishing as reflood time is approached.

Before the study was performed, an educated nuclear engineer might have guessed that critical heat flux (CHF) and critical flow would be important parameters. Figure 5-17 shows that CHF had a very small effect on total stored energy. CHF, as would be expected, influenced clad temperature very early in the transient, as shown in Figure 5-18. Its effect on PCT, however, was not large, and fuel temperature at the start of reflood would be barely affected by CHF.

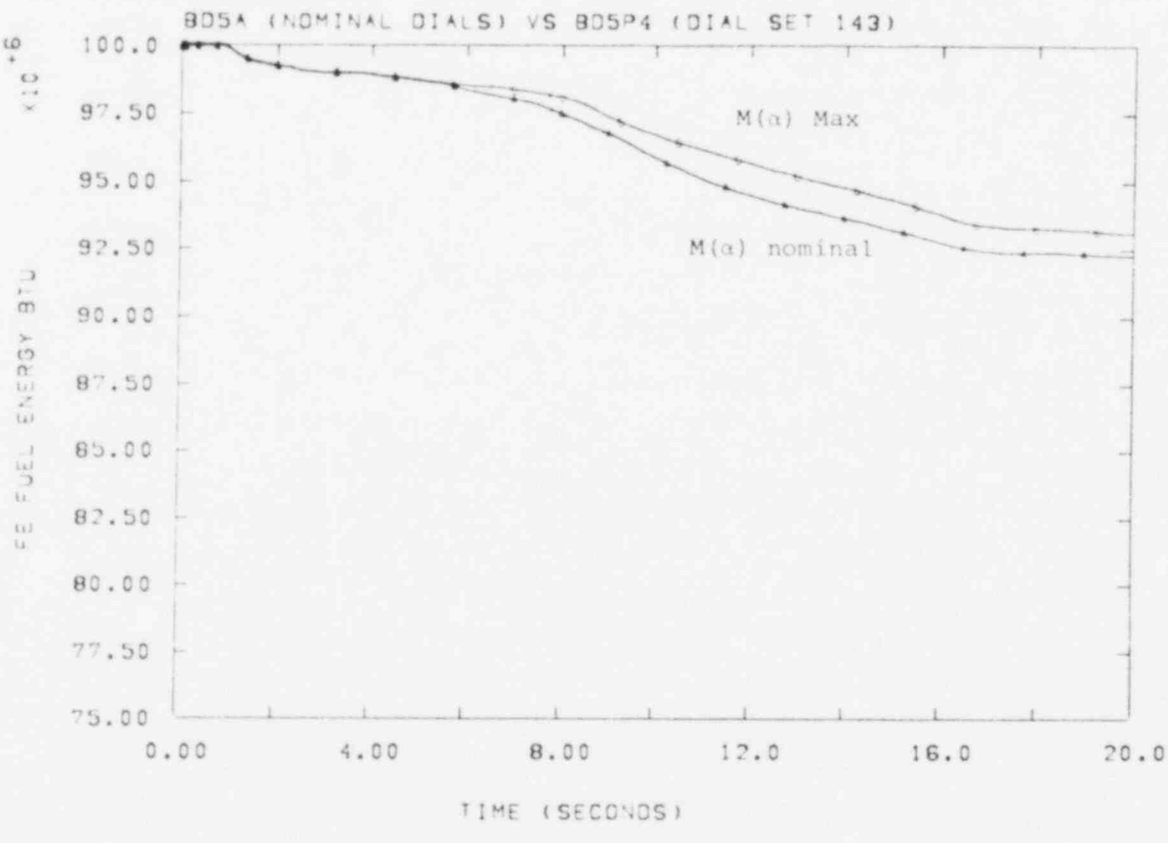


Figure 5-15 Effect of Two-Phase Pump Head Multiplier on Total Stored Energy

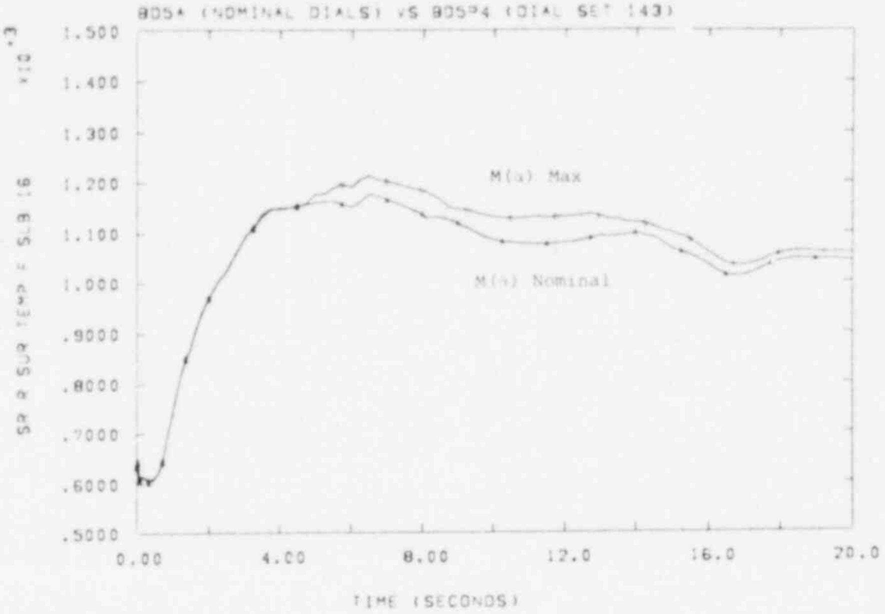


Figure 5-16 Effect of Two-Phase Pump Head Multiplier on PCT

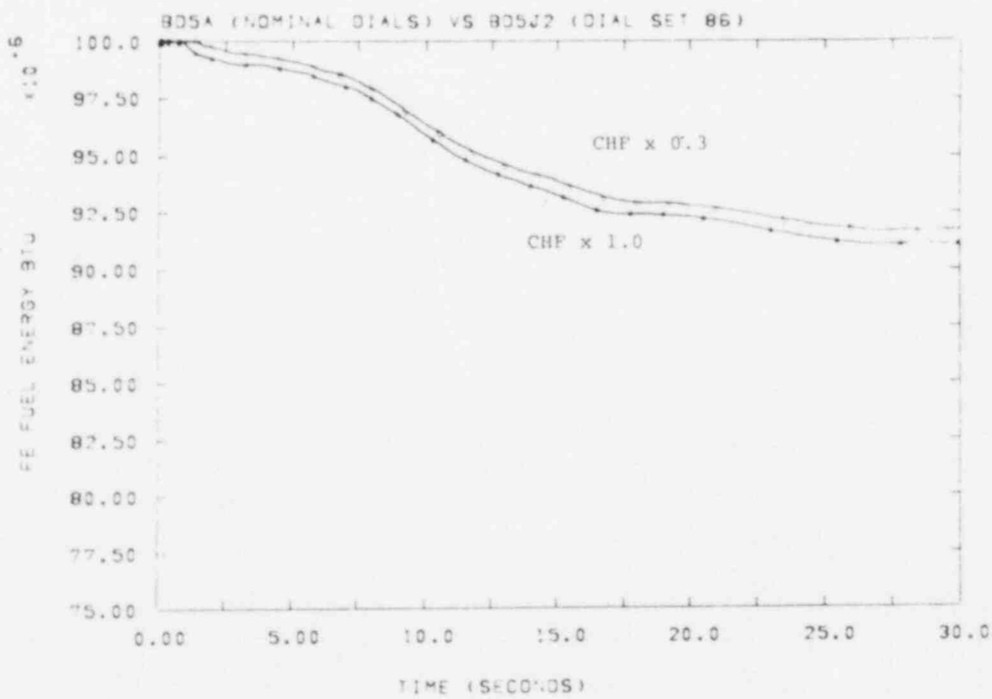


Figure 5-17 Effect of CHF Multiplier on Total Stored Energy

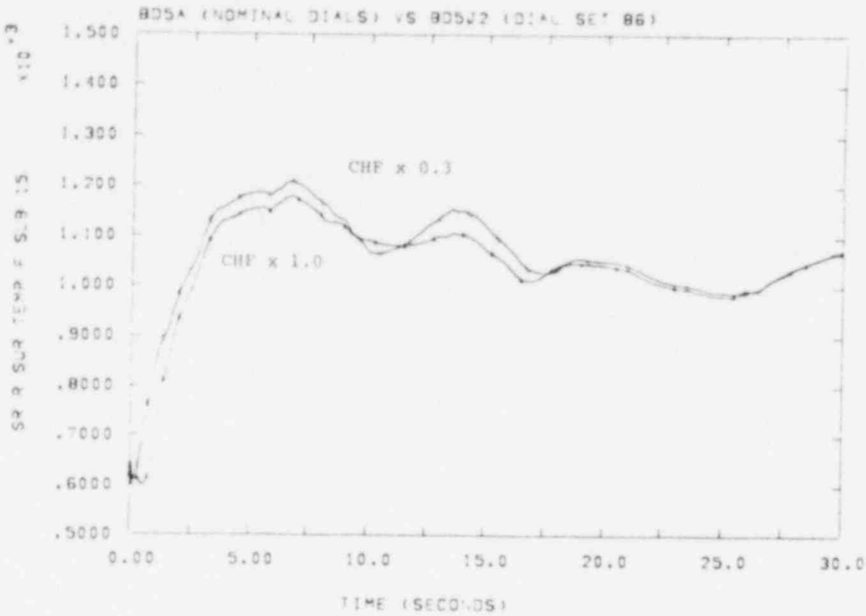


Figure 5-18 Effect of CHF Multiplier on PCT

The subcooled discharge coefficient, C_D, controls the vessel side of the blowdown during the early part of the transient. (The pump side of the break reaches saturation very early and critical flow is controlled by the saturated C_D.) Core flow is strongly influenced by C_D, but in a complex way. At some time and at some core elevation, flow will stagnate, producing DNB conditions, a decrease in heat transfer and an increase in clad temperature. Where and when the stagnation occurs is of fundamental importance to PCT, and the magnitude of C_D is, therefore, not linearly proportional to the magnitude of PCT. Star-point calculations were performed for C_D 3σ above (C_D = 1.2) and 3σ below (C_D = 0.7) the nominal value of 0.9. Table 5-4 indicates that PCT was more than six times as sensitive to C_D below nominal (26°F/σ) than above (4°F/σ). This was true in spite of the additional fact that the range above nominal was 50% larger than the range below. Figures 5-19 through 5-24 illustrate the effects of high C_D on fuel stored energy, PCT, vessel- and pump-side break flows, and bottom- and midplane-core flows. Figures 5-25 and 5-26 show the much larger effects on core stored energy and clad temperature observed for below nominal C_D. If these star-point observations were true for the whole data set, we should expect to see the relative importance of C_D increase as we eliminate the higher temperature cases. Indeed, when we sampled only those temperatures below 1100°F, the cross-product term, 1 x 5, was second in importance; for cases below 1200°F, the second most important term was 1 x $\overline{18}$. For higher temperature cutoffs, variable 1 no longer appeared. These results are inconclusive, however, because they appeared to be model-dependent. Furthermore, the two lower temperature sample sets contained only 23 and 45 calculations, respectively.* We have found it very risky to place much reliance on such small sample sizes.

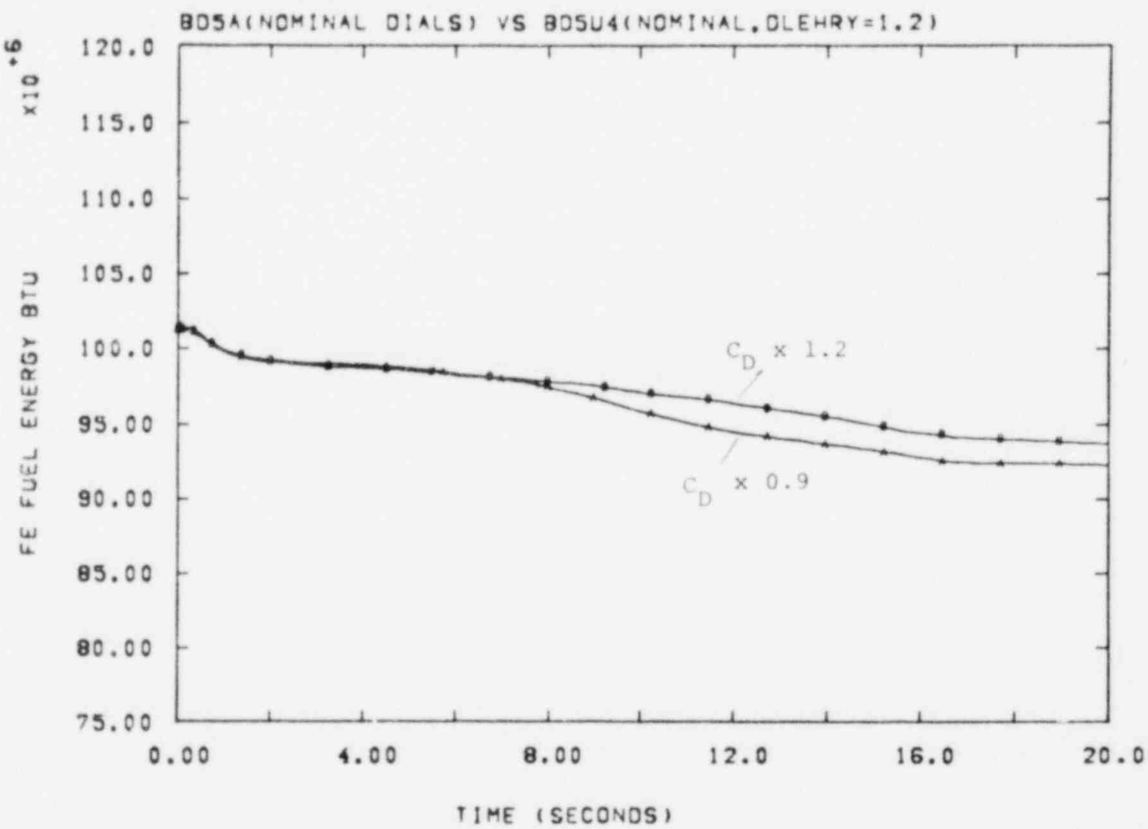


Figure 5-19 Effect of High Subcooled Discharge Coefficient on Total Stored Energy

*This reflects the intentional biasing of the cases toward higher temperatures.

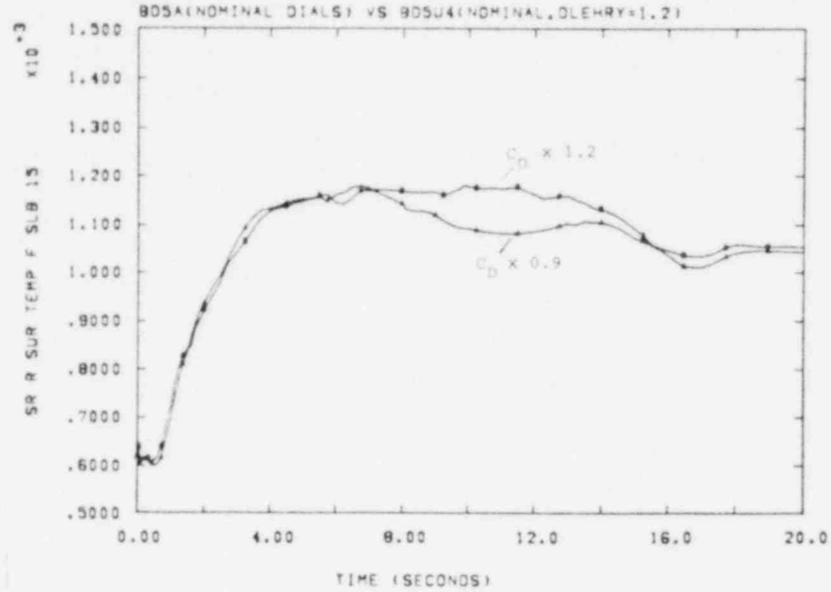


Figure 5-20 Effect of High Subcooled Discharge Coefficient on PCT

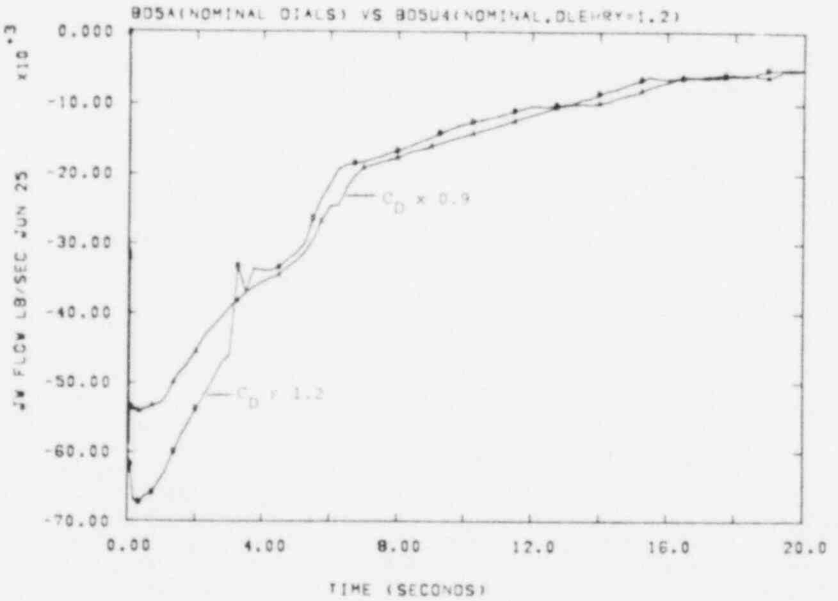


Figure 5-21 Effect of High Subcooled Discharge Coefficient on Vessel-Side Break Flow

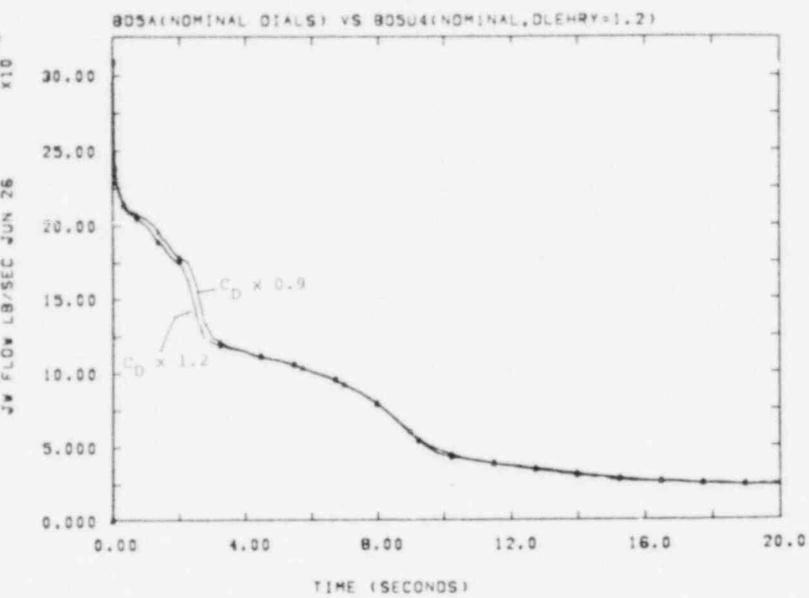


Figure 5-22 Effect of High Subcooled Discharge Coefficient on Pump-Side Break Flow

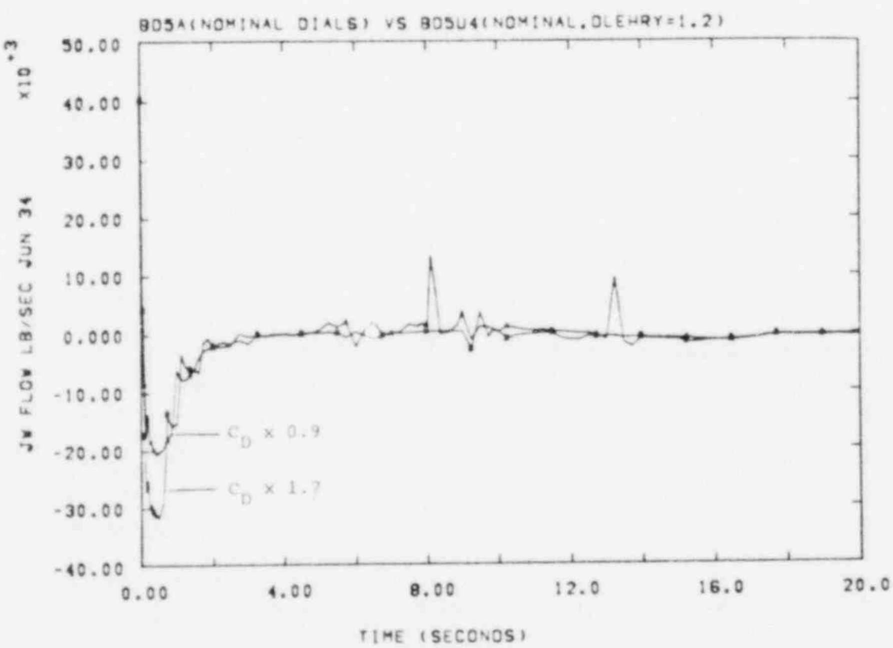


Figure 5-23 Effect of High Subcooled Discharge Coefficient on Flow at Core Bottom

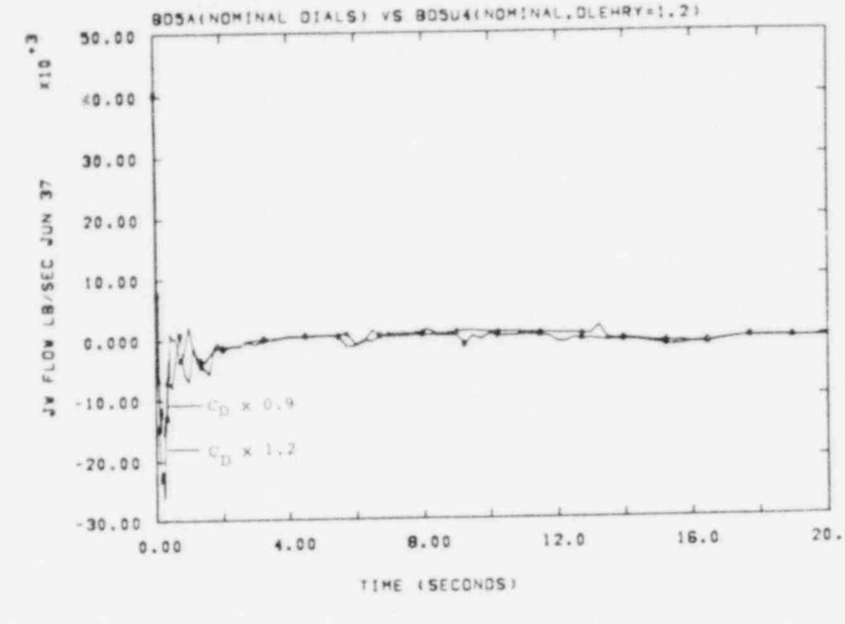


Figure 5-24 Effect on High Subcooled Discharge Coefficient on Flow at Core Midplane

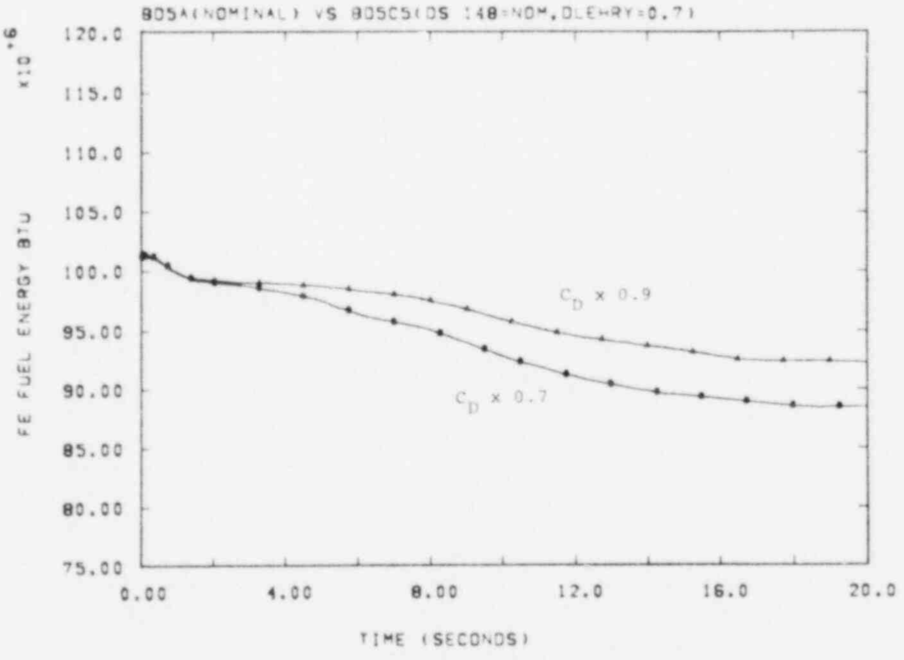


Figure 5-25 Effect of Low Subcooled Discharge Coefficient on Total Stored Energy

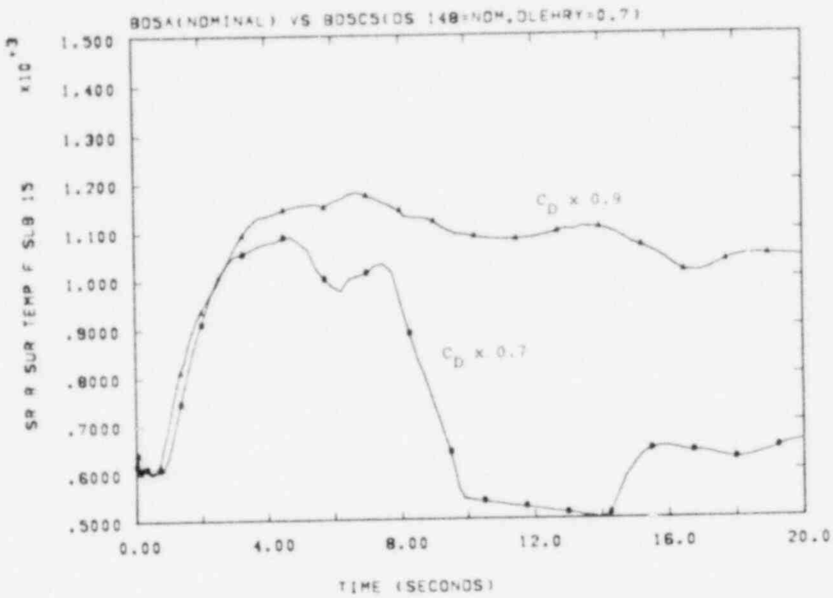


Figure 5-26 Effect of Low Subcooled Discharge Coefficient on PCT

It is perhaps troublesome that subcooled C_D appeared less important than the two-phase flow variables, slip and friction. A possible explanation might reside in PCT timing: If PCT occurred predominantly during the latter part of blowdown where two-phase effects would be expected to be important, then the relative importance of these variables would be understandable. Statistical attempts to subdivide the sample set based on time of PCT, however, were again inconclusive. No consistent behavior was observed.

Figures 5-27 and 5-28 confirm the small effect of saturated discharge coefficient on PCT. They do indicate, however, that temperatures at the start of reflood may depend strongly on the homogeneous equilibrium model (HEM), and this variable will need to be retained for future studies which include reflood PCT.

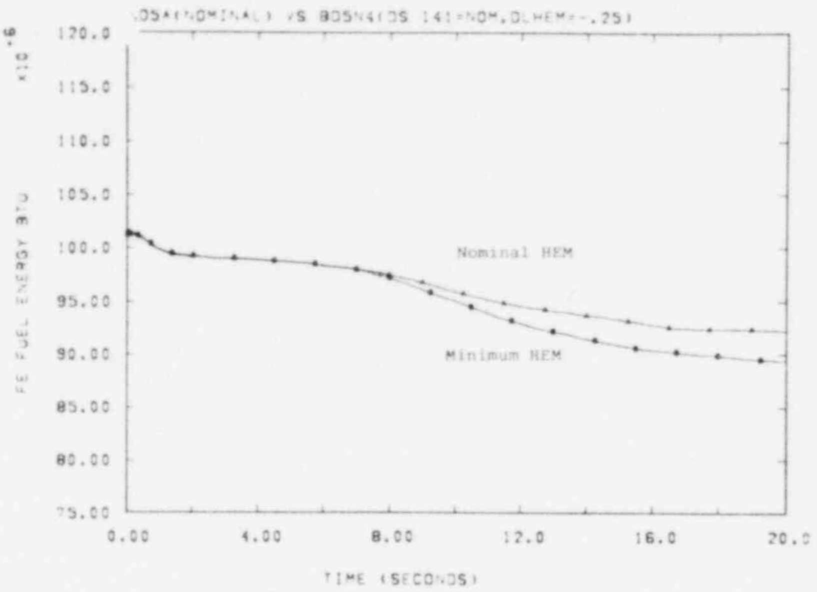


Figure 5-27 Effect of Saturated Discharge Coefficient on Total Stored Energy

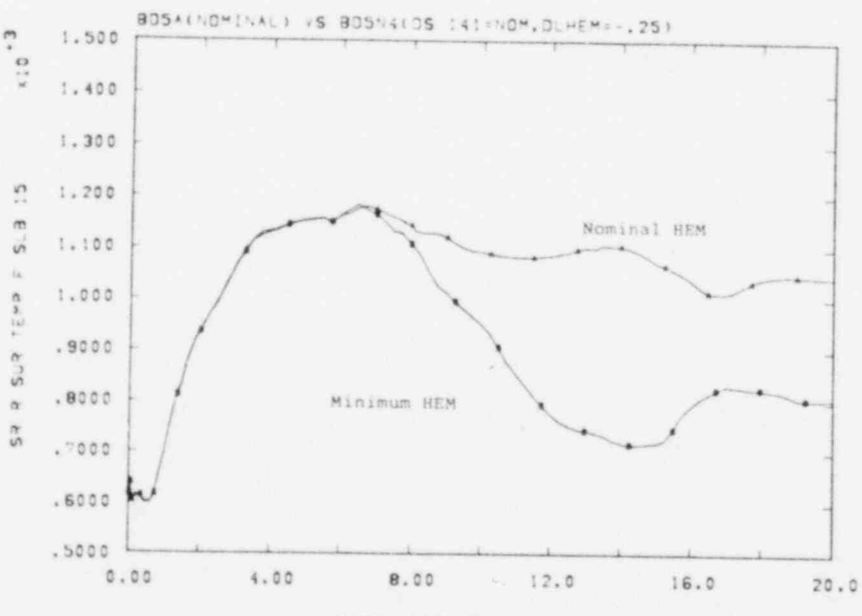


Figure 5-28 Effect of Saturated Discharge Coefficient on PCT

5.3.3 Metal-Water Reaction

Very late in the study, it was discovered that the metal-water reaction (MWR) dial had never been changed during the program because of a coding error in generic RELAP4/MOD6. For this reason, 6 MWR star-point calculations were performed for previous dial sets which had produced high temperatures. These results are summarized in Table 5-5. The first result is negative, indicating that the sensitivity of RELAP to time-step differences, etc., was more important than the differences in metal-water reaction dials. The table implies that variations in MWR dials do not affect PCT until temperatures approach 2000°F. Figure 5-29 shows the differences observed in clad temperature for a 3σ change in MWR. The extreme sensitivity of the MWR parameter to temperature is illustrated in the high-temperature calculation described by dial set 84. Figure 5-30 shows the clad temperature history in slab 14, just beneath the hot spot. The temperature has gone above 2400°F. The hot spot (Figure 5-31) reached a temperature at which the metal-water reaction began to generate much more heat than could be withdrawn by the fluid. A temperature runaway occurred and the code failed.

Table 5-5

Metal-Water Reaction at "Star Points"

T_{hi}(°F)	T_{lo}(°F)	Sensitivity (°F/σ)
1850	1857	- 2
1878	1852	9
1890	1883	2
2151	2077	12
2151	2105	15
2267	2185	27

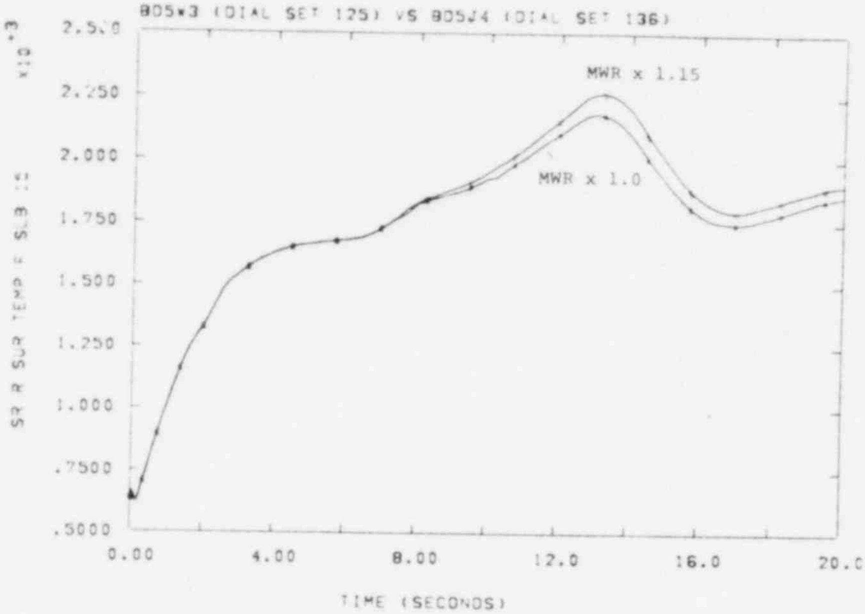


Figure 5-29 Effect of Metal-Water Reaction Dial on PCT

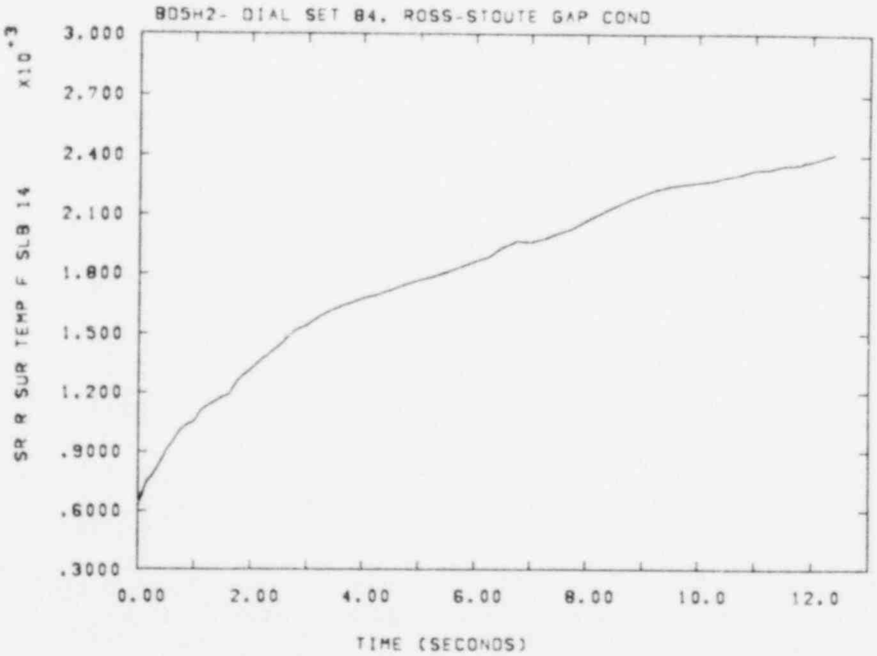


Figure 5-30 Clad Temperature, DS 84, Slab 14

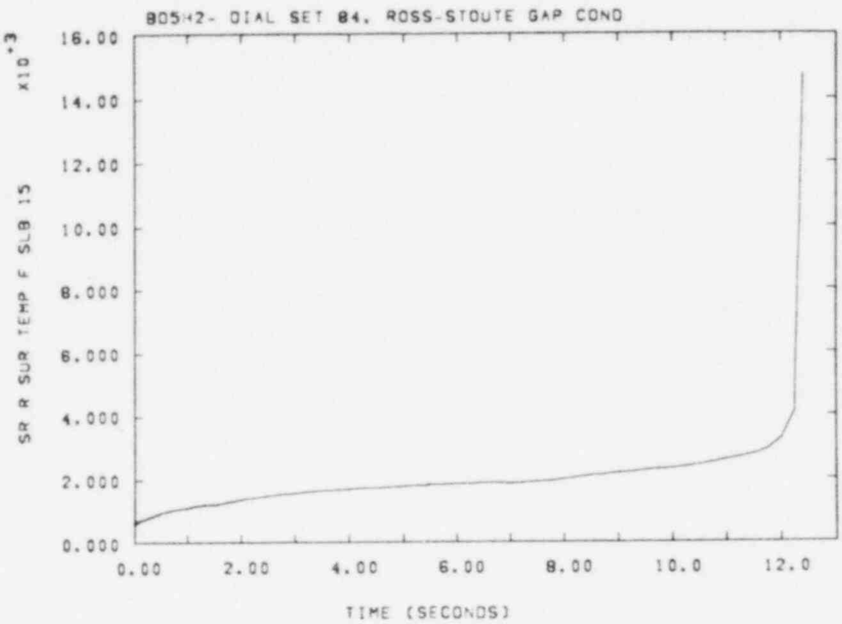


Figure 5-31 Clad Temperature, DS 84, Slab 15

All attempts to include the six star-point calculations for MWR into the response surface led to anomalous and unreasonable behavior. Variable transformations were attempted to somehow include the effect of temperature into variable 11. They all failed. As noted earlier, the statistical method would have permitted the coupling of variable 11 to another variable which was known to correlate with PCT (e.g., power, peaking factor, etc). That this did not occur is probably because of the small size of the MWR variable set and the fact that its sampling range was heavily skewed. For this reason, 11 was not included as a variable for the statistical study.

To learn more about the effects of MWR, we repeated one of the calculations which exhibited a PCT near the high end of the RELAP-produced distribution. In this calculation, however, the Baker-Just MWR parameters were selected rather than the Cathcart-Pawel values used for the statistical input set. At the temperatures encountered with this calculation, we expected the Baker-Just parameters to produce more energy, hence higher temperatures. Table 5-6 demonstrates that this indeed occurred. This table also indicates that surface temperatures for this dial set continue to increase after 20 s of reactor time, with the Baker-Just parameters causing the larger increase for each slab.

Table 5-6

PCT Values for Dial Set 72:
Cathcart-Pawel vs Baker-Just MWR Parameters

	PCT_{20}* (°F)	t_{PCT} (s)	PCT_{30}* (°F)	t_{PCT} (s)
Slab 14:				
B-J	2110	19.5	2193	25.0
C-P	2089	19.5	2165	25.0
Slab 15:				
B-J	2209	20.0	2474	30.0
C-P	2105	19.7	2192	30.0
Slab 16:				
B-J	2041	19.6	2053	30.0
C-P	2026	19.5	2036	30.0

*PCT_{20} means maximum temperature no later than 20 s, PCT_{30} no later than 30 s.

The most significant differences we observed between the two calculations were in the temperature histories. The temperatures shown in Figures 5-32 and 5-33 give an indication of the effect of Baker-Just vs Cathcart-Pawel values. Other quantities in the calculations were much more similar; the fuel stored energies shown in Figure 5-34, for example, appear to be virtually identical. Even core flows and volume temperatures in the region of largest PCT difference (Figures 5-35 and 5-36) were remarkably similar.

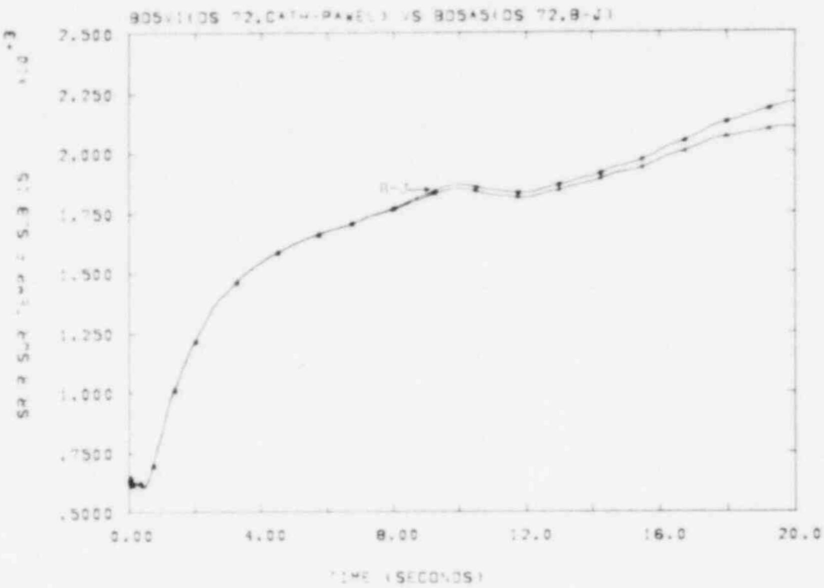


Figure 5-32 Slab 14 Temperature Histories, Cathcart-Pawel vs Baker-Just MWR

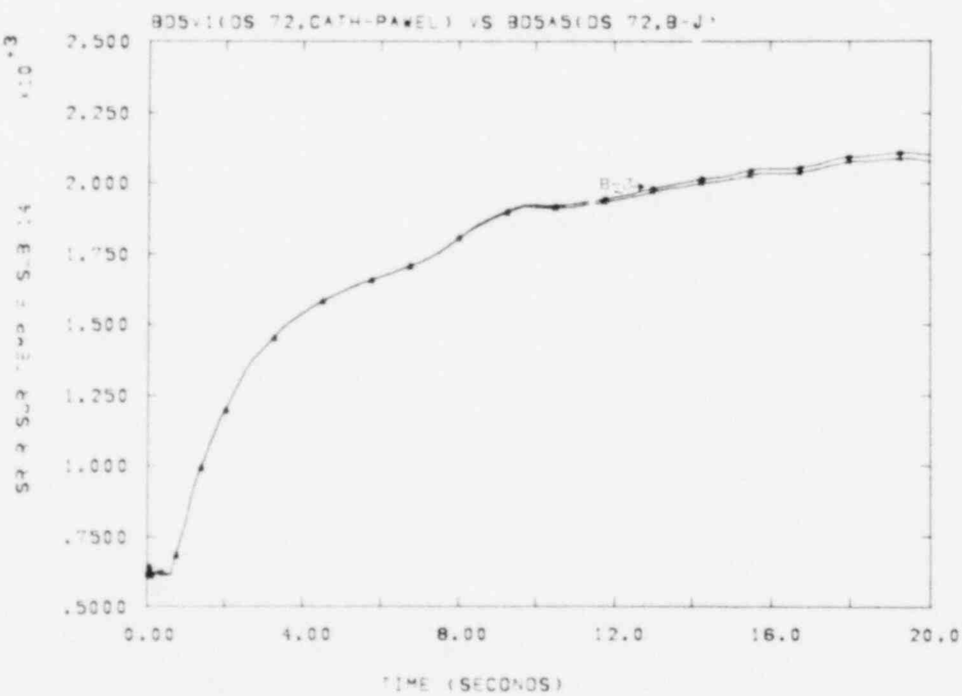


Figure 5-33 Slab 15 Temperature Histories, Cathcart-Pawel vs Baker-Just MWR

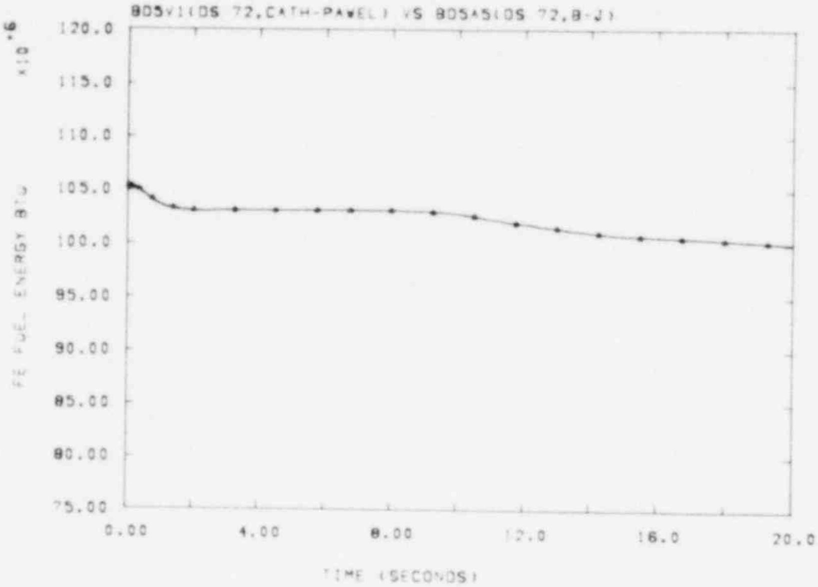


Figure 5-34 Fuel Stored Energies, Cathcart-Pawel and Baker-Just MWR

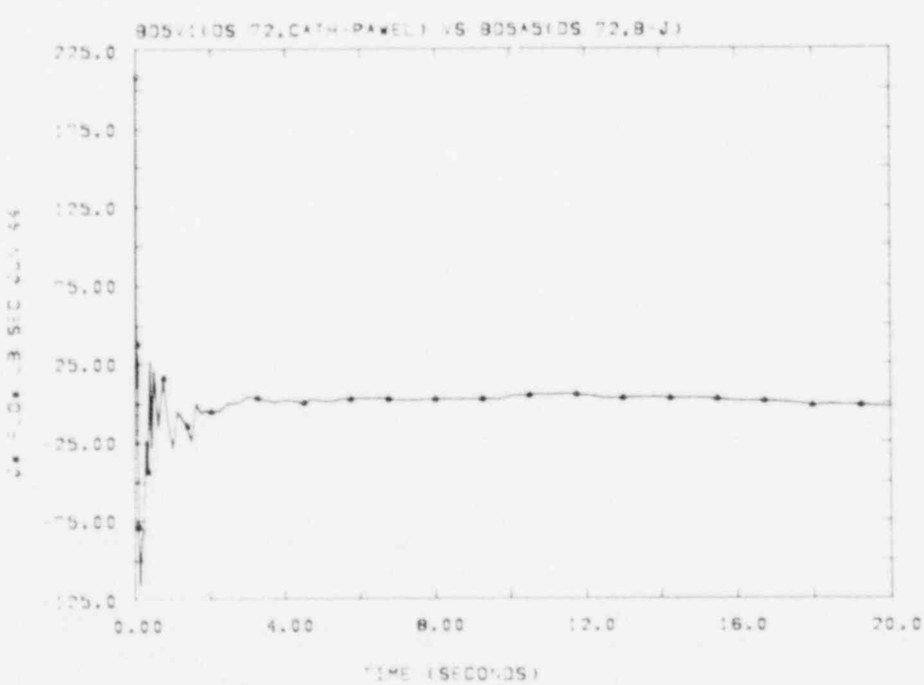


Figure 5-35 Axial Core Flows, Cathcart-Pawel and Baker-Just MWR

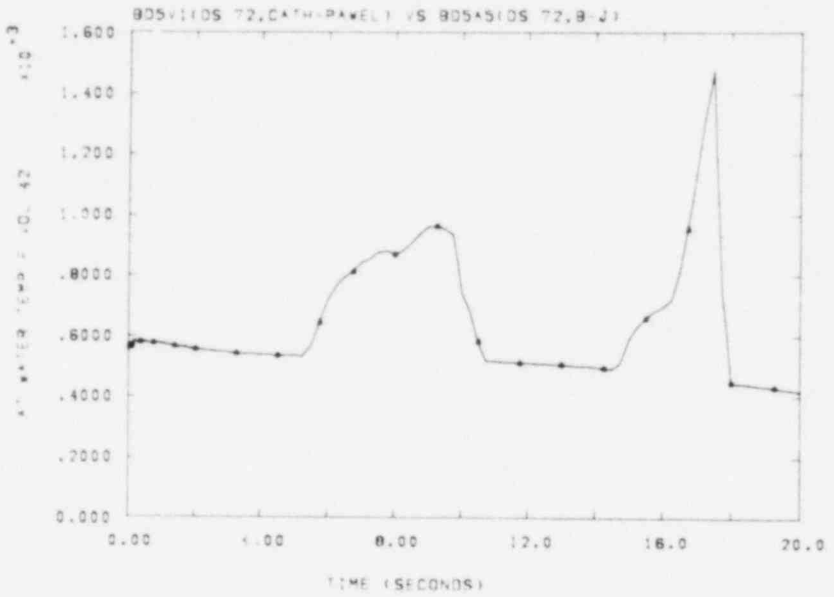


Figure 5-36 Core Volume Temperatures, Cathcart-Pawel and Baker-Just MWR

We conclude from this comparison that, for high temperatures, the MWR calculation has effects on PCT that may be predicted reasonably well. Indeed, at the temperature calculated, the difference between Cathcart-Pawel and Baker-Just parameters corresponds approximately to a 4σ variation in the statistical variable. PCT differences in Table 5-6 for 20-s runs are thus clearly consistent with the sensitivity listed in Table 5-5.

6. Sensitivity of the PCT Distribution to Changes in the Input Distributions

In this chapter we consider how changes in the distributions of the input variables affect the PCT distribution. In particular, we examine how changing the means and standard deviations of the input distributions affects the mean, standard deviation and 90th and 99th percentiles of the PCT distribution for each of the 12 different PCT response surfaces discussed in Section 3. This is done in two stages. First, a particular response surface is sampled 10 000 times for each of 512* different sets of changes to the input distributions to obtain 512 sets of estimates of the mean, standard deviation, and 90th and 99th percentiles of the corresponding PCT distribution, i.e., one PCT distribution for each set of input distributions. Next, these estimates are regressed on dummy variables representing the changes that have been made to the input distributions. Finally, the estimated regression coefficients are interpreted as sensitivities.

6.1 Determining a Set of Input Distributions

Each input variable, or its logarithm** in the case of M type variables, is assumed to be uniformly (17) or normally distributed (or, more accurately, half-normally distributed) above and below nominal or log (nominal), with each half normal having possibly a different variance. Using two half normal distributions insures equal probability above and below nominal. The allowable changes to the input distributions

*If a PCT model has k variables, then there are 2^{2k} possible input distributions to choose from (changing the mean and/or sigma for each of the k variables). In this report, we study only a fraction of this number by means of a fractional factorial design. The actual fraction used for a particular model depends on k in such way that 512 different sets of input distributions are always required for this study.

**All logarithms in this report are taken to base e.

are only to the means and standard deviations of the underlying half normal distributions. Variables 18, 19, and 20 are used with nominal values based on time-in-life.

Let the values for upper and lower limits and nominal for X_k from Table 5-1 be U_k, L_k and N_k, respectively, and let Y be a unit normal random variable, i.e., mean(Y) = 0 and variance(Y) = 1. Then, if X_k is an A variable, the sampled value of X_k is

$$\mu_k + \sigma_k^+ \cdot Y \quad , \qquad \text{if} \quad Y > 0$$

$$\mu_k + \sigma_k^- \cdot Y \quad , \qquad \text{if} \quad Y < 0$$

where

$$\mu_k = N_k \qquad \text{or} \quad N_k + (1/5)\ (U_k - N_k)^*$$

$$\sigma_k^+ = 1/3\ (U_k - N_k) \text{ or } \quad 1/6\ (U_k - N_k)$$

$$\sigma_k^- = 1/3\ (N_k - L_k) \text{ or } \quad 1/6\ (N_k - L_k) \quad .$$

That is, the sigma allowed for X_k is either 1/3 the upper (or lower) half-range or it is 1/2 of that (i.e., 1/6 the appropriate half-range).

If on the other hand X_k is an M variable, then the sampled value of log X_k is

$$\mu_k + \sigma_k^+ \cdot Y \quad , \quad \text{if} \quad Y > 0$$

$$\mu_k + \sigma_k^- \cdot Y \quad , \quad \text{if} \quad Y < 0$$

---

*A change in the mean of 1/5 the upper half range is a compromise. Too small a change is not meaningful and too large a change when coupled with the larger sigma can give too many samples outside the intended range.

where

$$\mu_k = \log(N_k) \quad \text{or} \quad \log(N_k) + 1/5 \log(U_k/N_k)$$

$$\sigma_k^+ = 1/3 \log(U_k/N_k) \quad \text{or} \quad 1/6 \log(U_k/N_k)$$

$$\sigma_k^- = 1/3 \log(N_k/L_k) \quad \text{or} \quad 1/6 \log(N_k/L_k).$$

The different combinations of input distributions are described by assigning a dummy variable, M, to each mean and a dummy variable S to each sigma so that $M_k = +1$ or -1 according as the mean of X_k is taken to be its larger value or is taken to be nominal. Similarly, $S_k = +1$ or -1 according as σ_k is taken to be its larger or its smaller value.

The sensitivities of the parameters of the PCT distribution are obtained by regressing Monte Carlo estimates of these parameters on the dummy variables, M_k and S_k. These estimates are obtained from the estimated PCT distribution resulting from sampling a particular surface 10 000 times.

The regression model used is mainly linear with the only interactions allowed being those between changes in the mean and sigma of the same variable*. This is expressed by writing, for example,

$$\text{mean(PCT)} = \alpha_o + \sum \beta_i M_i + \sum \gamma_i S_i + \sum \delta_i M_i S_i,$$

and using a regression package to estimate α_o, $\{\beta_i\}$, $\{\gamma_i\}$, and $\{\delta_i\}$.

Let the least squares estimates of these regression parameters be a_o, $\{b_i\}$, $\{c_i\}$, and $\{d_i\}$. Then we have mean(PCT) $\cong a_o + \sum b_i M_i + \sum c_i S_i + \sum d_i M_i S_i$, the interpretation of which is as follows.

---

*For models with 9 or 10 basic variables the regression subroutine used allowed a complete set of interactions but none were ever significant.

Suppose M_k changes from -1 to +1, i.e., the mean of X_k changes from its nominal value to its high value, then the mean of the PCT distribution changes by approximately $2b_k$. Suppose M_r changes from -1 to +1 and S_k changes from +1 to -1, then the mean of the PCT distribution changes by $2b_r - 2c_k$.

6.2 Results

The results of the distributional sensitivity studies for the mean, sigma, and 90th and 99th percentile of the PCT distribution are shown in Tables 6-1 through 6-4, respectively. In those tables two times the estimated regression parameters are rounded to the nearest integer.

Table 6-1a

Sensitivities of the Mean of the PCT Distribution to Changes in the Means and Sigmas of the Input Distributions as Estimated by Sampling the Designated PCT Response Surface 10 000 Times (Variables 1 through 10)

Model Code	Model Type	No. Vars.	R^2	a_o (°F)	RMSR (°F)	M/S	Variable 1	2	3	4	5	6	7	8	9	10
FE-9	Non L'	11	.9890	1224.	2.3	M			-7	+ 8		-18		+ 7		
	Lin					S										
CY-9	Non L'	13	.9880	1235.	2.2	M	+4	+ 6	-7	+10		-14		+ 7		
	Lin(C)					S										
B3-9	Non L'	9	.9909	1221.	2.1	M			-9	+ 9	-6	-16				
	Log					S										
C2-9	Non L'	13	.9902	1238.	2.0	M		+14	-7	+ 7		-14		+10		
	Log(C)					S										
B8-9	Std L"	9	.9904	1232.	2.1	M			-9	+ 9		-18				
	Lin					S										
B8-11	Std L"	10	.9887	1222.	2.4	M			-9	+ 9		-19				
	Lin					S										
B8-13	Std L"	10	.9880	1228.	2.4	M			-8	+ 8		-19				
	Lin					S						+ 3				
CA-9	Std L'	7	.9921	1239.	2.0	M			-8	+ 9		-17				
	Log					S										
CA-11	Std L'	7	.9904	1236.	2.2	M			-9	+ 9		-16				
	Log					S										
CG-9	Std L"	7	.9936	1240.	1.8	M			-8	+ 9		-16				
	Log					S										
CG-11	Std L"	7	.9921	1237.	2.0	M			-9	+ 9		-15				
	Log					S										
CG-13	Std L"	8	.9909	1221.	2.2	M			-7	+ 9		-19				
	Log					S										

Table 6-1b

Sensitivities of the Mean of the PCT Distribution to Changes in the Means and Sigmas of the Input Distributions as Estimated by Sampling the Designated PCT Response Surface 10 000 Times (Variables 12 through 16 and 18 through 21)

Model Code	Model Type	No. Vars.	R^2	a_o (°F)	RMSR (°F)	M/S	Variables 12	13	14	15	16	18*	19**	20*	21
FE-9	Non L' Lin	11	.9890	1224.	2.3	M	+6		+5			+19	+15	+24	
						S							+ 7		
CY-9	Non L' Lin(C)	13	.9880	1235.	2.2	M	+7					+17	+14	+23	
						S							+ 6		
B3-9	Non L' Log	9	.9909	1221.	2.1	M	+6					+17	+16	+28	
						S							+ 6		
C2-9	Non L' Log(C)	13	.9902	1238.	2.0	M	+6				+6	+15	+14	+23	
						S							+ 7		
B8-9	Std L" Lin	9	.9904	1232.	2.1	M	+8					+21	+16	+24	
						S							+ 7		
B8-11	Std L" Lin	10	.9887	1222.	2.4	M	+9		+6			+20	+16	+25	
						S							+ 7		
B8-13	Std L" Lin	10	.9880	1228.	2.4	M	+8					+19	+16	+24	
						S			-5				+ 7	+ 3	
CA-9	Std L' Log	7	.9921	1239.	2.0	M						+21	+15	+28	
						S							+ 7		
CA-11	Std L' Log	7	.9904	1236.	2.2	M						+21	+15	+29	
						S							+ 7		
CG-9	Std L" Log	7	.9936	1240.	1.8	M	+8					+22	+14	+28	
						S							+ 7		
CG-11	Std L" Log	7	.9921	1237.	2.0	M	+9					+21	+15	+29	
						S							+ 7		
CG-13	Std L" Log	8	.9909	1221.	2.2	M	+8					+21	+14	+28	
						S							+ 7		

*For peaking factor (18) and gap width (20), the ranges were ±16% and ±1.5 mils, respectively.

**19 is UO_2 thermal conductivity, not its reciprocal.

Table 6-2a

Sensitivities of the Sigma of the PCT Distribution to Changes in the Means and Sigmas of the Input Distributions as Estimated by Sampling the Designated PCT Response Surface 10 000 Times (Variables 1 through 10)

Model Code	Model Type	No. Vars.	R^2	a_o (°F)	RMSR (°F)	M/S	Variable 1	2	3	4	5	6	7	8	9	10
FE-9	Non L'	11	.9427	94.1	1.6	M										
	Lin					S						+4				
CY-9	Non L'	13	.9369	86.9	1.4	M										
	Lin(C)					S				+2		+2				
B3-9	Non L'	9	.9285	97.0	1.6	M				+2		-2				
	Log					S						+3				
C2-9	Non L'	13	.9397	84.5	1.5	M										
	Log(C)					S						+2		+2		
B8-9	Std L"	9	.9576	94.6	1.3	M								+2		
	Lin					S				+2		+3				
B8-11	Std L"	10	.9467	96.3	1.5	M								+2		
	Lin					S						+4				
B8-13	Std L"	10	.9500	94.1	1.5	M								+3		
	Lin					S						+3				
CA-9	Std L'	7	.9370	101.	1.5	M										
	Log					S				+2		+3				
CA-11	Std L'	7	.9268	105.	1.4	M										
	Log					S				+1		+2				
CG-9	Std L"	7	.9367	102.	1.5	M										
	Log					S						+3				
CG-11	Std L"	7	.9212	105.	1.5	M										
	Log					S				+1		+2				
CG-13	Std L"	8	.9234	102.	1.5	M							-3			
	Log					S				+1		+3				

Table 6-2b

Sensitivities of the Sigma of the PCT Distribution to Changes in the Means and Sigmas of the Input Distributions as Estimated by Sampling the Designated PCT Response Surface 10 000 Times (Variables 12 through 16 and 18 through 21)

Model Code	Model Type	No. Vars.	R^2	a_o (°F)	RMSR (°F)	M/S	Variables 12	13	14	15	16	18*	19**	20*	21
FE-9	Non L'	11	.9427	94.1	1.6	M								+5	
	Lin					S						+5	+7	+7	
CY-9	Non L'	13	.9369	86.9	1.4	M						+2			
	Lin(C)					S						+4	+7	+6	
B3-9	Non L'	9	.9285	97.0	1.6	M						+2			
	Log					S						+4	+6	+8	
C2-9	Non L'	13	.9397	84.5	1.5	M						+3	+2	+3	
	Log(C)					S						+3	+7	+7	
B8-9	Std L"	9	.9576	94.6	1.3	M									
	Lin					S						+6	+7	+6	
B8-11	Std L"	10	.9467	96.3	1.5	M								+4	
	Lin					S						+5	+7	+7	
B8-13	Std L"	10	.9500	94.1	1.5	M								+6	
	Lin					S						+5	+7	+7	
CA-9	Std L'	7	.9370	101.	1.5	M									
	Log					S						+5	+5	+8	
CA-11	Std L'	7	.9268	105.	1.4	M									
	Log					S						+6	+6	+5	
CG-9	Std L"	7	.9367	102.	1.5	M								+1	
	Log					S						+5	+6	+8	
CG-11	Std L"	7	.9212	105.	1.5	M									
	Log					S						+6	+5	+6	
CG-13	Std L"	8	.9234	102.	1.5	M									
	Log					S						+6	+5	+5	

*For peaking factor (18) and gap width (20), the ranges were ±16% and ±1.5 mils, respectively.

**19 is UO_2 thermal conductivity, not its reciprocal.

Table 6-3a

Sensitivities of the 90th Percentile of the PCT Distribution to Changes in the Means and Sigmas of the Input Distributions as Estimated by Sampling the Designated PCT Response Surface 10 000 Times (Variables 1 through 10)

Model Code	Model Type	No. Vars.	R^2	a_o (°F)	RMSR (°F)	M/S	Variable 1	2	3	4	5	6	7	8	9	10
FE-9	Non L'	11	.9923	1349.	2.3	M			- 7	+ 9		-17		+ 8		
	Lin					S										
CY-9	Non L'	13	.9873	1349.	2.6	M	+4	+ 5	- 7	+10		-14		+ 7		
	Lin(C)					S										
B3-9	Non L'	9	.9924	1349.	2.2	M			-10	+12	-6	-18				
	Log					S						+ 6				
C2-9	Non L'	13	.9904	1350.	2.5	M		+14	- 7	+ 8		-14		+12		
	Log(C)					S								+ 2		
B8-9	Std L"	9	.9915	1354.	2.2	M			- 9	+10		-17				
	Lin					S										
B8-11	Std L"	10	.9911	1350.	2.5	M			- 9	+ 9		-18				
	Lin					S										
B8-13	Std L"	10	.9831	1354.	3.5	M			- 8	+ 9		-20				
	Lin					S						+ 8				
CA-9	Std L'	7	.9919	1373.	2.2	M			- 9	+11		-18				
	Log					S										
CA-11	Std L'	7	.9896	1375.	2.4	M			-10	+10		-17				
	Log					S										
CG-9	Std L"	7	.9932	1374.	2.1	M			- 9	+10		-18				
	Log					S										
CG-11	Std L"	7	.9906	1376.	2.3	M			-10	+10		-16				
	Log					S										
CG-13	Std L"	8	.9892	1354.	2.4	M			- 8	+10		-20	-4			
	Log					S										

Table 6-3b

Sensitivities of the 90th Percentile of the PCT Distribution to Changes in the Means and Sigmas of the Input Distributions as Estimated by Sampling the Designated PCT Response Surface 10 000 Times (Variables 12 through 16 and 18 through 21)

Model Code	Model Type	No. Vars.	R^2	a_o (°F)	RMSR (°F)	M/S	Variables 12	13	14	15	16	18*	19**	20*	21
FE-9	Non L'	1[illegible]	.9923	1349.	2.3	M	+7		+5			+21	+16	+31	
	Lin					S						+5	+15	+13	
CY-9	Non L'	13	.9873	1349.	2.6	M	+8					+20	+16	+24	
	Lin(C)					S						+6	+14	+8	
B3-9	Non L'	9	.9924	1349.	2.2	M	+8					+20	+15	+29	
	Log					S						+5	+13	+12	
C2-9	Non L'	13	.9904	1350.	2.5	M	+8				+6	+19	+16	+26	
	Log(C)					S						+5	+16	+9	
B8-9	Std L"	9	.9915	1354.	2.2	M	+9					+22	+16	+23	
	Lin					S						+7	+16	+8	
B8-11	Std L"	10	.9911	1350.	2.5	M	+9		+6			+21	+16	+31	
	Lin					S						+6	+15	+12	
B8-13	Std L"	10	.9831	1354.	3.5	M	+8					+20	+16	+32	
	Lin					S						+5	+15	+14	
CA-9	Std L'	7	.9919	1373.	2.2	M						+23	+13	+30	
	Log					S						+6	+13	+11	
CA-11	Std L'	7	.9896	1375.	2.4	M						+20	+13	+28	
	Log					S						+4	+12	+9	
CG-9	Std L"	7	.9932	1374.	2.1	M	+9					+22	+13	+30	
	Log					S						+5	+12	+12	
CG-11	Std L"	7	.9906	1376.	2.3	M	+9					+20	+13	+28	
	Log					S						+4	+12	+9	
CG-13	Std L"	8	.9892	1354.	2.4	M	+9					+20	+13	+26	
	Log					S						+4	+12	+7	

*For peaking factor (18) and gap width (20), the ranges were ±16% and ±1.5 mils, respectively.

**19 is UO_2 thermal conductivity, not its reciprocal.

Table 6-4a

Sensitivities of the 99th Percentile of the PCT Distribution to Changes in the Means and Sigmas of the Input Distributions as Estimated by Sampling the Designated PCT Response Surface 10 000 Times (Variables 1 through 10)

Model Code	Model Type	No. Vars.	R^2	a_o (°F)	RMSR (°F)	M/S	Variable 1	2	3	4	5	6	7	8	9	10
FE-9	Non L'	11	.9775	1456.	5.2	M			- 7	+10		-17		+ 9		
	Lin					S						+ 5				
CY-9	Non L'	13	.9603	1446.	6.1	M			- 7	+11		-14		+ 8		
	Lin(C)					S										
B3-9	Non L'	9	.9728	1450.	5.2	M			-10	+14	-7	-20				
	Log					S				+ 6		+13				
C2-9	Non L'	13	.9779	1454.	5.2	M		+15	- 7	+10		-15		+14		
	Log(C)					S								+ 5		
B8-9	Std L"	9	.9693	1452.	5.3	M			- 9	+10		-16				
	Lin					S						+ 5				
B8-11	Std L"	10	.9761	1457.	5.2	M			- 8	+ 9		-17				
	Lin					S						+ 5				
B8-13	Std L"	10	.9713	1462.	6.0	M			- 7	+ 9		-20				
	Lin					S						+12				
CA-9	Std L'	7	.9744	1471.	4.8	M			- 9	+11		-19				
	Log					S						+ 6				
CA-11	Std L'	7	.9559	1464.	5.5	M			-10	+11		-17				
	Log					S						+ 6				
CG-9	Std L"	7	.9675	1473.	5.4	M			- 9	+11		-18				
	Log					S										
CG-11	Std L"	7	.9574	1466.	5.4	M			-10	+11		-16				
	Log					S						+ 6				
CG-13	Std L"	8	.9621	1443.	5.2	M			- 9	+12		-20	-5			
	Log					S						+ 8				

Table 6-4b

Sensitivities of the 99th Percentile of the PCT Distribution to Changes in the Means and Sigmas of the Input Distributions as Estimated by Sampling the Designated PCT Response Surface 10 000 Times (Variables 12 through 16 and 18 through 21)

Model Code	Model Type	No. Vars.	R^2	a_o (°F)	RMSR (°F)	M/S	Variables 12	13	14	15	16	18*	19**	20*	21
FE-9	Non L'	11	.9775	1456.	5.2	M	+ 8		+5			+22	+18	+34	
	Lin					S						+12	+31	+29	
CY-9	Non L'	13	.9603	1446.	6.1	M	+ 9					+23	+18	+25	
	Lin(C)					S						+14	+32	+17	
B3-9	Non L'	9	.9728	1450.	5.2	M	+ 9					+23	+13	+30	
	Log					S						+14	+18	+24	
C2-9	Non L'	13	.9779	1454.	5.2	M	+ 8				+6	+23	+20	+30	
	Log(C)					S						+13	+36	+21	
B8-9	Std L"	9	.9693	1452.	5.3	M	+ 9					+23	+17	+23	
	Lin					S						+14	+33	+15	
B8-11	Std L"	10	.9761	1457.	5.2	M	+ 9		+5			+22	+18	+33	
	Lin					S						+13	+30	+29	
B8-13	Std L"	10	.9713	1462.	6.0	M	+ 8					+21	+17	+36	
	Lin					S						+10	+28	+33	
CA-9	Std L'	7	.9744	1471.	4.8	M						+22	+12	+30	
	Log					S						+14	+20	+26	
CA-11	Std L'	7	.9559	1464.	5.5	M						+22	+13	+23	
	Log					S						+15	+22	+11	
CG-9	Std L"	7	.9675	1473.	5.4	M	+10					+22	+12	+30	
	Log					S						+13	+19	+26	
CG-11	Std L"	7	.9574	1466.	5.4	M	+10					+21	+13	+23	
	Log					S						+13	+22	+12	
CG-13	Std L"	8	.9621	1443.	5.2	M	+10					+21	+13	+23	
	Log					S						+12	+22	+10	

*For peaking factor (18) and gap width (20), the ranges were ±16% and ±1.5 mils, respectively.

**19 is UO_2 thermal conductivity, not its reciprocal.

Table 6-5 summarizes the PCT distribution sensitivities as calculated using statistical model CG-11. The data are shown in terms of °F per standardized change and °F per 1% change in nominal.

Table 6-5

Sensitivities of PCT Distribution to Changes in Input Means*

Variable		°F/σ_U**			°F/% Nominal		
		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

**$\sigma_U \equiv$ 1/3 upper 1/2 range

†Number in parenthesis is °F/Mil

The principal conclusions are:

- Except for the absense of any effect on the sigma of the PCT distribution of changing the distribution of variable 3 (slip) and 12 (power), there is general agreement among all modelling philosophies on the important changes and the magnitude of their effects. Again, the important changes are to the distributions of variables 3, 4, 6, 12, 18, 19, 20.

- In general, changing sigmas of the input distributions has little effect on the mean of the PCT distribution, and changing means has little effect on the sigma of the PCT distribution.

- In general, the effects are small. The biggest entries (in absolute value) in the tables for mean, sigma, and 90th and 99th percentiles are 29°F, 8°F, 32°F, and 36°F, respectively.

- The range of values of a_o in a table sometimes exceeds the magnitudes of the changes themselves. This means that the change produced in a PCT distribution parameter is better known than the base value of that parameter.

References

[1]RELAP4/MOD5, A Computer Program for Transient Thermal-Hydraulic Analysis of Nuclear Reactors and Related Systems, User's Manual, ANCR-NUREG-1335 (Idaho National Engineering Laboratory, September 1976), Vols I and II.

[2]RELAP4/MOD6, A Computer Program for Transient Thermal-Hydraulic Analysis of Nuclear Reactors and Related Systems, User's Manual, CDAP TR-003 (Idaho National Engineering Laboratory, January 1978).

[3]TRAC-P1: An Advanced Best Estimate Computer Program for PWR LOCA Analysis, NUREG/CR-0063, LA-7279-MS (Los Alamos Scientific Laboratory, June 1978), Vol 1.

[4]G. W. Johnsen, F. W. Childs, and J. M. Broughton, A Comparison of "Best-Estimate" and "Evaluation Model" LOCA Calculations: The BE/EM-Study, PG-R-76-009 (Idaho National Engineering Laboratory, December 1976).

[5]G. P. Steck, D. A. Dahlgren, and R. G. Easterling, Statistical Analysis of LOCA, FY 75 Report, SAND75-0653 (Albuquerque: Sandia Laboratories, December 1975).

[6]G. P. Steck, R. L. Iman, and D. A. Dahlgren, Probabilistic Analysis of LOCA, Annual Report for FY 1976, SAND76-0535, NUREG 766513 (Albuquerque: Sandia Laboratories, December 1976).

[7]M. Berman et al, LOCA Analyses Annual Report, Fiscal Year 1977, SAND78-0637, NUREG/CR-0154 (Albuquerque: Sandia Laboratories, June 1978).

[8]Light Water Reactor Safety Research Program Quarterly Report, October-December 1977, SAND78-0600 (Albuquerque: Sandia Laboratories, June 1978).

[9]Light Water Reactor Safety Research Program Quarterly Report, January-March 1978, SAND78-1511 (Albuquerque: Sandia Laboratories, October 1978).

[10]Light Water Reactor Safety Research Program Quarterly Report, April-June 1978, SAND78-1901 (Albuquerque: Sandia Laboratories, January 1979).

[11]Light Water Reactor Safety Research Program Quarterly Report, July-September 1978, SAND79-0359 (Albuquerque: Sandia Laboratories, April 1979).

[12]Light Water Reactor Safety Research Program Quarterly Report, October-December 1978, SAND79-0820 (Albuquerque: Sandia Laboatories, July 1979).

[13]Light Water Reactor Safety Research Program Quarterly Report, January-March 1979, SAND79-1542 (Albuquerque: Sandia Laboratories, to be published).

[14]Letter from C. Johnson (NRC) to D. A. Dahlgren (Sandia Laboratories), March 21, 1978, subject: Ranges of Parameters for Work Under FIN A-1205.

[15]Letter from C. Johnson (NRC) to M. Berman (Sandia Laboratories), May 3, 1978, subject: "Information Supplement to Letter of March 21, 1978."

[16]Memorandum, B. Sheron (NRC) for C. Johnson (NRC), March 24, 1978, subject: "The Treatment of Uncertainty Distributions for Peaking Factors to be used in Statistical LOCA Study."

[17]Memorandum, K. R. Katsma (EG&G Idaho) for H. H. Sullivan (EG&G Idaho), December 29, 1977, subject: "Parameters for Uncertainty Evaluation of PWR, KAT-38-77."

[18]M. D. McKay, W. J. Conover, and D. E. Whiteman, Report on the Application of Statistical Techniques to the Analysis of Computer Codes, LA-NUREG-6526-MS, NRC-4, September 1976.

[19]N. D. Cox, A Report on a Sensitivity Study of the Response Surface Method of Uncertainty Analysis of a PWR Model, RE-S-77-7 (EG&G Idaho, January 1977).

[20]G. P. Steck, R. G. Easterling, and R. L. Iman, Uncertainty Propagation Through Computer Codes (Proceedings, Probability Analysis of Nuclear Reactor Safety, Los Angeles, CA, May 8-10 1978).

[21]Letter from H. Chow (EG&G Idaho) for M. Berman (Sandia Laboratories), April 4, 1978, subject: "Approximation to New ANS Decay Heat Standard by Time-Dependent Multiplier, CHOW-1-78."

[22]Proposed Revised ANS Standard, Decay Heat Power in Light Water Reactors for Shutdown Times Less Than 10^4 Seconds, ANS 5.1 (American Nuclear Society, August 1977).

APPENDIX

Reproducibility of Calculated Results

Quite late in this program, we accidentally discovered that our combination of RELAP, computer operating system, and job execution procedure could produce different results for identical input sets. The discovery occurred when one calculation seemed to have disappeared from the system, so it was resubmitted; on resubmission, an unexplained system-generated job rerun occurred after the RELAP calculation was complete. Subsequently, output from the original run was located, so that we had three calculations that should have been identical, but were not. This event caused a great deal of concern, and we began a search for its possible source.

Of the trio of runs which raised the question of reproducibility, two produced the same PCT result. However, the three calculations were all terminated by different RELAP-detected errors, and a detailed comparison of output showed divergence of results as early as 9 reactor seconds. Five more calculations with this input set, including three restarts from one of the error-aborted runs, produced neither the error previously observed nor divergences in output. Sandia's computer operations personnel stated that they knew of no hardware or software error existing in the system at this time. The RELAP program, therefore, seemed the most likely source of the discrepancies.

Our original suspicion was that the code was in some way using a quantity which had not been properly initialized. RELAP is capable of accessing memory areas that are not explicitly declared in any storage allocation statements. Because of this, the job procedure used to preset storage to an "illegal" value did not reach all of the areas of memory that could be used by RELAP. After some investigation, a method was developed to control the initial state of all the memory being utilized. This method consists of loading and executing a "dummy" program, before the loading and execution of RELAP. The dummy program performs no function other than the declaration of storage areas sufficient for RELAP execution, thus allowing full presetting of memory.

For the purpose of broadening our information base on the possible frequency of irreproducible results, 43 more recalculations were performed with 14 of the statistical input sets. In these calculations, various legal and illegal numbers were used for presetting storage, both the old and new job procedures were employed, and both of Sandia's CDC 7000 series computers were used. A number of the dial sets selected for these runs were those with PCT results or temperature histories that seemed somewhat inconsistent, statistically, with the response model predictions (i.e., large RMS residuals). Many of these calculations were run for a reactor time of at least 20 seconds; most were carried out at least past the time of PCT. The set also included some short and repeated restart runs.

Of the 49 runs performed for comparison purposes by this point, only 2 differences in PCT were observed that might have consequences for the statistical analysis. These differences (20° and 62°F) occurred for calculations with the same dial set, again in conjunction with a system-caused rerun of a job for no apparent reason. (The dial set which produced these differences was one which, because of the difficulties with the metal-water reaction parameter, was not in fact used as part of the input for the response surface analysis.)

We observed 5 other divergences in output in the set of 49 calculations; in none of the five was there a difference in PCT as large as 1°F. Clearly, such small differences could have no significant impact on the statistical analysis. It should also be emphasized that differences in results were detected by full comparison of output files, to the limits of machine accuracy.

In another effort to assess the frequency of possibly irreproducible results, we performed a set of 100 calculations with input identical to that which had produced the significant PCT differences. Since those differences were felt to have stemmed from divergences very early in the calculations, this set of runs had a small time limit (approximately 0.05 seconds reactor time). The runs were divided into four equal groups: each of the two computers was used with either the old or the new job control sequence. Complete comparisons were then performed on the output. Apart from a frequent shift in the memory location of the first word of executable RELAP code, no differences in results were observed in the entire set of 100 runs. The memory shift appeared only in runs using the old job configuration. We also note that, in all our investigations, we found no evidence that the new job control procedure would fail to give reproducible results.

In summary, we were not able to uncover any clear reason for the occasional lack of reproducibility of RELAP output. The combinations of values used to preset memory were expected to force the code to behave in a way which would provide some clue, but that expectation was not fulfilled. We were able, however, to construct a job execution procedure which never yielded self-contradictory results. This method will of course be used in all subsequent calculations.

Two points should be emphasized: (1) The possibility exists that undetected errors were occurring in our computing system at the times we experienced difficulty, and (2) recalculation of some of the data actually used in the statistical analysis never showed divergences of numerical significance to the study.

DISTRIBUTION:

U. S. Nuclear Regulatory Commission
(350 copies for R4)
Div. of Document Control
Distribution Services Branch
7920 Norfolk Ave
Bethesda, MD 20014

U. S. Nuclear Regulatory Commission (22)
Washington, DC 20555

Office of Nuclear Regulatory Research
Attn: G. L. Bennett
S. Fabic
C. E. Johnson (10)
W. C. Lyon
G. Marino
H. H. Scott
L. Thompson
L. S. Tong
R. Van Houten

Office of Nuclear Reactor Regulation
Attn: N. Lauben
H. L. Ornstein
Z. R. Rosztoczy
B. Sheron

U. S. Nuclear Regulatory Commission
Executive Director for Operations
Washington, DC 20555
Attn: R. Moore

U. S. Nuclear Regulatory Commission
Office of Management and Program Analysis
Washington, DC 20555
Attn: L. Abramson

Department of Energy
Idaho National Engineering Laboratory
550 Second Street
Idaho Falls, ID 83401
Attn: W. Bixby

Idaho National Engineering Laboratory (2)
550 Second Street
Idaho Falls, ID 83401
Attn: P. North
J. Dearien

Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, NM 87545
Attn: M. McKay

University of Wisconsin
Dept. of Statistics
1210 West Dayton St.
Madison, WI 53706
Attn: W. G. Hunter

Intermountain Technologies, Inc.
1400 Benton Street
P.O. Box 1604
Idaho Falls, ID 83401
Attn: P. Davis

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304
Attn: B. Chu

Exxon Nuclear Company
Reload Licensing
2101 Horn Rapids Road
Richland, WA 99352
Attn: C. F. Owsley

Babcock and Wilcox (2)
P.O. Box 1200
Lynchburg, VA 24505
Attn: J. H. Taylow
A. Holler

Combustion Engineering (2)
P. O. Box 500
1000 Prospect Hill Rd.
Windsor, CT 06095
Attn: A. E. Scherer
J. H. Holderness

Westinghouse Electric (2)
PWR Systems Division
Box 355
Pittsburgh, PA 15230
Attn: D. F. Paddleford
J. A. Marshall

General Electric Co.
175 Curtner Avenue
San Jose, CA 95125
Attn: W. D'Ardenne

DISTRIBUTION (cont):

1223	R. G. Easterling
1223	I. J. Hall
4400	A. W. Snyder
4440	G. R. Otey
4441	M. Berman (10)
4441	T. J. Bartel
4441	B. W. Burnham
4441	L. D. Buxton
4441	R. K. Byers
4441	R. K. Cole
4441	L. N. Kmetyk
4441	J. F. Muir
4441	D. Tomasko
4443	D. A. Dahlgren
5641	G. P. Steck
8266	E. A. Aas
3141	T. L. Werner (5)
3151	W. L. Garner (3) For DOE/TIC (Unlimited Release)
3154	R. P. Campbell (25) For NRC Distribution to NTIS