COMBUSTION ENGINEERING, INC.

REPORT CENPD-153-NP, Rev. 1-NP

EVALUATION OF UNCERTAINTY IN THE
NUCLEAR POWER PEAKING MEASURED BY THE
SELF-POWERED, FIXED IN-CORE DETECTOR SYSTEM

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May 1980

T s report replaces the following two reports:
    CENPD-145, "INCA Method of Analyzing In-Core Detector Data in
                Power Reactors:

    CENPD-153, "Evaluation of Uncertainty in the Nuclear Form Factor
                Measured by Self-powered Fixed In-Core Detector Systems"

**POWER
SYSTEMS**

COMBUSTION ENGINEERING INC

8007110248

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ACKNOWLEDGEMENT

FOREWORD

This revision to CENPD-153 combines two previous reports: CENPD-145, "INCA Method of Analyzing In-core Detector Data in Power Reactors," April 1975, and CENPD-153, "Evaluation of Uncertainty in the Nuclear Form Factor Measured by Self-Powered, Fixed In-Core Detector Systems," August 1974. The revision represents an extension of the data base for the uncertainty analysis to include several plants and later cycle cores.

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IN THE NUCLEAR POWER PEAKING
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PART I

THE BASIC MEASUREMENT UNCERTAINTY

I.0 INTRODUCTION

Applicability, Purpose and Organization of the Report

The principal in-core instrumentation in Mark V fuel assembly reactors is provided by strings of four or five short rhodium, self-powered detectors arranged axially in the central water holes of about 20% of all fuel assemblies. Moveable detectors have been installed in some plants but have not been used in power distribution monitoring. This report is applicable to fixed rhodium detector systems when the signals are processed through the INCA/CECOR system of codes.

The purpose of the report is to quantify the numerical uncertainties associated with the use of the fixed in-core detector system in inferring the core power peaking factors:

F_q, the local peak pin power to core average power ratio.

F_{xy}, the planar peak pin power to planar average power ratio.

F_r, the axially integrated peak pin power to core average power ratio.

The measurement uncertainties determined for these peaking factors are in the form of 95%/95% probability/confidence one-sided tolerance limits and will be used in conjunction with Technical Specification limits on these quantities to establish appropriate LCO (Limiting Conditions of Operation) and LSSS (Limiting Safety System Settings) limits for plant operation and safety analysis.

This report is in three parts. Part I contains the determination of the uncertainty associated with the measurement of assembly average power in instrumented locations: the Basic Measurement Uncertainty. It includes uncertainties in all components of the assembly power, viz., in the raw signal, in the background correction factors, in the initial calibrated sensitivity, in the sensitivity depletion, and in the signal-to-power

conversion. The basic measurement uncertainty in assembly power is determined directly, without determining the uncertainty of the individual components, by comparing measured and calculated values as described in I.3.

Part II determines the software dependent uncertainty, called the synthesis uncertainty. This includes components due to the radial coupling from instrumented to uninstrumented assemblies, due to the axial expansion of the power profile and due to the translation of assembly power to pin power via the pin-to-box factors.

Part III contains the statistical model for the combination of the basic measurement uncertainty with the synthesis uncertainty and the final numerical results.

Continued Applicability

The analysis of this report is based on operational data from a limited but large sample of fuel cycles and reactors using 14x14 fuel and 4-detector arrangements for determination of the basic measurement uncertainty. Since this component is determined mainly by the hardware properties of the instrumentation (calibration and sensitivity depletion), it is expected to be insensitive to differences (size, fuel assembly geometry) in core design and detector arrangement. The numerical results of Chapter I.3 show that the variations observed between reactors and cycles, although statistically significant because of the large data base, are in fact small compared to the overall uncertainties. The synthesis uncertainty is principally dependent upon the number of axial detectors per string. As shown in Part II, 5-detector arrangements are expected to be conservatively bounded by the analysis made for 4-detector strings. Throughout this analysis, for both the basic measurement uncertainty and for the synthesis uncertainty, whenever statistical tests show that pooling of data from all reactors, all cycles or all time-points, etc., is not justified, the most unfavorable data have consistently been chosen as representative of the data base. For reload cycles analyzed subsequent to the completion of the analyses included in

the data base of this report, no departures of the uncertainties from that data base have been observed. For all of the above reasons it is therefore concluded that the data base for the uncertainties will remain applicable to all future reactors and cycles employing rhodium, self-powered, fixed in-core detectors in Mark V fuel.

Summary

The results of the analyses show that:

-F_q can be measured with an accuracy of 6.2%.

-F_{xy} can be measured with an accuracy of 5.3%.

-F_r can be measured with an accuracy of 6.0%.

Thus the overall measurement uncertainty is such that there is a 95 percent probability that at least 95 percent of the true F_q, F_{xy}, and F_r values will be less than the value inferred from the INCA/CECOR measurement plus 6.2, 5.3 and 6.0%, respectively.

I.1   IN-CORE INSTRUMENT SYSTEM DESCRIPTION

1.0   INTRODUCTION

The in-core instrumentation supplied in C-E reactor plants is primarily
based on self-powered rhodium detectors. In reactors using the Mark V fuel
assembly, the instruments are placed in the center water hole of selected
assemblies. In addition to these fixed detectors, the 3410 MWth and System
80 reactors are equipped with movable self-powered rhodium detectors which
can provide a continuous record of the axial flux distribution in each
instrumented assembly. In a few of the early plants (Maine Yankee and St.
Lucie) selected locations can be accessed by movable miniature fission
chambers. In addition, background cables have been provided in a number of
locations in all reactor cores. This topical report addresses the measurement
accuracy of fixed in-core rhodium detectors.

1.1   DESCRIPTION OF FIXED DETECTORS

1.1.1   Rhodium Detectors

The primary mechanism by which the neutron radiation incident on the rhodium
detector is converted to a signal is through neutron capture in the emitter
producing a capture product which decays through beta emission. Some of
the beta particles are energetic enough to escape from the emitter, resulting
in a positive charge on the emitter. Rhodium-103 has a 150-barn 2200 m/sec
capture cross section and its capture product (Rhodium-104) emits beta
particles possessing an end-point energy of 2.4 Mev with a 42-second half-
life.[†] The rhodium detectors are 40 cm long, and four or five of these
segments are located at selected axial poistions in each string. See
Figure 1-1. Table 1.I lists properties of the rhodium detectors for the
neutron spectrum in the Pool Test Reactor at Chalk River. The rhodium
detectors are 40 cm long with a diameter of approximately 18 mils and an
initial sensitivity, as determined by calibration in the Pool Test Reactor
at Chalk River, of typically 3.5×10^{-20} amp/nv.

[†] An isomeric state, Rh^{104m}, is also produced approximately 7.3% of the time
with a 4.41-min. half-life.

1.1.2 Background Detectors

The background detectors measure the signal generated in the detector
signal cable due to, for example, Compton and photoelectrons as a result of
gamma interaction with the cable materials as well as neutron activation of
the cable insulator. The electrons which could cause current flow in
addition to that of the emitter material are the results of the imbalance
between those leaving the center wire and those absorbed by the center
wire. In order to be representative of the background signal experienced
by the rhodium detectors, the background detector is manufactured identical
to the lead wire on the rhodium detector. It consists of an Inconel 600
lead wire and outer sheath with Al_2O_3 insulator. The physical dimensions
are identical to the detector lead wire, i.e., 0.040 inches O.D. with 0.006
inch diameter center lead. The background detector is full core length,
thus representing the worst case signal contribution to the axially spaced
rhodium detectors.

The background detector is read across a dropping resistor as are the
rhodium signals. The measured values are utilized to verify that the
required background correction is small.

1.2 DESCRIPTION OF IN-CORE INSTRUMENT ASSEMBLIES

The fixed instrument assemblies for the Palisades, Maine Yankee, Fort
Calhoun, Millstone, Calvert Cliffs and St. Lucie plants consist of chromel-
alumel thermocouples, four rhodium self-powered neutron detectors, and a
background cable in selected locations terminated at either the top or
bottom of the detector assembly. The four detectors are axially centered
at 20, 40, 60 and 80% of the core height. The newer C-E designs, including
Arkansas Nuclear One Unit 2, System 80 and the 3410 MWth plants, have five
rhodium self-powered detectors in a string, axially centered at 10, 30, 50,
70 and 90% of the core height.

1.3   DETECTOR LAYOUT

Detailed detector location maps for the operating, 14x14 fuel, plants are included in Chapter I.3 (see Figures 3-1 to 3-11). For the 3410-class, System 80 and Arkansas plants, standard layouts are shown in Figures 1-2 through 1-4, respectively.

1.4   INSTRUMENTATION AND READOUT

The instrumentation associated with the fixed in-core detectors is relatively simple, as shown in Figure 1-5. In essence, it consists of a load resistor for each detector, multiplexing system, amplifier, and A-D converter to digitize the signals. The output of the self-powered detectors is a low level current, which on flowing through a load resistor produces a measurable voltage. This voltage is amplified and then digitized by the A-D converter. The resulting digitized signal is fed to either a data-logger or to the plant computer. A complete scan of the in-core detectors can be accomplished in about 20 seconds.

To ensure that essentially all of the detector current flows through the 10^5 ohm load resistor, the leakage resistance of the cable (effectively in parallel with the load resistor) is maintained at a value greater than 10^8 ohms. This is checked periodically by placing an additional 10^5 ohm resistor in parallel and calculating the leakage resistance. This ensures that no more than 0.1% of the current flows through the leakage resistance.

TABLE 1.I

Properties of Self-Powered Detectors

Property	Rhodium Detector
Length	40 cm
Diameter	18 mils
Sensitivity in the PTR Spectrum	3.5×10^{-20} amp/nv

Figure 1-1

TYPICAL NEUTRON DETECTOR AND DETECTOR ASSEMBLY

BACKGROUND DETECTOR

S. S. PENFLEX SHEATH

OUTLET THERMOCOUPLE, TOP OF FUEL ASSEMBLY

4 RHODIUM DETECTORS CENTERED AT 20, 40, 60, and 80% CORE HEIGHT
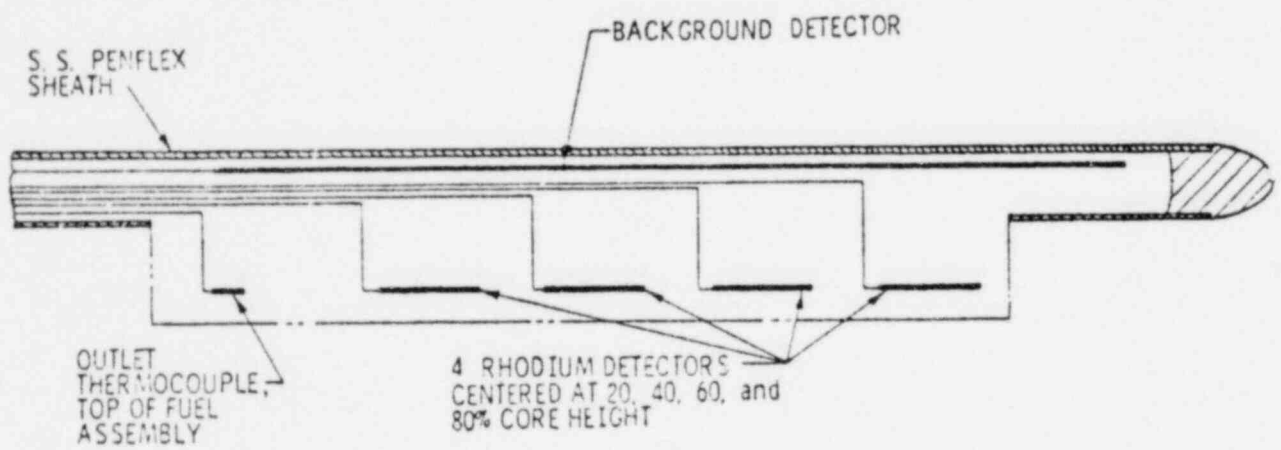
TYPICAL INSTRUMENT ASSEMBLY

Al_2O_3 DIELECTRIC

COAXIAL CABLE

RHODIUM EMITTER

INCONEL SHEATH (COLLECTOR)
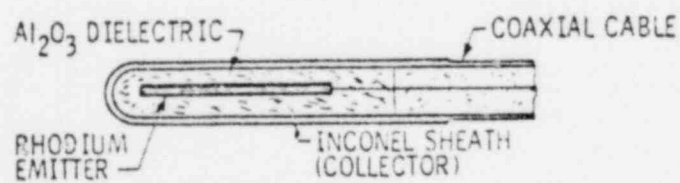
TYPICAL RHODIUM DETECTOR

Figure 1-2
LOADING & INSTRUMENT PATTERN
STANDARD 110 FIRST CYCLE CORE

BATCH ⎯⎤ ⎡⎯ BOX
⎯ INSTR.

| C | 1 | C | 2 | C | 3 | C | 4 |

| C 5 | C 6 | C+ 7 | C+ 8 | B 9 | C+ 10 | C+ 11 | C 12 | C 13 |
1 | | 2 | | 3 | | 4 | | 5

| C 14 | C. 15 | B 16 | A 17 | B 18 | A 19 | B 20 | A 21 | B 22 | C. 23 | C 24 |

| C 25 | C. 26 | B 27 | A 28 | B 29 | A 30 | B 31 | A 32 | B 33 | A 34 | B 35 | C. 36 | C 37 |
6 | | 7 | | 8 | | 9 | | 10 | | 11 | | 12

| C 38 | C. 39 | B 40 | A 41 | B 42 | A 43 | B 44 | A 45 | B 46 | A 47 | B 48 | A 49 | B 50 | C. 51 | C 52 |

| C 53 | B 54 | A 55 | B 56 | A 57 | B 58 | A 59 | B 60 | A 61 | B 62 | A 63 | B 64 | A 65 | B 66 | C 67 |
| 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 |

| C+ 68 | A 69 | B 70 | A 71 | B 72 | A 73 | B 74 | A 75 | B 76 | A 77 | B 78 | A 79 | B 80 | A 81 | C+ 82 |

C 83 | C 84
20 | | C+ 85 | B 86 | A 87 | B 88 | A 89 | B 90 | A 91 | B 92 | A 93 | B 94 | A 95 | B 96 | A 97 | B 98 | C+ 99 | 21
C 100 | 22 | | 23 | | 24 | | 25 | | 26 | | 27 | | 28 | C 101

| B 102 | A 103 | B 104 | A 105 | B 106 | A 107 | B 108 | A 109 | B 110 | A 111 | B 112 | A 113 | B 114 | A 115 | B 116 |

C 117 | | | | | | | | | | | | | | | C 118

| C+ 119 | B 120 | A 121 | B 122 | A 123 | B 124 | A 125 | B 126 | A 127 | B 128 | A 129 | B 130 | A 131 | B 132 | C+ 133 |
C 134 | 29 | | 30 | | 31 | | 32 | | 33 | | 34 | | 35 | C 135
36 | C+ 136 | A 137 | B 138 | A 139 | B 140 | A 141 | B 142 | A 143 | B 144 | A 145 | B 146 | A 147 | B 148 | A 149 | C+ 150 | 37

| C 151 | B 152 | A 153 | B 154 | A 155 | B 156 | A 157 | B 158 | A 159 | B 160 | A 161 | B 162 | A 163 | B 164 | C 165 |
| 38 | | 39 | | 40 | | 41 | | 42 | | 43 | | 44 |

| C 166 | C. 167 | B 168 | A 169 | B 170 | A 171 | B 172 | A 173 | B 174 | A 175 | B 176 | A 177 | B 178 | C. 179 | C 180 |

| C 181 | C. 182 | B 183 | A 184 | B 185 | A 186 | B 187 | A 188 | B 189 | A 190 | B 191 | C. 192 | C 193 |
45 | | 46 | | 47 | | 48 | | 49 | | 50 | | 51

| C 194 | C. 195 | B 196 | A 197 | B 198 | A 199 | B 200 | A 201 | B 202 | C. 203 | C 204 |

| C 205 | C 206 | C+ 207 | C+ 208 | B 209 | C+ 210 | C+ 211 | C 212 | C 213 |
52 | | 53 | | 54 | | 55 | | 56

| C 214 | C 215 | C 216 | C 217 |

I.1.6

Figure 1-3
LOADING & INSTRUMENT PATTERN
STANDARD SYSTEM 80 FIRST CYCLE CORE

BATCH —[BOX] — BOX
— INSTR.

C 1	C 2	C 3	C 4	C 5	C 6	C 7
						1

C 8	C_L+ 9	C_L+ 10	B_L 11	C_H+12	B_L 13	C_H+14	B_L 15	C_L+16	C_L+17	C 18
	2			3			4			

C 19	C_L 20	A 21	B_L 22	A 23	B_L 24	A 25	B_L 26	A 27	B_L 28	A 29	C_L 30	C 31
		5		6			7		8		9	

C 32	C_L 33	A 34	B_L 35	A 36	B_H 37	A 38	B_H 39	A 40	B_H 41	A 42	B_L 43	A 44	C_L 45	C 46
	10		11			12								

C_L+ 47	A 48	B_L 49	A 50	B_H 51	A 52	B_H 53	A 54	B_H 55	A 56	B_H 57	A 58	B_L 59	A 60	C_L+61
		13			14			15		16				

C 62	C_L+ 63	B_L 64	A 65	B_H 66	A 67	B_H 68	A 69	B_H 70	A 71	B_H 72	A 73	B_H 74	A 75	B_L 76	C_L+77	C 78
	17		18											19		

C 79	B_L 80	A 81	B_H 82	A 83	B_H 84	A 85	B_H 86	A 87	B_H 88	A 89	B_H 90	A 91	B_H 92	A 93	B_L 94	C 95
	20			21			22			23			24			25

C 96	C_H+97	B_L 98	A 99	B_H 100	A 101	B_H 102	A 103	B_H 104	A 105	B_H 106	A 107	B_H 108	A 109	B_L 110	C_H+111	C 112
	26				27			28								

C 113	B_L 114	A 115	B_H 116	A 117	B_H 118	A 119	B_H 120	A 121	B_H 122	A 123	B_H 124	A 125	B_H 126	A 127	B_L 128	C 129
	29						30	31				32	33			34

C 130	C_H+131	B_L 132	A 133	B_H134	A 135	B_H 136	A 137	B_H 138	A 139	B_H 140	A 141	B_H 142	A 143	B_L 144	C_H+145	C 146
35				36			37					38				

C 147	B_L 148	A 149	B_H150	A 151	B_H 152	A 153	B_H 154	A 155	B_H 156	A 157	B_H158	A 159	B_H 160	A 161	B_L 162	C 163
		39								40			41			

C 164	C_L+ 165	B_L 166	A 167	B_H168	A 169	B_H 170	A 171	B_H 172	A 173	B_H 174	A 175	B_H176	A 177	B_L 178	C_L+ 179	C 180
	42			43			44						45		46	

C_L+ 181	A 182	B_L 183	A 184	B_H 185	A 186	B_H 187	A 188	B_H 189	A 190	B_H191	A 192	B_L 193	A 194	C_L+195
47						48		49		50				

C 196	C_L 197	A 198	B_L 199	A 200	B_H 201	A 202	B_H 203	A 204	B_H 205	A 206	B_L 207	A 208	C_L 209	C 210
	51										52		53	

C 211	C_L 212	A 213	B_L 214	A 215	B_L 216	A 217	B_L 218	A 219	B_L 220	A 221	C_L 222	C 223
	54		55			56			57			

C 224	C_L+ 225	C_L+ 226	B_L 227	C_H+228	B_L 229	C_H+230	B_L 231	C_L+ 232	C_L+ 233	C 234
				58			59			60

C 235	C 236	C 237	C 238	C 239	C 240	C 241
61						

I.1.7

Figure 1-4
LOADING & INSTRUMENT PATTERN
ARKANSAS NUCLEAR UNIT 2 FIRST CYCLE CORE

BATCH —|— BOX

—|— INSTR.
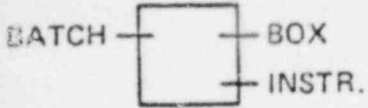
| C4 1 | C3 2 | C3 3 | C3 4 | C4 5 |

| C4 6 | C2 7 | C1 8 | B+ 9 | A 10 | B+ 11 | C1 12 | C2 13 | C4 14 |
| | 1 | | 2 | | 3 | | 4 | |

| C5 15 | C2 16 | A 17 | B+ 18 | A 19 | B+ 20 | A 21 | B+ 22 | A 23 | C2 24 | C5 25 |

| C4 26 | C2 27 | A 28 | B+ 29 | A 30 | B+ 31 | A 32 | B+ 33 | A 34 | B+ 35 | A 36 | C2 37 | C4 38 |
| | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | |

| C2 39 | A 40 | B+ 41 | A 42 | B+ 43 | A 44 | B+ 45 | A 46 | B+ 47 | A 48 | B+ 49 | A 50 | C2 51 |

| C4 52 | C1 53 | B+ 54 | A 55 | B+ 56 | A 57 | B+ 58 | A 59 | B+ 60 | A 61 | B+ 62 | A 63 | B+ 64 | C1 65 | C4 66 |
| 11 | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | | |

| C3 67 | B+ 68 | A 69 | B+ 70 | A 71 | B+ 72 | A 73 | B+ 74 | A 75 | B+ 76 | A 77 | B+ 78 | A 79 | B+ 80 | C3 81 |
| | 18 | | | | | | | | | | | | 19 | |

| C3 82 | A 83 | B+ 84 | A 85 | B+ 86 | A 87 | B+ 88 | A 89 | B+ 90 | A 91 | B+ 92 | A 93 | B+ 94 | A 95 | C3 96 |
| | 20 | | 21 | | 22 | | 23 | | 24 | | 25 | | | |

| C3 97 | B+ 98 | A 99 | B+ 100 | A 101 | B+ 102 | A 103 | B+ 104 | A 105 | B+ 106 | A 107 | B+ 108 | A 109 | B+ 110 | C3 111 |
| | 26 | | | | | | | | | | | | 27 | |

| C4 112 | C1 113 | B+ 114 | A 115 | B+ 116 | A 117 | B+ 118 | A 119 | B+ 120 | A 121 | B+ 122 | A 123 | B+ 124 | C1 125 | C4 126 |
| | 28 | | 29 | | 30 | | 31 | | 32 | | 33 | | | 34 |

| C2 127 | A 128 | B+ 129 | A 130 | B+ 131 | A 132 | B+ 133 | A 134 | B+ 135 | A 136 | B+ 137 | A 138 | C2 139 |

| C4 140 | C2 141 | A 142 | B+ 143 | A 144 | B+ 145 | A 146 | B+ 147 | A 148 | B+ 149 | A 150 | C2 151 | C4 152 |
| | 35 | | 36 | | 37 | | 38 | | 39 | | 40 | |

| C5 153 | C2 154 | A 155 | B+ 156 | A 157 | B+ 158 | A 159 | B+ 160 | A 161 | C2 162 | C5 163 |

| C4 164 | C2 165 | C1 166 | B+ 167 | A 168 | B+ 169 | C1 170 | C2 171 | C4 172 |
| | 41 | | 42 | | 43 | | 44 | |

| C4 173 | C3 174 | C3 175 | C3 176 | C4 177 |

Figure 1-5

IN-CORE INSTRUMENTATION WIRING DIAGRAM
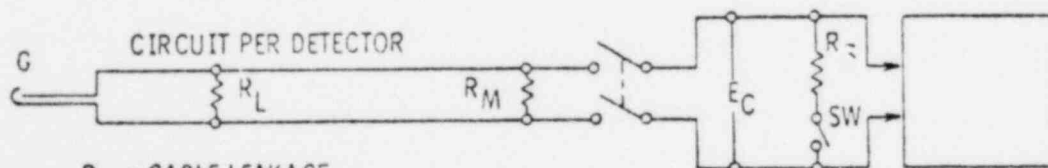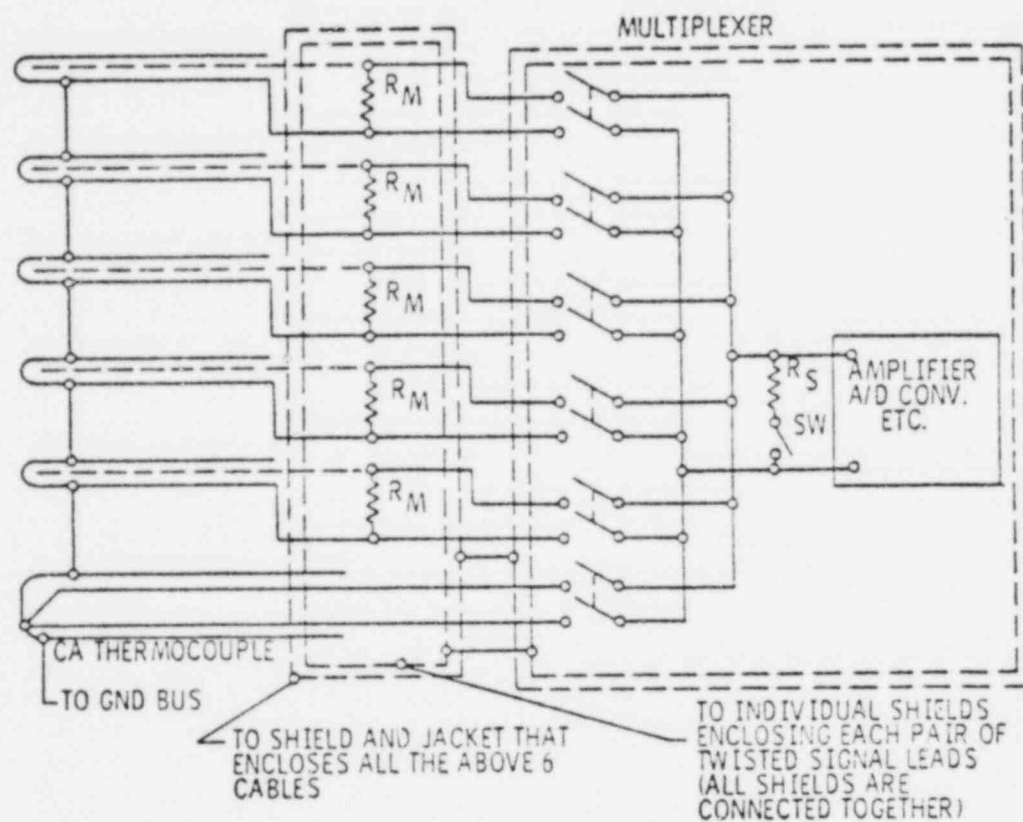
R_L - CABLE LEAKAGE

R_M - DETECTOR MEASURING RESISTANCE (e.g. $50 \times 10^3 \, \Omega$)

R_S - SPECIAL RESISTOR (e.g. $20 \times 10^3 \, \Omega$)

I.2   MEASUREMENT TECHNIQUES, CALIBRATION, REPRODUCIBILITY

2.0   GENERAL

During normal operating conditions, signals proportional to the rhodium
activation rates are obtained from the various detectors. These signals
are related to local power by use of calculated signal-to-power conversion
factors for the appropriate core conditions (see Chapter II.1). The measured
signals are corrected for background, calibration, and depletion.

These effects (background, calibration, and depletion) individually contribute
to the overall uncertainty associated with use of the in-core instruments
for measurement of power peaking. The approach employed for determination
of this uncertainty does not provide for a separate determination of these
components. Instead, a comparison of measured and predicted powers (Chapter
I.3) gives the combined uncertainty due to background, calibration, depletion
and signal-to-power conversion. The purpose of the following discussion
is, therefore, only to show that the individual effects are sufficiently
well understood, and that the uncertainty component due to calibration as
determined in separate measurements is small and consistent with the overall
result determined from the power reactor comparisons.

2.1   FIXED IN-CORE DETECTORS

2.1.1   System Performance

The fixed in-core detector systems in C-E operating reactors have been
found, over the past several years, to operate effectively and dependably
with 100% availability. There have been brief periods of time during which
they could not be automatically scanned due to unavailability of the plant
computer. However, it was still possible to read the detector signals
during these periods manually.

In all reactors, there have been some detectors which were damaged during installation and others which failed during operation. Early failures at Palisades, where the highest detector signal loss occurred, were attributed to fracture of the detector cable adjacent to the braze at the detector. Modification of the design for later application has substantially improved operational reliability.

The impact of failed detectors on the determination of core power distributions has not been a serious problem because of the ample initial supply of detector channels.

2.1.2   Detector Calibration and Reproducibility

Detector calibration is carried out by the vendor, Reuter-Stokes Canada, Ltd., using the Pool Test Reactor (PTR) and the ZED-2 reactor at Chalk River Nuclear Laboratories. All detectors are calibrated relative to standard detectors. This relative calibration is performed in the PTR where the detectors are loaded into a calibration fixture. The fixture is a lucite rod about 3 cm in diameter with ten locations, one of which is reserved for the standard detector.

The major uncertainty in the relative calibration is due to the slightly different flux levels in the calibration locations. They are measured at approximately yearly intervals. The calibration uncertainty has been determined by repeating the calibration letting the detector occupy different positions in the calibration fixtures. Deviations between pairs of such measurements indicate the accuracy. Table 2.I shows results from a set of such reproducibility experiments. Analysis of the data in the table yields a sample standard deviation for the difference between two measurements of 0.43% for a sample size of n=18 (the standards remain in the same location). The sample standard deviation associated with an individual measurement is therefore $0.43/\sqrt{2} = 0.31\%$. This estimate of the relative calibration uncertainty may be compared with the overall, basic measurement uncertainty as determined in Chapter I.3 (see Table 3.I) which is in the range of 1.66-1.93%

for the standard deviation. Thus, the calibration uncertainty represents only a fraction of the total uncertainty.

All rhodium detectors are calibrated using this method. While the calibration environment in the PTR is different than in an operating PWR (PTR is a pool reactor with a highly thermalized neutron spectrum, different gamma spectra and lower water temperature), the procedure is adequate because a relative, not absolute, calibration is needed. Any changes resulting from the PWR enrvironment are reflected directly in the uncertainty component evaluated in Chapter I.3.

Absolute calibration of the detectors is carried out using cobalt wires attached to the outside of selected detectors for exposure in standard conditions. The wires are absolutely counted and their activations interpreted to give the absolute flux at the detector location. The uncertainty in the measured absolute flux is $\pm$ 4-6% which, in turn, is reflected as a similar uncertainty in the absolute sensitivity of the detectors. Absolute calibration of the detectors, although useful, is by no means as important as their relative inter-calibration since the reactor power level is determined by calorimetric measurements and calculations.

An additional measure of the reproducibility of the detector signals under operating conditions has been obtained by accumulating a large number of readings during power operation at Palisades. During several periods of steady state operation, repeated measurements were obtained from all 180 rhodium in-core detectors. After known bad detectors and those affected by slight control rod movements had been eliminated, about 4800 duplicate measurements of detector signals were compared. The results of this evaluation are shown in Table 2.II. By comparing sequential pairs of measurements, the standard deviation between pairs of readings was found to be 0.35%, averaged over the total data set. The sample standard deviation of a single measurement is found to be 0.25% which is consistent with the estimate obtained from the PTR measurements.

The above two sets of measurements, the initial calibration and the repeat measurements during operation, have evaluated the same physical characteristic, namely the ability of the detector to yield the same signal when irradiated in the same flux.

2.1.3   Detector Linearity

At normal power reactor flux levels, rhodium self-powered detectors respond linearly to the incident flux because in all cases their signal is directly proportional to their reaction rates. Calibration measurements carried out in PTR and repeated in ZED-2 give calibration factors in close agreement despite the fact that the reactors differ in flux level by a ratio of 4.5.

Work carried out by Böck, et al.[2.1] also shows a linear response to neutron flux for self-powered detectors.

2.1.4   Detector Depletion

In order to interpret the signals accurately from fixed in-core detectors, it is necessary to properly represent the effects of detector depletion. Rhodium detectors have a significant depletion rate because of the magnitude of the cross sections. They deplete about 1.4% per full power month of operation, resulting in roughly 25% depletion over one cycle. The depletion properties of detectors are summarized in Table 2.III.

The rhodium detector sensitivity is related to the total charge accumulated. As shown by Laaksonen and Saastamoinen[2.2] the relative sensitivity ($\frac{S}{S_0}$), at any time (t) is related to the fraction $\frac{Q}{Q_\infty}$, of total available charge collected to that time as follows:

$$\frac{S(t)}{S_0} = (1 - \frac{Q(t)}{Q_\infty})^n \qquad (2.1)$$

Q_∞ is a property of the detector and is essentially independent of the spectrum in which the detector is used. It is determined from measurements in controlled conditions and is provided to C-E by the detector vendor. Theoretical considerations indicate that the actual depletion behavior is bounded by a linear curve (n = 1.0) for a spatially flat absorption rate in the detector wire, and by a depletion that varies by the square root (n=0.5) of the relative depletion for a fictitious case where the absorption lies entirely on the surface of the emitter. Realistic absorption distributions within the wire are intermediate between the two extremes as shown in Figure 2-1. For a neutron spectrum similar to that expected in C-E reactors, Saastamoinen predicts an n close to .75. Small variations about this value are insignificant for cores with detectors of approximately the same age, since the detectors are normalized among themselves and then related to the calorimetric power determination for purposes of inferring absolute quantities. In practice, the value of the exponent is determined from operating data for detectors of varying age and located in symmetric locations. The value of n thus derived accounts for any errors in the depletion dependence of the signal-to-power conversion factor. Errors due to the choice of constants in Equation (2.1) are automatically included in the basic box power measurement uncertainty because of the method used to estimate it. See Chapter I.3.

2.1.5   Background

The term "background" is used for the sum of all currents generated in the detector and cable which are not the result of neutron interaction with the detector emitter itself. The main contributors to the background signal are cable "self" signal, detector cable cross talk, and gamma induced background.

The cable "self" signal is due to (γ,e) reactions in the sheath and lead wire, neutron activation of the aluminum in the insulation, and pickup of externally generated electrons such as from neutron activation of the manganese in the stainless steel Penflex sheathing.

Detector and cable cross talk effects are due to decay electrons from the emitter impinging on adjacent detectors and cables.

An additional contribution to the background is due to the gamma sensitivity of the detector. The gamma field impinging on the detector causes photo and Compton electrons to be ejected from the emitter and collector. This signal is proportional to the local neutron flux since the gamma field is neutron induced.

These effects result in a background which is of the order of 1% of the detector signal. The background is compensated by means of calculated factors that depend on axial position, i.e., length of lead cable in active core region. A 1% correction is assumed for the detector with the longest lead cable and other detectors in each string are adjusted according to lead cable length. The correction factors are verified by comparison with measured background.

2.2   REFERENCES

2.1   H. Böck, P Gebureck, D. Stegemann, "Transient Response of Self-Powered Neutron Detectors," Nucl. Inst. and Meth., 123 (117), 1975.

2.2   T. Laaksonen and J. Saastamoinen, "Calculational Studies of Sensitivity Characteristics and Their Burnup Behavior for Rhodium Self-Powered Neutron Detectors," Paper presented at IAEE Specialists Meeting on In-Core Instrumentation and Failed Fuel Detection and Location, Toronto, Ontario, Canada, 1974.

TABLE 2.I

Repeat Measurements of Reactor Calibration
of Rhodium Detectors

Detector #	Position 1	S_1 [1]	Position 2	S_2 [1]	$\Delta S = S_2 - S_1$
Standard	1	1.0000	1	1.0000	0 %
2RH4-1R1	2	1.0095	7	1.0001	-.94
2	3	1.0083	8	1.0116	.33
4	4	1.0001	9	1.0065	.64
5	5	1.0031	10	1.0037	.06
6R2	6	1.0050	2	1.0098	.48
7	7	1.0066	3	1.0029	-.37
8	8	1.0009	4	.9964	-.45
9	9	1.0127	5	1.0091	-.36
10R1	10	1.0118	6	1.0086	-.32
Standard	1	1.0000	1	1.0000	0
2RH4-48	2	1.0123	6	1.0101	-.23
49	3	1.0194	7	1.0170	-.16
50	4	1.0162	8	1.0126	-.36
51	5	1.0176	9	1.0117	-.59
52	6	1.0211	10	1.0165	-.46
53	7	1.0170	2	1.0099	-.71
54	8	1.0109	3	1.0151	.42
55R1	9	1.0187	4	1.0140	-.47
56	10	1.0163	5	1.0136	-.27

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1) Relative sensitivity

TABLE 2.II

Reproducibility Data for Rhodium Detectors

Date	Reactor Power	Number of Comparisons	Standard Deviation
10/22/74	433 Mw	3143	0.39%
5/4/73	720 Mw	141	0.35%
6/25/73	712 Mw	1521	0.24%
		4805	$S_D = 0.35\%$

For A Single Measurement

$$S = \frac{S_D}{\sqrt{2}} = 0.25\%$$

TABLE 2.III

Depletion Properties
of Rhodium-103 Detectors

Property	Value
σ_{a1}(PWR Spectrum)	9 b
σ_{a2}(PWR Spectrum)	75 b
Depletion Rate in 10^{13}nv flux (Maxwellian)	0.23% per month
Monthly Depletion Rate in PWR Spectrum	1.4% per month

Figure 2-1

RELATIVE RHODIUM TOTAL SENSITIVITY
vs INTEGRATED DETECTOR CHARGE
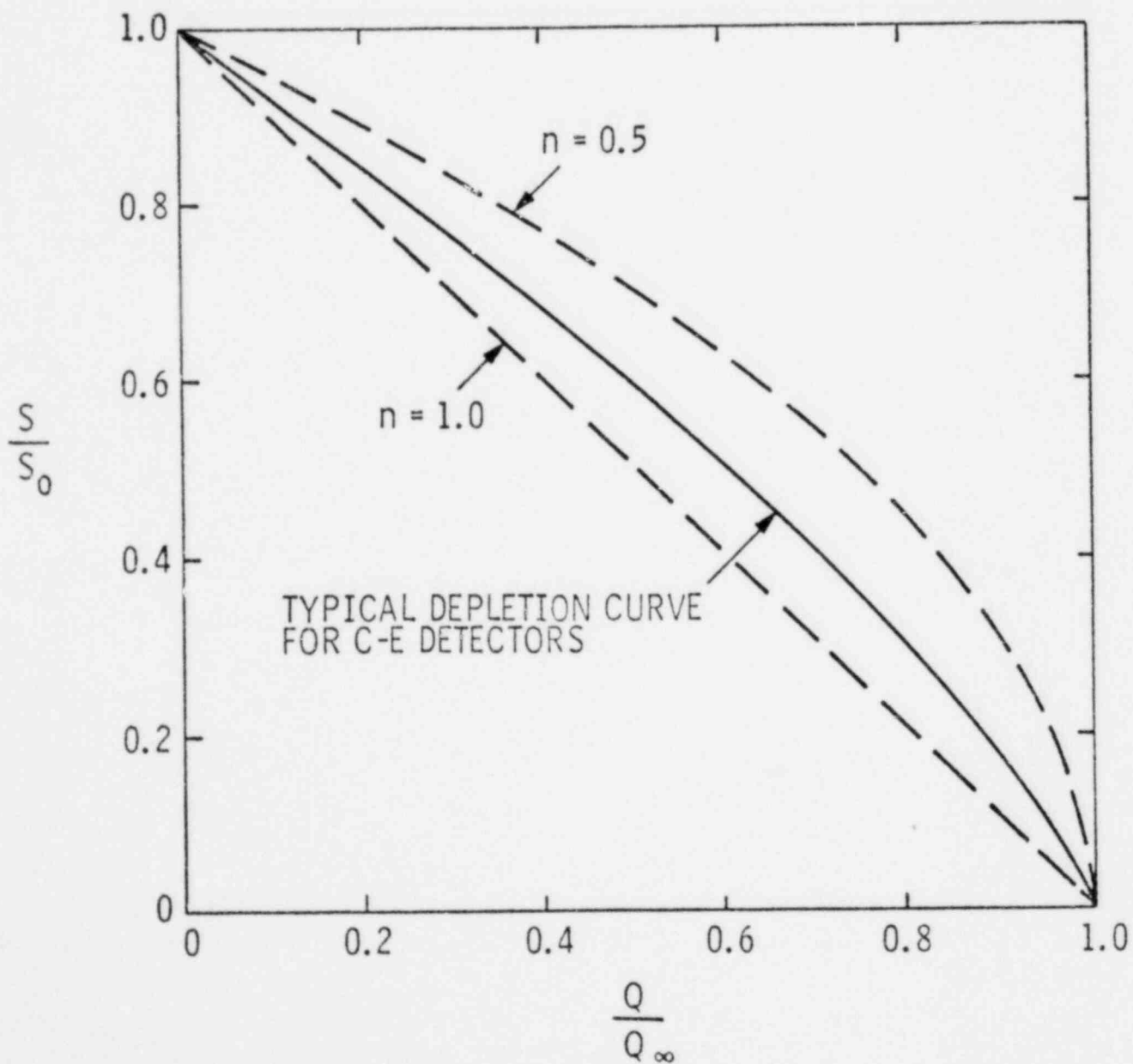
I.3　　　BASIC BOX POWER MEASUREMENT UNCERTAINTY FOR F_q, F_{xy} AND F_r

3.0　　　INTRODUCTION

3.0.1　　Description of Method

The uncertainty to be attributed to the fuel assembly power distribution
can be obtained by comparing detailed calculations of the fuel assembly box
powers with those inferred from in-core measurements with the INCA system
using fixed, in-core rhodium detectors[3.1]. The resulting deviation is a
reflection of both measurement and calculational uncertainties and errors.
In particular, it is often affected adversely by approximations in various
features of the calculational model, such as inaccurate representations of
the core geometry produced by simplifications in the spatial mesh, by
inadequate theory for the core shroud, reflector and core barrel, or by
cross section reactivity biases. As the theoretical model of the core is
improved in areas of known weakness, the deviations are observed to decrease
and will eventually reach a level which is typical of detector uncertainties
alone. By eliminating systematic radial and axial shifts from the calculation,
improved calculational results can be achieved which approach truth and
lead to deviations which approach the measurement uncertainty from a conserva-
tive direction.

Such comparisons of measured and calculated box powers have been made for
several C-E reactors through several cycles. These include the first three
cycles of Calvert Cliffs Unit 1, the first two cycles of Calvert Cliffs
Unit 2, Millstone Unit 2, and St. Lucie Unit 1, for the 217 assembly cores,
and the fourth and fifth cycles of the 133 assembly Fort Calhoun core.
Overall, comparisons have been made at some 170 time points with on the
order of 30-40 instrumented assemblies at each time. The operating data
are described in Section 3.1.

Estimates have been made of 1) the uncertainty of radial power sharing (σ_{F_r}) by comparing axially summed measured and calculated box powers for all levels in all instrumented boxes with intact detector strings; 2) the overall peak power uncertainty (σ_{F_q}) by comparing all the box powers for all instrumented assemblies with intact detectors at all detector levels; and 3) the planar peak power uncertainty ($\sigma_{F_{xy}}$) by comparing the box powers at all locations with intact detectors at each detector level. The calculational and statistical models are described in Sections 3.2 and 3.3.

3.0.2   Summary of Results

The estimates of uncertainty for the pooled data, as well as the number of degrees of freedom, are summarized in Table 3.1 for all these quantities. The results are described in Section 3.4.

3.1   DESCRIPTION OF OPERATING DATA

3.1.1   Description of Measured Data

The measured data consist of the powers in assemblies with fixed in-core rhodium detectors. The conversion of detector signals to box powers by the in-core analysis system is described in detail in Part II. It is achieved through the use of signal to power conversion factors (W') calculated as a function of assembly burnup from fine-mesh 2-D PDQ calculations which account for the rhodium detectors, and through the use of depletion dependent sensitivity factors including initial calibration and background corrections. Calculational errors in these factors are therefore included when comparing the measured assembly power with the true power distribution.

The measured data are examined in three ways to provide estimates of the uncertainties on F_r, F_q and F_{xy}. For F_r, the sum of the powers from each level in the instrumented boxes with fully intact strings is used. For F_{xy} at each detector level, the powers in the instrumented boxes over the length of the valid detectors are used. The powers over the length of each intact detector for all instrumented boxes at all levels are used for the F_q uncertainty analysis.

3.1.2   Operating Histories

Except for initial startup and escalation to power at beginning of cycle (BOC) and coastdowns at end of cycle (EOC), all plants operated at essentially full power with all rods out (ARO) or with only small rod bite. INCA measurements, called CECOR snapshots, were taken periodically throughout each cycle. The overall operating histories, core descriptions and instrument locations for all reactors are given below, together with the actual snapshots and the failed detectors at each time point.

3.1.2.1   Calvert Cliffs (CC) Unit 1

CC Unit 1 has operated through 3 cycles. The loading pattern and instrument locations for the first cycle are shown in Figure 3-1. After power escalation, the core operated with ARO 100% power from 850 to 15,500 MWD/T. This was followed by coastdown with the lead rod bank (Bank 5) inserted less than 18% until EOC at 16.7 GWD/T.[†] Table 3.II lists the CECOR snapshots with the pertinent data including failed detectors used for the comparisons to determine measurement uncertainties.

The second cycle of Unit 1 operated with ARO at 100% power until 5000 MWD/T. From then until 7500 MWD/T it operated at a stretch power of 102%, followed by 90% power operation until EOC at a cycle burnup of 8325 MWD/T, all ARO except at EOC. The loading and instrument patterns are shown on Figure 3-2. The snapshot operating data are given in Table 3.III.

The loading map and instrument pattern for Cycle 3 are shown in Figure 3-3. The core operated at 95-100% power from 1600 MWD/T until EOC at 9440 MWD/T, with occasional lead bank insertions of 5-10%. Table 3.IV summarizes the operating data for the snapshots.

[†]The lead bank rods for all 217 assembly cores are in assemblies 19, 26, 36, 103, 109, 115, 182, 192 and 199.

3.1.2.2   St. Lucie Unit 1

St. Lucie Unit 1 has operated through three complete cycles. The loading and instrument pattern for Cycle 1A are shown in Figure 3-4. The core operated at 100% power from about 2000 MWD/T until EOC at 12.4 GWD/T. There were small lead bank insertions (5-10%) from 10 GWD/T until EOC with a 3% bite on the other rods from 11 GWD/T to EOC. The operating data for the snapshots are given in Table 3.V.

The second cycle operated essentially at 100% power from 300 MWD/T to EOC in a mostly ARO condition with occasional 5-10% insertion of the lead bank. Figure 3-5 shows the loading and instrument patterns and Table 3.VI gives the operating data.

3.1.2.3   Millstone Unit 2

Millstone Unit 2 has operated through two complete cycles. The loading pattern and instrument map are shown in Figure 3-6. During the first cycle, the core did not reach ARO full power operation until 1400 MWD/T. After that, it operated at full power until EOC at 15.1 GWD/T with a 5-10% lead bank insertion from 9 GWD/T on. The snapshot operating data are shown in Table 3.VII.

The second cycle loading map and instrument pattern are given in Figure 3-7. It operated at 100% power from 200 MWD/T until very near EOC at 9.2 GWD/T, with about a 10% lead bank insertion during most of the cycle. Table 3.VIII gives the comparison snapshots operating data.

3.1.2.4   Calvert Cliffs (CC) Unit 2

CC Unit 2 has operated through one complete cycle. The loading map and instrument pattern for the first cycle are given in Figure 3-8. It operated ARO at 100% power from 400 MWD/T until 8250 MWD/T. It then went to stretch power until 12 GWD/T followed by 70% operation from 12 to 14 GWD/T, and 90%

power operation until EOC at 16.2 GWD/T. During the latter period the lead bank was inserted less than 10% with a 3% bite insertion for the rest of the rods. Table 3.X gives the operating conditions at the snapshot points.

The loading map and instrument pattern for the second cycle are given in Figure 3-9 The core has operated at 95-100% power from 300 MWD/T until 4000 MWD/T with frequent lead bank rod insertions of less than 5-10%. Table 3.X summarizes the available snapshot operating data.

3.1.2.5   Fort Calhoun Unit 1

Fort Calhoun Unit 1 has operated through five complete cycles. The loading map and instrument pattern for the fourth cycle are given in Fig. 3-10. It essentially operated ARO at full power throughout the cycle. The snapshot operating data are given in Table 3.X1.

The fifth cycle loading map and instrument pattern are given in Figure 3-11. The core has again operated ARO at full power. Table 3.X11 gives the comparison snapshot operating data.

3.2 DESCRIPTION OF CALCULATIONS

3.2.1 Description of Basic Core Follow Models

The 3-D spatial calculations performed to generate the information for this chapter were done with the coarse mesh, higher order difference diffusion theory ROCS code (References 3.2, 3.3, 3.4) in two neutron energy groups. Each fuel assembly was represented by 4 nodes in the x-y direction. A quarter core configuration was used with zero current boundary conditions along the axes. The core was thus assumed to be quadrant symmetric in a reflected sense. Any asymmetries actually occurring were included in the full core power comparisons of instrumented boxes. The external boundary conditions were represented as albedos calculated in 2-D, 4 group fine-mesh PDQ[3.5] representations of the core, in which the reflector and shroud cross sections were generated in such a way that the material albedos matched those from a multigroup S_8 transport solution. The cross sections for the basic fuel cells were generated by the CEPAK code[3.6], accounting for the correct leakage and soluble boron concentration in the spectrum calculation.

Axially, the 136.7 inch high 217 assembly cores were represented by 24 nodes. The 128 inch high Ft. Calhoun core was represented by 21 nodes. The mesh spacings for both core types are shown in Figure 3-12. Each detector level for either core type is represented by 2 axial meshes. The axial albedo boundary conditions are obtained from fine-mesh PDQ calculations.

The 3-D model for each reactor and cycle was depeleted in a core follow mode, which simulated the actual core operation from BOC to EOC. The actual ROCS depletion step structures for all of the cores and cycles are shown in Tables 3.XIII through 3.XXIII. The cases which were used for comparisons with the measurements are denoted by asterisks.

3.2.2 Correction of Calculation for Radial Shifts

Comparisons of calculated and measured radial signal distributions for core instruments have revealed the presence of systematic errors, corresponding to radial shifts in the calculated distributions. These are attributable to theoretical modeling inaccuracies, which include spatial mesh effects, inadequate reflector treatments, and cross section reactivity biases. Since these systematic errors in the calculations are related only to the gross radial power shape, they should not be included in the assessment of incore detector measurement error.

The corrected calculated distribution C is then used as the basis for comparisons
to determine the measurement uncertainties. For the F_r uncertainties, the

radial shift is used on the radial distribution of the axially summed powers in the instrumented boxes. For F_{xy} and F_q, the radial shift is calculated at each level, [

]

3.3 STATISTICAL MODEL FOR CALCULATION OF ASSEMBLY POWER DISTRIBUTION UNCERTAINTIES

3.3.1 Definitions

$C_i(L)$ Calculated corrected value of the assembly power in instrument location i at instrument level L.

$M_i(L)$ Measured value of the assembly power in instrument location i at instrument level L.

$D_i(L)$ Difference between calculated and measured value of the assembly power in instrument location i at instrument level L.

C_i Calculated value of the axially summed assembly power from each level of intact instrument string location i;

$$\sum_{L=1}^{N_{LEV}} C_i(L).$$

M_i Measured value of the axially summed assembly power from each level in intact instrument string location i;

$$\sum_{L=1}^{N_{LEV}} M_i(L).$$

D_i Difference between calculated and measured value of the axially integrated assembly power in intact instrument location i.

$N(L)$ Number of intact instruments at detector level L $(L=1,..,N_{LEV})$.

N_S Number of intact instrument strings in the core.

N_{LEV} Number of detector levels; = 4.

N_{DET}	Number of intact instruments in core.
N_{DEG}	Total number of degrees freedom.
N_{TOT}	Total number of data points.
σ_D	The standard deviation of the differences between measurement and calculation
σ_M	The measurement standard deviation relative to the true power.
σ_C	The calculation standard deviation relative to the true power.

The basic relationship for σ_M is:

$$\sigma_M^2 = \sigma_D^2 - \sigma_C^2 \qquad (3.5)$$

Because the calculations have been corrected to represent a close approximation of truth, it is expected that σ_C^2 will be small. Equation (3.5) shows that:

$$\sigma_M^2 \leq \sigma_D^2 \qquad (3.6)$$

Therefore, the unbiased sample variance, S_D^2, corresponding to σ_D^2, will be used to construct an upper bound for σ_M^2. Similarly, it can be shown that the one-sided tolerance limits satisfy

$$k_M S_M < k_D S_D \qquad (3.7)$$

where S_M denotes the sample variance corresponding to σ_M, and k_M and k_D are probability/confidence factors.

3.3.2 The Sample Variance for the Difference Between Calculation and Measurement

3.3.2.1 F_r Uncertainty: $S_{D_{Fr}}$

For the F_r measurement uncertainty the axially summed measured and calculated assembly powers in all the intact detector string locations (N_S) are compared. The normalization is:

$$\sum_{i=1}^{N_S} C_i = \sum_{i=1}^{N_S} M_i = N_S \qquad (3.8)$$

The differences are given as:

$$D_i = C_i - M_i, \qquad i=1,\ldots,N_S \qquad (3.9)$$

$$\bar{D} = \frac{1}{N_S} \sum_{i=1}^{N_S} D_i \qquad (3.10)$$

The bias $\bar{D}$ is identically zero because of the normalization. The sample variance of the difference is then:

$$S_{D_{Fr}}^2 = \frac{1}{N_S-1} \sum_{i=1}^{N_S} (D_i - \bar{D})^2 = \frac{1}{N_S-1} \sum_{i=1}^{N_S} D_i^2 \qquad (3.11)$$

3.3.2.2 F_q Uncertainty: $S_{D_{Fq}}$

For the F_q measurement uncertainty the measured and calculated assembly powers for all intact detector locations at all levels in the core (N_{DET}) are compared. The overall normalization is:

$$\sum_{L=1}^{N_{LEV}} \sum_{i=1}^{N(L)} C_i(L) = \sum_{L=1}^{N_{LEV}} \sum_{i=1}^{N(L)} M_i(L) = N_{DET} \qquad (3.12)$$

[

] where the total number of intact detectors N_{DET} is given by

$$N_{DET} = \sum_{L=1}^{N_{LEV}} N(L) \qquad (3.13)$$

The differences are given as:

$$D_i(L) = C_i(L) - M_i(L), \quad i=1,..,N(L),$$
$$L=1,..,N_{LEV} \qquad (3.14)$$

$$\bar{D} = \frac{1}{N_{DET}} \sum_{L=1}^{N_{LEV}} \sum_{i=1}^{N(L)} D_i(L) \qquad (3.15)$$

The bias is again identically zero because of the normalization. The sample variance of the difference is then:

$$S_{D_{Fq}}^2 = \frac{1}{N_{DET}-4} \sum_{L=1}^{N_{LEV}} \sum_{i=1}^{N(L)} D_i^2(L) \qquad (3.16)$$

3.3.2.3 $\underline{F_{xy}}$ Uncertainty: $S_{D_{Fxy}}$

For the F_{xy} measurement uncertainty the measured and calculated assembly powers are compared at each level L for all intact detector locations, N(L). The normalization is:

$$\sum_{i=1}^{N(L)} C_i(L) = \sum_{i=1}^{N(L)} M_i(L) = N(L) \tag{3.17}$$

The differences are given as:

$$D_i(L) = C_i(L) - M_i(L), \quad i=1,..,N(L) \tag{3.18}$$

with a bias

$$\bar{D} = \frac{1}{N(L)} \sum_{i=1}^{N(L)} D_i(L) \tag{3.19}$$

equal to zero because of the normalization.

The sample variance of the difference at level L is then:

$$S_{D_{Fxy}}^2(L) = \frac{1}{N(L)-1} \sum_{i=1}^{N(L)} D_i^2(L) \tag{3.20}$$

3.3.2.4 Summary

The sample variances based on Equations 3.11, 3.16 and 3.20 are unbiased estimates of the true variances for F_r, F_q and F_{xy}.

3.3.3 Procedur: for Pooling Estimates

The estimates for the variances discussed above are applicable to individual comparisons. Pooling for the whole data set is achieved by calculating the variance over the entire set of comparison cases, $\ell=1,..,K$, i.e.,

$$S_{D_K}^2 = \sum_{\ell=1}^{K} \sum_{j=1}^{M_\ell} (D_{j\ell} - \bar{D})^2 / \sum_{\ell=1}^{K} (N_\ell) \qquad (3.21)$$

where M_ℓ is the number of data points and N_ℓ is the number of degrees of freedom in each comparison case ℓ. Since the overall bias remains identically zero,

$$S_{D_K}^2 = \sum_{\ell=1}^{K} \sum_{j=1}^{M_\ell} (D_{j\ell})^2 / \sum_{\ell=1}^{K} (N_\ell) \qquad (3.22)$$

Using the sample variances, this is equivalent to:

$$S_{D_K}^2 = \frac{\sum_{\ell=1}^{K} (M_\ell - 1) \, S_{D\ell}^2}{\sum_{\ell=1}^{K} (N_\ell)} \qquad (3.23)$$

with the total number of degrees of freedom equal to

$$N_{DEG} = \sum_{\ell=1}^{K} (N_\ell) \qquad (3.24)$$

and the total number of data points

$$N_{TOT} = \sum_{\ell=1}^{K} (M_\ell) \qquad (3.25)$$

The total number of data points and degrees of freedom can then be used to determine the k value to obtain the one-sided tolerance limit at the 95%/95% probability/confidence level.

3.3.4   Procedure for Testing Poolability

3.3.5   Procedure for Computing One-sided Tolerance Limits

GENERAL PROCEDURE FOR JUSTIFYING AND CONFIRMING POOLABILITY

[

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3.4   EVALUATION OF MEASUREMENT UNCERTAINTY

3.4.1   Random Component of Observed Differences Between Calculation and Measurement, S_D, for the Various Reactors

The method of estimating σ_D (and σ_M) was described in detail in 3.3. The data for the quantities of interest are summarized below for each reactor.

3.4.1.1   Calvert Cliffs Unit 1

Table 3.XXIVa gives the comparison results for the first cycle operation. Figures 3-13a through 3-13e show typical maps near BOC at 850 MWD/T after escalation to full power for the 4 levels and for the axially summed comparisons. The results of level pooling for F_{xy} and time point pooling for all three quantities as well as the Bartlett test results are summarized in Table 3.XXIVb.

For F_{xy}, pooling the levels satisfies the Bartlett test except at three time points with the value at 10 GWD/T only marginally failing, as shown. When the level values are pooled over timepoints, this leads to results which do not satisfy the Bartlett test, as shown in Table 3.XXIVb. Therefore, as a conservative measure of the F_{xy} uncertainty for this cycle, the pooled level value at the worst time point is taken. This is the value given at the bottom of Table 3.XXIVa.

Table 3.XXIVb also shows that pooling the values for the F_r and F_q uncertainty for all times does not satisfy the Bartlett test. Again, as a conservative estimate of the cycle uncertainties, the worst values are used and are given in Table 3.XXIVa. In general, the pooled F_{xy} level and F_q values are very close because the average axial power shapes across the detector levels are relatively flat, with maximum variations on the order of 10-15%. When the axial shapes across the detectors become flatter, as with depletion, the values become essentially identical, as seen in Tables 3.XXIVa and b.

Table 3.XXVa gives the comparison results for the second cycle together with the overall pooled second cycle uncertainty estimates. Figure 3-14 shows typical BOC maps after power escalation at 989 MWD/T. The results of the Bartlett tests for pooling are given in Table 6.XXVb. These show that the levels pool and the values for all time points pool. The relatively low values of F_{calc} in the Bartlett tests for time point pooling, especially for F_r, are an indication that the data at the various time points are very similar. The level pooling does not display such a behavior, indicating that it is a time point pooling effect. Power distributions show less than a 1-2% variation throughout the cycle so that essentially the same situation is repeated and presented to the ROCS calculation and the CECOR measurement at each time point. A systematic, but unknown, error in the calculation or in the measurement will therefore be able to dominate the sample variance and provide such a correlation effect. The pooled values are the overall values given in Table 3.XXVa.

Table 3.XXVIa gives the data for cycle 3, while Figure 3-15 shows typical BOC3 maps during power escalation at 1200 MWD/T and 91% power. Table 3.XXVIb gives the pooling and Bartlett test results confirming that all levels and time points pool. The overall pooled values are given in Table 3.XXVIa.

3.4.1.2   St. Lucie Unit 1

Table 3.XXVIIa gives the first cycle results for St. Lucie while Figure 3-16 shows a cycle 1 map during power escalation at 880 MWD/T and 50% power. The pooling and Bartlett test results are given in Table 3.XXVIIb. The F_{xy} level values pool at all time points, but the F_{xy} and F_q values do not pool over time points. The F_r values do. As a consequence, the estimates for the cycle given in Table 3.XXVIIa are the pooled F_r values and the worst time point values for F_{xy} and F_q.

Table 3.XXVIIIa gives the comparison results for the second cycle of St. Lucie. Figure 3-17 shows the BOC maps at 1360 MWD/T after escalation to full power. All levels and time points pool to give the overall values in Table 3.XXVIIIa. The results of the pooling and Bartlett tests are given in Table 3.XXVIIIb. The low values of F_{calc} for the Bartlett test are again associated with power distributions varying only slightly (~2%) throughout life.

3.4.1.3   Millstone Unit 2

Table 3.XXIXa presents the cycle 1 comparison results and Figure 3-18 gives the BOC power comparisons at 1350 MWD/T after power escalation to full power. The levels pool at all time points except at 13,000 MWD/T where the Bartlett test is failed, but the values do not pool over time points as shown in Table 3.XXIXb. As a consequence, the estimates for the cycle uncertainties given in Table 3.XXIXa are taken as the worst values occurring during the cycle.

The second cycle results are given in Table 3.XXXa and maps at 500 MWD/T after escalation to full power are given in Figure 3-19. Table 3.XXXb shows that the four levels fail to pool at each time point with level 4 being consistently high throughout the cycle. As a consequence, the values for the worst level (level 4) are used for the time point pooling of F_{xy}. The values for F_{xy} as well as F_r and F_q pool over time points. The low values of F_{calc} for the time point pooling, particularly for F_{xy} at level 4, reveal that the actual measured power distributions change very little throughout life. These overall values are summarized in Table 3.XXXa.

3.4.1.4   Calvert Cliffs Unit 2

The comparison results for Cycle 1 of Calvert Cliffs Unit 2 are given in Table 3.XXXIa with BOC maps at 1400 MWD/T after power escalation given in Figure 3-20. The pooling and Bartlett test results are given in Table 3.XXXIb. For F_{xy}, the levels pool except at four time points, with the

Bartlett test only being marginally failed at the second time point. However, all the quantities fail the test for pooling over the time points. As a consequence, the values at the worst time points are taken as conservative estimates of the uncertainties for the entire cycle and are the values in Table 3.XXXIa.

The comparison results for the second cycle are given in Table 3.XXXIIa. The maps at 810 MWD/T after power escalation are given in Figure 3-21. All levels and time points pool to give the overall values in Table 3.XXXIIa. The results of the pooling and Bartlett tests are given in Table 3.XXXIIb.

3.4.1.5   Fort Calhoun Unit 1

Table 3.XXXIIIa presents the cycle 4 comparison results and Figure 3-22 gives the power comparisons at 1000 MWD/T. All the levels and time points pool to give the overall results in the table. The results of the pooling and Bartlett tests are given in Table 3.XXXIIIb. The low values of F_{calc} in the Bartlett test are again the result of the very small variation of the power distributions throughout life.

The comparison results for the fifth cycle are given in Table XXXIVa and the maps at 300 MWD/T are given in Figure 3-23. The results of the pooling studies are given in Table 3.XXXIVb and again show the similarity of the data and that both levels and time points pool. The overall pooled measurement uncertainties are given in Table 3.XXXIVa.

3.4.2   Summary of Measurement Uncertainty

The standard deviation of the differences assigned for each reactor cycle is summarized in Table 3.XXXV. These represent the pooled values for later cycles and the worst values for the first cycles, except for the St. Lucie

F_r value which is pooled over time.

The results of pooling the data over all cycles and over only either the first or later cycles are given in Table 3.XXXVI together with results of the Bartlett tests. This shows that pooling is not justified even though the spread between the minimum and maximum uncertainties is relatively small. Hence the basic measurement uncertainty is cycle and plant dependent. Therefore, as a conservative measure of the overall uncertainties the worst values, coming from Calvert Cliffs (CC) Unit 1 Cycle 3, will be used, data for which are in Table 3.XXVIa. Examination of the data for F_q, F_{xy}, and F_r in this table shows a small variation of the sample variances with time in the cycle. This is expected on physical grounds because the power distribution remains relatively constant throughout the cycle. Hence, pooling is justified. Confirmation of this justification is provided by statistical tests as described in the following paragraph.

Normality tests (3.7) on the F_q/F_{xy} distribution of differences indicate that the hypothesis of normality is not unreasonable at each individual time point. This is shown in Table 3.XXXVII. For the set of time point pooled data, the D-prime test indicates that the distribution may not be normal. The sample distribution is given and compared to a normal distribution in Figure 3-24. Non-normality is associated with the double-peaked nature exhibited by the sample. The upper end of the distribution, which is important for the one-sided tolerance limit, is close to the normal shape however. Since the distribution may be non-normal, poolability (combining time points) is tested according to Reference 3.9; i.e., the time points represent successive sequences of observations and the observed differences in each sequence are classified according to the quartiles of the entire pooled set. The χ^2-test is then applied to test the homogeneity of the data. Because the power distribution remains nearly the same throughout the cycle, it is expected that the measurement error will remain virtually the same throughout the cycle. This is reflected in the non-normality which indicates that the differences observed have systematic, but unknown components. The χ^2-test further confirms this. The test result χ^2 (with

66 degrees of freedom) $\cong$ 25.0 indicates considerable homogeneity. The data is in fact more homogeneous than may be expected on the basis of random errors only. The physical reason for this is that some of the calculative error, conservatively, remains in the observed differences. Since the calculative error that remains is dominated by systematic, but unknown effects, the results is a relatively large contribution to the sample variance which remains fairly constant with burnup because the power distribution itself does not change much with burnup. Pooling of the data is therefore justified.

Determination of a one-sided tolerance limit for Calvert Cliffs Unit 1 Cycle 3 at the 95/95 probability/confidence level is done according to Reference 3.11. [

]

Figure 3-25 provides similar information for the F_q data of St. Lucie Unit 1 Cycle 2. This indicates a nearly similar distribution for the cycle that exhibits the uncertainties closest to the worst cycle. Figure 3-25 is included for illustrative purposes only. The data is not pooled with that of Calvert Cliffs Unit 1 Cycle 3.

When the F_r distribution of differences for CC Unit 1 Cycle 3 are tested for normality, they pass the W test at all time points and pass the D-prime test for the whole cycle at the 54% level. This is shown in Table 3.XXXVIII. The overall CC Unit 1 Cycle 3 distribution for F_r uncertainties is given in Figure 3-26. This shows that only [   ] of the points lie above the 95/95 one-sided tolerance limit.

The overall uncertainty to be applied to all cycles and plants is taken from the worst case of Table 3.XXXV as discussed above. Since this table

gives the sample standard deviations as absolute values, referred to an average power of unity, a conversion is necessary to obtain the final sample standard deviation in percent of peak power. Table 3.I quotes the measurement uncertainty in percent of peak power. These were obtained from the absolute values in Table 3.XXXV by dividing by the minimum peak box assembly power occurring during the cycle. Table 3.I also gives the associated number of degrees of freedom for use when combining the basic measurement uncertainty with other uncertainties in order to obtain the overall uncertainty. Further, the 95/95 probability/confidence limits on the basic measurement uncertainties for assembly powers are listed in Table 3.I.

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3.9   W. J. Conover, "Practical Non-parametric Statistics," P. 150,
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3.10 D. B. Owen, "Factors for One-sided Tolerance Limits and for Variables
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3.11 W. J. Conover, Ibid., P. 117.

TABLE 3.1

Summary of Uncertainties[†]
For the Measurement of Peak Assembly Power

Quantity	S	Number of Degrees of Freedom	$k_{95/95}$	kS
F_r	[ ]	681	1.725	[ ]
F_{xy}		185	1.801	
F_q		185	1.801	

[†]Quoted in percent of peak assembly value

TABLE 3.II

Calvert Cliffs Unit 1 Cycle 1

Comparison Snapshot Operating Data

Burnup	Power Level	Rod Insertion	Failed Detectors			
			Level 1	Level 2	Level 3	Level 4
850	100%	0%	None	None	23	None
3000	"	"	20	"	"	"
4000	"	"	"	"	"	"
5000	"	"	"	"	"	"
6000	"	"	"	"	"	"
7000	"	"	"	"	"	"
8000	"	"	"	"	"	"
9000	"	"	"	"	"	"
10000	"	"	"	"	"	35
11000	"	"	"	"	"	"
12000	"	"	"	"	"	"
13000	"	"	"	"	"	"
14000	"	"	20,26	"	"	35,8
15000	"	"	"	"	"	"
16000	95%	0%	"	35	"	"

TABLE 3.III

Calvert Cliffs Unit 1 Cycle 2

Comparison Snapshot Operating Data

			Failed Detectors			
Burnup	Power Level	Rod* Insertion	Level 1	Level 2	Level 3	Level 4
234	90%	0%	3,14,15,25,44,1,7	3,14,15,18,25,31,	3,14,15,25,44,1,7	3,14,15,25,44,1,7
332	100%	"	"	1,7,44	"	"
989	"	"	"	"	"	"
1436	"	"	"	"	"	"
1747	"	"	"	"	"	"
2087	"	"	"	"	"	"
2717	"	"	"	"	"	3,14,15,25,30,44,1,7
3338	"	"	"	3,14,15,18,25,31,43,		3,14,15,25,30,33,
3969	"	"	"	44,1,7	"	44,1,7
4184	"	"	"	3,14,15,18,24,25,31,	"	"
5057	102%	"	"	43,44,1,7	"	"
6006	"	"	"	"	"	2,3,14,15,25,30,
6446	104%	"	"	"	"	33,44,1,7
6924	103%	"	"	"	"	"
7334	104%	"	"	3,14,15,18,24,25,31,	3,14,15,25,29,44,	"
7555	102%	"	"	42,43,1,7,44	1,7	"
8258	97%	3%	"	"	"	"

*Lead Bank

TABLE 3.IV
Calvert Cliffs Unit 1 Cycle 3
Comparison Snapshot Operating Data

Failed Detectors

Burnup	Power Level	Rod* Insertion	Level 1	Level 2	Level 3	Level 4
495	85%	0%	4,5,6,16,19,22,23,33	4,6,23,33,35,42	3,4,5,6,16,19,23,33	4,5,6,23,33
1202	91%	"	"	"	"	"
1611	93%	"	"	"	"	"
2021	99%	"	"	4,6,23,33,34,35,42	"	4,5,6,23,33,34
3011	94%	"	"	"	"	"
3811	95%	"	4,5,6,16,19,21,22,23,33	"	3,4,5,6,16,19,23,33,34	"
4626	"	"	"	"	"	4,5,6,23,33,34,45
5434	94%	"	"	"	"	"
5849	97%	7%	"	"	"	"
5994	96%	0%	"	"	"	"
6442	94%	"	4,5,6,16,19,21,22,23,33,34	"	"	"
6658	"	"	"	"	"	4,5,6,20,23,33,34,45
6658	95%	"	"	"	"	"
6869	"	"	"	"	3,4,5,6,8,16,19,23,33,34	"
7147	"	"	"	"	"	"
7327	87%	7%	"	"	"	"
7554	96%	"	"	"	3,4,5,6,8,16,19,21,23,33,34	"
7738	96%	"	"	"	"	"
7964	100%	"	"	"	"	"
8149	96%	"	"	"	"	"
8578	98%	8%	"	"	"	"
8822	100%	2%	"	"	"	"
9042	"	"	"	"	"	"
9440	"	0%	"	"	"	"

*Lead Bank

TABLE 3.V

St. Lucie Cycle 1

Comparison Snapshot Operating Data

			Failed Detectors			
Burnup	Power Level	Rod* Insertion	Level 1	Level 2	Level 3	Level 4
888	51%	0	43	None	32	4,17
2139	100%	"	"	"	"	"
2982	"	"	"	"	"	"
3420	95%	"	"	"	"	"
4903	100%	"	"	"	"	"
5513	"	"	"	"	"	"
6029	"	"	"	"	"	"
6489	"	"	"	"	"	"
7093	"	"	"	"	"	"
8976	"	"	"	"	None	"
9910	"	"	41,43	15	"	"
11359	"	"	34,41,43	"	"	"
12414	"	6.2	"	"	"	"

*Lead Bank

TABLE 3.VI
St. Lucie Cycle 2
Comparison Snapshot Operating Data

				Failed Detectors		
Burnup	Power Level	Rod* Insertion	Level 1	Level 2	Level 3	Level 4
189	90%	5%	6,29,43	29	11,29	23,29
317	98%	7%	"	"	29	"
560	98%	1%	"	"	"	"
1054	100%	9%	"	"	"	"
1361	"	1%	"	"	"	"
1726	"	"	"	"	"	"
2234	"	"	"	"	"	"
2724	"	"	"		29,32	9,23,29
3132	"	3%	"	"	"	"
3649	"	1%	"	"	"	"
4078	"	"	"	"	"	"
4200	"	"	"	"	"	"
4643	"	"	"	"	"	"
5087	"	16%	"	"	"	"
5424	"	1%	"	"	"	"
5948	"	"	"	"	"	"
6368	"	"	"	"	"	"
7030	"	"	"	"	29	9,18,23,29
7382	"	"	"	"	"	"
'885	"	"	"	"	"	"
8370	"	"	"	"	"	"

*Lead Bank

TABLE 3.VII

Millstone II Cycle 1

Comparison Snapshot Operating Data

| | | | | Failed Detectors | | |
Burnup	Power Level	Rod* Insertion	Level 1	Level 2	Level 3	Level 4
1350	100%	0	8,27	16	None	None
2100	"	"	"	16,27	"	"
3350	"	"	"	"	"	"
4000	"	"	"	"	35	"
5100	"	"	"	"	"	"
6200	"	"	"	"	"	"
7500	"	"	8,10.27	"	"	"
9000	"	8%	"	"	"	"
10200	"	4%	8,10,17,18,27	16,17,27	"	"
11300	"	7%	"	"	"	"
12000	"	"	"	"	"	"
13100	93%	9%	"	"	"	"
14700	100%	"	"	"	"	"
15094	"	"	"	"	"	"

*Lead Bank

TABLE 3.VIII
Millstone II Cycle 2
Comparison Snapshot Operating Data

			Failed Detectors			
Burnup	Power Level	Rod* Insertion	Level 1	Level 2	Level 3	Level 4
200	100%	12%	2,8,18,21,27,35	18,27,28,29	4,6,7,9,18,19,39,43	None
500	"	8%	"	"	4,6,7,9,18,19,28,39,43	"
1000	"	5%	"	"	"	25
1500	"	7%	"	"	"	"
2000	"	"	"	"	4,5,6,7,9,18,19,28,39,43	"
2400	"	8%	"	"	"	"
2800	"	"	2,8,18,21,27	16,18,27,28,29	4,5,6,7,9,18,19,28,43	"
3300	"	9%	"	"	"	"
3800	"	8%	"	"	"	"
4300	"	"	"	"	"	"
4800	"	"	"	"	"	"
5200	96%	7%	"	"	"	"
5300	100%	"	2,8,10,18,21,27	"	"	"
5800	"	"	"	"	"	"
6300	"	"	"	"	"	"
6800	"	6%	"	"	"	9,25
7300	"	"	"	"	1 4,5,6,7,9,18,19,28,43	"
7800	"	4%	"	"	"	"
8300	"	5%	"	"	"	"
8700	99%	6%	"	"	"	"
9100	96%	7%	"	"	"	"
9232	94%	"	"	"	"	"

*Lead Bank

TABLE 3.IX

Calvert Cliffs Unit 2 Cycle 1

Comparison Snapshot Operating Data

			Failed Detectors			
Burnup	Power Level	Rod* Insertion	Level 1	Level 2	Level 3	Level 4
1440	100%	0%	None	32	18	None
3330	"	"	42	"	29	"
5630	"	"	"	31,32,35	26,29,41	22,29
6230	"	"	"	"	"	"
6880	"	"	"	"	"	"
7435	"	"	"	"	"	"
8750	105%	"	"	"	"	"
9980	103%	5%	"	"	18,26,29,41	"
10200	"	3%	"	"	"	18,22,29
10675	"	"	"	"	"	"
11980	"	"	"	"	"	22,23,28,29
12840	72%	"	"	14,31,32,35	"	"
13810	"	"	"	14,29,31,32,35	"	22,23,28,29,38

*Lead Bank

TABLE 3.X
Calvert Cliffs Unit 2 Cycle 2
Comparison Snapshot Operating Data

Burnup	Power Level	Rod* Insertion	Failed Detectors			
			Level 1	Level 2	Level 3	Level 4
200	80%	0%	4,26,42	4,26,32,42	4,8,26,42	4,26,39,42
280	87%	9%	"	"	"	4,26,39,42,37
389	89%	8%	"	"	4,26,42	4,26,39,42
495	84%	"	4,15,26,42	"	1,4,26,42	4,13,26,39,42
809	"	0%	"	"	"	"
1273	"	23%	"	"	"	"
1438	98%	0%	"	"	"	"
1698	"	8%	"	"	1,4,8,26,42	"
3519	99%	0%	"	"	"	"
3943	"	"	"	"	"	"

*Lead Bank

TABLE 3.XI

Fort Calhoun Unit 1 Cycle 4
Comparison Snapshot Operating Data

Burnup	Power Level	Rod* Insertion	Failed Detectors Level 1	Level 2	Level 3	Level 4
200	100%	0%	10,11,23,25,28	11,16,23,25,28	1,10,11,16,28	1,11,16,21,22,28
1000	100%	0%	1,10,11,12,17,23,25	1,4,11,16,23,25	1,3,11,16,18	1,11,13,16,17,21,22,27
2000	100%	0%	10,11,12,17,23,25	1,5,6,11,16,17,23,25	1,3,6,11,18,23	1,13,14,16,17,21,22
3000	100%	0%	"	1,5,6,11,16,17,23,25	1,3,11,18	1,13,14,16,17,21,22,27,28
4000	100%	0%	"	5,6,11,17,23,25	1,3,6,18,23,24	1,6,13,14,17,21,22,23,24
5000	100%	0%	"	5,6,11,16,23,25	1,3,6,23,24,26	"
6000	100%	0%	"	5,6,11,17,23,25	"	"
7000	100%	0%	"	5,6,11,17,23,25	"	"
8200	100%	0%	10,12,17,23,24,25	5,6,11,17,21,25	1,3,6,16,23,24,26	6,13,14,17,21,22,23,24

*All rods out

TABLE 3.XII

Fort Calhoun Unit 1 Cycle 5

Comparison Snapshot Operating Data

			Failed Detectors			
Burnup	Power Level	Rod* Insertion	Level 1	Level 2	Level 3	Level 4
300	100%	0%	1,9,10,12,16,24	1,9,16,23,24	1,6,9,16,23,24	1,9,13,14,16,22,23,24
1000	100%	0%	1,9,10,16,24	"	"	"
2000	100%	0%	1,9,10,16,24	"	"	"
3000	100%	0%	1,9,10,12,16,24	"	"	"
4000	100%	0%	1,9,10,16,23,24	"	"	"
5000	100%	0%	1,9,10,16,24	"	"	"
6000	100%	0%	1,9,10,16,24	"	"	"

*All rods out

TABLE 3.XIII
Calvert Cliffs Unit 1 Cycle 1

ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	20%	0%	
01	100	50%	"	
02	500	80%	"	
03	850	100%	"	★
04	1000	"	"	
05	2000	"	"	
06	3000	"	"	★
07	4000	"	"	★
08	5000	"	"	★
09	6000	"	"	★
10	7000	"	"	★
11	8000	"	"	★
12	9000	"	"	★
13	10000	"	"	★
14	11000	"	"	★
15	12000	"	"	★
16	13000	"	"	★
17	14000	"	"	★
18	15000	"	"	★
19	15500	"	"	
20	16000	95%	"	★
21	16500	68%	18%	
22	16670	57%	"	

[†]Lead Bank

TABLE 3.XIV
Calvert Cliffs Unit 1 Cycle 2
ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	49%	0%	
01	:5	70%	"	
02	150	80%	"	
03	200	90%	"	⋆
04	325	100%	"	⋆
05	990	"	"	⋆
06	1436	"	"	⋆
07	1746	"	"	⋆
08	2087	"	"	⋆
09	2722	"	"	⋆
10	3341	"	"	⋆
11	3970	"	"	⋆
12	4192	"	"	⋆
13	5056	102%	"	⋆
14	6000	101%	"	⋆
15	6446	103%	"	⋆
16	7000	"	"	⋆
17	7360	"	"	⋆
18	7600	90%	"	⋆
19	8280	"	3.2%	⋆
20	8325	"	"	

[†]Lead Bank

TABLE 3.XV
Calvert Cliffs Unit 1 Cycle 3
ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	27%	50%	
01	177	84%	0%	
02	495	82%	"	*
03	801	57%	50%	
04	1202	91%	0%	*
05	1611	93%	"	*
06	2021	99%	"	*
07	2238	"	15.8%	
08	2582	93%	0%	
09	3011	94%	"	*
10	3811	95%	"	*
11	4626	"	"	*
12	5434	94%	"	*
13	5849	97%	7.2%	*
14	5994	96%	0%	
15	6442	94%		*
16	6658	"	"	*
17	6658	"	"	*
18	6869	0%	"	
19	6869	95%	"	*
20	7147	"	"	*
21	7327	87%	6.7%	*
22	7554	96%	"	*
23	7738	"	"	*
24	7964	100%	"	*
25	8149	95%	"	*
26	8578	98%	8.2%	*
27	8969	100%	0%	*
28	9440	"	"	

[†] Lead Bank

TABLE 3.XVI
St. Lucie Cycle 1
ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]		Comparisons
Core Reconstituted - Cycle 1A					
03	780	0%	0%		
04	780	30%	"		
05	875	51%	"		*
06	1320	81%	"		
07	1750	90%	"		
08	2190	100%	"		*
09	3000	"	"		*
10	3440	95%	"		*
11	4410	100%	"		
12	4900	"	"		*
13	5500	"	"		*
14	6000	"	"		*
15	6490	"	"		*
16	7000	"	"		*
17	7500	"	"		
18	8000	"	"		
19	8975	"	"		*
20	9500	"	"		
21	9910	"	3%		*
22	10305	"	17%	3.4%[††]	
23	11360	"	5%	"	*
24	12376	"	5%	"	*

[†] Lead Bank

[††] Other Rods

TABLE 3.XVII
St. Lucie Cycle 2
ROCS Maneuver Structure

Man #	Bu	Power	Rods†	Comparisons
00	0	50%	0%	
01	0	30%	5%	
02	189	90%	"	★
03	317	98%	7%	★
04	560	98%	9%	★
05	560	"	"	
06	1054	100%	"	★
07	1361	"	1%	★
08	1726	"	"	★
09	2234	"	"	★
10	2356	85%	3%	★
11	2724	100%	1%	★
12	3132	"	3%	★
13	3649	"	1%	★
14	4078	"	"	★
15	4200	"	"	
16	4200	"	"	★
17	4643	"	"	★
18	4643	"	"	
19	5087	"	16%	★
20	5087	"	"	
21	5424		1%	★
22	5948	"	"	★
23	6368	"	"	★
24	6458	"	"	
25	6458	"	"	★
26	7030	"	"	★
27	7382	"	"	★
28	7885	"	"	★
29	8382	"	"	★

---

† Lead Bank

TABLE 3.XVIII
Millstone II Cycle 1
ROCS Maneuver Structure

Man #	Bu	Power	Rods†	Comparisons
00	0	20%	0%	
01	100	50%	"	
02	300	"	"	
03	600	51%	47%	
04	650	"	0%	
05	850	81%	"	
06	985	"	27%	
07	1150	"	47%	
08	1275	88%	0%	
09	1350	100%	"	*
10	1700	94%	26%	
11	2100	100%	0%	*
12	2800	"	"	
13	3350	"	"	*
14	4000	"	"	*
15	4300	75%	"	
16	4700	100%	"	
17	5100	"	"	*
18	5700	"	"	
19	6200	"	"	*
20	6900	"	"	
21	7500	"	"	*
22	7900	"	"	
23	8500	"	6%	
24	9000	"	8%	*
25	9400	"	"	
26	10200		4%	*

---

†Lead Bank

TABLE 3.XVIII

Millstone II Cycle 1 (Continued)

ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
27	11000	97%	19%	
28	11300	100%	7%	⋆
29	12000	"	"	⋆
30	12600	"	"	
31	13100	93%	9%	⋆
32	13700	100%	"	
33	14200	"	"	
34	14700	"	"	⋆
35	15094	"	"	⋆

———————

[†]Lead Bank

TABLE 3.XIX
Millstone II Cycle 2
ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	50%	10.4%	
01	70	96%	23.5%	
02	200	100%	12.9%	★
03	500	"	7.7%	★
04	1000	"	5.0%	★
05	1500	"	7.1%	★
06	2000	"	"	★
07	2400	"	8.2%	★
08	2800	"	"	★
09	3300	"	8.8%	★
10	3800	"	7.7%	★
11	4300	"	"	★
12	4800	"	"	★
13	5200	96%	7.1%	★
14	5300	100%	"	★
15	5800	"	"	★
16	6300	"	"	★
17	6800	"	6.4%	★
18	7300	"	6.0%	★
19	7800	"	4.3%	★
20	8300	"	5.3%	★
21	8700	99%	5.5%	★
22	9100	96%	6.6%	★
23	9232.3	94%	"	★

[†]Lead Bank

TABLE 3.XX
Calvert Cliffs Unit 2 Cycle 1
ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	50%	0%	
01	200	80%	"	
02	325	"	"	
03	400	100%	"	
04	650	"	25%	
05	1000	"	0%	
06	1440	"	"	*
07	2473	"	"	
08	3331	0%	"	
09	3331	100%	"	*
10	4088	"	"	
11	4400	"	"	
12	5000	"	"	
13	5631	"	"	*
14	6230	"	"	*
15	6880	"	"	*
16	7435	"	"	*
17	8261	106%		
18	8751	105%	2.5%	*
19	9169	95%	10%	
20	9983	103%	5%	*
21	10205	"	"	*
22	1675	"	"	*
23	11116	97%	"	
24	11979	103%	"	*
25	12369	78%	"	
26	12837	72%	"	*

[†]Lead Bank

TABLE 3.XX
Calvert Cliffs Unit 2 Cycle 1 (Continued)
ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
27	12959	105%	5%	
28	12959	72%	"	
29	13283	"	"	
30	13811	"	"	★
31	13811	74%	3.4%	
32	14313	66%	"	
33	15185	90%	"	
34	15525	91%	"	
35	16182	"	"	

[†]Lead Bank

TABLE 3.XXI
Calvert Cliffs Unit 2 Cycle 2
ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	49%	2%	
01	22	"	"	
02	33	80%	0%	
03	200	"	"	
04	200	94%	"	
05	280	"	10%	*
06	280	88%	9%	
07	389	90%	"	*
08	389	89%	8%	
09	495	84%	"	
10	558	97%	9%	*
11	809	"	0%	*
12	809	"	"	
13	1273	"	23%	*
14	1438	98%	0%	*
15	1698	"	8.4%	*
16	1914	"	0%	
17	2095	92%	6.7%	
18	2267	93%	9%	
19	2518	98%	0%	
20	2950	"	"	
21	3141	"	"	
22	3397	92%	13 .%	
23	3519	99%	"	*
24	3943	100%	"	*

[†]Lead Bank

TABLE 3.XXII
Fort Calhoun Unit 1 Cycle 4
ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	100%	0%	
01	200	"	"	★
02	500	"	"	
03	1000	"	"	★
04	2000	"	"	★
05	3000	"	"	★
06	4000	"	"	★
07	5000	"	"	★
08	6000	"	"	★
09	7000	"	"	★
10	8000	"	"	
11	8200	100%	0%	★

[†]All rods out

TABLE 3.XXIII

Fort Calhoun Unit 1 Cycle 5

ROCS Maneuver Structure

Man #	Bu	Power	Rods[+]	Comparisons
00	0	100%	0%	
01	300	"	"	*
02	1000	"	"	*
03	2000	"	"	*
04	3000	"	"	*
05	4000	"	"	*
06	5000	"	"	*
07	6000	"	"	*
08	7000	"	"	
09	8000	"	"	
10	9000	"	"	
11	10000	100%	0%	

+All rods out

TABLE 3.XXIVa
Calvert Cliffs Unit 1 Cycle 1
Standard Deviation of Difference Between Calculation and Measurement
And Results of Bartlett Tests for Data Pooling

$$S_{Fxy} (N(L))$$

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
850		45		45		44		45		179		44
3K		44		"		"		"		178		43
4K		"		"		"		"		178		"
5K		"		"		"		"		178		"
6K		"		"		"		"		178		"
7K		"		"		"		"		178		"
8K		"		"		"		"		178		"
9K		"		"		"		"		178		"
10K		"		"		"		44		177		42
11K		"		"		"		"		177		"
12K		"		"		"		"		177		"
13K		"		"		"		"		177		"
14K		"		"		"		43		175		40
15K		43		"		"		"		175		"
16K		"		44		"		"		174		"

Overall

	S_D	N_{DEG}
F_{xy}		2597
F_q		2597
F_r		618

+Worst Value

I.3.52

TABLE 3.XXIVb
Calvert Cliffs Unit 1 Cycle 1
Results of Data Pooling and Bartlett Tests

F_{xy} Pooled Level Results*

Burnup	S_{Fxy}	$F(3,\infty)$ Calc	N_{DEG}
850			175
3000			174
4000			174
5000			174
6000			174
7000			174
8000			174
9000			174
10000†			173
11000			173
12000			173
13000			173
14000			172
15000†			171
16000†			170

Pooled Time Point Results**

	S_D	$F(14,\infty)$ Calc	N_{DEG}
F_{xy} ††			2597
F_q ††			2597
F_r ††			618

* For level pooling, $F(3,\infty) < 2.60$ in order to pass at the 5% significance level.
† Levels fail to pool
** For time point pooling, $F(14,\infty) < 1.69$ in order to pass at the 5% significance level.
†† Time points fail to pool.
  + Worst Value

TABLE 3.XXVa

Calvert Cliffs Unit 1 Cycle 2

Standard Deviation of Difference Between Calculation and Measurement

And Results of Bartlett Tests for Data Pooling

$$S_{Fxy}\,(N(L))$$

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
234		38		36		38		38		150		36
332		"		"		"		"		150		"
989		"		"		"		"		150		"
1436		"		"		"		"		150		"
1747		"		"		"		"		150		"
2087		"		"		"		"		150		"
2717		"		"		"		37		149		35
3338		"		35		"		36		147		33
3969		"		34		"		"		146		32
4184		"		"		"		"		146		"
5057		"		"		"		"		146		"
6006		"		"		"		35		145		31
6446		"		"		"		"		145		"
6924		"		"		"		"		145		"
7334		"		33		37		"		143		29
7555		"		"		"		"		143		"
8258		"		"		"		"		143		"

Overall

	S_D	N_{DEG}
F_{xy}		2431
F_q		2431
F_r		543

I.3.55

F_{xy} Pooled Level Results*

Burnup	S_{Fxy}	$F(3,\infty)$ Calc	N_{DEG}
234			146
332			146
989			146
1436			146
1747			146
2087			146
2717			145
3338			143
3969			142
4184			142
5057			142
6006			141
6446			141
6924			141
7334			139
7555			139
8258			139

Pooled Time Point Results**

	S_D	$F(16,\infty)$ Calc	N_{DEG}
F_{xy}			2431
F_q			2431
F_r			543

* For level pooling, $F(3,\infty) < 2.60$ in order to pass at the 5% significance level.

** For time point pooling, $F(16,\infty) < 1.62$ in order to pass at the 5% significance level.

TABLE 3.XXVIa

Calvert Cliffs Unit 1 Cycle 3

Standard Deviation of Difference Between Calculation and Measurement
And Results of Bartlett Tests for Data Pooling

S_{Fxy} (N(L))

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
495		37		39		37		40		153		34
1202		"		"		"		"		153		"
1611		"		"		"		"		153		"
2021		"		38		"		39		151		33
3011		"		"		::		"		151		"
3811		36		"		36		"		149		32
4626		"		"		"		38		148		31
5434		"		"		"		"		148		"
5849		"		"		"		"		148		"
6442		35		"		"		"		147		"
6658		"		"		"		37		146		30
6658		"		"		"		"		146		"
6869		"		"		35		"		145		29
7147		"		"		"		"		145		"
7327		"		"		"		"		145		"
7554		"		"		34		"		144		"
7738		"		"		"		"		144		"
7964		"		"		"		"		144		"
8149		"		"		"		"		144		"
8578		"		"		"		"		144		"
8822		"		"		"		"		144		"
9042		"		"		"		"		144		"
9440		"		"		"		"		144		"

Overall

	S_D	N_{DEG}
F_{xy}		3288
F_q		3288
F_r		681

I.3.56

TABLE 3.XXVIb
Calvert Cliffs Unit 1 Cycle 3
Results of Data Pooling and Bartlett Tests

F_{xy} Pooled Level Results*					Pooled Time Point Results**		
Burnup	S_{Fxy}	F(3,∞) Calc	N_{DEG}			S_D	F(22,∞) Calc	N_{DEG}
495			149		F_{xy}			3288
1202			149					
1611			149					
2021			147		F_q			3288
3011			147					
3811			145					
4626			144		F_r			681
5434			144					
5849			144					
6442			143					
6658			142					
6658			142					
6869			141					
7147			141					
7327			141					
7554			140					
7738			140					
7964			140					
8149			140					
8578			140					
8822			140					
9042			140					
9440			140					

* For level pooling, F(3,∞) <2.60 in order to pass at the 5% significance level.

** For time point pooling, F(22,∞) <1.53 in order to pass at the 5% significance level.

TABLE 3.XXVIIa

St. Lucie Unit 1 Cycle 1

Standard Deviation of Difference Between Calculation and Measurement and Results of Bartlett Tests for Data Pooling

$$S_{Fxy} (N(L))$$

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
888		44		45		44		43		176		41
2139		"		"		"		"		176		"
2982		"		"		"		"		176		"
3420		"		"		"		"		176		"
4903		"		"		"		"		176		"
5513		"		"		"		"		176		"
6029		"		"		"		"		176		"
6489		"		"		"		"		176		"
7093		"		"		"		"		176		"
8976		"		"		45		"		177		42
9910		43		44		"		"		175		40
11359		42		"		"		"		174		39
12414		"		"		"				174		"

Overall

	S_D	N_{DEG}
F_{xy}		2232
F_q		2232
F_r		516

+Worst value

TABLE 3.XXVIIb

St. Lucie Unit 1 Cycle 1

Results of Data Pooling and Bartlett Tests

F_{xy} Pooled Level Results*					Pooled Time Point Results**		
Burnup	S_{Fxy}	$F(3,\infty)$ Calc	N_{DEG}		S_D	$F(12,\infty)$ Calc	N_{DEG}
888			172	F_{xy}††			2232
2139			172				
2982			172	F_q††			2232
3420			172				
4903			172	F_r			516
5513			172				
6029			172				
6489			172				
7093			172				
8976			173				
9910			171				
11359			170				
12414			170				

* For level pooling, $F(3,\infty) < 2.60$ in order to pass at the 5% significance level.

** For time point pooling, $F(12,\infty) < 1.75$ in order to pass at the 5% significance level.

†† Time points fail to pool.

+ Worst Value

TABLE 3.XXVIIIa

St. Lucie Unit 1 Cycle 2

Standard Deviation of Difference Between Calculation and Measurement and Results of Bartlett Tests for Data Pooling

$$S_{Fxy} \; (N(L))$$

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
189		42		44		43		43		172		40
317		"		"		44		"		173		41
560		"		"		"		"		173		"
1054		"		"		"		"		173		"
1361		"		"		"		"		173		"
1726		"		"		"		"		173		"
2234		"		"		"		"		173		"
2724		"		"		43		42		171		39
3132		"		"		"		"		171		"
3649		"		"		"		"		171		"
4078		"		"		"		"		171		"
4200		"		"		"		"		171		"
4643		"		"		"		"		171		"
5087		"		"		"		"		171		"
5424		"		"		"		"		171		"
5948		"		"		"		"		171		"
6368		"		"		"		"		171		"
7030		"		"		44		41		171		"
7382		"		"		"		"		171		"
7885		"		"		"		"		171		"
8370		"		"		"		"		171		"

Overall

	S_D	N_{DEG}
F_{xy}		3520
F_q		3520
F_r		811

TABLE 3.XXVIIIb
St. Lucie Unit 1 Cycle 2
Results of Data Pooling and Bartlett Tests

F_{xy} **Pooled Level Results***

Burnup	S_{Fxy}	$F(3,\infty)$ Calc	N_{DEG}
189			168
317			169
560			169
1054			169
1361			169
1726			169
2234			169
2724			167
3132			167
3649			167
4078			167
4200			167
4643			167
5087			167
5424			167
5948			167
6368			167
7030			167
7382			167
7885			167
8370			167

Pooled Time Point Results**

	S_D	$F(20,\infty)$ Calc	N_{DEG}
F_{xy}			3520
F_q			3520
F_r			811

* For level pooling, $F(3,\infty) < 2.60$ in order to pass at the 5% significance level.

** For time point pooling, $F(20,\infty) < 1.57$ in order to pass at the 5% significance level.

TABLE 3.XXIXa

Millstone Unit 2 Cycle 1

Standard Deviation of Difference Between Calculation and Measurement and Results of Bartlett Tests for Data Pooling

Burnup	S_{Fxy} (N(L))								S_{Fq}	N_{DET}	S_{Fr}	N_S
	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)				
1350		43		44		45		45		177		42
2100		"		43		"		"		176		"
3350		"		"		"		"		176		"
4000		"		"		44		"		175		41
5100		"		"		"		"		175		"
6200		"		"		"		"		175		"
7500		42		"		"		"		174		40
9000		"		"		"		"		174		"
10200		40		42		"		"		171		38
11300		"		"		"		"		171		"
12000		"		"		"		"		171		"
13100		"		"		"		"		171		"
14700		"		"		"		"		171		"
15094		"		"		"		"		171		"

Overall

	S_D	N_{DEG}
F_{xy}		2372
F_q		2372
F_r		543

+Worst Value

I.3.62

TABLE 3.XXIXb

Millstone Unit 2 Cycle 1

Results of Data Pooling and Bartlett Tests

F_{xy} Pooled Level Results*				Pooled Time Point Results**		
Burnup	S_{Fxy}	$F(3,\infty)$ Calc	N_{DEG}		S_D	$F(13,\infty)$ Calc	N_{DEG}
1350			173			
2100			171	F_{xy}††		2372
3350			171			
4000			171			
5100			171	F_q††		2372
6200			171			
7500			170			
9000			170	F_r††		543
10200			167			
11300			167			
12000			167			
13100†			167			
14700			167			
15094			167			

* For level pooling, $F(3,\infty) <2.60$ in order to pass at the 5% significance level.

† Levels fail to pool

** For time point pooling, $F(13,\infty) <1.70$ in order to pass at the 5% significance level.

†† Time points fail to pool.

+ Worst Value

TABLE 3.XXXa

Millstone Unit 2 Cycle 2

Standard Deviation of Difference Between Calculation and Measurement
And Results of Bartlett Tests for Data Pooling

S_{Fxy} (N(L))

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
200		39		41		37		45		162		30
500		"		"		36		"		161		"
1000		"		"		"		44		160		29
1500		"		"		"		"		160		"
2000		"		"		35		"		159		28
2400		"		"		"		"		159		"
2800		40		40		36		"		160		29
3300		"				"		"		160		"
3800		"				"		"		160		"
4300		"				"		"		160		"
4800		"				"		"		160		"
5300		39				"		"		159		28
5800		"				"		"		159		"
6300		"				"		"		159		"
6800		"				"		43		158		"
7300		"				35		"		157		27
7800		"				"		"		157		"
8300		"				"		"		157		"
8700		"				"		"		157		"
9100		"		"		"		"		157		"
9232		"		"		"		"		157		"

Overall

	S_D	N_{DEG}
F_{xy}		898
F_q		3254
F_r		571

TABLE 3.XXXb
Millstone Unit 2 Cycle 2
Results of Data Pooling and Bartlett Tests

F_{xy} Pooled Level Results*†

Pooled Time Point Results**

Burnup	S_{Fxy}	F(3,∞) Calc	N_{DEG}		S_D	F(20,∞) Calc	N_{DEG}
200			158				
500			157	F			
1000			156	All values			3254
1500			156	Level 4 values			898
2000			155	only			
2400			155				
2800			156	F_q			3254
3300			156				
3800			156	F_r			571
4300			156				
4800			156				
5300			155				
5800			155				
6300			153				
6800			153				
7300			153				
7800			153				
8300			153				
8700			153				
9100			153				
9232			153				

* For level pooling, F(3,∞) <2.60 in order to pass at the 5% significance level.

† Levels fail to pool at all time points

** For time point pooling, F(20,∞) <1.57 in order to pass at the 5% significance level.

\+ Worst value

TABLE 3.XXXIa

Calvert Cliffs Unit 2 Cycle 1

Standard Deviation of Difference Between Calculation and Measurement and Results of Bartlett Tests for Data Pooling

$$S_{Fxy} (N(L))$$

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
1440		45		44		44		45		178		43
3330		44		"		"		"		177		42
5630		"		42		42		43		171		37
6230		"		"		"		"		171		"
6880		"		"		"		"		171		"
7435		"		"		"		"		171		"
8750		"		"		"		"		171		"
9980		"		"		41		"		170		36
10675		"		"		"		42		169		"
11980		"		"		"		41		168		34
12840		"		41		"		"		167		33
13810		"		40		"		40		165		32

Overall

	S_D	N_{DEG}
F_{xy}		2001
F_q		2001
F_r		429

+Worst value

TABLE 3.XXXIb

Calvert Cliffs Unit 2 Cycle 1

Results of Data Pooling and Bartlett Tests

F_{xy} Pooled Level Results*				Pooled Time Point Results**		
Burnup	S_{Fxy}	$F(3,\infty)$ Calc	N_{DEG}	S_D	$F(11,\infty)$ Calc	N_{DEG}
1440			174			
3330†			173	F_{xy}††		2001
5630			167			
6230			167			
6880			167	F_q††		2001
7435			167			
8750			167			
9980			166	F_r††		429
10675†			165			
11980†			164			
12840			163			
13810†			161			

* For level pooling, $F(3,\infty) < 2.60$ in order to pass at the 5% significance level.

† Levels fail to poo

** For time point pooling, $F(11,\infty) < 1.79$ in order to pass at the 5% significance level.

†† Time points fail to pool.

TABLE 3.XXXIIa

Calvert Cliffs Unit 2 Cycle 2

Standard Deviation of Difference Between Calculation and Measurement
and Results of Bartlett Tests for Data Pooling

$$S_{Fxy} (N(L))$$

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
200		42		41		41		41		165		39
280		"		"		41		40		164		38
389		"		"		42		41		166		40
495		41		"		41		40		163		37
909		"		"		"		"		163		"
1273		"		"		"		"		163		"
1438		"		"		"		"		163		"
1698		"		"		40		"		162		36
1914		"		"		"		"		162		"
2095		"		"		"		"		162		"
2518		"		"		"		"		162		"
3141		"		"		"		"		162		"
3519		"		"		"		"		162		"
3943		"		"		"		"		162		"

Overall

	S_D	N_{DEG}
F_{xy}	[ ]	2225
F_q		2225
F_r		503

I.3.68

TABLE 3.XXXIIb

Calvert Cliffs Unit 2 Cycle 2

Results of Data Pooling and Bartlett Tests

F_{xy} Pooled Level Results*					Pooled Time Point Results**		
Burnup	S_{Fxy}	$F(3,\infty)$ Calc	N_{DEG}			S_D	$F(13,\infty)$ Calc	N_{DEG}
200			161				
280			160	F_{xy}			2225
389			160				
495			159	F_q			2225
809			159				
1273			159				
1438			159	F_r			503
1698			158				
1914			158				
2095			158				
2518			158				
3141			158				
3519			158				
3943			158				

* For level pooling, $F(3,\infty) < 2.60$ in order to pass at the 5% significance level.

** For time point pooling, $F(13,\infty) < 1.70$ in order to pass at the 5% significance level.

TABLE 3.XXXIIIa

Fort Calhoun Unit 1 Cycle 4

Standard Deviation of Difference between Calculation and Measurement and Results of Bartlett Tests for Data Pooling

S_{Fxy} (N(L))

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
200		23		23		23		22		91		19
1000		21		22		23		20		86		13
2000		22		20		22		21		85		12
3000		22		20		24		19		85		10
4000		22		22		22		19		85		12
5000		22		22		22		19		85		11
6000		22		22		22		19		85		12
7000		22		22		2?		19		85		12
8200		22		22		21		20		85		11

Overall

	S_D	N_{DEG}
F_{xy}		736
F_q		736
F_r		103

I.3.70

TABLE 3.XXXIIIb

Fort Calhoun Unit 1 Cycle 4

Results of Data Pooling and Bartlett Tests

$\overline{F}_{xy}$ Pooled Level Results*				Pooled Time Point Results**		
Burnup	S_{Fxy}	$F_{calc}(3,\infty)$	N_{DEG}	S_D	$F_{calc}(8,\infty)$	N_{DEG}
200			87	F_{xy}		736
1000			82	F_q		736
2000			81	F_r		103
3000			81			
4000			81			
5000			81			
6000			81			
7000			81			
8200			81			

*   For level pooling, $F(3,\infty) < 2.60$ in order to pass at the 5% significance level.

**   For time point pooling, $F(8,\infty) < 1.94$ in order to pass at the 5% significance level.

TABLE 3.XXXIVa

Fort Calhoun Unit 1 Cycle 5

Standard Deviation of Difference Between Calculation and Measurement
and Results of Bartlett Tests for Data Pooling

$$S_{Fxy} (N(L))$$

Burnup	Level 1	N(1)	Level 2	N(2)	Level 3	N(3)	Level 4	N(4)	S_{Fq}	N_{DET}	S_{Fr}	N_S
300	[	22	[	23	[	22	[	20	[	87	[	17
1000		23		23		22		20		88		18
2000		23		23		22		20		88		18
3000		22		23		22		20		87		17
4000		22		23		22		20		87		18
5000		23		23		22		20		88		18
6000	]	23	]	23	]	22	]	20	]	88	]	18

Overall

	S_D	N_{DEG}
F_{xy}	[ ]	585
F_q	[ ]	585
F_r	[ ]	117

TABLE 3.XXXIVb
Fort Calhoun Unit 1 Cycle 5
Results of Data Pooling and Bartlett Tests

F_{xy} Pooled Level Results*				Pooled Time Point Results**		
Burnup	$S_{F_{xy}}$	$F_{calc}(3,\infty)$	N_{DEG}	S_D	$F_{calc}(6,\infty)$	N_{DEG}
300			83	F_{xy}		585
1000			84	F_q		585
2000			84	F_r		117
3000			83			
4000			83			
5000			84			
6000			84			

* For level pooling, $F(3,\infty) < 2.60$ in order to pass at the 5% significance level.

** For time point pooling, $F(6,\infty) < 2.10$ in order to pass at the 5% significance level.

TABLE 3.XXXV

Summary of Standard Deviations of
Comparisons Between Calculations and Measurement

Reactor	S_{Fxy}	N_{DEG}	S_{Fq}	N_{DEG}	S_{Fr}	N_{DEG}
Calvert Cliffs Unit 1 Cycle 1		2597		2597		618
Calvert Cliffs Unit 1 Cycle 2		2431		2431		543
Calvert Cliffs Unit 1 Cycle 3		3288		3288		681
St. Lucie Unit 1 Cycle 1		2232		2232		516
St. Lucie Unit 1 Cycle 2		3520		3520		811
Millstone Unit 2 Cycle 1		2372		2372		543
Millstone Unit 2 Cycle 2		898		3254		571
Calvert Cliffs Unit 2 Cycle 1		2001		2001		429
Calvert Cliffs Unit 2 Cycle 2		2225		2225		503
Fort Calhoun Unit 1 Cycle 4		736		736		103
Fort Calhoun Unit 1 Cycle 5		585		585		117

+Worst Value

TABLE 3.XXXVI
Results of Data Pooling and Bartlett Tests

All Cycles[†]

	S_D	$F(10,\infty)$ calc	$F(10,\infty)$ Theoretical, $\alpha=5\%$	N_{DEG}
F_{xy}			1.8	22,885[†]
F_q			1.8	25,241[†]
F_r			1.8	5,435[†]

First Cycles[†]

	S_D	$F(3,\infty)$ calc	$F(3,\infty)$ Theoretical, $\alpha=5\%$	N_{DEG}
F_{xy}			2.6	9202[†]
F_q			2.6	9292[†]
F_r			2.6	9106[†]

Later Cycles[†]

	S_D	$F(6,\infty)$ calc	$F(6,\infty)$ Theoretical, $\alpha=5\%$	N_{DEG}
F_{xy}			2.1	13,683[†]
F_q			2.1	16,039[†]
F_r			2.1	3,329[†]

[†] Fail to pool

TABLE 3.XXXVII

Calvert Cliffs Unit 1 Cycle 3

D' Normality Test on F_q

Burnup	N_{DET}	S_{Fq}	D'	$\alpha(\%)$
495	153			
1202	153			
1611	153			
2021	151			
3011	151			
3811	149			
4626	148			
5434	148			
5849	148			
6442	147			
6656	146			
6658	146			
6869	145			
7147	145			
7327	145			
7554	144			
7738	144			
7964	144			
8149	144			
8578	144			
8822	144			
9042	144			
9440	144			

Total Sample Size = 3380

TABLE 3.XXXVIII

Calvert Cliffs Unit 1 Cycle 3

W Normality Test on F_r

Burnup	N_S	S_{Fr}	W	P(%)
495	34			
1202	34			
1611	34			
2021	33			
3011	33			
3811	32			
4626	31			
5434	31			
5849	31			
6442	31			
6658	30			
6658	30			
6869	29			
7147	29			
7327	29			
7554	29			
7738	29			
7964	29			
8149	29			
8578	29			
8822	29			
9042	29			
9440	29			

FIGURE 3-1
LOADING & INSTRUMENT PATTERN
CALVERT CLIFFS UNIT I CYCLE 1

BATCH BOX
INSTR.

| C | 1 | C | 2 | C | 3 | C | 4 |

| C 5 | C 6 | C+ 7 | C+ 8 | B 9 | C+ 10 | C+ 11 | C 12 | C 13 |
1

| C 14 | C. 15 | B 16 | A 17 | B 18 | A 19 | B 20 | A 21 | B 22 | C. 23 | C 24 |
2 3

| C 25 | C. 26 | B 27 | A 28 | B 29 | A 30 | B 31 | A 32 | B 33 | A 34 | B 35 | C. 36 | C 37 |
4 5 6

| C 38 | C. 39 | B 40 | A 41 | B 42 | A 43 | B 44 | A 45 | B 46 | A 47 | B 48 | A 49 | B 50 | C. 51 | C 52 |
7 8 9 10

| C 53 | B 54 | A 55 | B 56 | A 57 | BX 58 | A 59 | B 60 | A 61 | B 62 | A 63 | B 64 | A 65 | B 66 | C 67 |
11 12 13

| C+ 68 | A 69 | B 70 | A 71 | B 72 | A 73 | B 74 | A 75 | B 76 | A 77 | B 78 | A 79 | B 80 | A 81 | C+ 82 |
14 15 16 17

| C 83 | | | | | | | | | | | | | | | C 84 |

| C+ 85 | B 86 | A 87 | B 88 | A 89 | B 90 | A 91 | B 92 | A 93 | B 94 | A 95 | B 96 | A 97 | B 98 | C+ 99 |
18 19

| C 100 | | | | | | | | | | | | | | | C 101 |
20

| B 102 | A 103 | B 104 | A 105 | B 106 | A 107 | B 108 | A 109 | B 110 | A 111 | B 112 | A 113 | B 114 | A 115 | B 116 |

| C 117 | | | | | | | | | | | | | | | C 118 |
21 22 23 24 25 26

| C+ 119 | B 120 | A 121 | B 122 | A 123 | B 124 | A 125 | B 126 | A 127 | B 128 | A 129 | B 130 | A 131 | B 132 | C+ 133 |

| C 134 | | | | | | | | | | | | | | | C 135 |
27 31

| C+ 136 | A 137 | B 138 | A 139 | BX 140 | A 141 | B 142 | A 143 | B 144 | A 145 | BX 146 | A 147 | B 148 | A 149 | C+ 150 |
28 29 30

| C 151 | B 152 | A 153 | B 154 | A 155 | B 156 | A 157 | B 158 | A 159 | B 160 | A 161 | B 162 | A 163 | B 164 | C 165 |
32 33 34 35

| C 166 | C. 167 | B 168 | A 169 | B 170 | A 171 | B 172 | A 173 | B 174 | A 175 | B 176 | A 177 | B 178 | C. 179 | C 180 |
36 37 38 39

| C 181 | C. 182 | B 183 | A 184 | B 185 | A 186 | B 187 | A 188 | B 189 | A 190 | B 191 | C. 192 | C 193 |
40 41 42

| C 194 | C. 195 | B 196 | A 197 | B 198 | A 199 | B 200 | A 201 | B 202 | C. 203 | C 204 |
43 44

| C 205 | C 206 | C+ 207 | C+ 208 | B 209 | C+ 210 | C+ 211 | C 212 | C 213 |
45

| C 214 | C 215 | C 216 | C 217 |

* BX INDICATES TEST ASSEMBLY

FIGURE 3-2
LOADING & INSTRUMENT PATTERN
CALVERT CLIFFS UNIT I CYCLE 2

BATCH BOX

INSTR.

| D 1 | D 2 | D 3 | D 4 |

| D 5 | D 6 | D 7 | C 8 | B 9 | C 10 | D 11 | D 12 | D 13 |

1

| D 14 | D 15 | C+ 16 | B 17 | B 18 | D 19 | B 20 | B 21 | C+ 22 | D 23 | D 24 |

2   3

| D 25 | C 26 | B 27 | B 28 | D 29 | B 30 | B 31 | B 32 | D 33 | B 34 | B 35 | C 36 | D 37 |

4   5   6

| D 38 | D 39 | B 40 | D 41 | B 42 | B 43 | C. 44 | C 45 | C. 46 | B 47 | B 48 | D 49 | B 50 | D 51 | D 52 |

7   8   9   10

| D 53 | C+ 54 | B 55 | B 56 | BX 57 | C 58 | C 59 | C. 60 | C 61 | C 62 | B 63 | B 64 | B 65 | C+ 66 | D 67 |

11   12   13

| D 68 | B 69 | D 70 | B 71 | C 72 | B 73 | C+ 74 | C 75 | C+ 76 | B 77 | C 78 | B 79 | D 80 | B 81 | D 82 |

| D 83 | 14   15   16   17 | D 84 |

| C 85 | B 86 | B 87 | C. 88 | C 89 | C+ 90 | B 91 | C 92 | B 93 | C+ 94 | C 95 | C. 96 | B 97 | B 98 | C 99 |

| D 100 | 18   19 | D 101 |

20

| B 102 | D 103 | B 104 | C 105 | C. 106 | C 107 | C 108 | B 109 | C 110 | C 111 | C. 112 | C 113 | B 114 | D 115 | B 116 |

| D 117 | 21   22   23   24   25   26 | D 118 |

| C 119 | B 120 | B 121 | C. 122 | C 123 | C+ 124 | B 125 | C 126 | B 127 | C+ 128 | C 129 | C. 130 | B 131 | B 132 | C 133 |

| D 134 | 27 | D 135 |

| D 136 | B 137 | D 138 | B 139 | C 140 | B 141 | C+ 142 | C 143 | C+ 144 | B 145 | C 146 | B 147 | D 148 | B 149 | D 150 |

28   29   30   31

| D 151 | C+ 152 | B 153 | B 154 | B 155 | C 156 | C 157 | C. 158 | C 159 | C 160 | BX 161 | B 162 | B 163 | C+ 164 | D 165 |

32   33   34   35

| D 166 | D 167 | B 168 | D 169 | B 170 | B 171 | C. 172 | C 173 | C. 174 | B 175 | B 176 | D 177 | B 178 | D 179 | D 180 |

36   37   38   39

| C 181 | C 182 | B 183 | B 184 | D 185 | B 186 | B 187 | B 188 | D 189 | B 190 | B 191 | C 192 | D 193 |

40   41   42

| D 194 | D 195 | C+ 196 | B 197 | B 198 | D 199 | B 200 | B 201 | C+ 202 | D 203 | D 204 |

43   44

| D 205 | D 206 | D 207 | C 208 | B 209 | C 210 | D 211 | D 212 | D 213 |

45

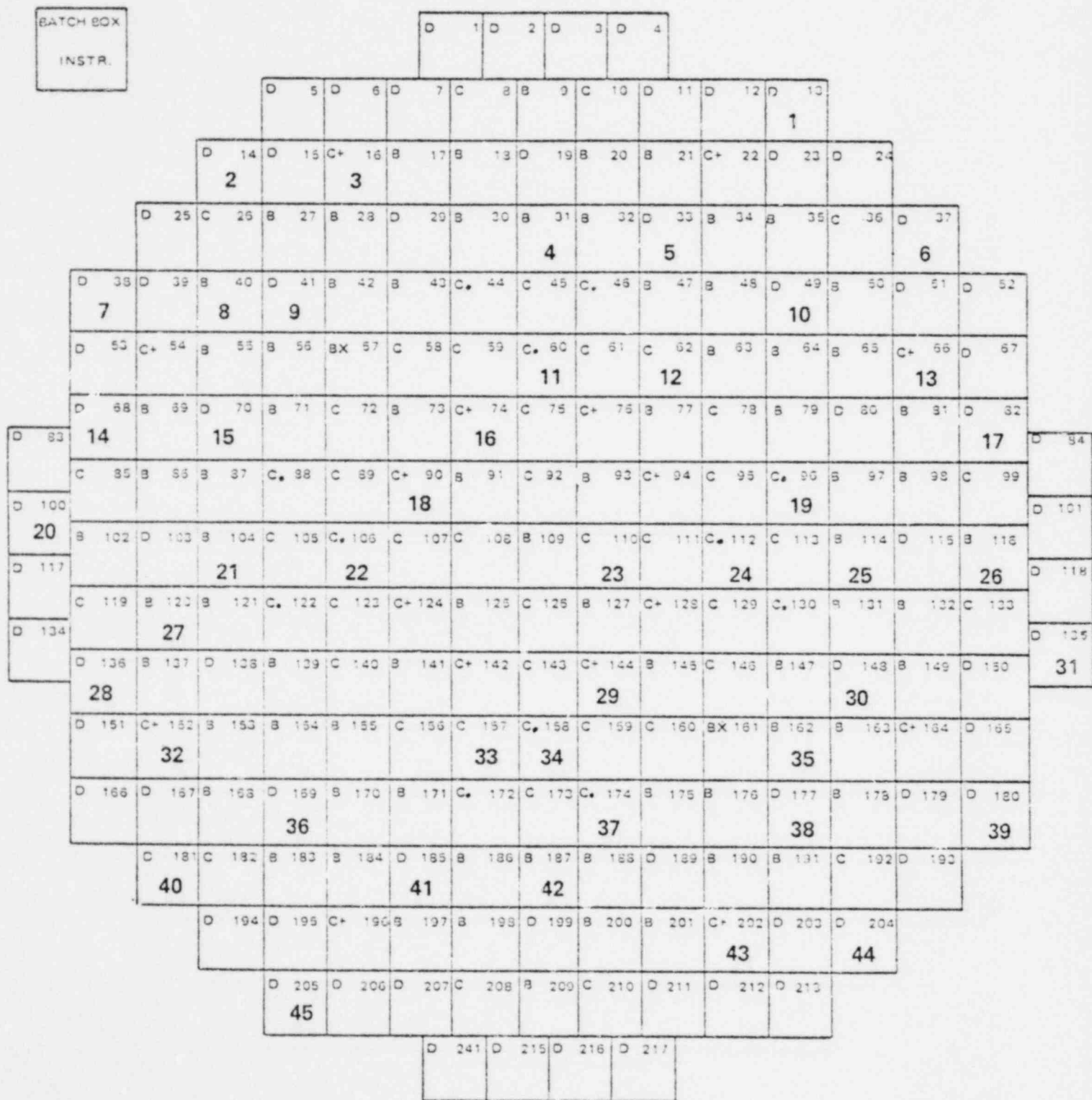| D 241 | D 215 | D 216 | D 217 |

* BX INDICATES TEST ASSEMBLY

I.3.79

FIGURE 3-3
LOADING & INSTRUMENT PATTERN
CALVERT CLIFFS UNIT 1 CYCLE 3

BATCH BOX

INSTR.

* BX INDICATES TEST ASSEMBLY

FIGURE 3-4
LOADING & INSTRUMENT PATTERN
ST. LUCIE CYCLE 1

BATCH BOX
INSTR.

I.3.81

FIGURE 3-5
LOADING & INSTRUMENT PATTERN
ST. LUCIE CYCLE 2

BATCH BOX

INSTR.

FIGURE 3-6
LOADING & INSTRUMENT PATTERN
MILLSTONE II CYCLE 1
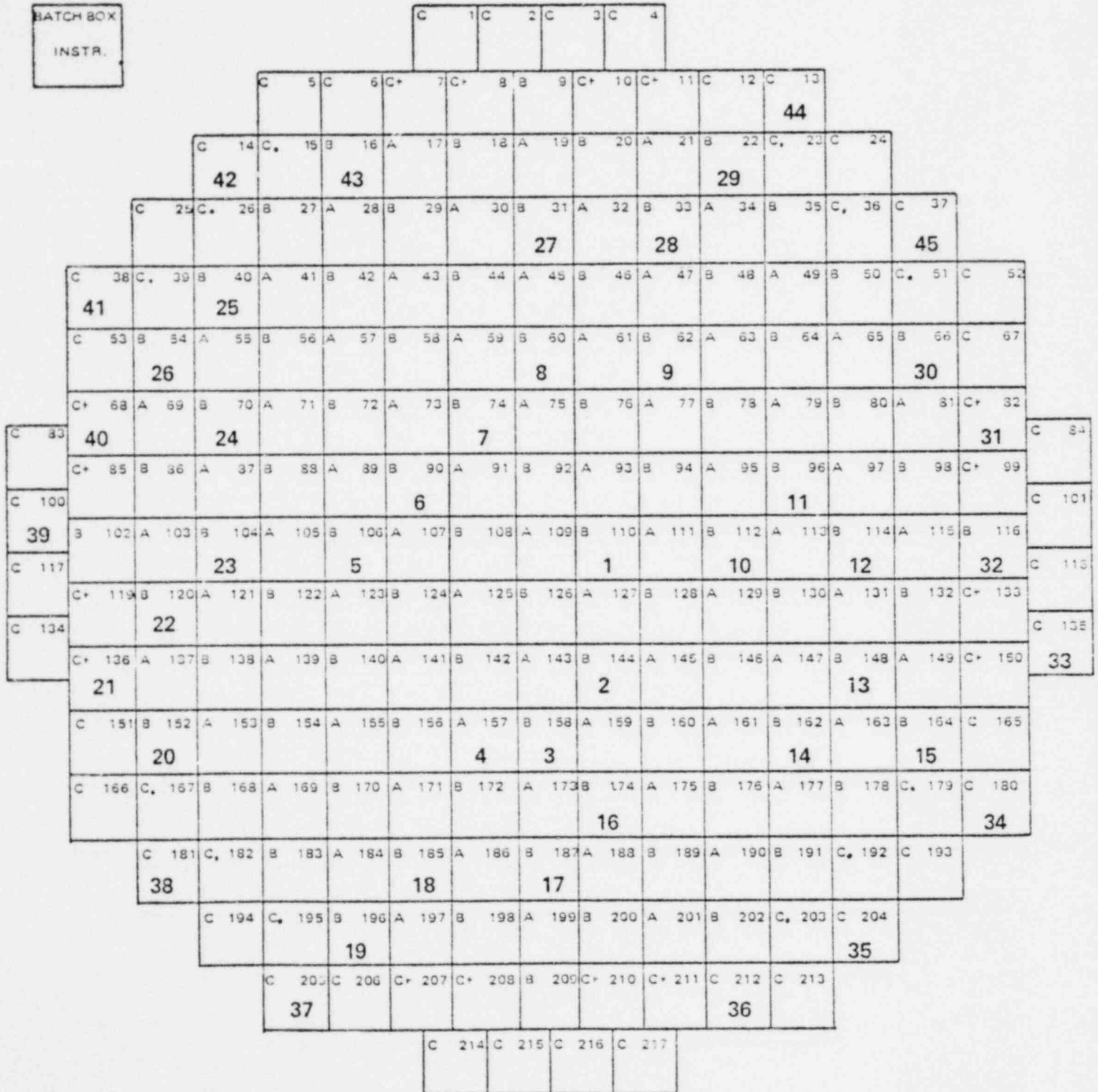
BATCH BOX

INSTR.

FIGURE 3-7
LOADING & INSTRUMENT PATTERN
MILLSTONE II CYCLE 2

I.3.84
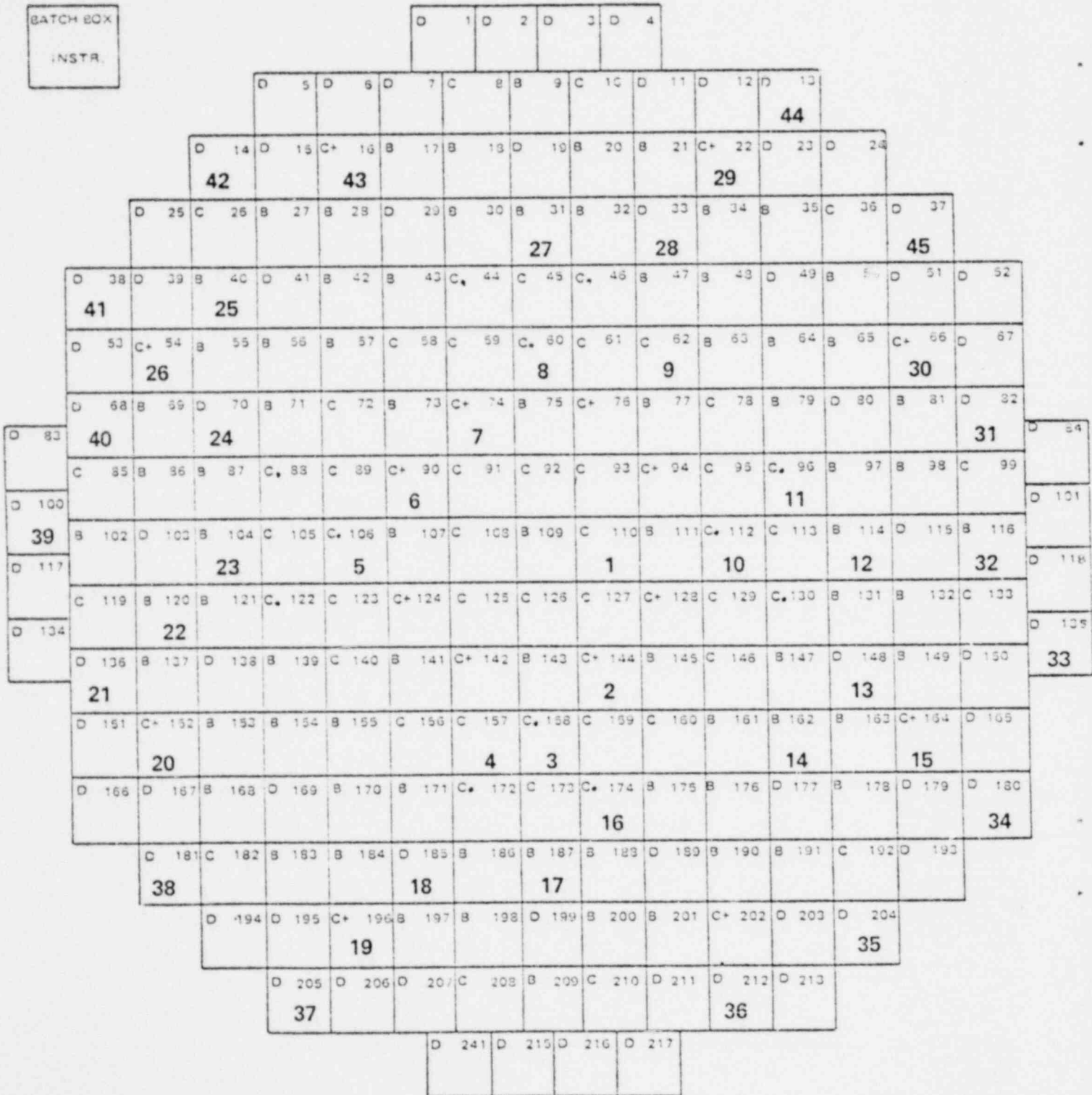
FIGURE 3-8
LOADING & INSTRUMENT PATTERN
CALVERT CLIFFS UNIT 2 CYCLE 1

FIGURE 3-9
LOADING & INSTRUMENT PATTERN
CALVERT CLIFFS UNIT 2 CYCLE 2

BATCH BOX
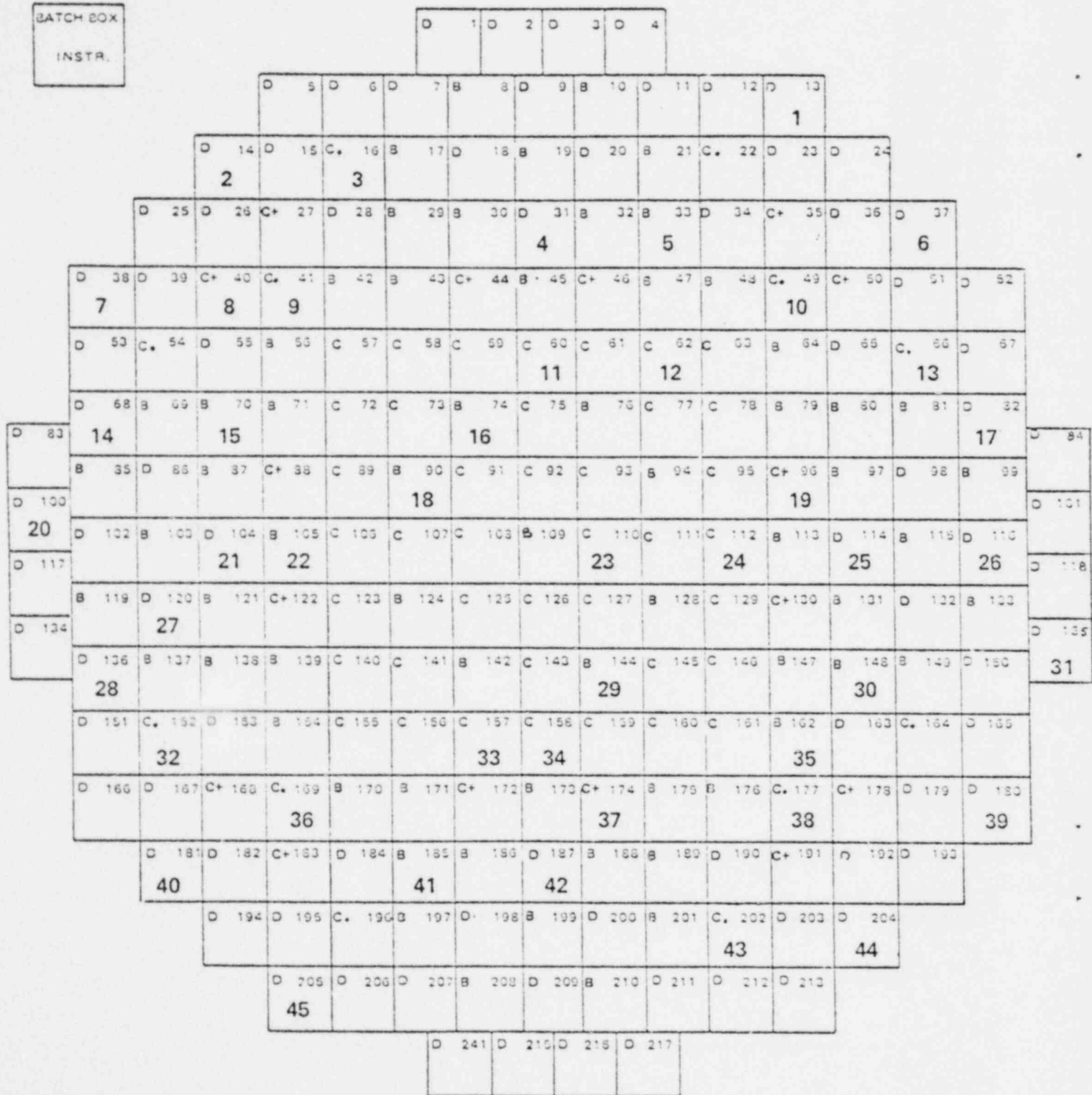
INSTR.

Figure 3-10
LOADING & INSTRUMENT PATTERN
FORT CALHOUN UNIT 1 CYCLE 4

BATCH — ⬚ — BOX
— INSTR.

| F 1 | F/ 2 | F/ 3 | F 4 |

| E 5 | F 6 | F/ 7 | D 8 | E/ 9 | D 10 | F/ 11 | F 12 | E 13 |

| E 14 | F 15 | A 16 | E/ 17 | D 18 | E/ 19 | D 20 | E/ 21 | A 22 | F 23 | E 24 |
| | | | | 2 | | | | | | 1 |

| F 25 | A 26 | D• 27 | D 28 | D 29 | C 30 | D 31 | D 32 | D• 33 | A• 34 | F 35 |
| | 6 | | 5 | | 4 | | 3 | | | |

| F/ 36 | E/ 37 | D 38 | E 39 | A• 40 | E 41 | A• 42 | E 43 | D 44 | E/ 45 | F/ 46 |

F 47	D 49	D 50	D 51	A• 52	D 53	D 54	D 55	A• 56	D 57	D 58	D 59	F 48
10		9				8	7					
F/ 60												F/ 61
	E/ 62	E/ 63	C 64	E 65	D 66	B/S 67	D 68	E 69	C 70	E/ 71	E/ 72	11
F/ 73	17		16		15		14		13		12	F/ 74
	D 75	D 76	D 77	A• 78	D 79	D 80	D 81	A• 82	D 83	D 84	D 85	
F 86				20		19		18				F 87

| F/ 88 | E/ 89 | D 90 | E 91 | A• 92 | E 93 | A• 94 | E 95 | D 96 | E/ 97 | F/ 98 |
| 22 | | | | | | | | | | 21 |

| F 99 | A• 100 | D• 101 | D 102 | D 103 | C 104 | D 105 | D 106 | D• 107 | A• 108 | F 109 |
| | | | 26 | | 25 | | 24 | | 23 | |

| E 110 | F 111 | A• 112 | E/ 113 | D 114 | E/ 115 | D 116 | E/ 117 | A• 118 | F 119 | E 120 |
| 28 | | | | 27 | | | | | | |

| E 121 | F 122 | F/ 123 | D 124 | E/ 125 | D 126 | F/ 127 | F 128 | E 129 |

| F 130 | F/ 131 | F/ 132 | F 133 |

I.3.87

Figure 3-11

LOADING & INSTRUMENT PATTERN
FORT CALHOUN UNIT 1 CYCLE 5

BATCH ── ┌──── BOX
         │
         └──── INSTR.

| G | 1 | G | 2 | G | 3 | G | 4 |

| G 5 | G 6 | G 7 | D 8 | F 9 | D 10 | G 11 | G 12 | G 13 |

| G 14 | G 15 | D 16 | F 17 | F/ 18 | F/ 19 | F/ 20 | F 21 | D 22 | G 23 | G 24 |
| | | | | 2 | | | | | | 1 |

| G 25 | D 26 | F 27 | E/ 28 | E 29 | D* 30 | E 31 | E/ 32 | F 33 | D 34 | G 35 |
| | 6 | | 5 | | 4 | | 3 | | | |

| G 36 | F 37 | E/ 38 | F 39 | E/ 40 | F/ 41 | E/ 42 | F 43 | E/ 44 | F 45 | G 46 |

G 47											G 48
10	D 49	F/ 50	E 51	E/ 52	E 53	E 54	E 55	E/ 56	E 57	F/ 58	D 59	
G 60		9					8	7				G 61
	F 62	F/ 63	D* 64	F/ 65	E 66	D 67	E 68	F/ 69	D* 70	F/ 71	F 72	11
G 73	17		16		15		14		13		12	G 74
	D 75	F/ 76	E 77	E/ 78	E 79	E 80	E 81	E/ 82	E 83	F/ 84	D 85	
G 86				20		19		18				G 87

| G 88 | F 89 | E/ 90 | F 91 | E/ 92 | F/ 93 | E/ 94 | F 95 | E/ 96 | F 97 | G 98 |
| 22 | | | | | | | | | | 21 |

| G 99 | D 100 | F 101 | E/ 102 | E 103 | D* 104 | E 105 | E/ 106 | F 107 | D 108 | G 109 |
| | | | 26 | | 25 | | 24 | | 23 | |

| G 110 | G 111 | D 112 | F 113 | F/ 114 | F/ 115 | F/ 116 | F 117 | D 118 | G 119 | G 120 |
| 28 | | | | 27 | | | | | | |

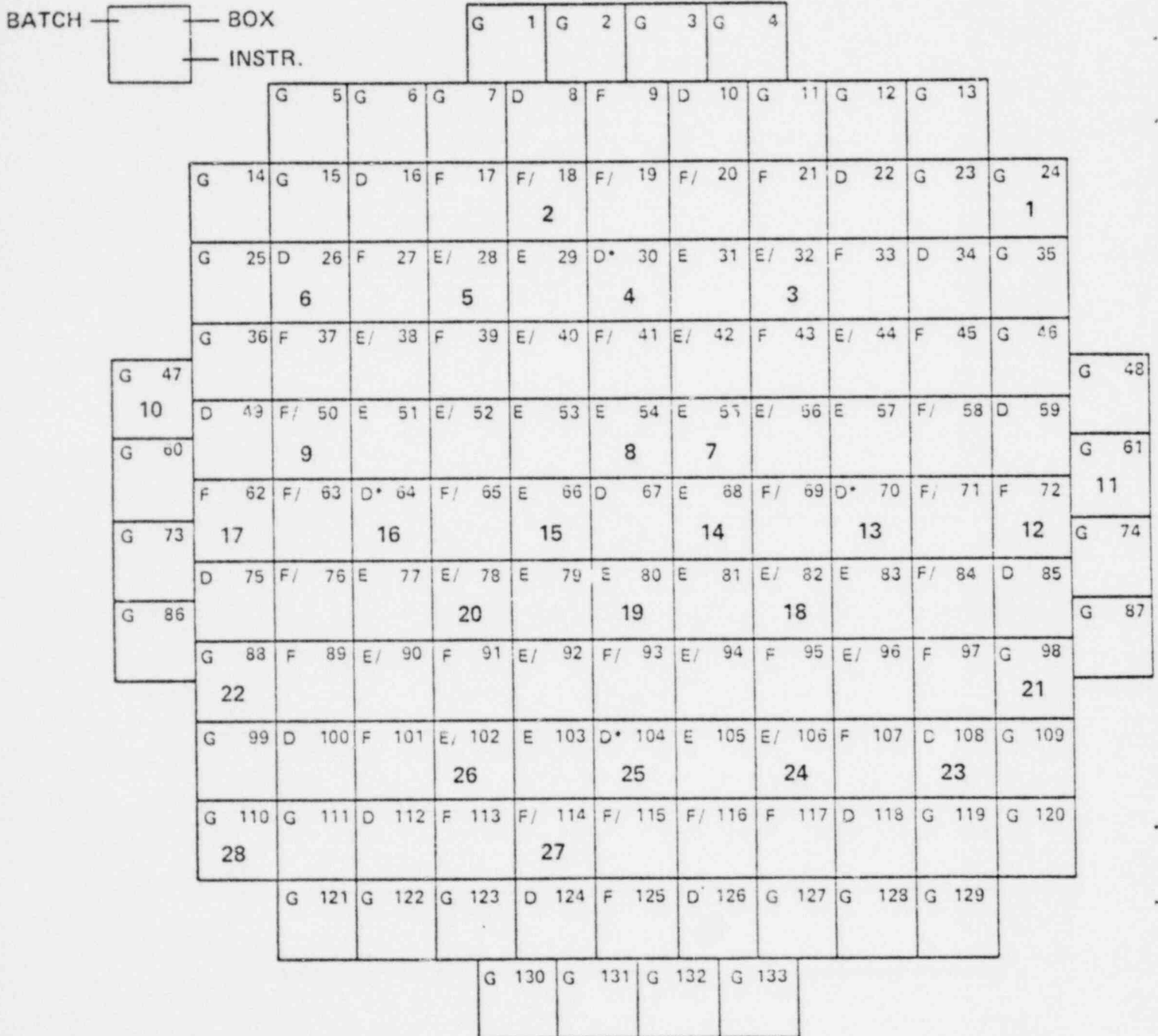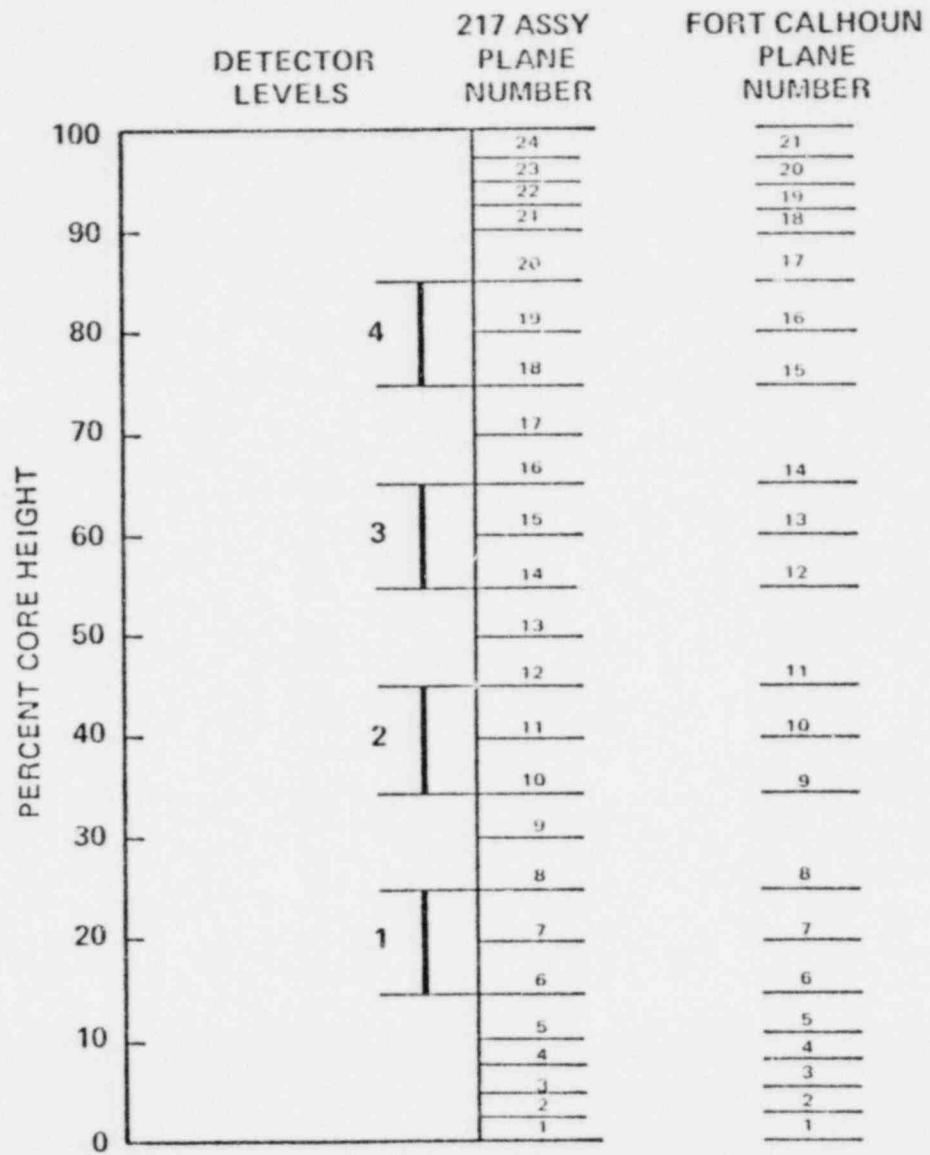| G 121 | G 122 | G 123 | D 124 | F 125 | D 126 | G 127 | G 128 | G 129 |

| G 130 | G 131 | G 132 | G 133 |

Figure 3-12
ROCS AXIAL MESH STRUCTURE

FIGURE 3-13a

COMPARISONS OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 1 AT 850 MWD/T

LEVEL 1

FIGURE **3-13b**

COMPARISON OF MEASURED AND CALCULATED POWERS
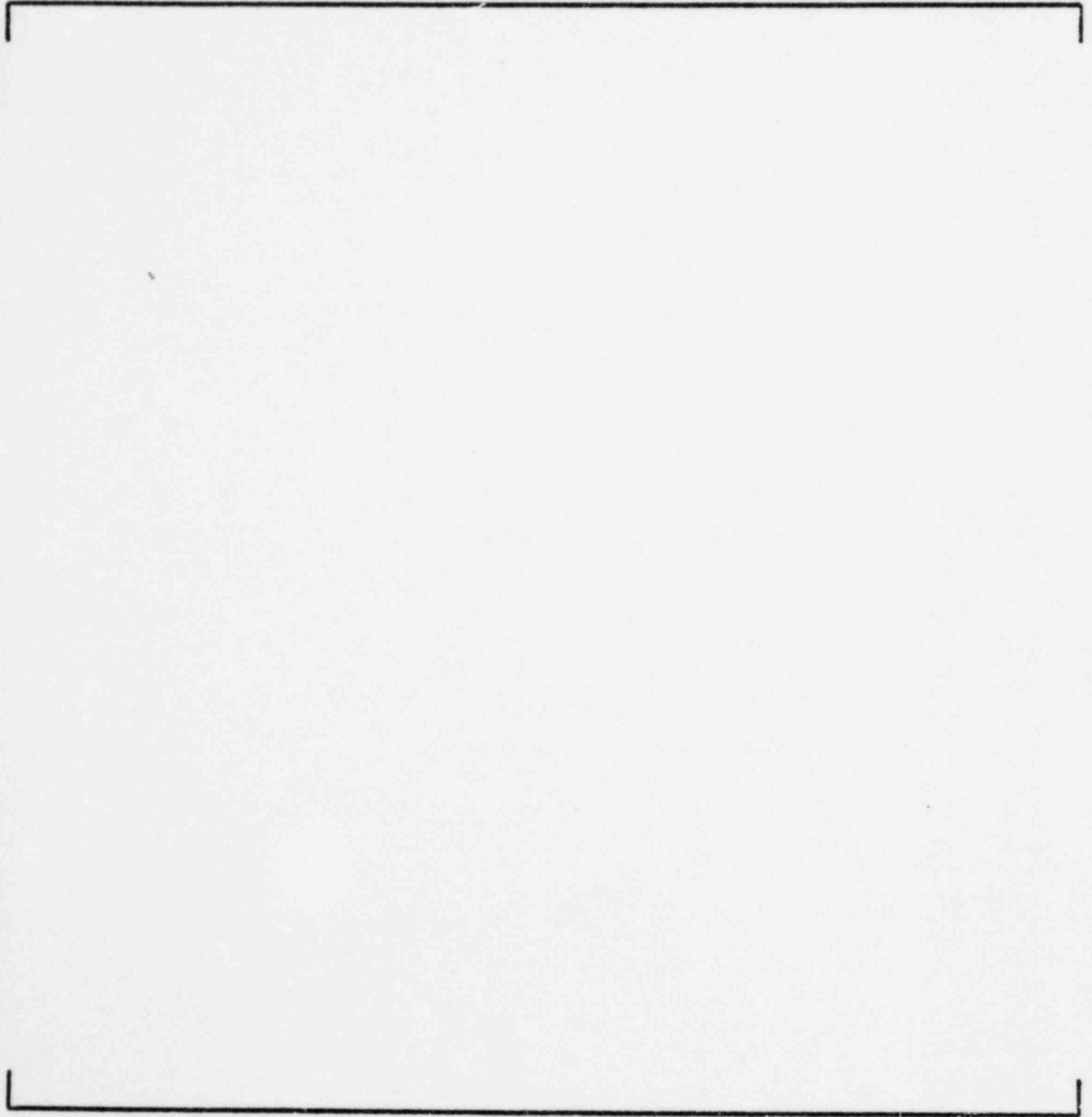CALVERT CLIFFS UNIT 1 CYCLE 1 AT 850 MWD/T

LEVEL 2

FIGURE 3-13c

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 1 AT 850 MWD/T
LEVEL 3

FIGURE 3-13d

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 1 AT 850 MWD/T
LEVEL 4

FIGURE 3-13e

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 1 AT 850 MWD/T
SUMMED LEVELS

FIGURE 3-13e

I.3.94

FIGURE 3-14a

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 2 AT 989 MWD/T
LEVEL 1

FIGURE 3-14b

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 2 AT 989 MWD/T
LEVEL 2

FIGURE 3-14c

COMPARISON OF MEASURED AND CALCULATED POWERS
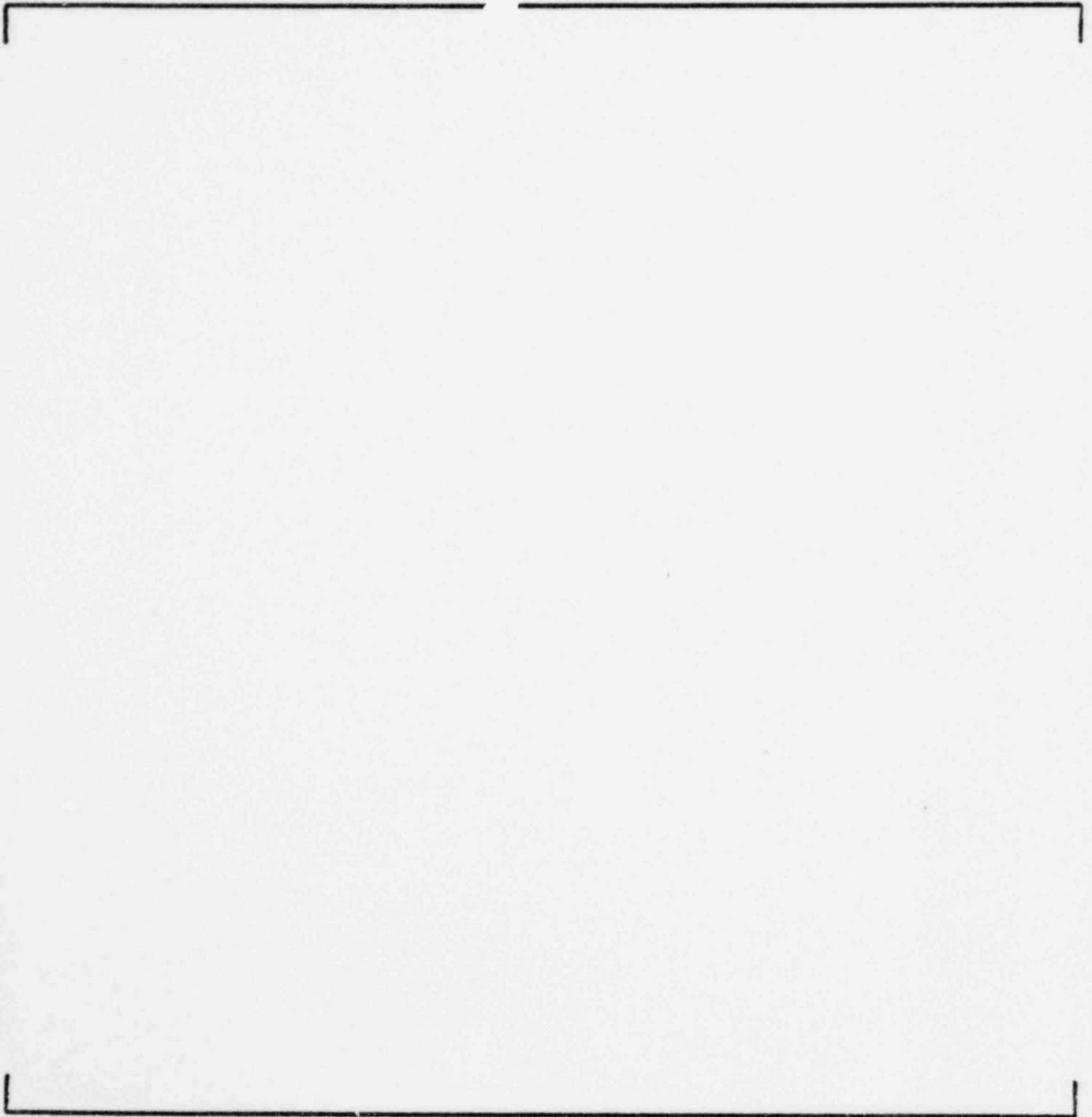CALVERT CLIFFS UNIT 1 CYCLE 2 AT 989 MWD/T
LEVEL 3

FIGURE 3-14d

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 2 AT 989 MWD/T
LEVEL 4

FIGURE 3-14e

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 2 AT 989 MWD/T
SUMMED LEVELS

FIGURE 3-14e

I.3.99

FIGURE 3-15a

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 3 at 1202 MWD/T
LEVEL 1

FIGURE 3-15b

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 3 at 1202 MWD/T
LEVEL 2

FIGURE 3-15b

I.3.101

FIGURE 3-15c

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 3 AT 1202 MWD/T

LEVEL 3

FIGURE 3-15d

COMPARISON OF MEASURED AND CALCULATED POWERS
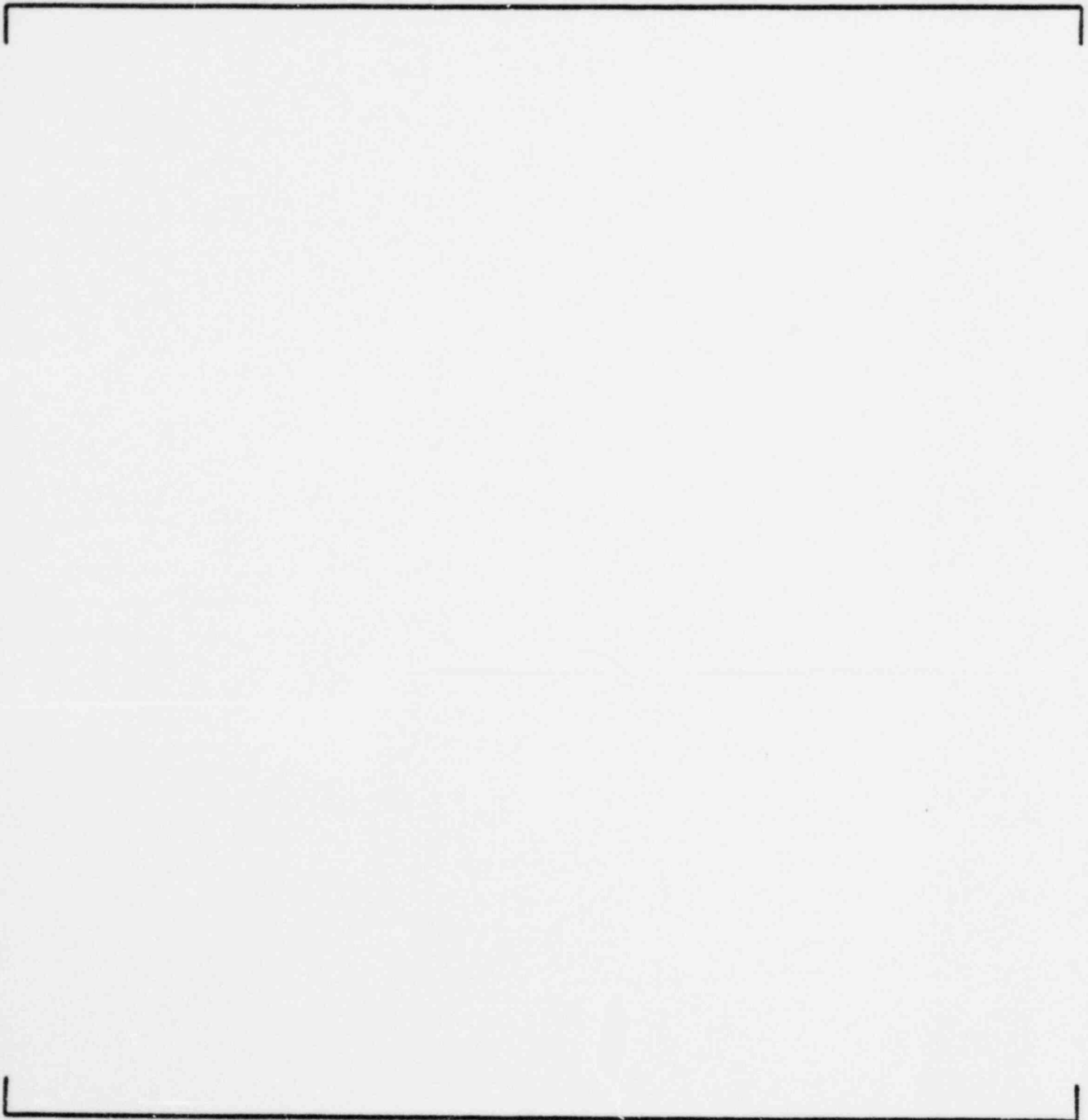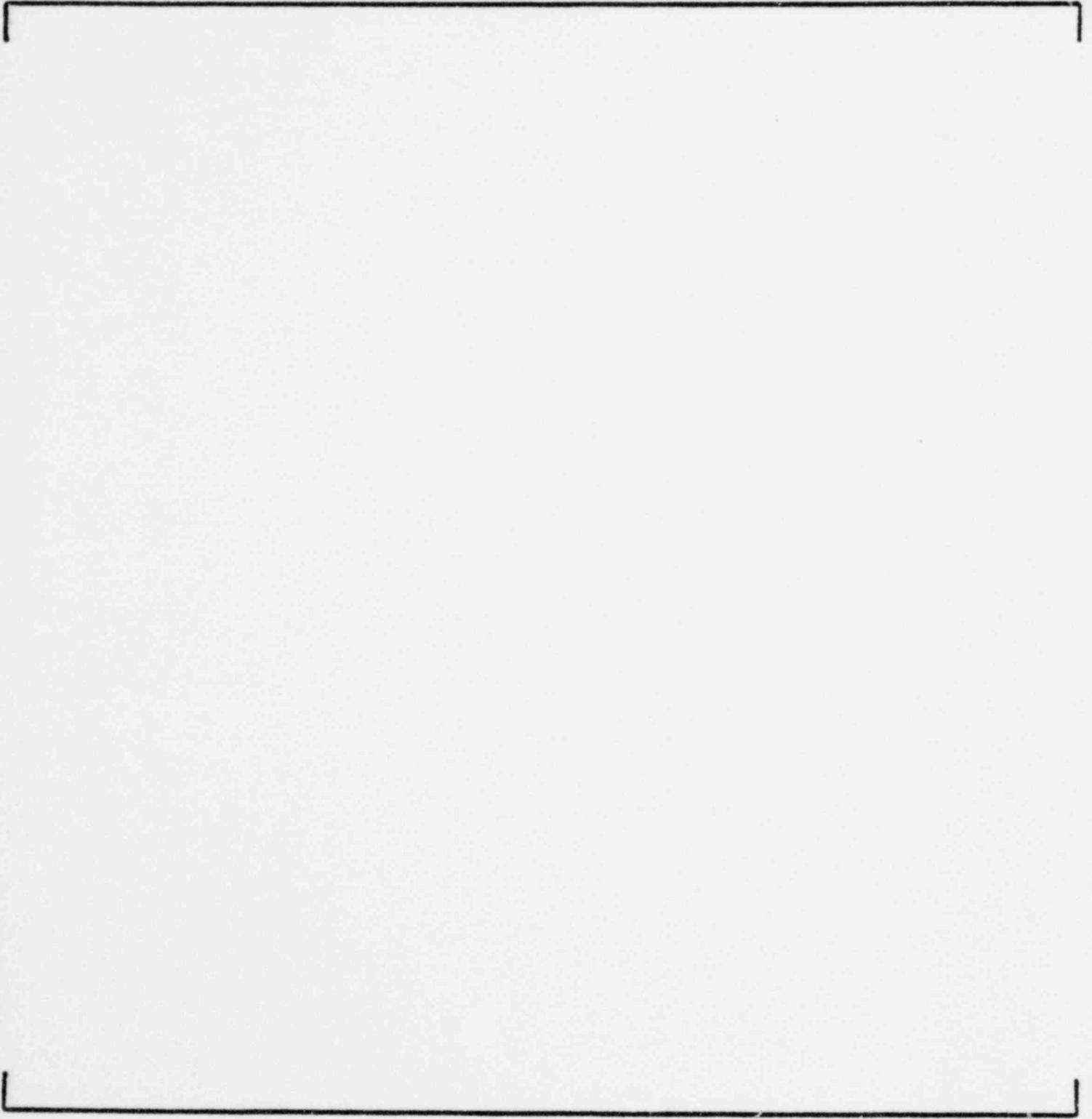CALVERT CLIFFS UNIT 1 CYCLE 3 AT 1202 MWD/T

LEVEL 4

FIGURE 3-15e

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 1 CYCLE 3 AT 1202 MWD/T
SUMMED LEVELS

FIGURE 3-16a

COMPARISON OF MEASURED AND CALCULATED POWERS
ST. LUCIE CYCLE 1 AT 888 MWD/T
LEVEL 1

FIGURE 3-16b

COMPARISON OF MEASURED AND CALCULATED POWERS
ST. LUCIE CYCLE 1 AT 888 MWD/T
LEVEL 2

FIGURE 3-16c

COMPARISON OF MEASURED AND CALCULATED POWERS
ST. LUCIE CYCLE 1 AT 888 MWD/T
LEVEL 3

FIGURE 3-16d

COMPARISON OF MEASURED AND CALCULATED POWERS
ST. LUCIE CYCLE 1 AT 888 MWD/T
LEVEL 4

FIGURE 3-16e

COMPARISON OF MEASURED AND CALCULATED POWERS
ST. LUCIE CYCLE 1 AT 888 MWD/T
SUMMED LEVELS
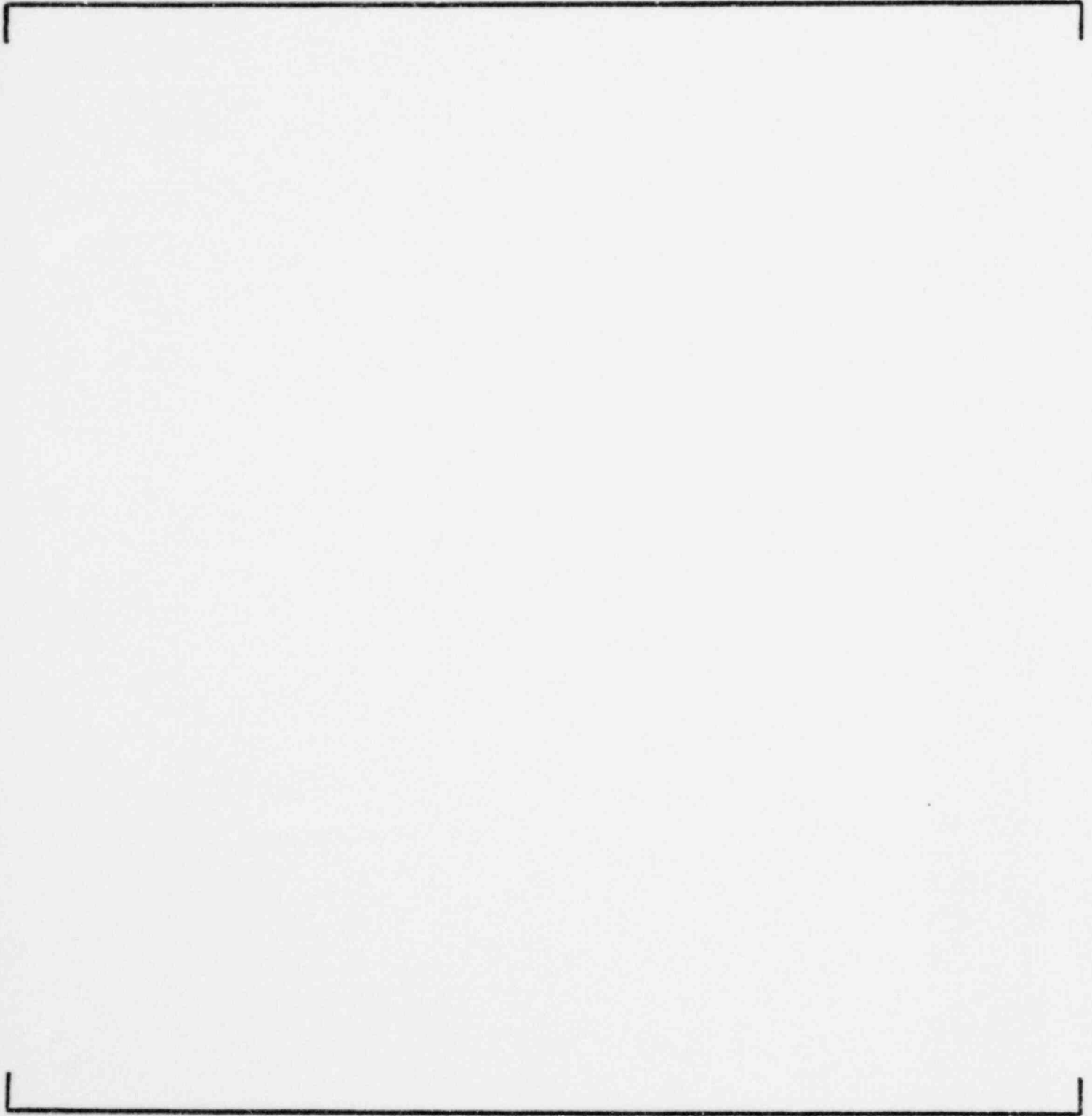
FIGURE 3-17a

COMPARISON OF MEASURED AND CALCULATED POWERS
ST. LUCIE CYCLE 2 AT 1361 MWD/T
LEVEL 1

FIGURE 3-17b

COMPARISON OF MEASURED AND CALCULATED POWERS

ST. LUCIE CYCLE 2 AT 1361 MWD/T

LEVEL 2
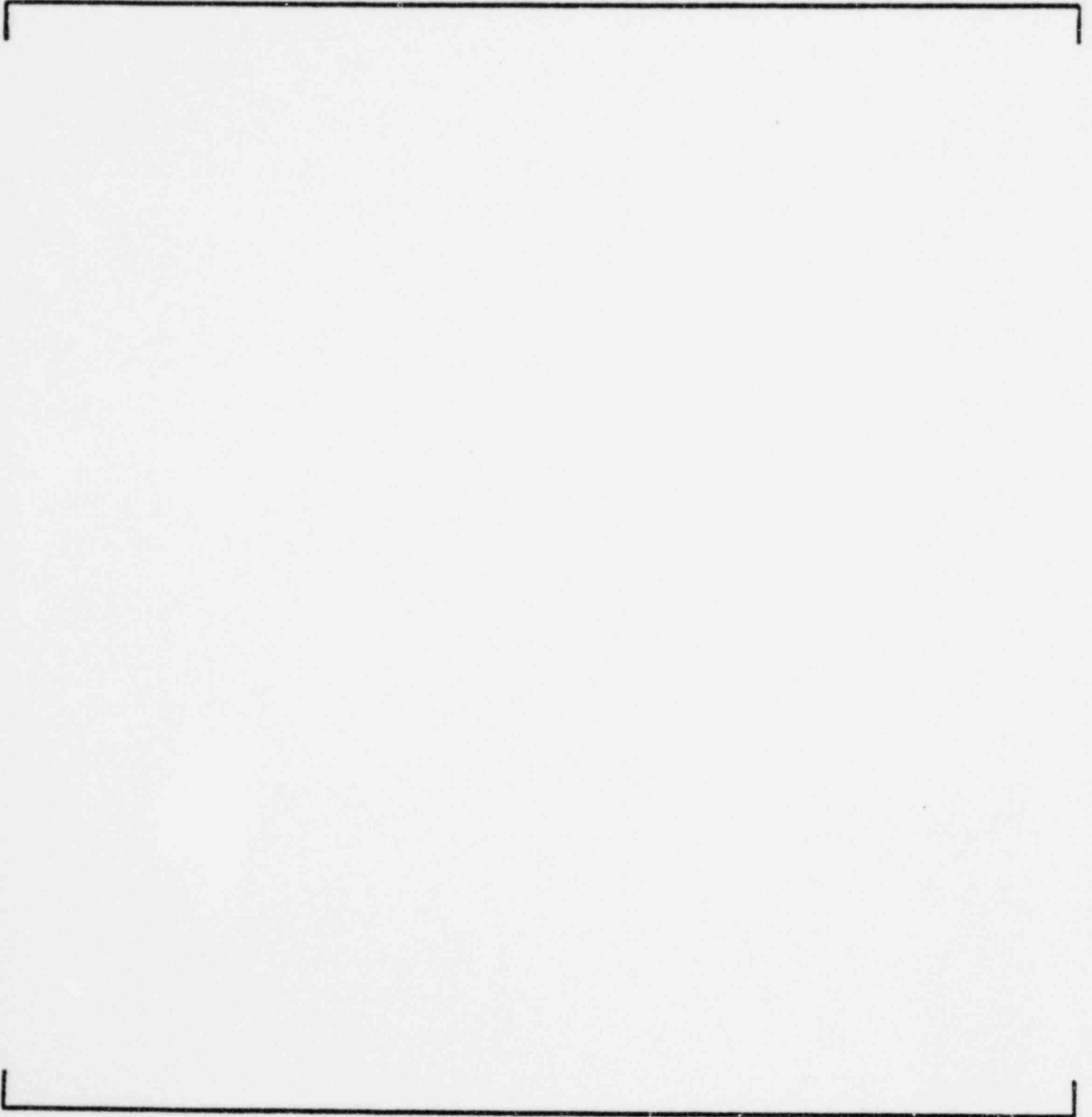
FIGURE 3-17c

COMPARISON OF MEASURED AND CALCULATED POWERS
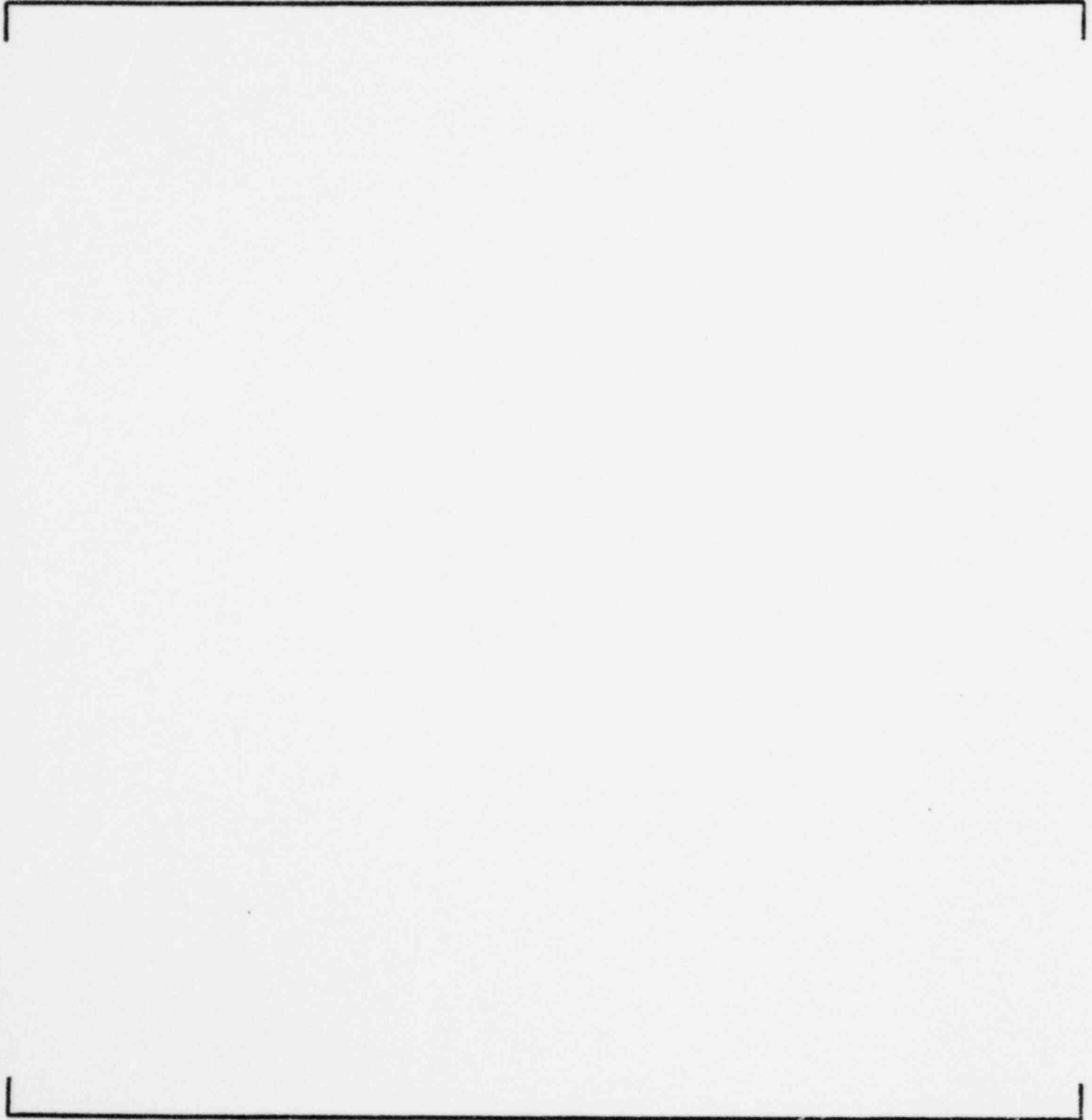ST. LUCIE CYCLE 2 AT 1361 MWD/T
LEVEL 3

FIGURE 3-17c

FIGURE 3-17d

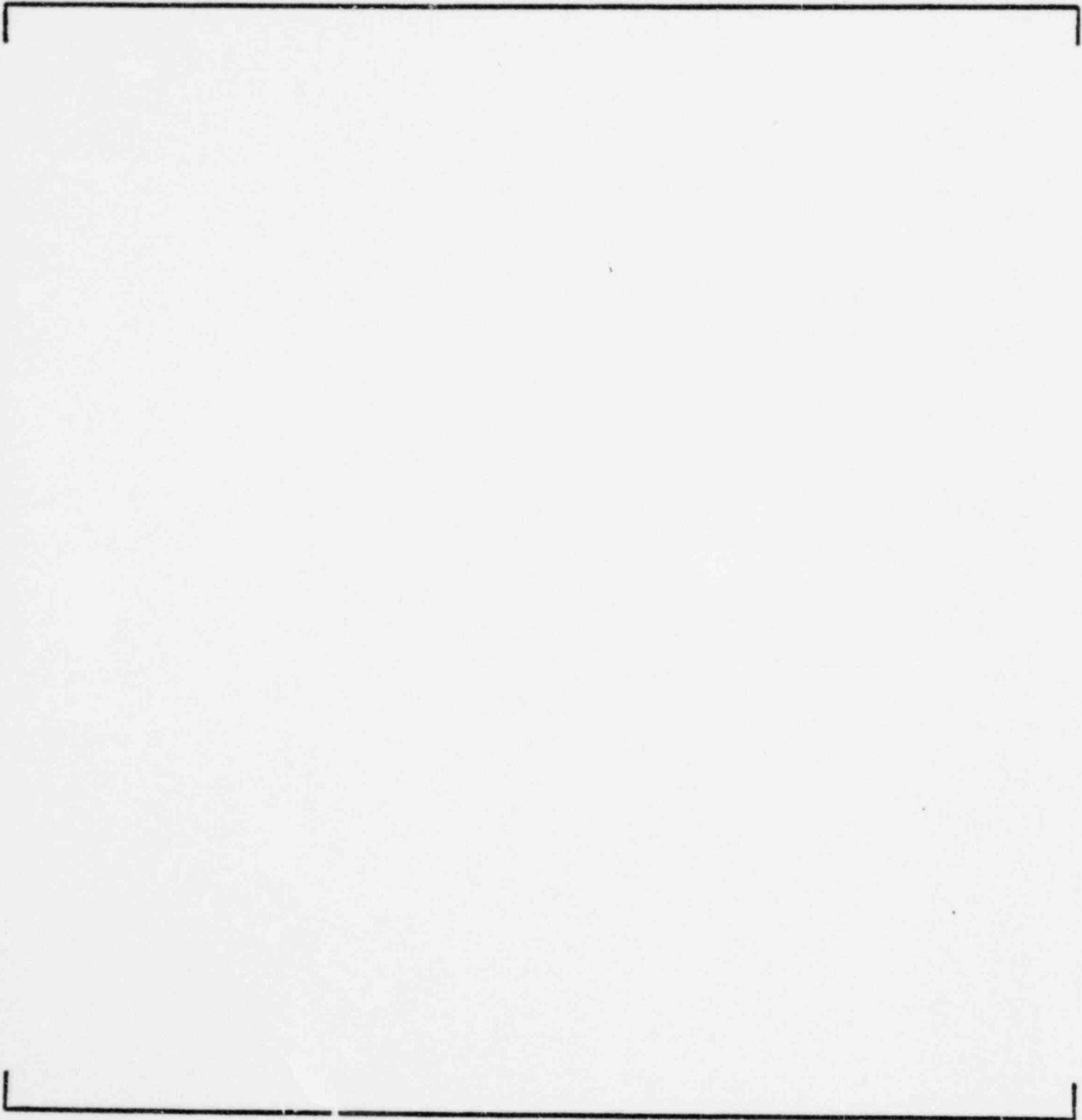COMPARISON OF MEASURED AND CALCULATED POWERS
ST. LUCIE CYCLE 2 AT 1361 MWD/T
LEVEL 4

FIGURE 3-17e

COMPARISON OF MEASURED AND CALCULATED POWERS
ST. LUCIE CYCLE 2 AT 1361 MWD/T
SUMMED LEVELS
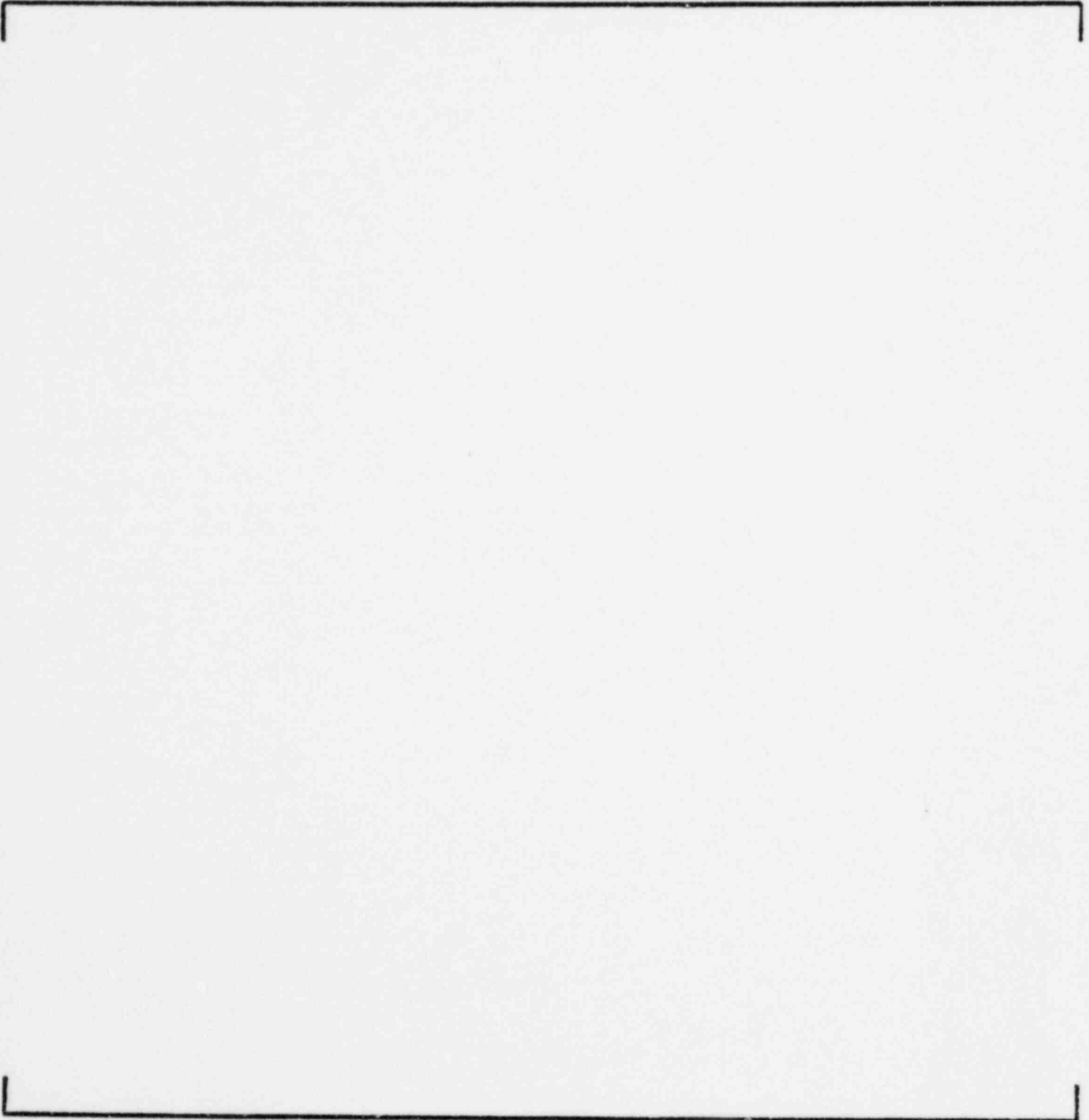
FIGURE 3-18a

COMPARISON OF MEASURED AND CALCULATED POWERS

MILLSTONE II CYCLE 1 AT 1350 MWD/T

LEVEL 1
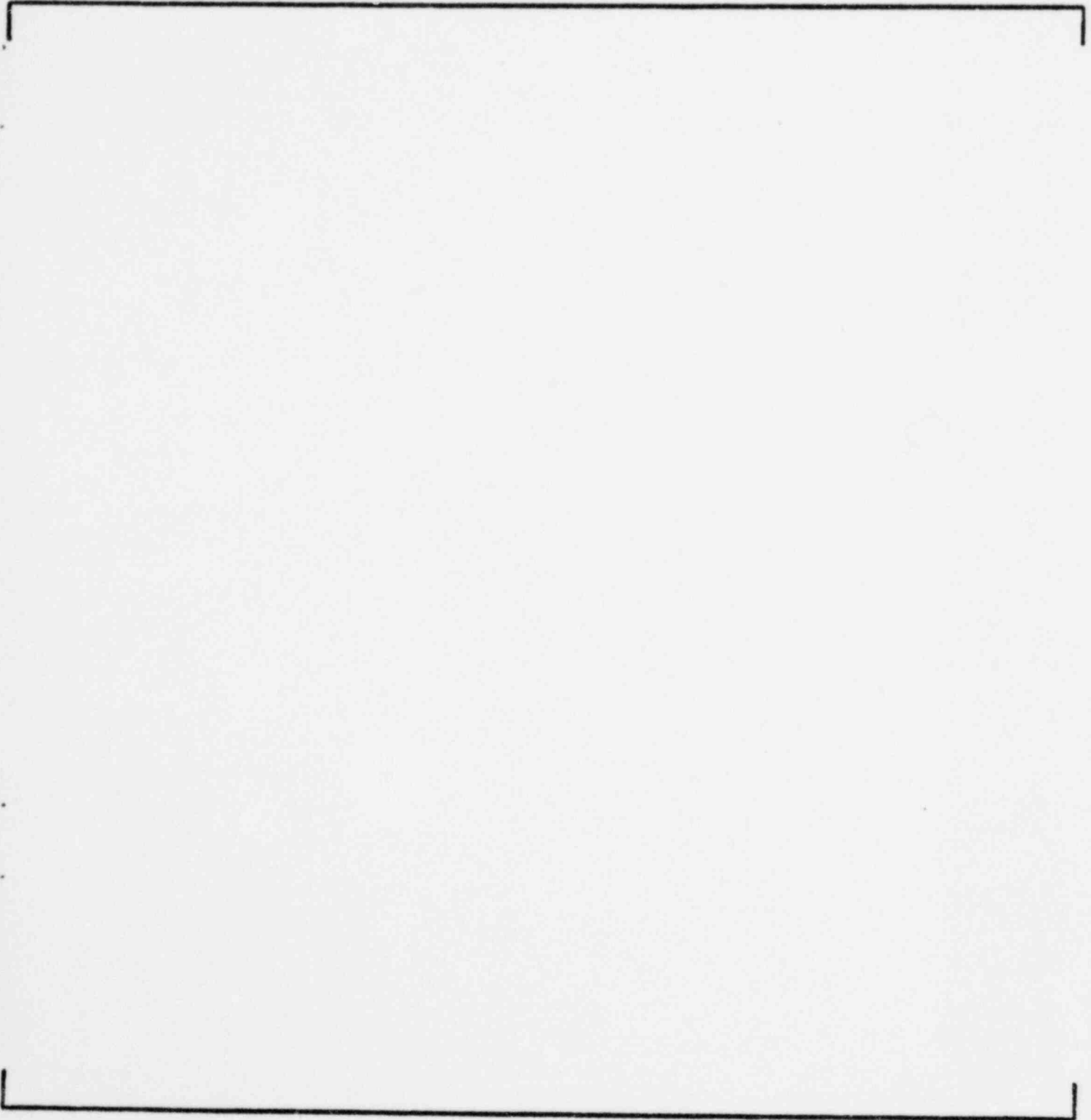
FIGURE 3-18b

COMPARISON OF MEASURED AND CALCULATED POWERS
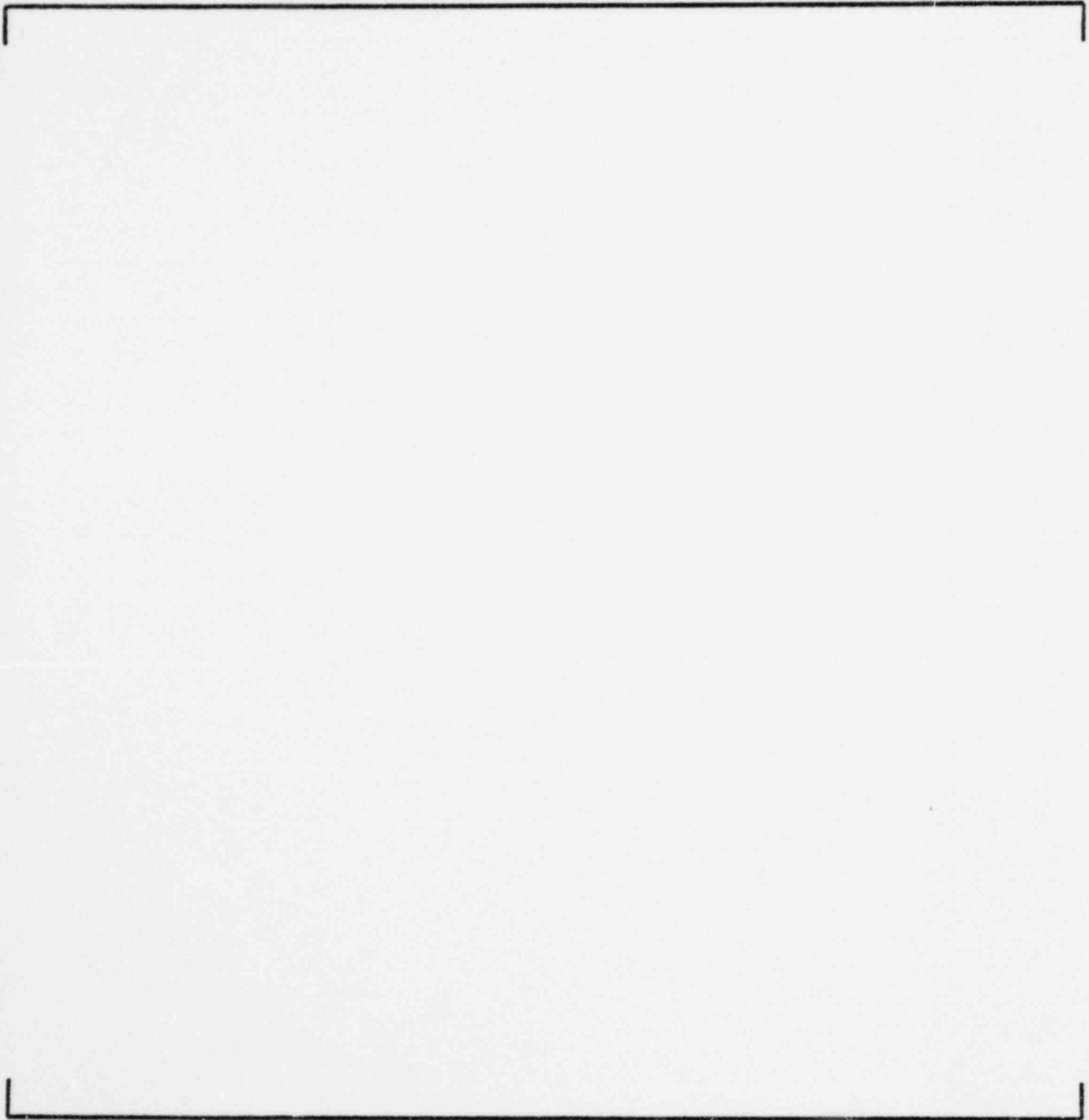### M LLSTONE II CYCLE 1 AT 1350 MWD/T
LEVEL 2

FIGURE 3-18c

COMPARISON OF MEASURED AND CALCULATED POWERS
MILLSTONE II CYCLE 1 AT 1350 MWD/T
LEVEL 3

FIGURE 3-18d

COMPARISON OF MEASURED AND CALCULATED POWERS
MILLSTONE II CYCLE 1 AT 1350 MWD/T
LEVEL 4

FIGURE 3-18e

COMPARISON OF MEASURED AND CALCULATED POWERS

MILLSTONE II CYCLE 1 AT 1350 MWD/T
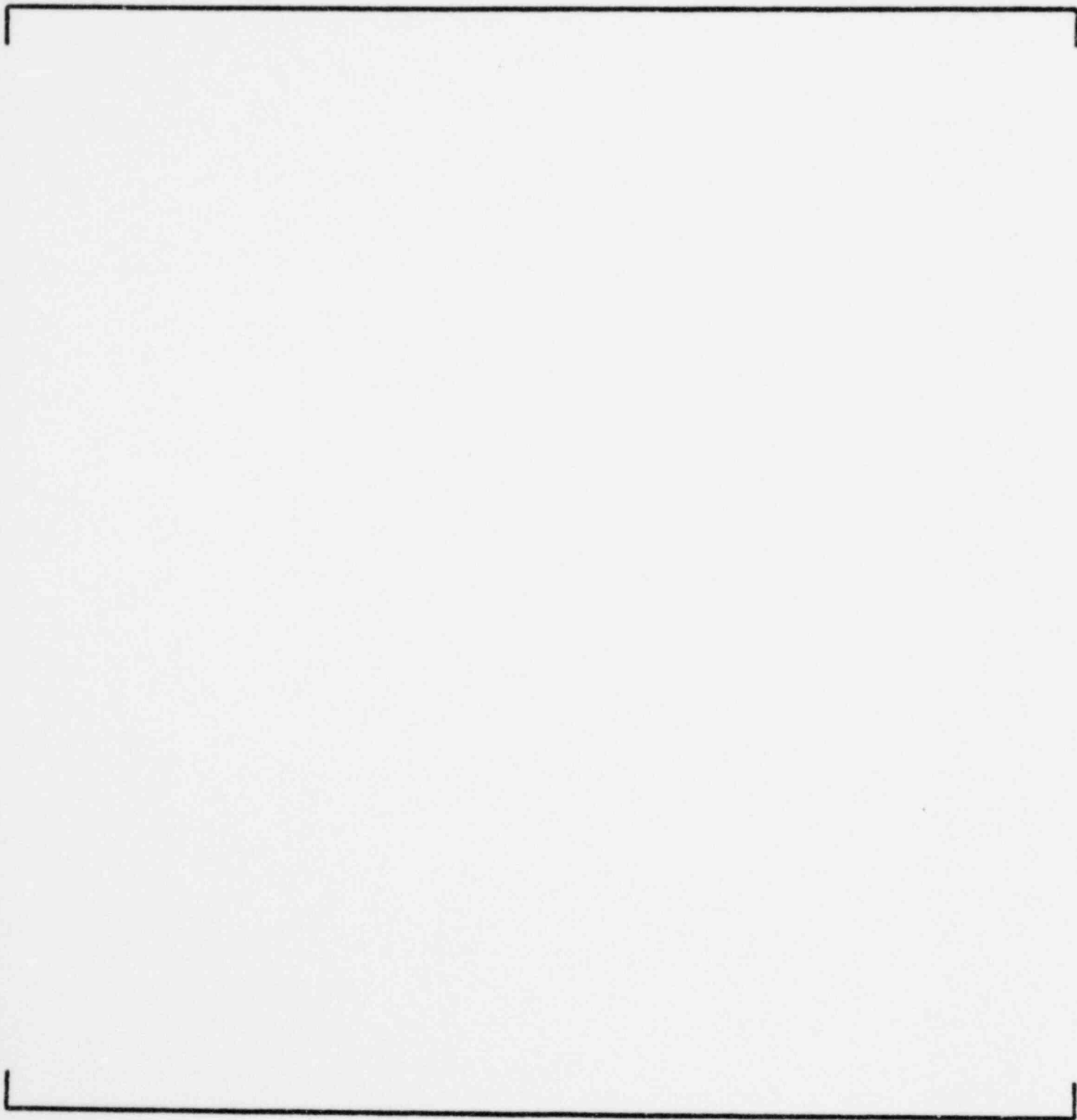
SUMMED LEVELS

FIGURE 3-19a

COMPARISON OF MEASURED AND CALCULATED POWERS
MILLSTONE II CYCLE 2 AT 500 MWD/T
LEVEL 1
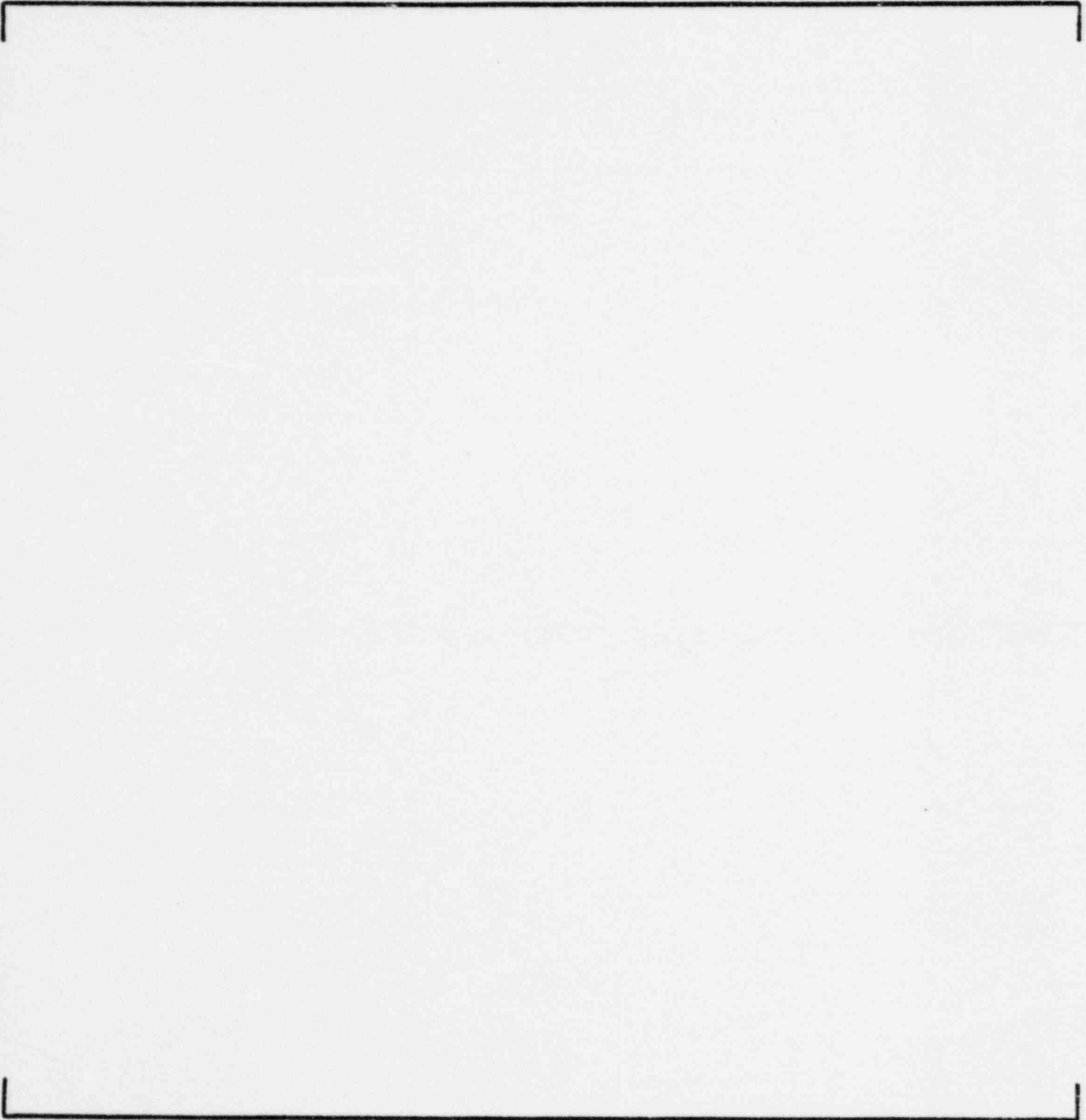
FIGURE 3-19b

COMPARISON OF MEASURED AND CALCULATED POWERS
MILLSTONE II CYCLE 2 AT 500 MWD/T
LEVEL 2
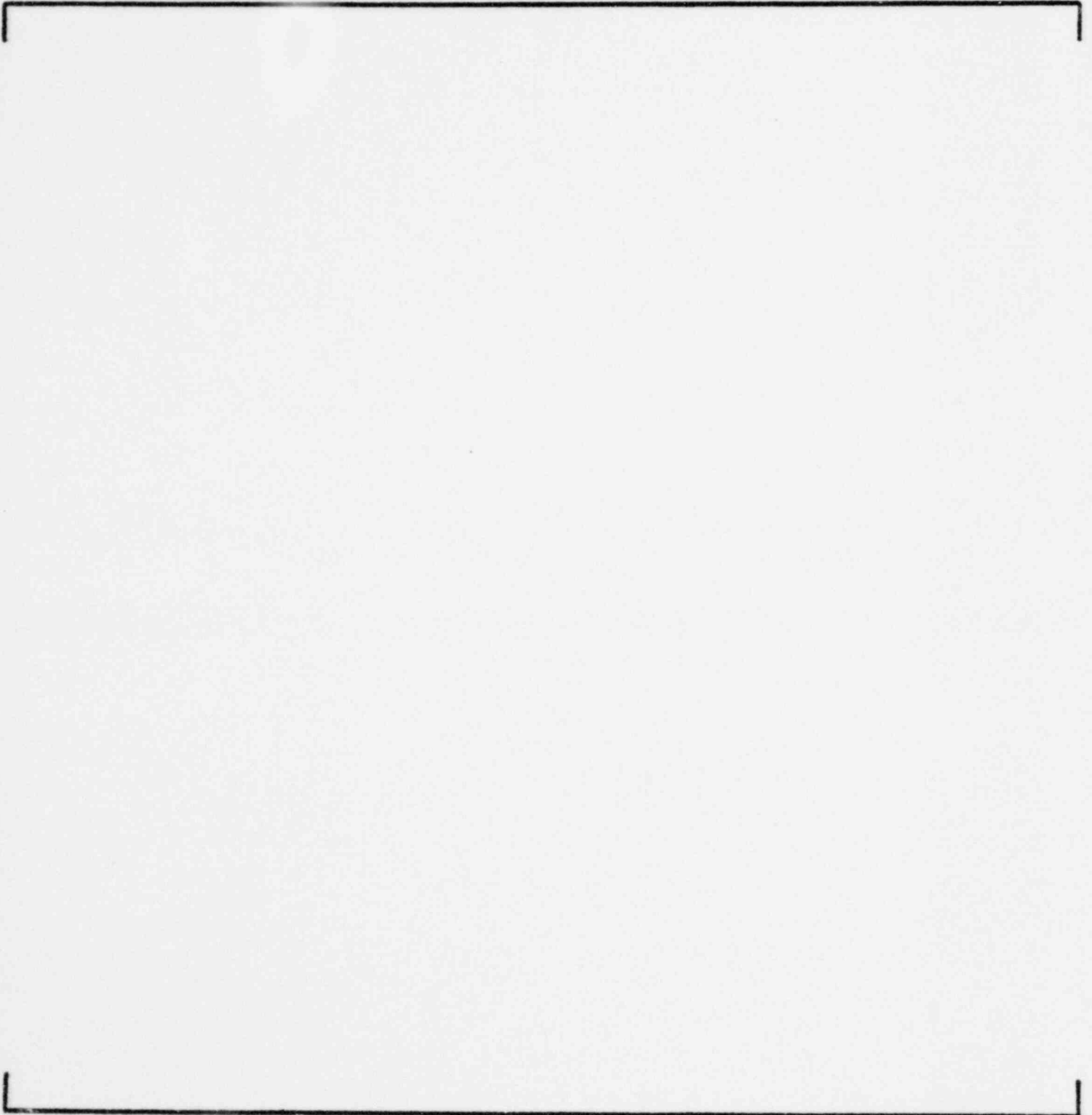
FIGURE 3-19b
I.3.121

FIGURE 3-19c

COMPARISON OF MEASURED AND CALCULATED POWERS
MILLSTONE II CYCLE 2 AT 500 MWD/T
LEVEL 3

FIGURE 3-19d

COMPARISON OF MEASURED AND CALCULATED POWERS
MILLSTONE II CYCLE 2 AT 500 MWD/T
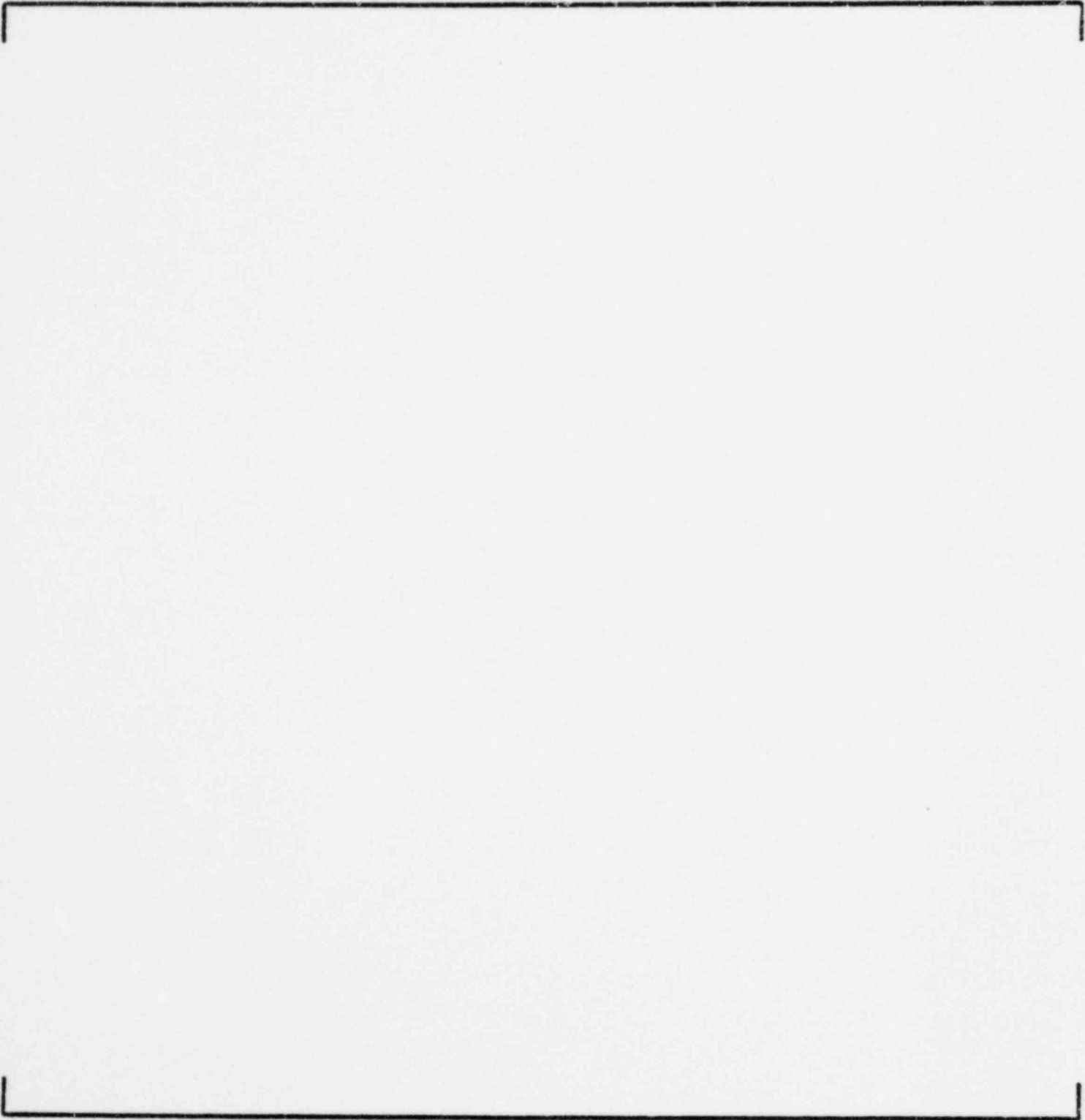LEVEL 4

FIGURE 3-19d

I.3.123

FIGURE 3-19e

COMPARISON OF MEASURED AND CALCULATED POWERS
MILLSTONE II CYCLE 2 AT 500 MWD/T
SUMMED LEVELS
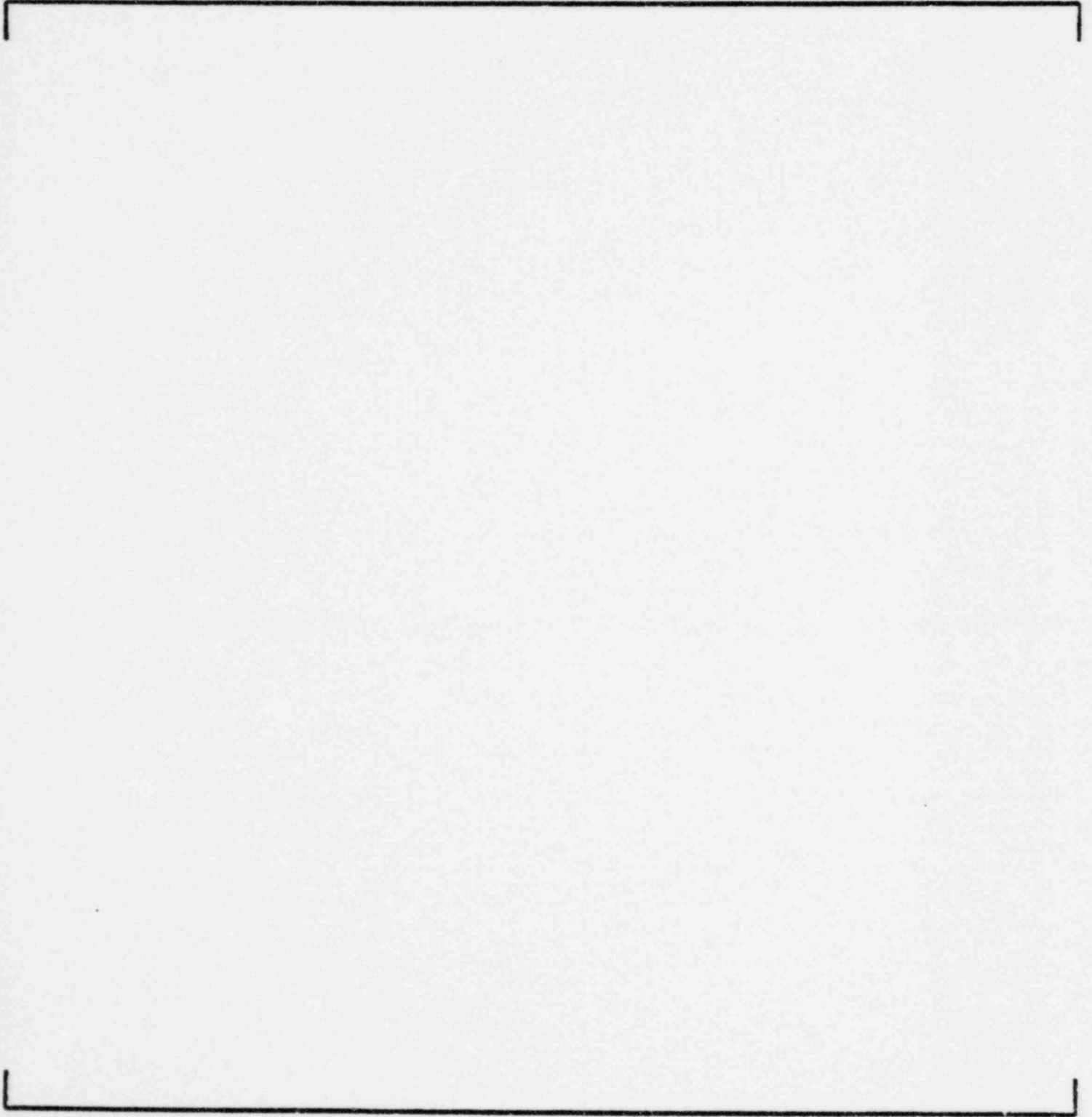
FIGURE 3-20a

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 1 AT 1440 MWD/T
LEVEL 1
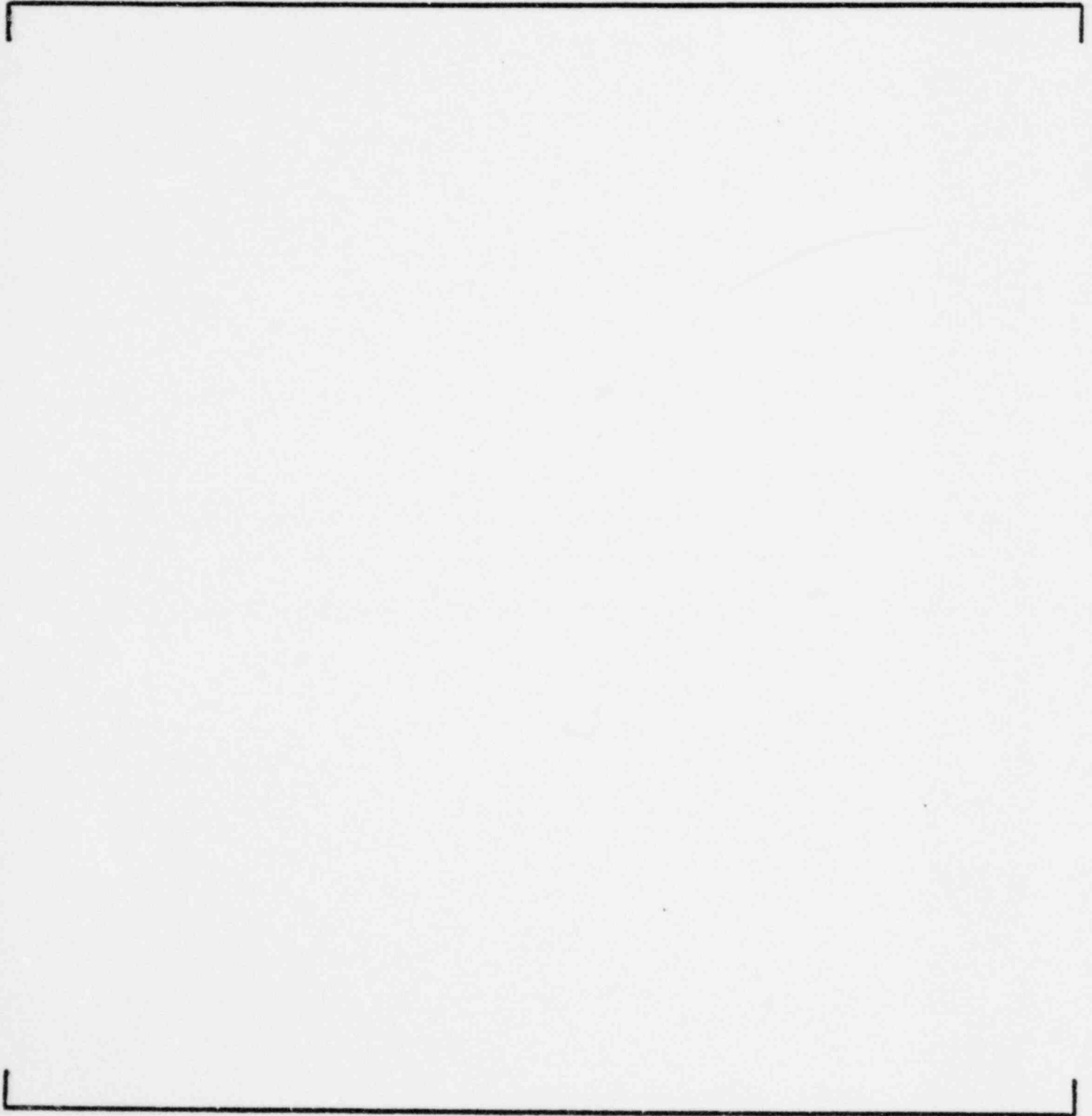
FIGURE 3-20b

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 1 at 1440 MWD/T
LEVEL 2
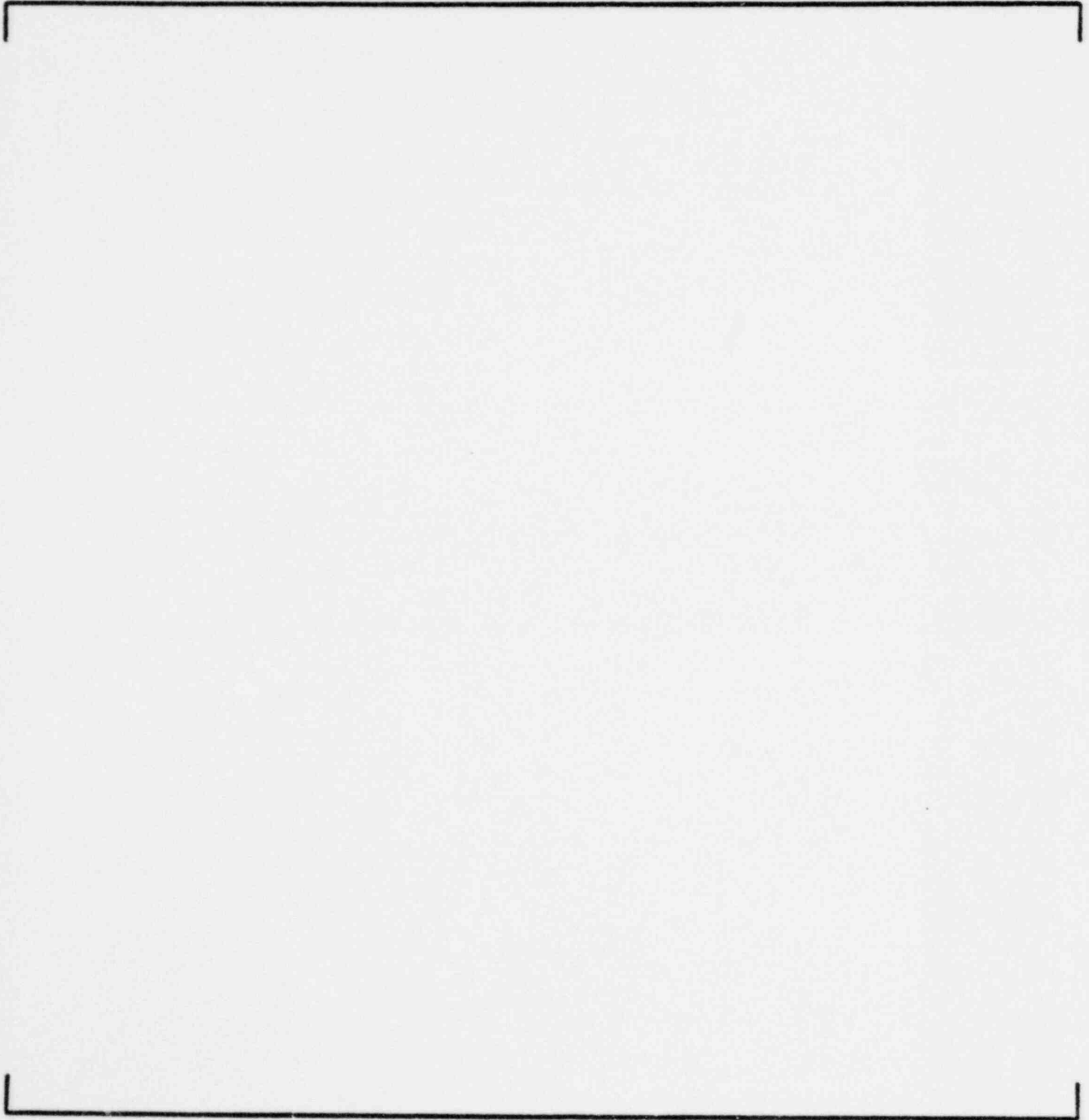
FIGURE 3-20c

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 1 AT 1440 MWD/T
LEVEL 3
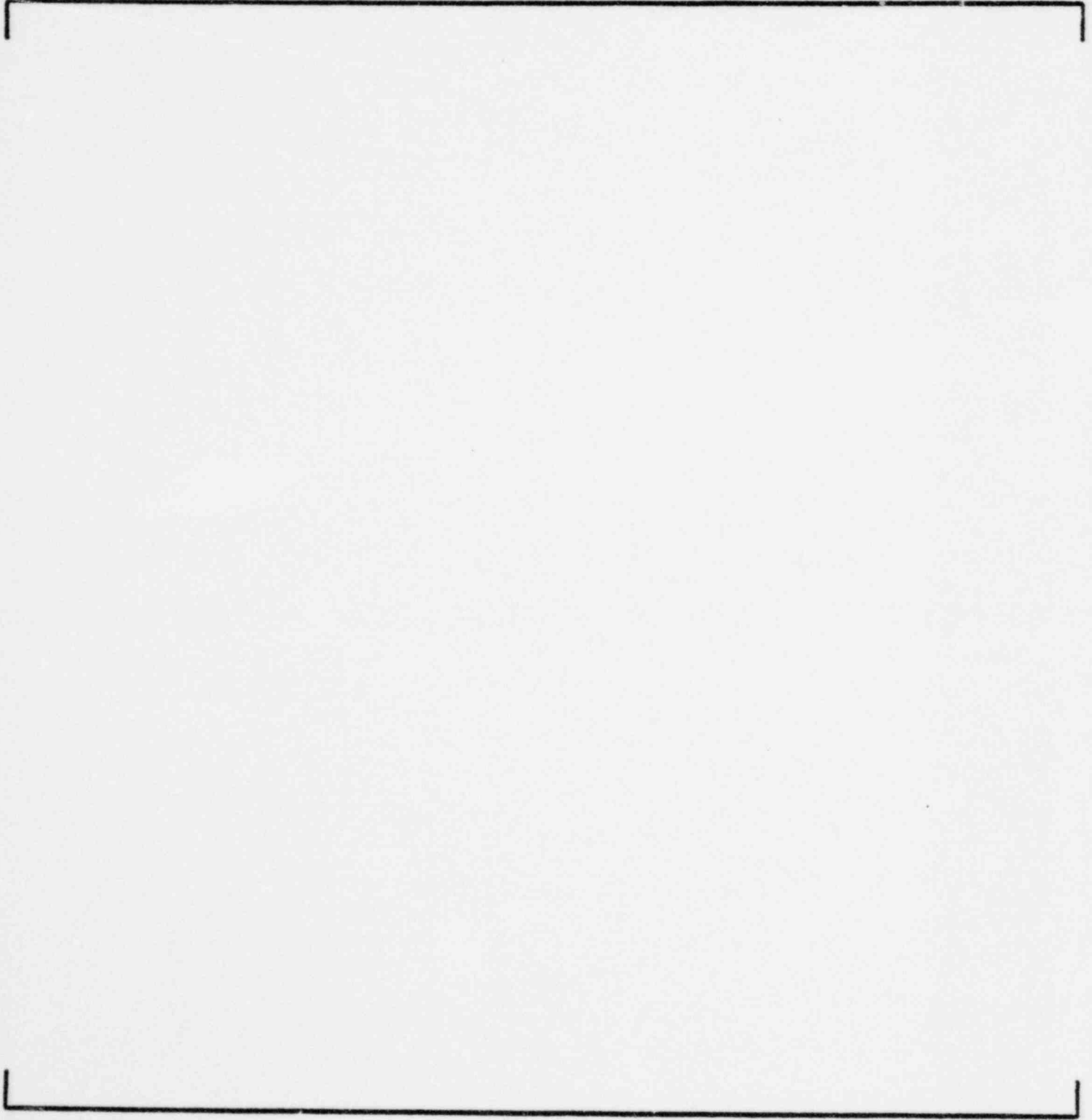
FIGURE 3-20d

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 1 AT 1440 MWD/T
LEVEL 4

I.3.128
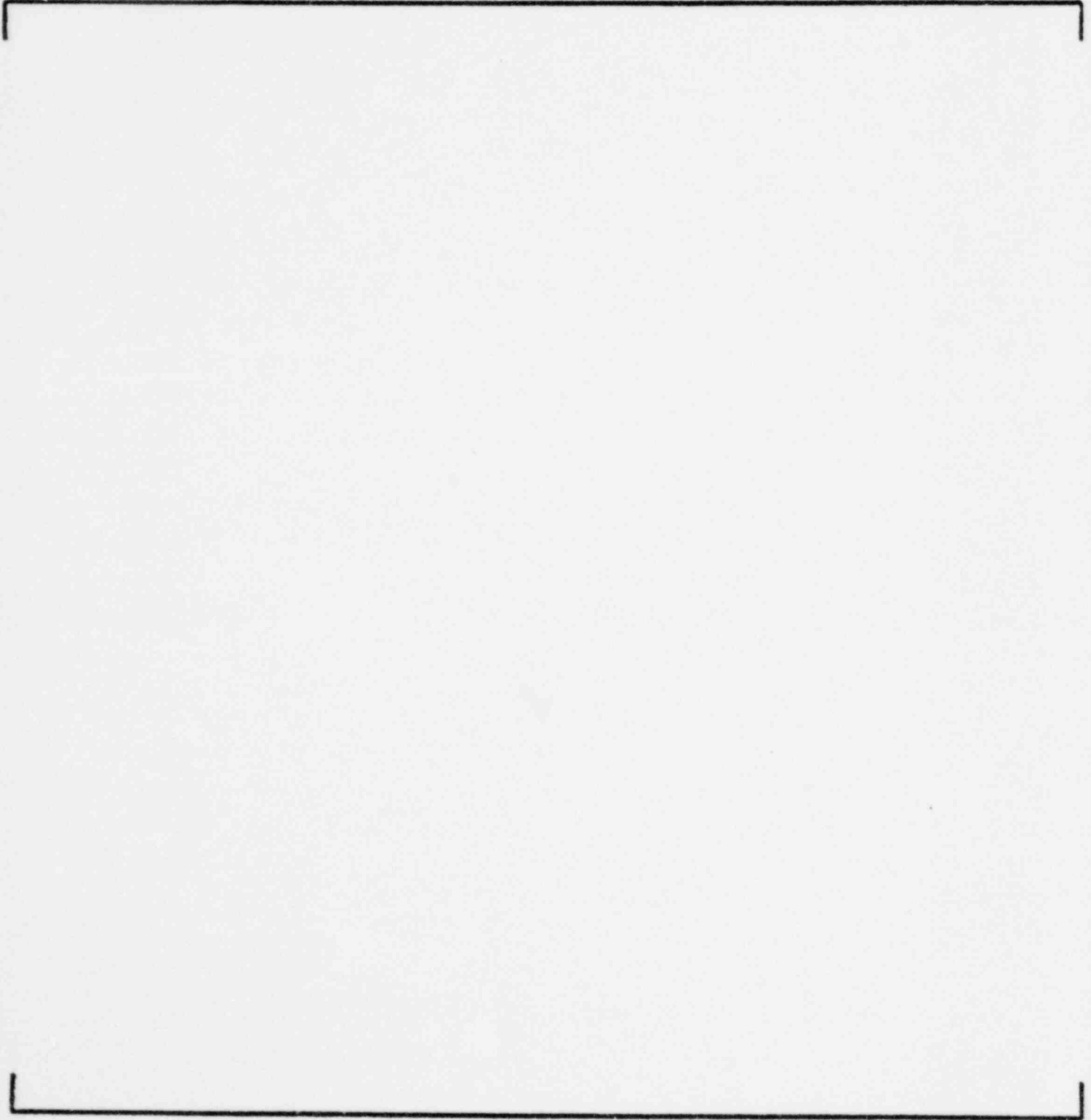
FIGURE 3-20e

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 1 AT 1440 MWD/T
SUMMED LEVELS
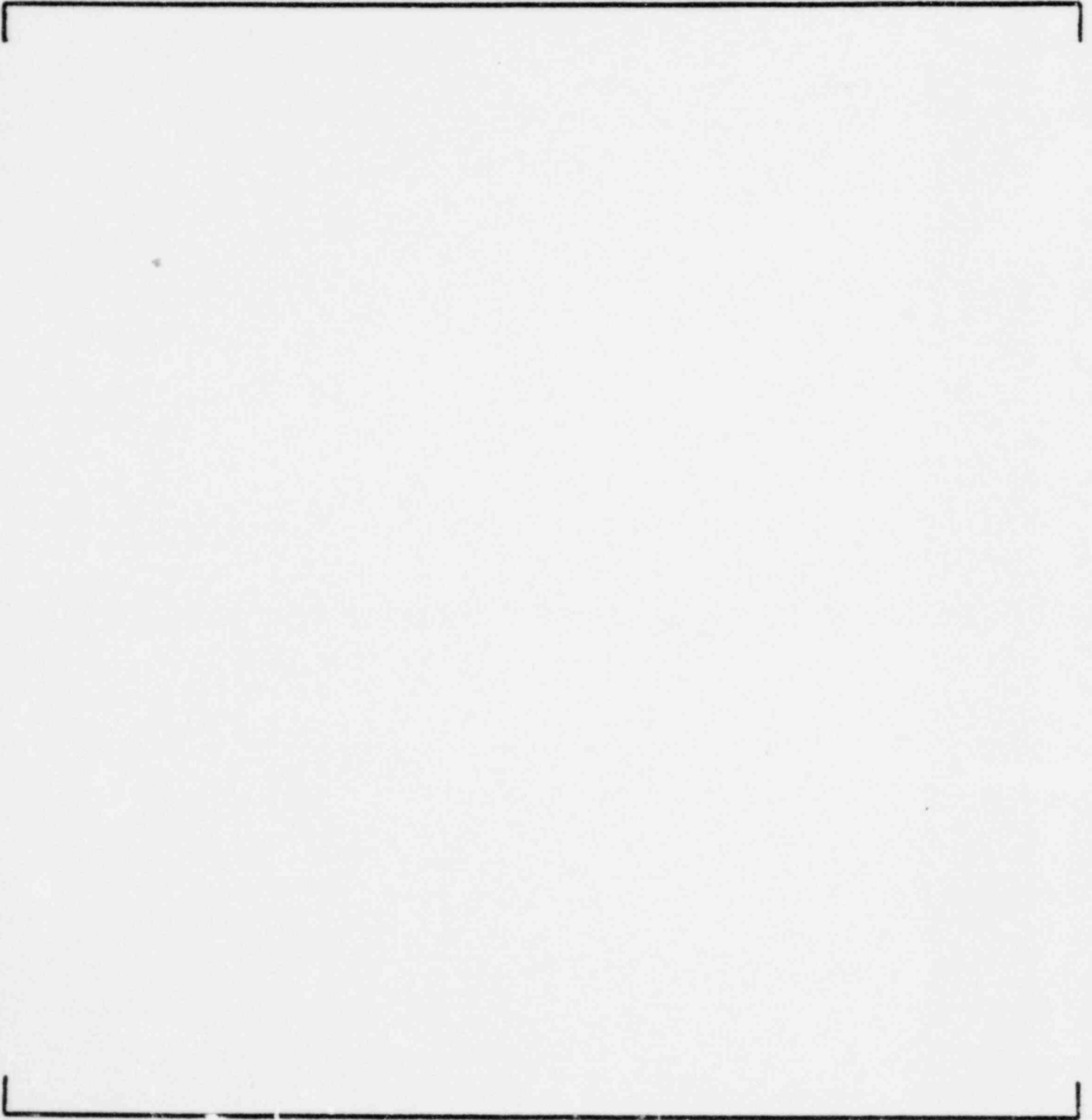
FIGURE 3-21a

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 2 AT 809 MWD/T
LEVEL 1

FIGURE 3-21b

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 2 AT 809 MWD/T
LEVEL 2

FIGURE 3-21c

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 2 AT 809 MWD/T
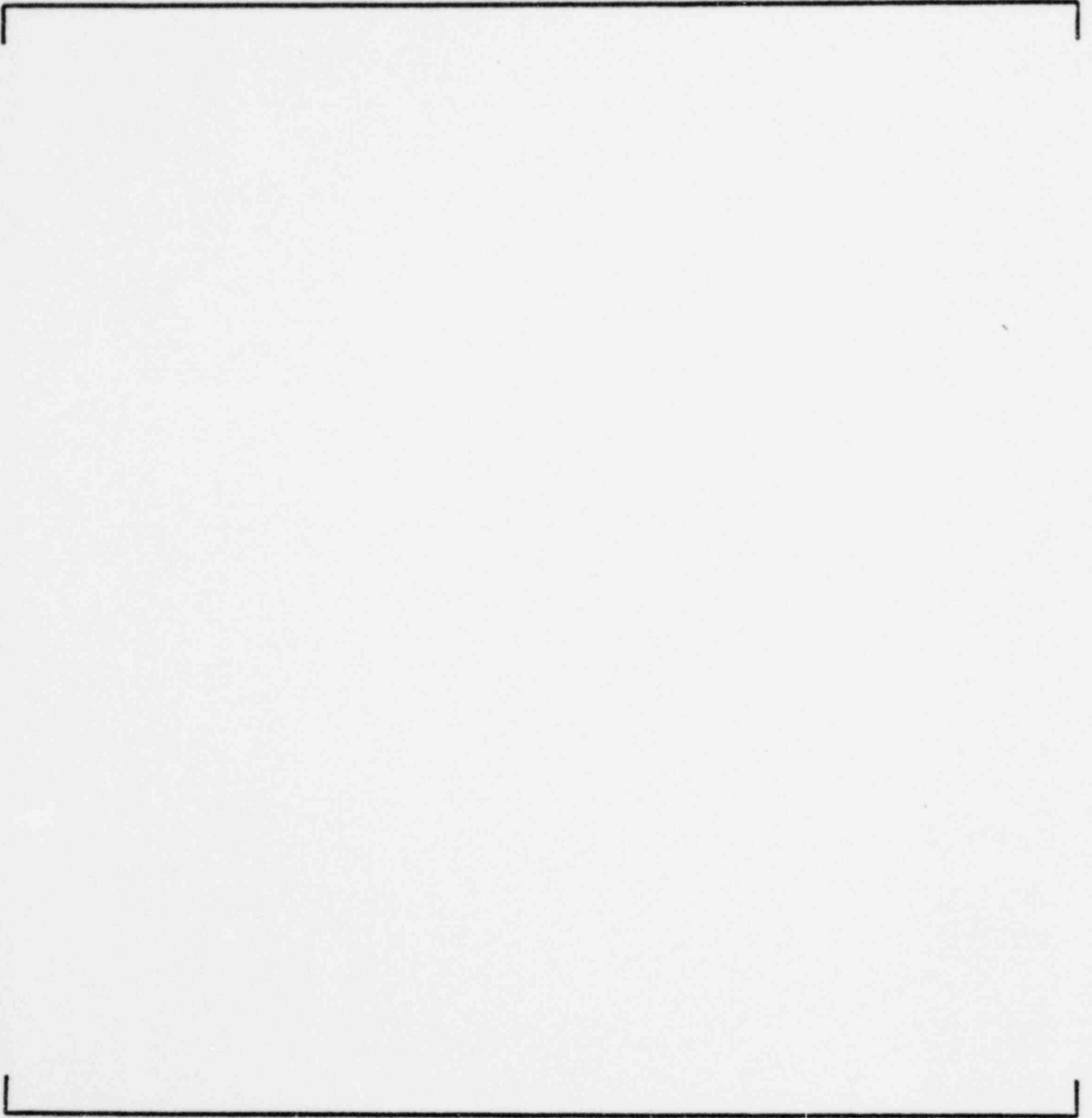LEVEL 3

FIGURE 3-21d

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 2 AT 809 MWD/T
LEVEL 4
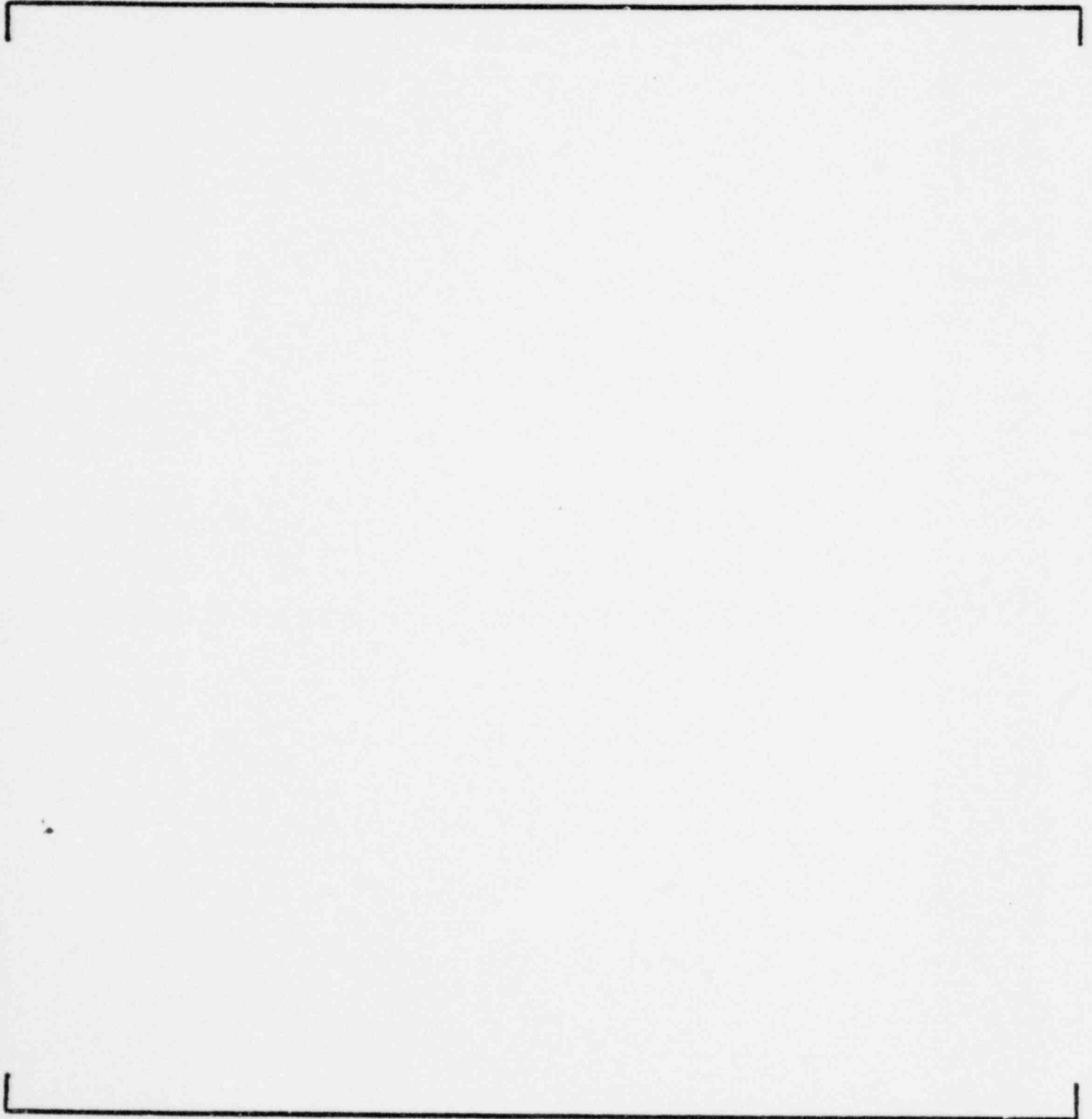
FIGURE 3-21e

COMPARISON OF MEASURED AND CALCULATED POWERS
CALVERT CLIFFS UNIT 2 CYCLE 2 AT 809 MWD/T
SUMMED LEVELS

Figure 3-22a
COMPARISON OF MEASURED AND CALCULATED POWERS
FORT CALHOUN UNIT 1 CYCLE 4 AT 1000 MWD/T
LEVEL 1
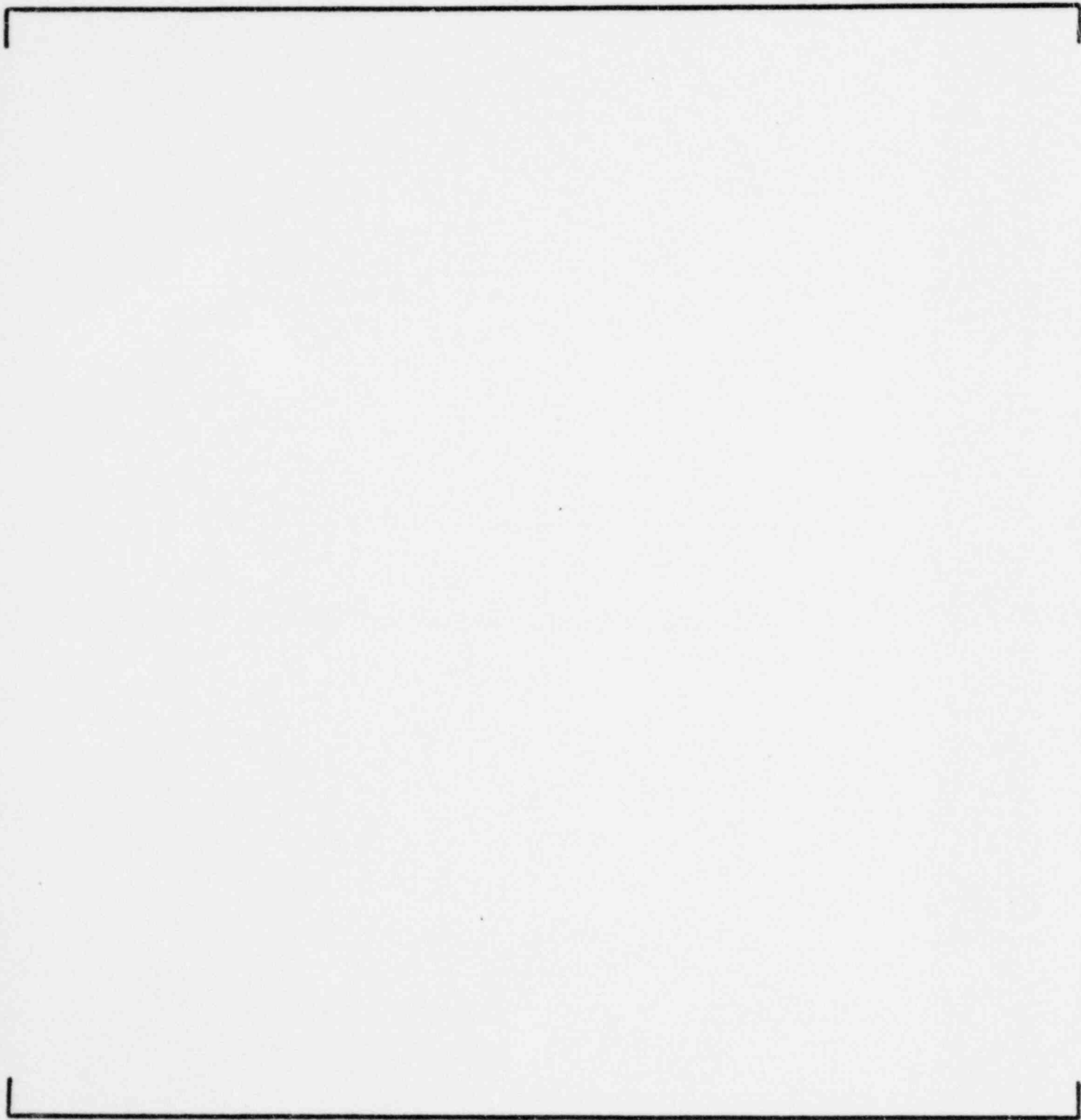
Figure 3-22b
COMPARISON OF MEASURED AND CALCULATED POWERS
FORT CALHOUN UNIT 1 CYCLE 4 AT 1000 MWD/T
LEVEL 2
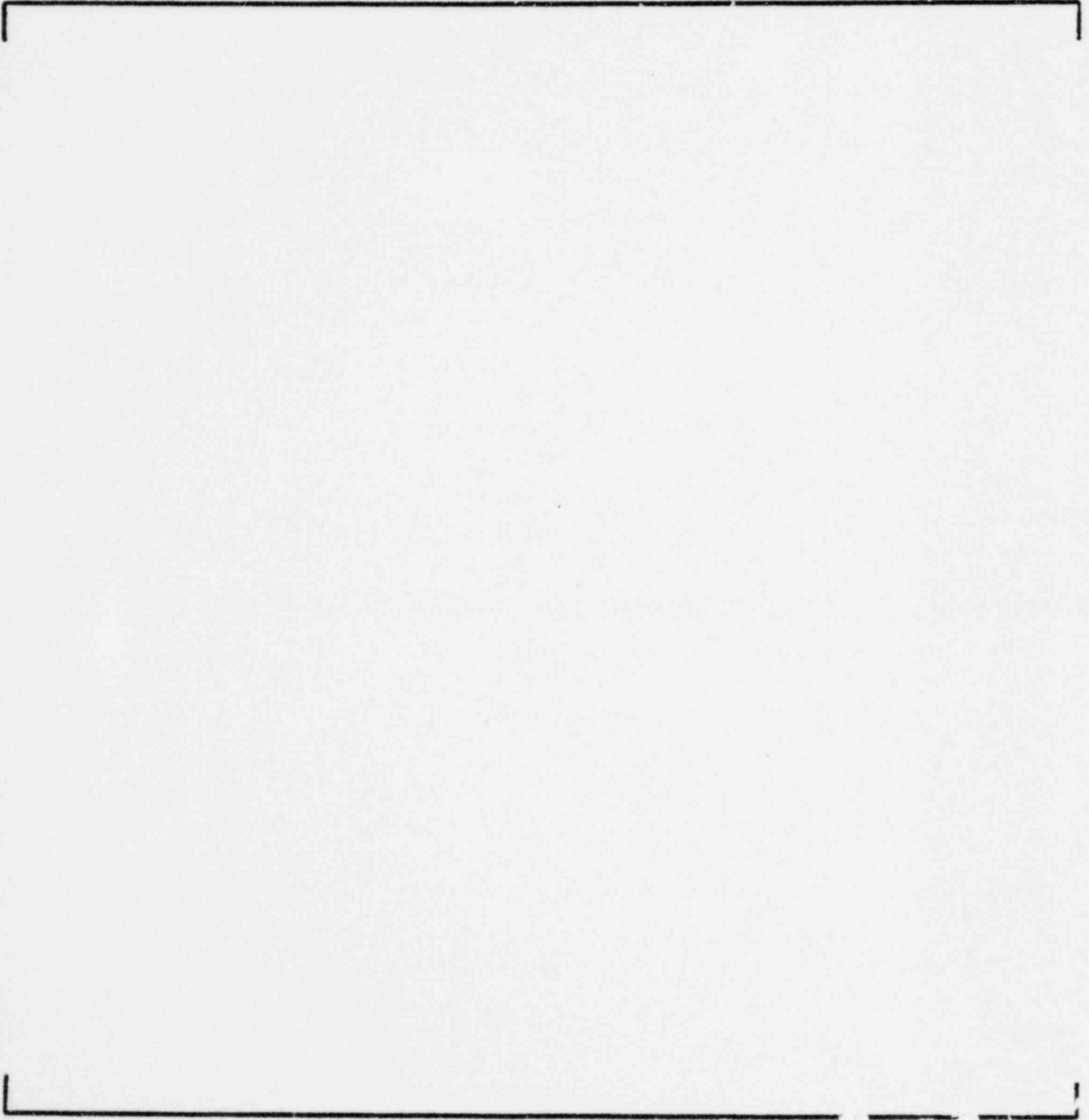
Figure 3-22c
COMPARISON OF MEASURED AND CALCULATED POWERS
FORT CALHOUN UNIT 1 CYCLE 4 AT 1000 MWD/T
LEVEL 3

Figure 3-22d
COMPARISON OF MEASURED AND CALCULATED POWERS
FORT CALHOUN UNIT 1 CYCLE 4 AT 1000 MWD/T
LEVEL 4
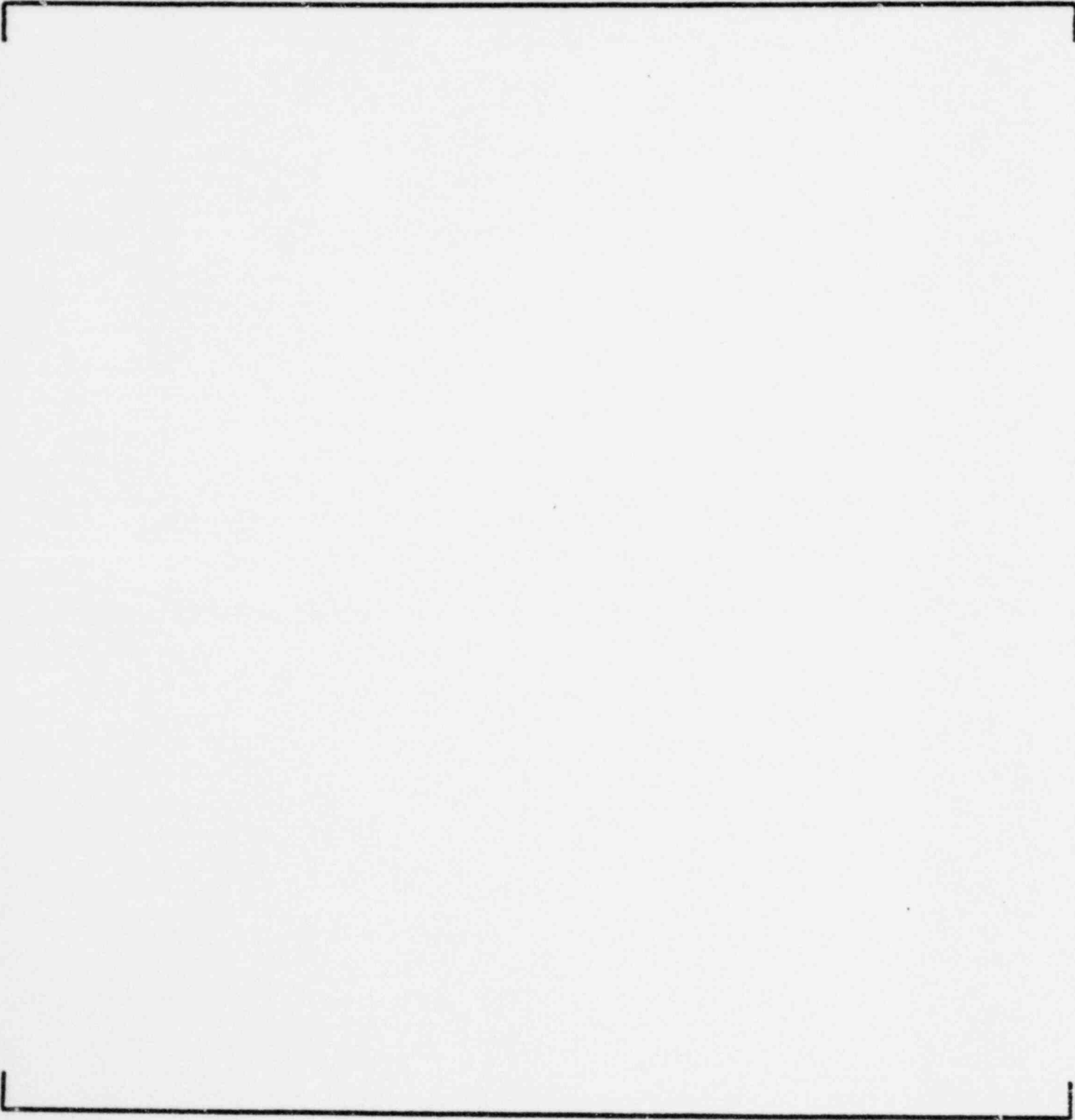
Figure 3-23a
COMPARISON OF MEASURED AND CALCULATED POWERS
FORT CALHOUN UNIT 1 CYCLE 5 AT 300 MWD/T
LEVEL 1
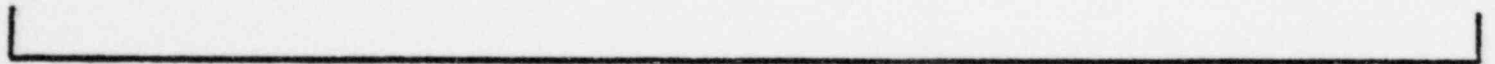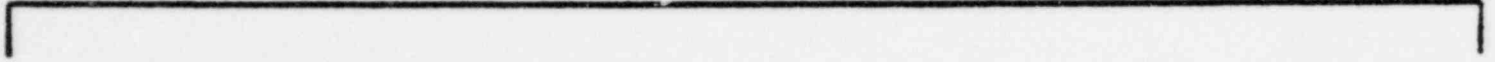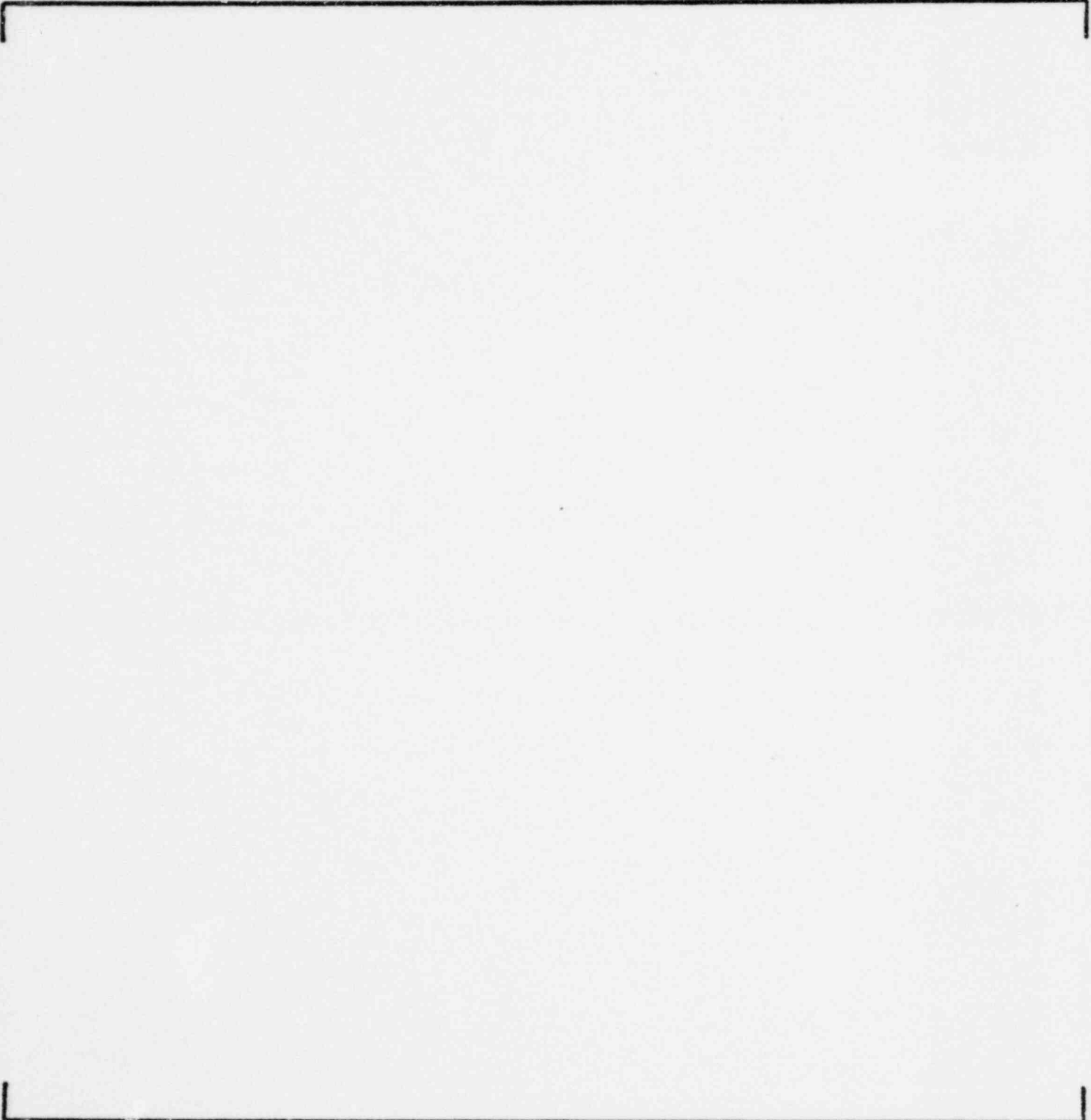
Figure 3-23c
COMPARISON OF MEASURED AND CALCULATED POWERS
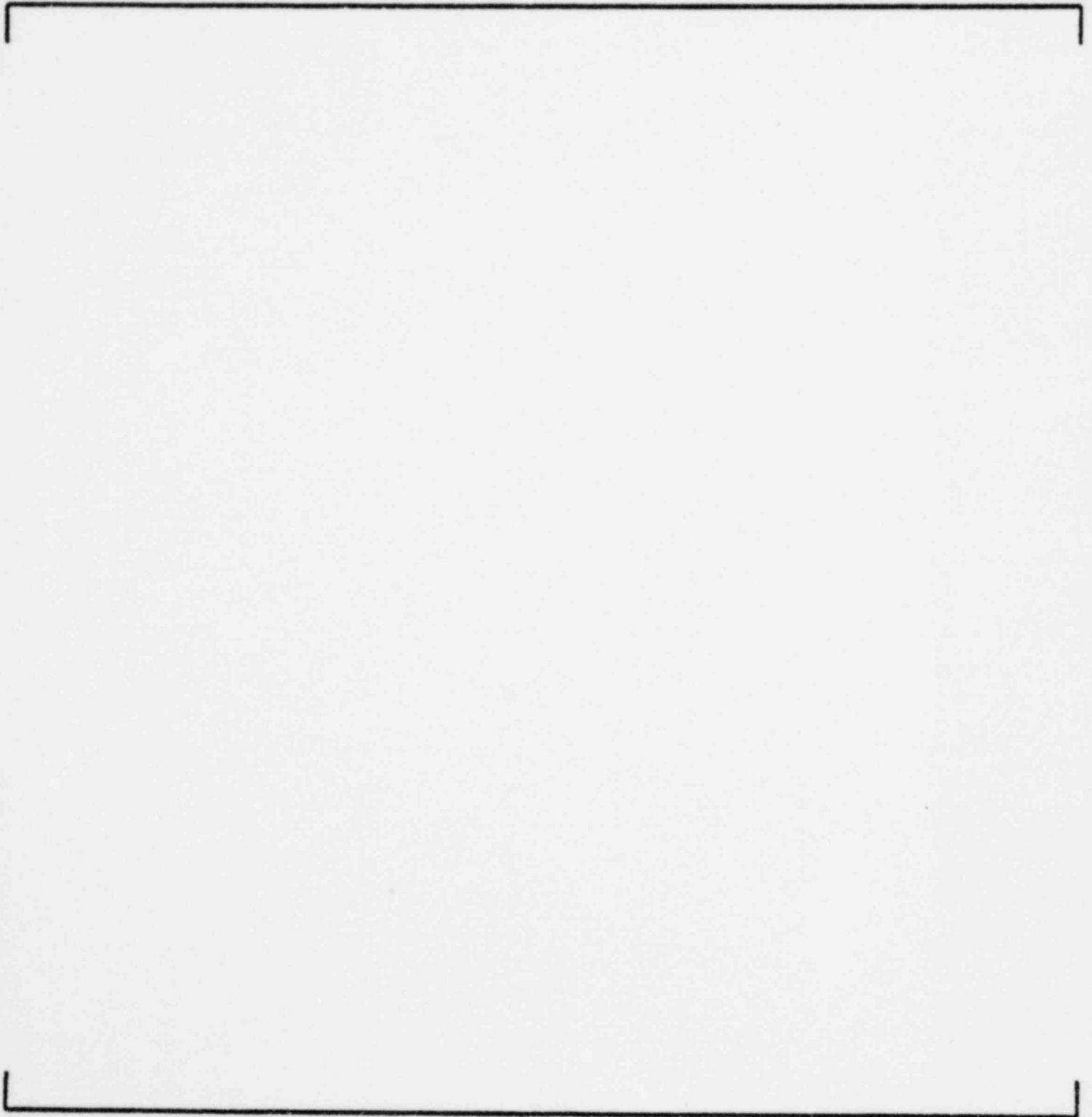FORT CALHOUN UNIT 1 CYCLE 5 AT 300 MWD/T
LEVEL 3
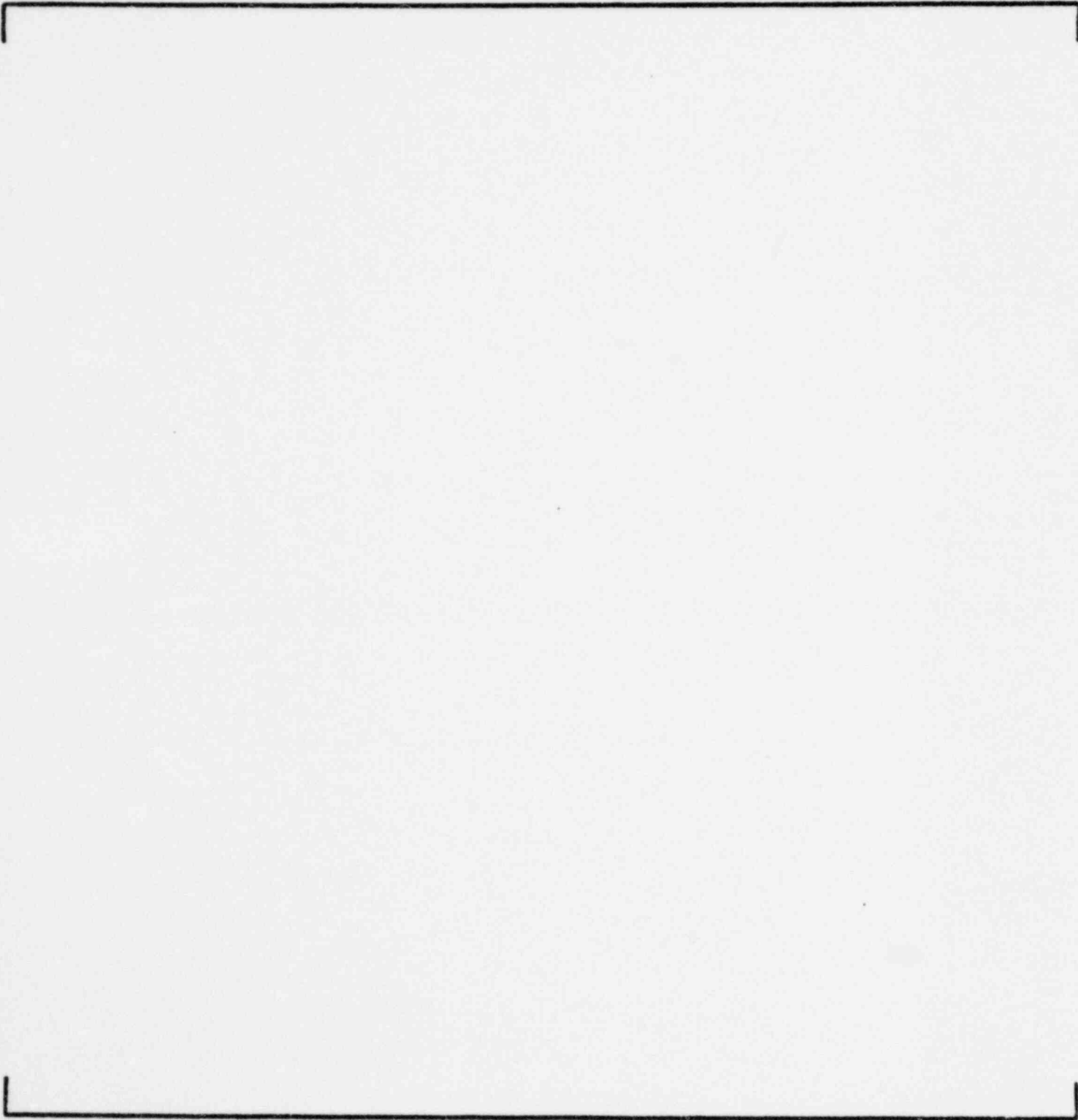
Figure 3-23d
COMPARISON OF MEASURED AND CALCULATED POWERS
FORT CALHOUN UNIT 1 CYCLE 5 AT 300 MWD/T
LEVEL 4
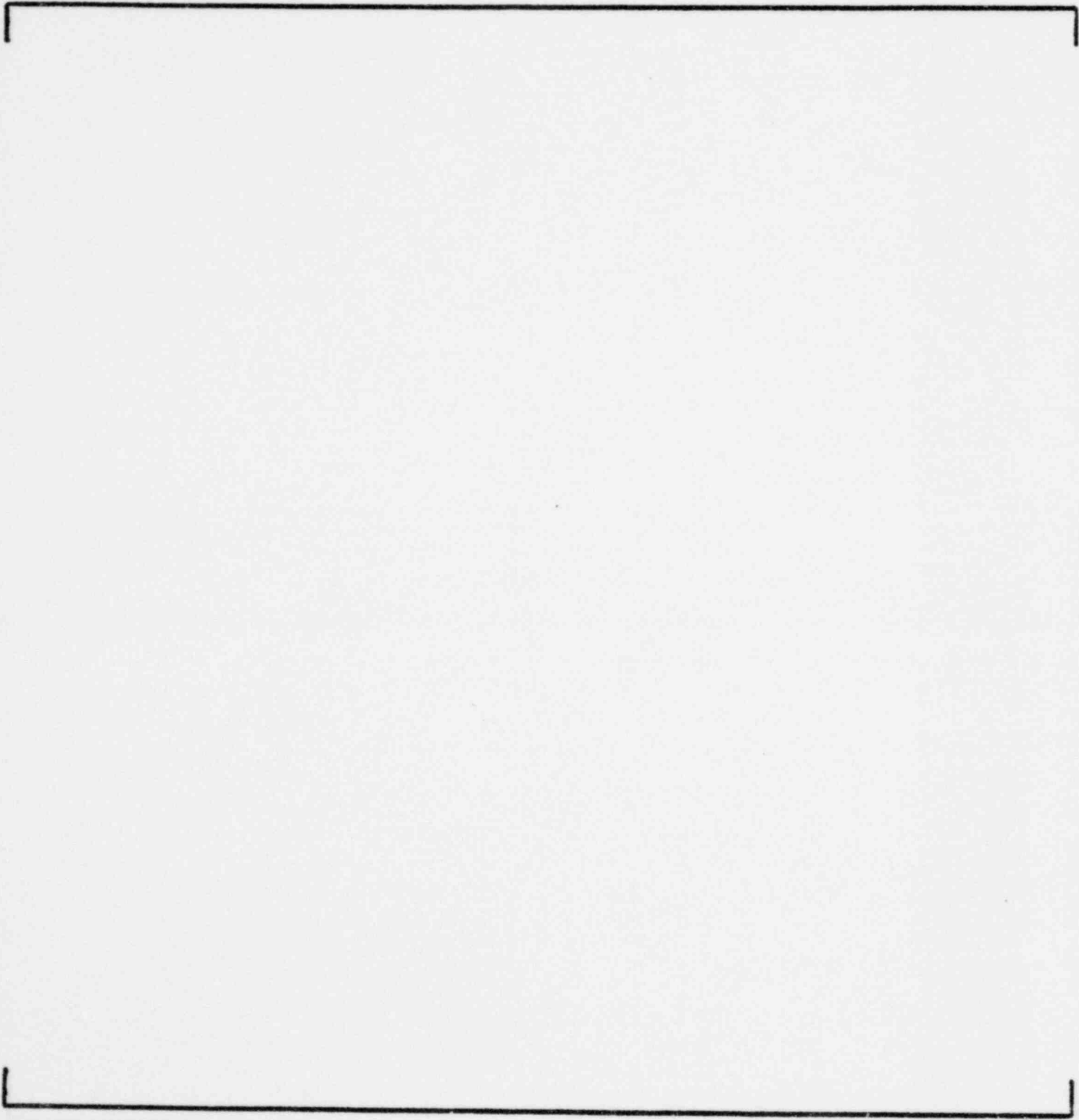
Figure 3-23e
COMPARISON OF MEASURED AND CALCULATED POWERS
FORT CALHOUN UNIT 1 CYCLE 5 AT 300 MWD/T
SUMMED LEVELS

Figure 3-24
DISTRIBUTION OF DEVIATIONS IN F_q
CALVERT CLIFFS UNIT 1 CYCLE 3
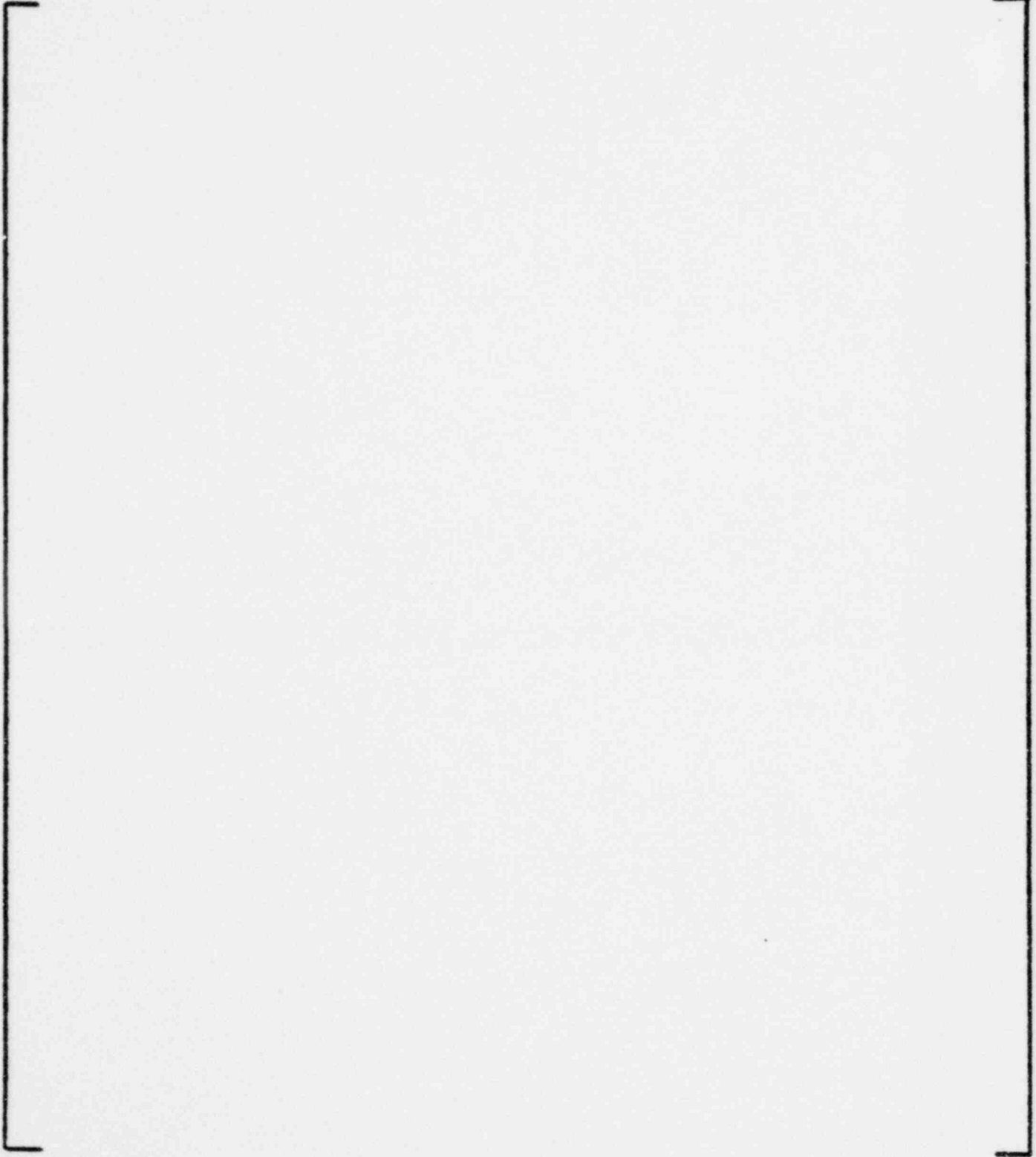
Figure 3-25
DISTRIBUTION OF DEVIATIONS IN F_q
ST. LUCIE CYCLE 2
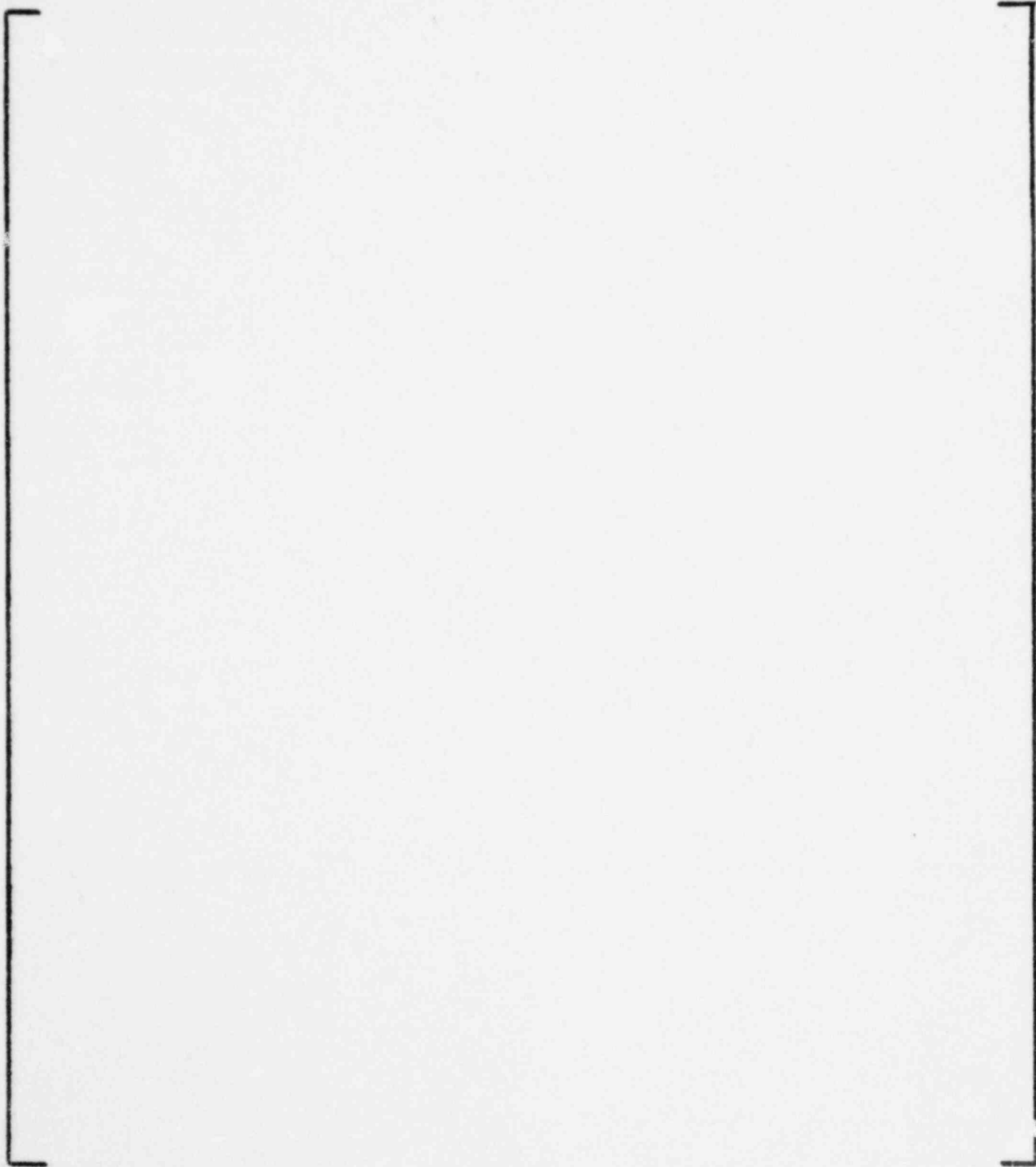
Figure 3-26

DISTRIBUTION OF DEVIATIONS IN F_r
CALVERT CLIFFS UNIT 1 CYCLE 3
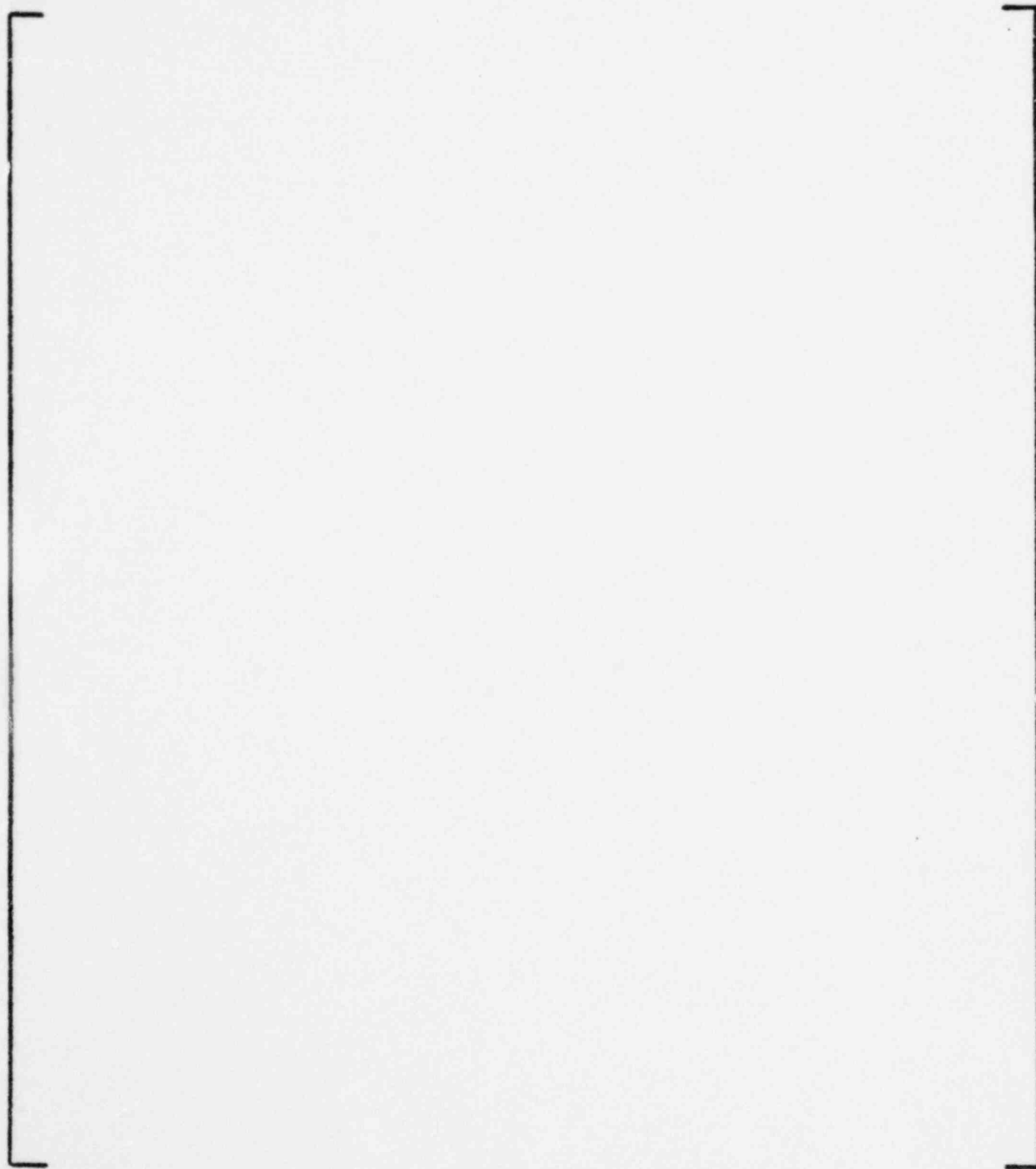
EVALUATION OF UNCERTAINTY
IN THE NUCLEAR POWER PEAKING
MEASURED BY THE SELF-POWERED, FIXED IN-CORE
DETECTOR SYSTEM

PART II

SOFTWARE SYNTHESIS UNCERTAINTIES

II.0   INTRODUCTION

The INCA system provides a method of synthesizing signals from self-powered, fixed in-core detectors into detailed three-dimensional assembly and peak pin power distributions. The actual synthesis is done in the CECOR program using libraries of precalculated coefficients generated by standard diffusion and transport theory methods, and processed by codes in the INCA system. In this part of the report the basic CECOR methods and theory are described as well as the generation of the INCA libraries. Further, an evaluation is made of the uncertainties associated with the CECOR synthesis by carrying out a computer simulation of the process. These uncertainties are combined in Part III with the basic measurement uncertainties evaluated in Part I to provide the overall uncertainties.

The synthesis of the signals into three-dimensional power distributions is carried out in the CECOR program. This is done by using precalculated power-to-signal ratios to obtain the powers in instrumented assemblies at each detector level. The powers in uninstrumented assemblies are then obtained through the use of precalculated coupling coefficients which relate the power in an assembly to the average power in its neighbors. The axial power distribution in each assembly is then obtained using a few mode Fourier expansion. The peak pin powers are constructed using precalculated pin/box factors. The CECOR methods are described in Chapter 1.

Chapter 2 describes the generation of the various INCA coefficients used in the CECOR process. The coefficients are obtained from detailed multi-group diffusion theory calculations and are processed by codes in the INCA system to provide the INCA libraries.

The uncertainties associated with the CECOR synthesis process are evaluated in Chapter 3. This is done by using a computer simulation over three cycles in which signals are taken from three-dimensional calculations. These are processed through CECOR using INCA libraries generated according to the procedures in Chapter 2. The resulting CECOR power distributions are then compared to the calculated power distributions to evaluate the synthesis uncertainties.

II.1   INCA ANALYTICAL METHODS

1.0   GENERAL

The C-E in-core detector signal analysis system, INCA, was originally
developed and described in 1969[1.1]. Since then, many improvements have
been made and the code has evolved to the present INCA/CECOR system[1.2-1.5]
which is in use for all C-E reactors. It provides a method to synthesize
a limited number of fixed, self-powered in-core detector readings into
detailed full-core radial and axial distributions for assembly and peak pin
powers.

Basically, the system uses prefit data from detailed, two-dimensional,
multi-group diffusion theory calculations to convert detector readings to
local box power values through the use of power/signal (W) factors. These
are provided for instrumented assemblies at each axial detector level in
the core. The planar power distributions at each detector level are obtained
through the use of pre-calculated average coupling coefficients <CC>,
which relate the power in an uninstrumented assembly to the average power
in its neighboring assemblies. The axial power distributions are obtained
by a few mode Fourier expansion which matches the box powers at each detector
level. Subsequently, the peak pin powers in each assembly are obtained by
the application of pin/box (F_p) factors which are pre-calculated using fine
mesh, two-dimensional transport theory corrected diffusion theory.

This chapter describes the analytical methods in detail, starting with the
conversion of signal to power. This is followed by a discussion of the
radial expansion, axial synthesis, the determination of pin peaking, and
the types of edited output quantities.

1.1   DESCRIPTION OF CECOR METHODS

1.1.1   Definitions and System Description

In the following list of symbols, the integer i designates a fuel assembly or cell and the control rod it contains in the plan view, while n (1,2,3,4 or 5) indicates the axial detector level or position. The axial coordinate (z) is measured from the bottom of the core.

α_n =   distance from the top of the nth detector to the core bottom.

β_n =   distance from the bottom of the nth detector to the core bottom.

H_i =   distance from the bottom of control rod i to the core bottom.

S_k =   distance from the bottom of the kth rod bank region to the core bottom ("rod bank region" is defined below).

δ_{rod} =   dead band or uncertainty in rod location; [   ]

L_i =   length of a part-length rod in assembly i.

I_{in}^{Rh} =   rhodium detector background corrected current or signal from the nth axial detector of fuel assembly i.

P_{in} =   power in assembly i integrated only over the length of axial detector n.

$P_i(z)$=   power in assembly i per unit axial length at height z.

P_i =   total power generated in fuel assembly i.

P_B =   total power generated in a given batch of fuel assemblies.

P_C =   total core power, normalized to calorimetric power.

W_{in} =   power-to-signal coefficient which relates the integrated power in assembly i over the length of detector n to the signal from detector n.

$CALIB_{in}$=   calibration factor in terms of rhodium activation per Rh atom per unit Maxwellian flux, $\emptyset_o^{MAX}$, impinging on the detector sheath.

V_{in}^{Rh} =   volume of the nth rhodium detector located in assembly i.

$\sigma_a^{Rh}(N^{Rh})$= microscopic neutron absorption cross section of a rhodium detector as a function of Rh concentration, N^{Rh}.

S_{in}^{Rh} =   sensitivity of rhodium detector n located at assembly i, relating detector current produced per unit Maxwellian flux at the detector sheath.

W_{in}^i = ratio of the power in assembly i integrated over the length of the nth detector to the rhodium detector activation per Rh atom.

$\langle CC \rangle_{in}$ = average coupling coefficient for assembly i at the nth detector level.

p_{jn}^i = power in assembly j (neighboring assembly i) integrated over the length of the axial detector n.

N_i = number of neighboring assemblies to assembly i.

h = assembly pitch.

M_{in}^2 = neutron migration area at assembly i, level n.

$k_{\infty in}$ = infinite multiplication factor at assembly i, level n.

$I_{\ell n}$ = the set of instrumented boxes neighboring an uninstrumented box ℓ at level n.

$U_{\ell n}$ = the set of uninstrumented boxes neighboring an uninstrumented box ℓ at level n.

U_n = the total number of uninstrumented boxes at level n.

B_i = axial fitting parameter for assembly i, as a function of core height, H, and extrapolation distance, δ_i.

The axial configuration for a typical 4 detector level system is shown in Figure 1-1. The various axial portions of the core with different control rod bank configurations or patterns are defined as control rod bank regions. The coefficients used in each axial zone or control rod bank region are taken from the library for the corresponding rod configuration pattern. By finding these sets, the entire control bank configuration can be specified in terms of the population of each set and its withdrawal, S_k, as indicated in Figure 1-1.

To find the various rod bank sets, one scans all values of H_i to see which rods have their H_i within a specified dead band, δ_{rod}, about the first one examined. The dead band represents the uncertainty in measuring rod positions and in keeping the rods aligned in a bank, and is generally taken as [   ] The process is then repeated for the remaining rods. The members of a set, distinguished by their i indices, are then compared with the membership of certain banks known in the library and distinguished by indices j. From

this procedure, the core configuration can be described completely as follows: the lowest axial rod bank region from 0 to S_i is bank j^0 pattern, the next region from S_1 to S_2 is bank j^1 pattern, etc., until the height of the upper bank limit is equal to the full core height. Normally, it is expected that only two to four rod banks will be present and thus the total number of possible bank configurations in the library will be less than fifteen, so the sorting among various alternative configurations is rapid.

Part-length control rods require special treatment since both the top and bottom of the poisoned section define bank region limits. This can be done by adding to the array of rod withdrawal values the additional values $H_i + L_i$, where L_i is the length of the part-length rod in assembly i.

1.1.2   Signal-to-Box Power Conversion

The power integral over a detector level in an instrumented assembly is obtained by multiplying the background corrected integrated detector signal by constants measured and supplied by the manufacturer, and constants calculated from fine-mesh, two-dimensional, multi-group diffusion theory calculations. The signal-to-box power conversion for an instrumented assembly i at detector level n is expressed by:

$$P_{in} = I_{in}^{Rh} W_{in} \qquad (1.1)$$

where

$$W_{in} = \frac{CALIB_{in} \; W'_{in}}{S_{in}^{Rh}} \qquad (1.2)$$

$$CALIB_{in} = \frac{\displaystyle\int_E \int_{V_{in}^{Rh}} \sigma_a^{Rh}(N^{Rh}) \; \emptyset \; (\underline{r}, E) \; d\underline{r} \; dE}{\emptyset_o^{MAX}} \qquad (1.3)$$

$$W'_{in} = \frac{P_{in}^{Rh}}{\iint\limits_{EV_{in}^{Rh}} \sigma_a (N^{Rh}) \, \emptyset \, d\underline{r} \, dE} \qquad (1.4)$$

consistent with the definitions in 1.1.1.

The detector sensitivity, S, relates the current, I, produced by the detector to the incident neutron flux at the surface of the detector. The initial sensitivity and relative calibration of the sensitivity are supplied by the vendor. As described in Chapter I.2, the sensitivity as a function of depletion for a given detector is determined by

$$S^{Rh}(t) = S_o \left(1 - \frac{Q(t)}{Q_\infty}\right)^n \qquad (1.5)$$

where

S_o = the initial sensitivity for the detector, supplied by the vendor.

$\frac{Q(t)}{Q_\infty}$ = the fraction of the total available charge for the detector at time t, where Q_∞ is supplied by the vendor.

n = the experimentally determined fitting parameter.

The W' are calculated for each assembly with a detector as a function of life from fine-mesh, 2-D planar depletion calculations using multi-group diffusion theory. The W' are then fit as a function of assembly burnup for each detector location. In current C-E cores, control rods do not enter instrumented assemblies. As a consequence, the W' presently are only calculated for unrodded configurations. Future C-E core design include control rods in instrumented assemblies. For such cores the W' will be calculated for each control rod region. If the axial length of a detector corresponds to more than one rod region, the W' will be obtained by volume weighting the values for the respective rod regions.

1.1.3   Planar Power Distributions

At each detector level the powers in the uninstrumented assemblies are determined from the measured powers in instrumented assemblies. This is accomplished through the use of radial coupling coefficients.

The average coupling coefficient of an assembly at detector level n is defined as the ratio of the average power in the surrounding boxes to the power in the assembly itself. For the usual case of a cell surrounded by four boxes, this is

$$<CC>_{in} = \frac{\sum\limits_{j=1}^{4} P_{jn}^i}{4P_{in}} \qquad (1.6)$$

where P_{jn}^i denotes the power in boxes neighboring cell i. More generally,

$$<CC>_{in} = \frac{\sum\limits_{j=1}^{N_i} P_{jn}^i}{N_i P_{in}} \qquad (1.7)$$

where N_i is the number of neighbors of box i.

The average coupling coefficient given by Eq. (1.7) is insensitive to mild power tilts across the core. In addition it has been found that local perturbation effects in a cell (e.g., from rods) essentially affect the coupling coefficient for only the subject box, i.e.,

$$\delta<CC>_{in} = \frac{-h^2}{N_i M_{in}^2} \delta k_{\infty in} \qquad (1.8)$$

as can be derived from the modified one-group diffusion equation. Eq. (1.8) has, in fact, been tested and found to accurately predict such perturbations in $\langle CC \rangle_{in}$.

In practice, the coefficients are pre-calculated from Eq. (1.7) using box power distributions obtained from either 2-D fine-mesh or 3-D coarse-mesh depletion calculations using multi-group diffusion theory, and are then fit as a function of burnup for each assembly. Explicit sets of burnup fitted coefficients are prepared for each control rod configuration or rod bank region. The actual values of $\langle CC \rangle_{in}$ used in CECOR are obtained from these sets of fitted coefficients using average assembly burnup values obtained by integration over detector level n. When a detector level is penetrated by more than one rod bank region, the coefficients are obtained by volume weighting respective values for each rod bank region.

Knowing the average coupling coefficient values at a given detector level, the power in any uninstrumented box ℓ may be obtained from:

$$
P_{\ell n} = \frac{\sum\limits_{j=1}^{N_\ell} P_{jn}^\ell}{N_\ell \langle CC \rangle_{\ell n}}
\tag{1.9}
$$

Originally[1.1], INCA worked on the octant or quarter core basis, where symmetry was assumed and all instrument readings were reflected into the octant of interest. As a consequence, each uninstrumented box was surrounded by four instrumented boxes and Eq. (1.9) itself could be solved directly for each uninstrumented box. In the actual CECOR full core calculation, each uninstrumented box is not surrounded by four instrumented neighbors. In fact, many boxes have only one or two instrumented neighbors; and some have none. As a result, Eq. (1.9) cannot be solved directly for each uninstrumented box alone, since some of the neighboring powers are also unknown. However, at each level n, the equation may be written for every uninstrumented box, $\ell = 1, \ldots, U_n$, and then rearranged with the unknown powers

on one side of the equation and the known powers on the other. Thus, if $I_{\ell n}$ and $U_{\ell n}$ are the sets of instrumented and uninstrumented boxes neighboring ℓ, respectively, then

$$N_\ell <CC>_{\ell n} P_{\ell n} - \sum_{j \varepsilon U_{\ell n}} P^\ell_{jn} = \sum_{j \varepsilon I_{\ell n}} P^\ell_{jn}, \quad \ell = 1,\ldots,U_n \qquad (1.10)$$

where the summation on the left hand side is over uninstrumented neighbors, and the summation on the right hand side is over instrumented neighbors. When all the equations for each uninstrumented box are written and grouped, a $U_n \times U_n$ matrix equation results:

$$A \underline{P} = \underline{S} \qquad (1.11)$$

where for the unknown power $P_{\ell n}$, the ℓ-th row of the matrix A has $N_\ell <CC>_{\ell n}$ on the diagonal and -1 on the off-diagonals for those uninstrumented boxes which neighbor box ℓ. The matrix A is symmetric when each assembly is coupled to all its neighbors. In addition, A is very sparse, with elements on the diagonal and N_ℓ (usually 3 or 4) other elements in any row ℓ. If uninstrumented assemblies are surrounded by four instrumented assemblies this new CECOR formulation reverts back to the original INCA scheme.

The solution for the unknown powers is obtained by solving Eq. (1.11). Symbolically:

$$\underline{P} = A^{-1} \underline{S} \qquad (1.12)$$

This system is solved at each detector level.

Since the matrix can be large (on the order of 200x200), efficient solution routines are needed. From the standpoint of speed and memory requirements, a modification of the conjugate gradient method[1.6] which takes advantage of the unique nature of the A matrix is used.

A feature of this formulation is that if an instrument fails, the box is simply treated as uninstrumented and the resulting larger set of equations

is solved. For this to work, average coupling coefficients are precalculated
and provided for all boxes, uninstrumented or instrumented. This concept
also provides a way of checking detectors, since the actual detector power
may be compared to the deduced power obtained by treating the box as
uninstrumented. If the difference exceeds a predetermined criterion, it is
an indication that either the detector has failed or a local perturbation
may have occurred.

1.1.4 Axial Power Distribution

Using the power in the assembly at each detector level, the detailed axial
shape can be synthesized by using a Fourier expansion. This axial fitting
technique is described in detail in Reference 1.4. Basically, the axial
power distribution in an assembly is represented as the sum of the first N
Fourier modes

$$P_i(z) = \sum_{n=1}^{N} a_n \sin n \pi B_i z \tag{1.13}$$

where $P_i(z)$ is the power per unit length for assembly i, a_n are the unknown
combining coefficients, z is the axial elevation in fraction of the core
height, H, and B_i is the fitting parameter given by

$$B_i = \frac{H}{H+2\delta_i} \tag{1.14}$$

Note that δ_i is essentially an extrapolation distance. The N combining
coefficients, and thus the axial power distributions are obtained by matching
the box power at each level to the integral of Eq. (1.13) over the axial
extent of each of the N detectors. Thus,

$$P_{in} = \int_{\beta_n}^{\alpha_n} dz \ (\sum_{n=1}^{N} a_n \sin n \pi B_i z), \ n=1,\ldots,N \qquad (1.15)$$

is used to solve for the a_n values for assembly i, where β_n and α_n are the elevations for the bottom and top of detector level n, respectively. For instrumented assemblies, the P_{in} values are obtained directly from detector measurements. For uninstrumented assemblies, the values are obtained from planar power distribution solutions at each level, using the coupling coefficient formulation described in 1.1.3.

For four-detector systems, the fit is performed with three modes matching the bottom three detectors and three modes for the top three detectors. The distribution in the top or bottom half of the core is the appropriate fit. Four modes could also be used to match all 4 levels simultaneously. The accuracy in the axial synthesis and the magnitude of the axial peak-to-average power is essentially the same, although slightly better using 4 modes at once. For five axial detectors, one fit used over the whole range and five Fourier modes is used. This results in a significant improvement in the fitted results, especially for the more extreme shapes. This means that the accuracy of the axial synthesis is higher for a five detector system.

This is illustrated by a comparison of the two axial synthesis schemes using 4 or 5 detectors in the analysis of a variety of one-dimensional shapes[1.4]. The analysis is based on 17 axial shapes, ranging from typical to highly skewed in nature. A small representative sample of the shapes analyzed is shown in Figure 1-2. The statistical results are given in Table 1.I. These show that the single and overlapping expansions have essentially equivalent errors for the four level system, and that the five level system is clearly superior overall.

A larger base of 846 typical axial shapes from one- and three-dimensional calculations for both first and later cycle cores was similarly analyzed

with 4 and 5 level synthesis schemes. A sample of representative shapes is shown in Figure 1-3. The superiority of the five level system is again evident from this analysis, as indicated by the results in Table 1.II.

An important parameter in the Fourier expansion is the extrapolation distance (δ) or fitting parameter B. For 4 detector systems, B is a function of core life and is radial core zone dependent. B is obtained from nominal 3-D design depletion studies. It is chosen for each zone so as to drive the error in fitting the axial peak to average power ratio in each assembly towards zero. Figure 1-4 shows the characteristic behavior of B for a reload core in which the peripheral outer new fuel has a different shape than the inner old fuel. When five or more detector segments are available, a single depletion independent value of B can be used throughout the core.

1.1.5 Total Power

Determination of radial and axial power distributions for the assemblies is completed using the methodology described in the previous sections. The total powers generated in each assembly, P_i, are obtained by integration over the axial shapes. Summation over the assemblies in a batch gives batch power, P_B, and summation over the batches gives the reactor power, P_C. The batch, assembly, axial assembly nodal, and core power are all normalized to the calorimetric power. The nodal burnups are updated by integrating the energy production over the elapsed time since the previous time point. This information is used to update the assembly, batch and core exposure counters. These, in turn, provide information advantageous to fuel management, and are used to evaluate the fits for INCA coefficients. Detailed edits of the assembly data are described in 1.2.

1.1.6 Peak Pin Power Distributions

Detailed three-dimensional peak pin power distributions are obtained axially at each node for each assembly through the use of precalculated pin/box (F_p) factors, which are fit to the assembly burnup. The pin/box factor is

defined as the ratio of the maximum 1-pin power in the box to the average
pin power in the box. The precalculated values are obtained from detailed
two-dimensional depletion calculations, using multi-group, transport theory
corrected diffusion theory, for each rod bank configuration or region. The
peak pin power at any axial location is then obtained using

$$P_{pi}(z) = F_{pi}(z) \, P_i(z) \qquad\qquad (1.16)$$

where $F_{pi}(z)$ is taken from the appropriate coefficient set and evaluated
with the local assembly burnup at that elevation.

The 3-D pin power distributions can then be examined to find the peak pin
power (F_{qi}) for each assembly and for the core (F_q). Axial integrals can
be formed to find the peak pin channel power (F_{ri}) for each assembly and
for the core (F_r). Further, the peak pin power to the average pin power
can be obtained for each axial elevation, $F_{xy}(z)$, and for the core as a
whole, (F_{xy}). Conversions are also made to give peak linear rates in terms
of actual powers rather than as ratios. The code also provides most of the
parameters required to estimate DNB ratios. The DNBR calculation is not
performed in INCA/CECOR, but in external programs, so it is not treated in
this topical report. An overview of the edits is given in 1.2.

1.1.7   Detection of Azimuthal Flux Tilt

An algorithm is present in the CECOR code which provides guidance regarding
the presence and magnitude of an azimuthal power tilt in the reactor. It
uses symmetric groups of instruments to detect and compute the magnitude of
the ratio of the first harmonic to the fundamental mode. Precalculated
fundamental and first harmonic form functions are used in the process. If
the flux in a three-dimensional system is expanded in a harmonic series,
i.e.,

$$\emptyset \, (r,\theta) = \emptyset_0 \, (r, \, \theta) + \sum_{i=1}^{\infty} a_i \emptyset_i (r,\theta) \qquad\qquad (1.17)$$

and is truncated after two terms, the following basic equation results:

$$\phi(r,\theta) \cong \phi_0(r,\theta) \left\{ 1 + a_1 \frac{\phi_1(r,\theta)}{\phi_0(r,\theta)} \right\} \tag{1.18}$$

Thus, the ratio of total flux to the first harmonic flux is

$$\frac{\phi(r,\theta)}{\phi_0(r,\theta)} = \left\{ 1 + a_1 \, f(r,\theta) \right\} \tag{1.19}$$

Analogously, from bare cylinder theory,

$$f_B(r,\theta) = g(r)f(\theta) = \frac{J_1(r)}{J_0(r)} \cos\theta \tag{1.20}$$

This suggests the following functional form for use in reflected heterogeneous systems:

$$f(r,\theta) = g(r) \, f(\theta) = \left\{ \frac{\phi_1(r,\theta)}{\phi_0(r,\theta)\cos\theta} \right\} \cos\theta \tag{1.21}$$

In CECOR, indications of any azimuthal flux tilting are obtained by comparing the signals from symmetrically located detectors at each level and fitting them to the functional form:

$$\phi(r,\theta) = \phi_0(r,\theta) \left\{ 1 + sg(r) \cos (\theta - \theta_0) \right\} \tag{1.22}$$

where the fundamental flux pattern is ϕ_0, the first harmonic tilt amplitude, s, and the orientation of the tilt, θ_0. The functional g(r) is used to relate the tilt signals from different radial groups, and is obtained from 2-D diffusion theory calculations, where little sensitivity to fuel depletion is noted.

II.1.13

Estimates of s and θ_0 are obtained for each symmetric group for each axial level of detectors. The amplitudes aand angles are then vectorially combined to obtain the best statistical estimate for s. Additionally, the components are weighted by the square of $g(r)$, since symmetric groups farthest from the core center provide the best estimates of tilt.

Several comments can be made concerning use of this algorithm to perceive power tilts:

(1) The method formally considers first harmonic flux tilts, such as those caused by mild xenon oscillations and not higher mode tilts, i.e., those caused by sudden local perturbations such as dropped control elements.

(2) A "noise" level exists where tilts indicated from individual groups are not well orientated with those from other groups. The deviations in tilt magnitude between the groups are generally less than 1%, however, and cause no operational concern.

(3) Tilts larger than 2-5% indicate a higher possibility of a power tilt of some kind, and usually require close surveillance to continue operation.

(4) Tilts higher than 10% indicate a high probability of either a flux tilt or an instrument problem. Simulated ejected control rod tests have shown that this type of tilt is large and leads to an indicated amplitude as large as 25%.

The tilt monitoring system is used to detect small tilts from the nominal symmetric design. Allowable tilts are currently limited to the range of 2 to 5% before the operator must intervene to reduce the tilt. The actual limits on the tilt are imposed through the Technical Specifications for each plant. For these small tilts, the system works adequately. Tilts due to unanticipated events would generally be larger than this and will be

detected, although the accuracy of the determination will decrease with the increasing tilting. However, such cases will be disallowed by the monitoring system, and corrective action will be taken.

1.2 DESCRIPTION OF INCA/CECOR EDITS

The INCA/CECOR programs calculate the assembly power in every bundle at all axial heights (usually every 2% in core height). They then use a local peaking factor at each of these axial nodes to determine the hottest pin. The assembly power at each node is used to increment the burnup history at each node in proportion to the energy extracted from the core in the period covered by the CECOR case.

These three quantities: box power, pin power, and box burnup at every node in the core, are available for editing in various ways for the convenience of the user. They are searched to find the core maximum value of each, integrated radially for axial (1-D) averages, and integrated axially for radial (2-D) averages. Other axial integrations cover just the instrumented regions. Powers are edited both in absolute (MW or kw/ft, values for determining limits, and are normalized to core average power for comparison with design models.

Normal editing in CECOR includes the following:

	CECOR Edits	Number of Values
Each instrument:	signal at each level	(4-5)
	burnup at each level	(4-5)
	power at each level	(4-5)
	alarm limit at each level	(4-5)
Each assembly:	burnup at instrument levels	(4-5)
	average burnup	(1)
	maximum burnup	(1)
	power at instrument levels -MW	(4-5)
	integrated power	(1)
	average relative power density	(1)
	maximum power	(1)
	maximum 1-pin linear heat rate - kw/ft	(1)
	max. relative pin power (3-D peak)	(1)
	integrated radial peaking factor (F_r)	(1)
	planar radial peaking factor (F_{xy})	(1)
	axial shape index (ASI)	(1)
	peak of axial distribution (F_z)	(1)

Other than instrument level and axially integrated data, the following assembly quantities may be in a table or displayed graphically:

Each assembly:	box axial power distribution - normalized to core	(50)
	box axial power distribution - normalized to assembly	(50)
	peak pin axial power distribution - normalized to core	(50)
	axial burnup distribution	(50)

Also several overall core quantities can be edited:

Core: core burnup   (1)

         core power - MW   (1)

         average axial power distribution (50)

         average axial burnup distribution (50)

         peak of axial power   (1)

         peak of axial burnup   (1)

         axial shape index

         maximum of all the "each box"
         quantities   ($\sim$10)

         batchwise burnups   ($\sim$4-6)

1.3 REFERENCES

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TABLE 1.I

Error* Analysis of the Axial Peak to Average
Power Ratio for 1-D Axial Shapes

Case	Mean Error	Standard Deviation	Maximum Error
4 detectors centered at 20, 40, 60, 80% of core height			
2 sets of 3 modes	0.1%	3.5%	9.3%
1 set of 4 modes	0.5%	3.1%	8.4%
5 detectors centered at 10, 30, 50, 70, 90% of core height			
2 sets of 3 modes	0.0%	1.2%	2.7%
1 set of 5 modes	0.2%	0.7%	1.5%

$$* \text{ \% error} = \frac{\text{real-fit}}{\text{real}} \times 100$$

TABLE 1.II

Error* Analysis of the Axial Peak to Average
Power Rates for All Shapes

Case	Mean Error	Standard Deviation	Maximum Error
4 detectors	0.1%	1.4%	+12%
5 detectors	0.1%	0.8%	- 6%

---

* % error = $\dfrac{real-fit}{real} \times 100$

Figure 1-1
AXIAL CONTROL ROD AND DETECTOR ARRANGEMENT
FOR FOUR DETECTOR SYSTEM
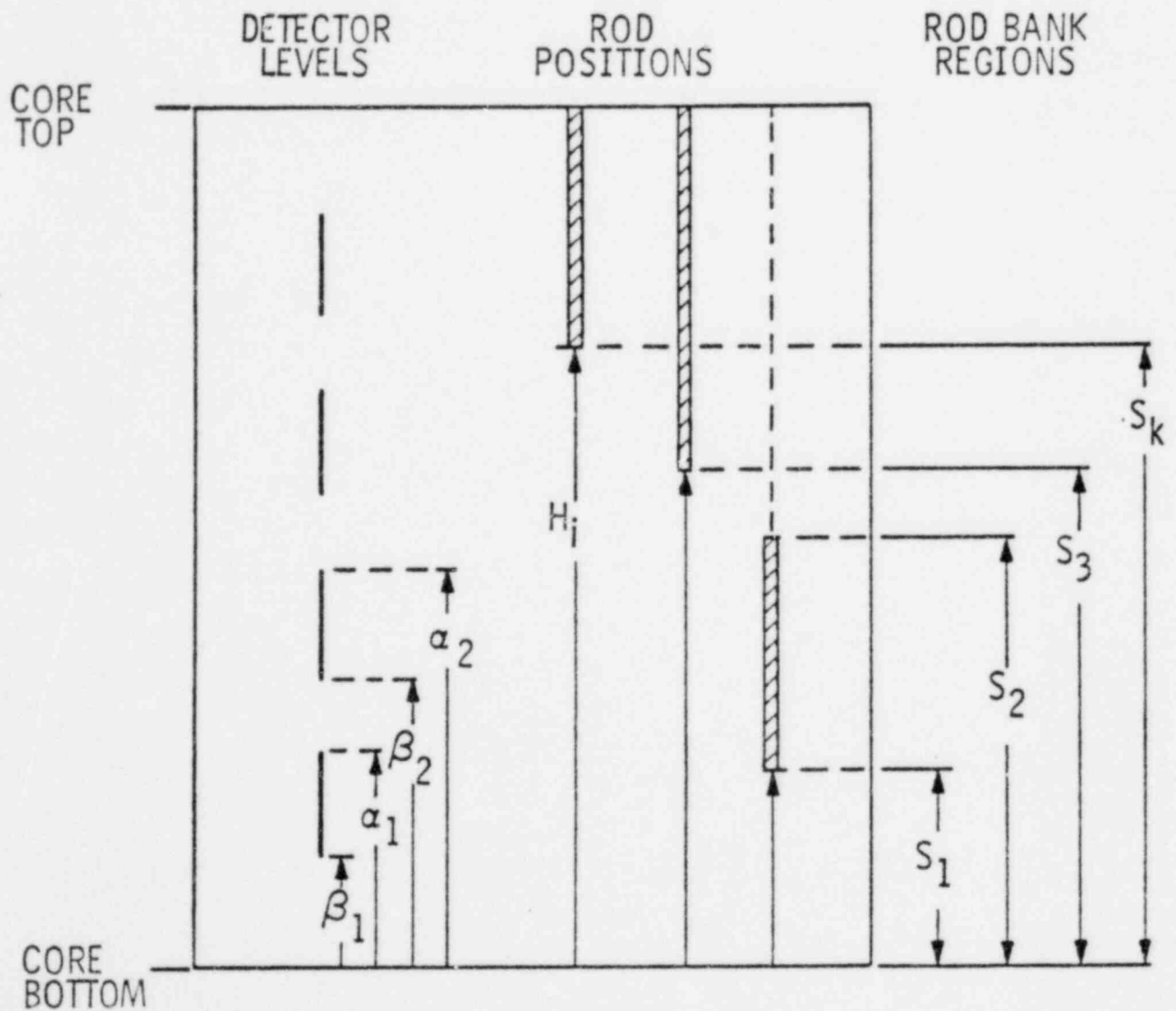
Figure 1-2
REPRESENTATIVE AXIAL SHAPES FROM ONE-DIMENSIONAL ANALYSES
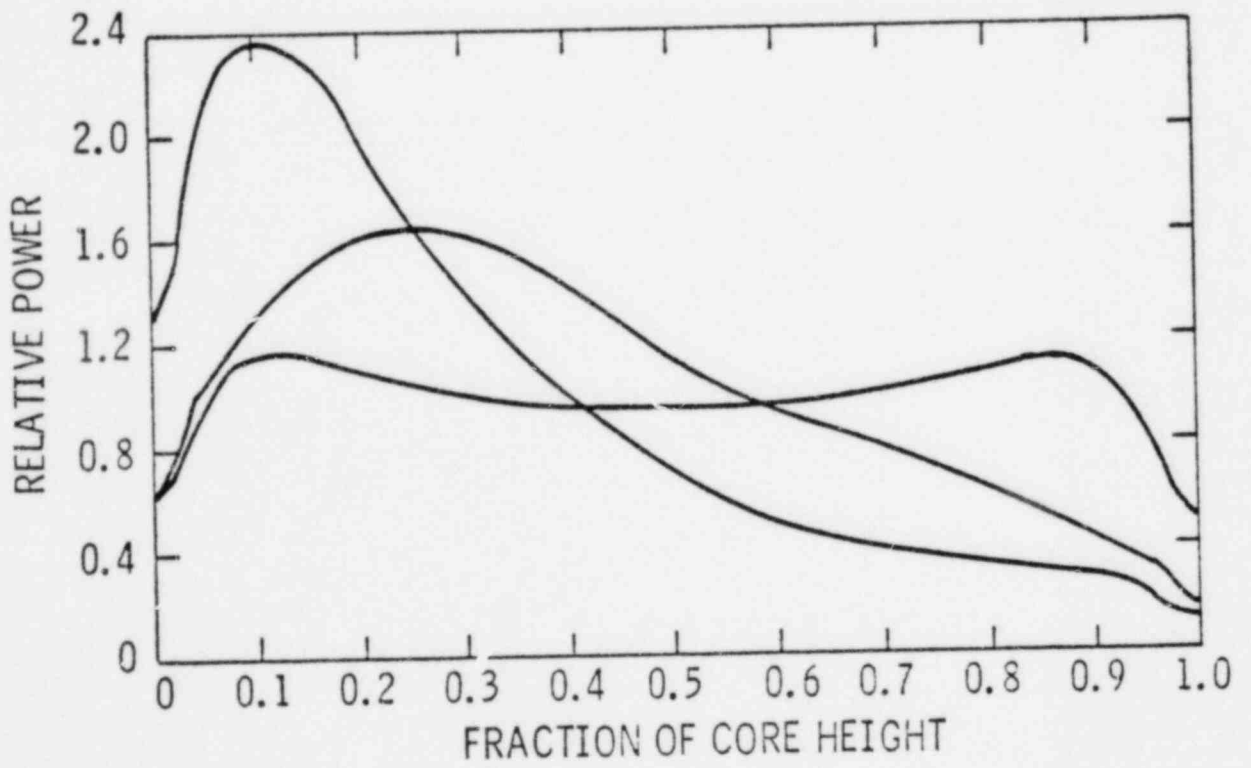
Figure 1-3
TYPICAL AXIAL SHAPES
ONE- AND THREE-DIMENSIONAL ANALYSIS
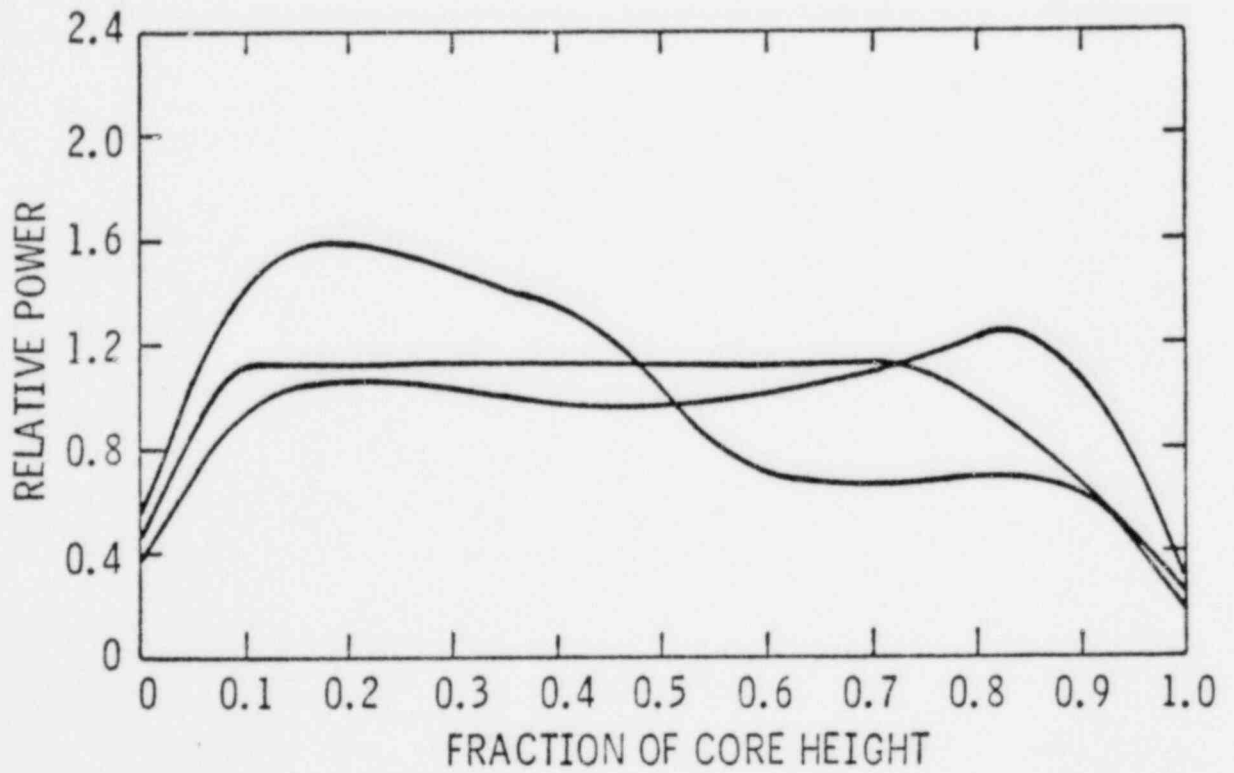
Figure 1-4
TYPICAL CYCLE 2
CECOR AXIAL BOUNDARY CONDITIONS
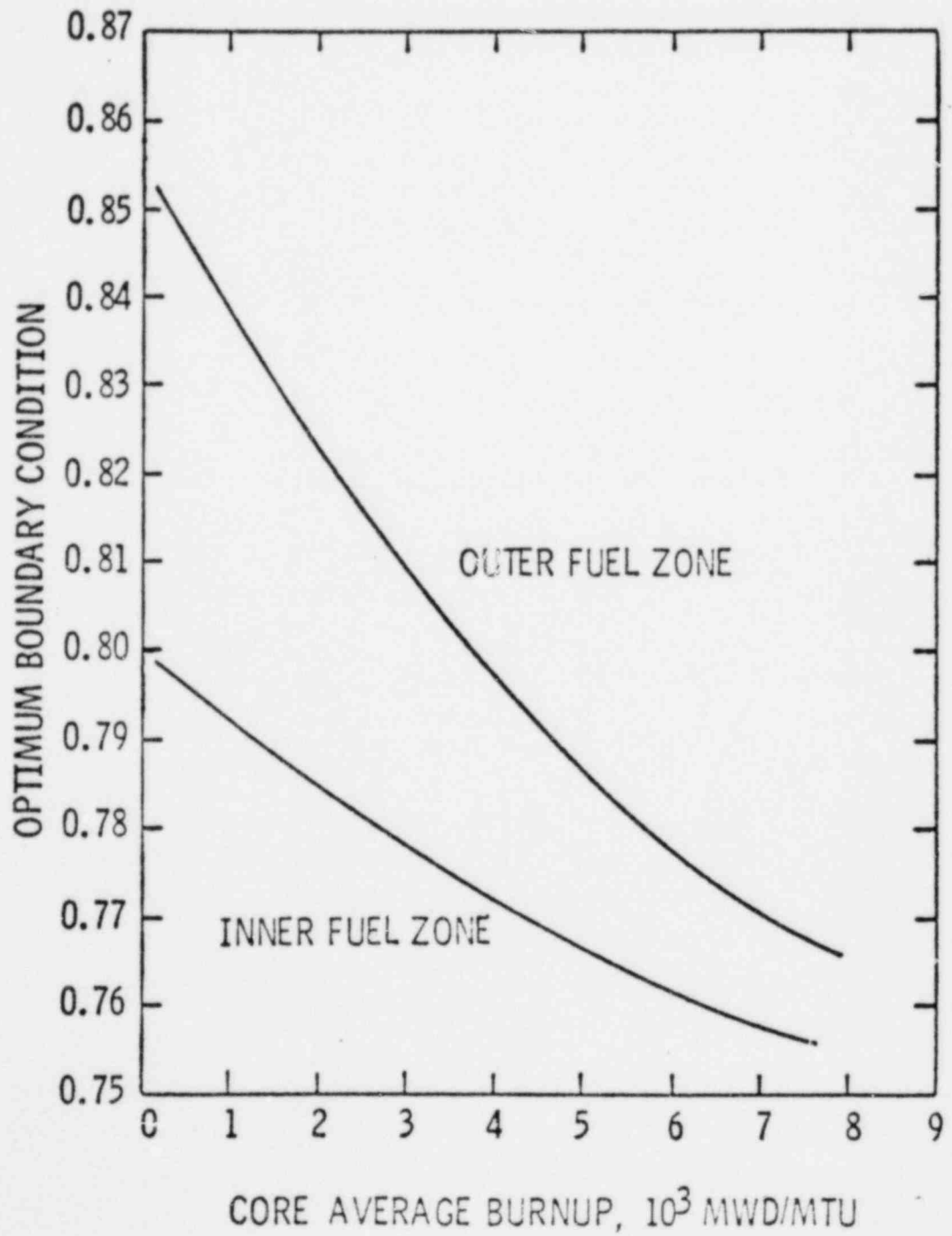
II.2   INCA LIBRARIES

2.0   INTRODUCTION

The INCA/CECOR system relies on the use of a large library of predetermined coefficients which are used to convert the measured signals into detailed, three-dimensional assembly and peak pin power distributions. The values of these coefficients depend on the assembly and axial location, core configuration, control rod configuration, and the local assembly or nodal burnup.

The library coefficients $<CC>$, W', and F_p defined in Chapter 1 are based on detailed, two-dimensional depletion calculations[2.1] using multi-group diffusion theory. Each assembly, instrument, and pin cell is explicitly represented in these calculations for each normal control rod configuration. The coefficient values are calculated for each assembly and instrument, and are fit as functions of the local burnup for each assembly. The two-dimensional calculations are taken to represent explicit axial regions or planes in the core.

For first cycles, which have separable power distributions, a core average plane is used with the various control rod configurations for cores with either four or five detector levels. For later cycles, which generally do not have separable power distributions, a plane representing the axial mid-region of the core is currently used. This leads to acceptable uncertainties, as shown in Part II. The use of several different planes to represent the different axial regions of the core would lead to lower uncertainties, since the axial variation of the coefficients would be included. The $<CC>$ could also be obtained directly from the normal, reload 3-D calculations. Multi-level coefficients may be used in the future for reload cores with either four or five detector levels. This will lead to lower synthesis uncertainties than those quoted in Part II.

The following sections describe the actual form of the coefficient library and the processes used in its generation.

2.1 FORMALISM

2.1.1 Signal-to-Box Power Conversion Factors

The coefficient W'_{in} has been defined in Section 1.1.2 as the conversion
factor which relates the integrated power in assembly i over the length of
detector n to the rhodium activation. These values are based on 2-D fine-
mesh calculations which explicitly represent the rhodium detector for every
instrumented assembly. For new core designs where rods are present in
instrumented assemblies, the values of W'_{in} are calculated for every rod
bank configuration.

The behavior of W' with burnup is illustrated in Figure 2-1 for typical assembies
in each batch of a first cycle core. The burnup dependence is represented using
cubic polynomial fits as a function of assembly burnup. Thus, W'(i,n) is computed
in CECOR using

$$W'(i,n) = W^o(i,n) \cdot \sum_{j=0}^{3} A_j(i,n) \cdot BU^j(i,n) \qquad (2.1)$$

where

$W^o(i,n) = $ initial value of $W'(i,n)$.

$BU(i,n) = $ the average exposure in assembly i over the axial extent of
detector n.

$A_j(i,n) = $ fitted polynomial coefficient in INCA library.

The $A_j(i,n)$ coefficients are normally updated once per cycle, while the burnup
values $BU(i,n)$ are updated for each time step in CECOR.

2.1.2   Single Pin Power Peaking Factors

The one pin peaking factor, F_p, is defined as the ratio of the maximum pin power in an assembly to the average pin power in that assembly. In general, F_p depends on the assembly type, fuel burnup, core location, and control rod configuration. Therefore, it is calculated for every assembly in the plane for each rod bank configuration. The relative range of values for F_p is quite large, varying from 1.1 to greater than 2.0 in some peripheral or rodded fuel assemblies. Additionally, the shape of F_p with burnup differs among assemblies, as is illustrated in Figure 2-2. The burnup dependence is represented by fits of up to the third order for each assembly of each control rod configuration. Thus, the local pin peaking factor for axial node k of assembly i is obtained in CECOR using

$$F_p(i,k) = F_p^{\,o}(i,m) \cdot \sum_{j=0}^{3} R_j(i,m) \cdot BU^j(i,k) \qquad (2.2)$$

where

$F_p^o(i,m)$ = initial value of F_p for assembly i, control rod configuration m.

$BU(i,k)$ = exposure at axial node k of assembly i.

$R_j(i,m)$ = fitted library coefficient for assembly i, control rod
              configuration m.

2.1.3   Coupling Coefficients

The average coupling coefficient, $\langle CC \rangle_{in}$, has been defined in Section 1.1.3 as the ratio of the average power of neighboring boxes to the average power of assembly i at detector level n. Its value depends on the assembly type, location, burnup, neighboring assemblies, and control rod configuration.

A comparison of typical shapes of $\langle CC \rangle$ with burnup for rodded and unrodded assemblies is shown in Figure 2-3. The calculated values of $\langle CC \rangle$ are fit as a

function of assembly burnup over the detector length. By having values for every assembly, an instrumented location can simply be treated as uninstrumented for the purpose of eliminating failed detector signals, or as a diagnostic method of testing for failing detectors.

The INCA library representation for $\langle CC \rangle_{in}$ uses a cubic polynomial fit with burnup, i.e.,

$$\langle CC \rangle(i,n) = \langle CC \rangle^{\circ}(i,m) \cdot \sum_{j=0}^{3} G_j(i,m) \cdot BU^j(i,n) \qquad (2.3)$$

where

$\langle CC \rangle^{\circ}(i,m)$ = initial value of $\langle CC \rangle$ for assembly i, configuration m.

$BU(i,n)$ = average exposure in assembly i over detector level n.

$G_j(i,m)$ = fitted library coefficient for assembly i, control rod configuration m.

2.1.4 Azimuthal Tilt Functions

As described in Section 1.1.7, use is made of radial functions, g(r), derived from two-dimensional diffusion theory solutions to detect small flux tilts. These tilt functions closely approximate the J_1/J_0 ratio predicted from bare cylinder theory. A typical g(r) is shown in Figure 2-4 along with the analogous cylinder functions. The smoothness of the function is readily seen. The burnup dependence of these functions has been found to be insignificant over the length of the cycle.

2.1.5 Axial Fitting Parameters

The axial fitting parameter, B, is precalculated by radial fuel zone as a function of core-average burnup based on normal, 3-D depletion studies with the ROCS code.[2.2, 2.3] The method of calculating B is described in Section 1.1.4. In CECOR, the individual assembly values of B are obtained from the corresponding zonal fits as a function of core-average burnup.

2.2 GENERATION AND QUALITY ASSURANCE OF INCA LIBRARIES

It is apparent from the previous sections that the INCA libraries are both large and complex. In a typical application, approximately 5000 coefficients must be stored and retrieved upon demand. An automated computer code system has been developed to facilitate both the generation and quality assurance of these libraries. The sequence of steps required to produce a typical library is shown schematically in Figure 2-5.

The generation of the basic data required for INCA, i.e., the pointwise powers, fluxes, and concentrations, is currently performed through standard fine mesh diffusion theory calculations using the PDQ-7 computer code[2.1]. Approximately 15 such calculations are required. Primary editing of the PDQ-7 files is performed by the CERISE code, a proprietary code of C-E. This operation transforms the pointwise PDQ-7 data into assembly-wise data required by INCA. Summary files are written for use in Paths B-D in Figure 2-5. Detector signals consistent with the library are also generated for testing the completed library.

The generation of the INCA library is indicated in Path B of Figure 2-5 and is the work of the INCLIB code, a C-E proprietary code. At this stage, libraries are available for quality assurance testing and then actual use at the reactor site.

All the codes[2.1-6] used in generating the libraries and their functions are given in Table 2.I. These codes are quality assured and maintained in accordance with internal quality assurance procedures for computer codes. To adequately test the library, the INCA code is executed using the file created in Step B and the signals in Step A in a fashion identical to the manner in which the PDQ-7 cases were executed. The results are stored and compared to the original CERISE data (Step D).

Final testing of the INCA program and libraries must be performed at the reactor site. Sample test cases from the above effort serve to verify the coding and the data. Test results and procedures are properly recorded and documented for future reference.

2.3   REFERENCES

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TABLE 2.I

Summary of Computer Codes Used
in Generation of INCA Libraries

CODE	TYPE	DESCRIPTION	TYPICAL NUMBER OF CASES
DIT/CEPAK (2.4,2.5, 2.6)	Cross section generation	standard design depletion calculations	5 depletions (of ~10 time steps each)
PDQ-7 (2.1)	2-D fine mesh 2 or 4 group diffusion theory calculations	standard unrodded design 2-D depletion plus several rodded cases	15 cases
ROCS (2.2,2 3)	3-D coarse mesh 2-group diffusion theory calculations	standard unrodded design 3-D depletion	10 cases
CERISE	PDQ-editor	provides edited information (i.e., detector signals, assembly power, etc.)	one for each PDQ-case
INCLIB	INCA library generator	fits all INCA coefficients to burnup and provides properly formatted library	one per core

Figure 2-1
POWER TO RHODIUM SIGNAL CONVERSION FACTORS
vs ASSEMBLY AVERAGE BURNUP
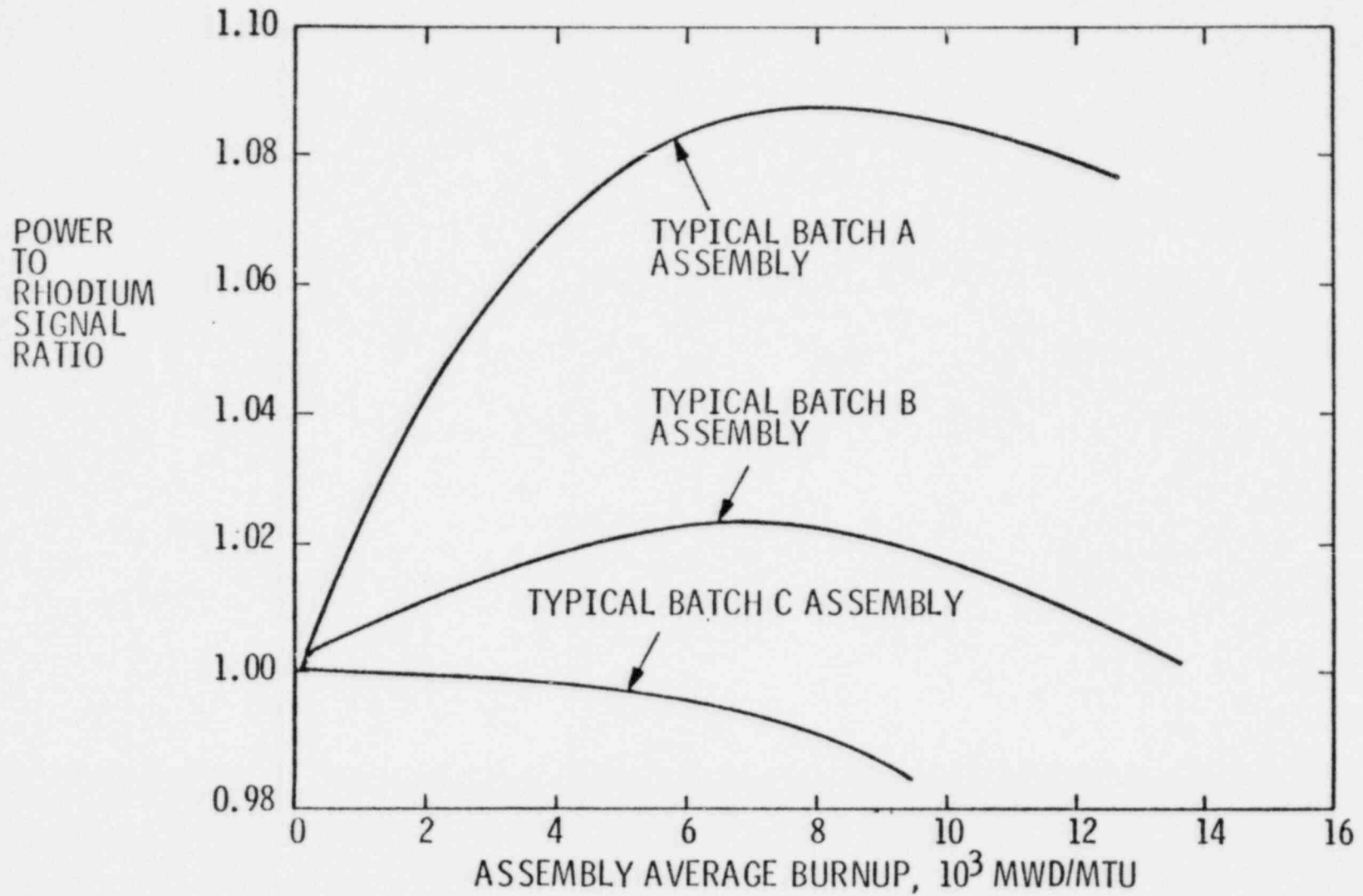
II.2.8

Figure 2-2
SINGLE PIN PEAKING FACTOR VARIATION WITH BURNUP
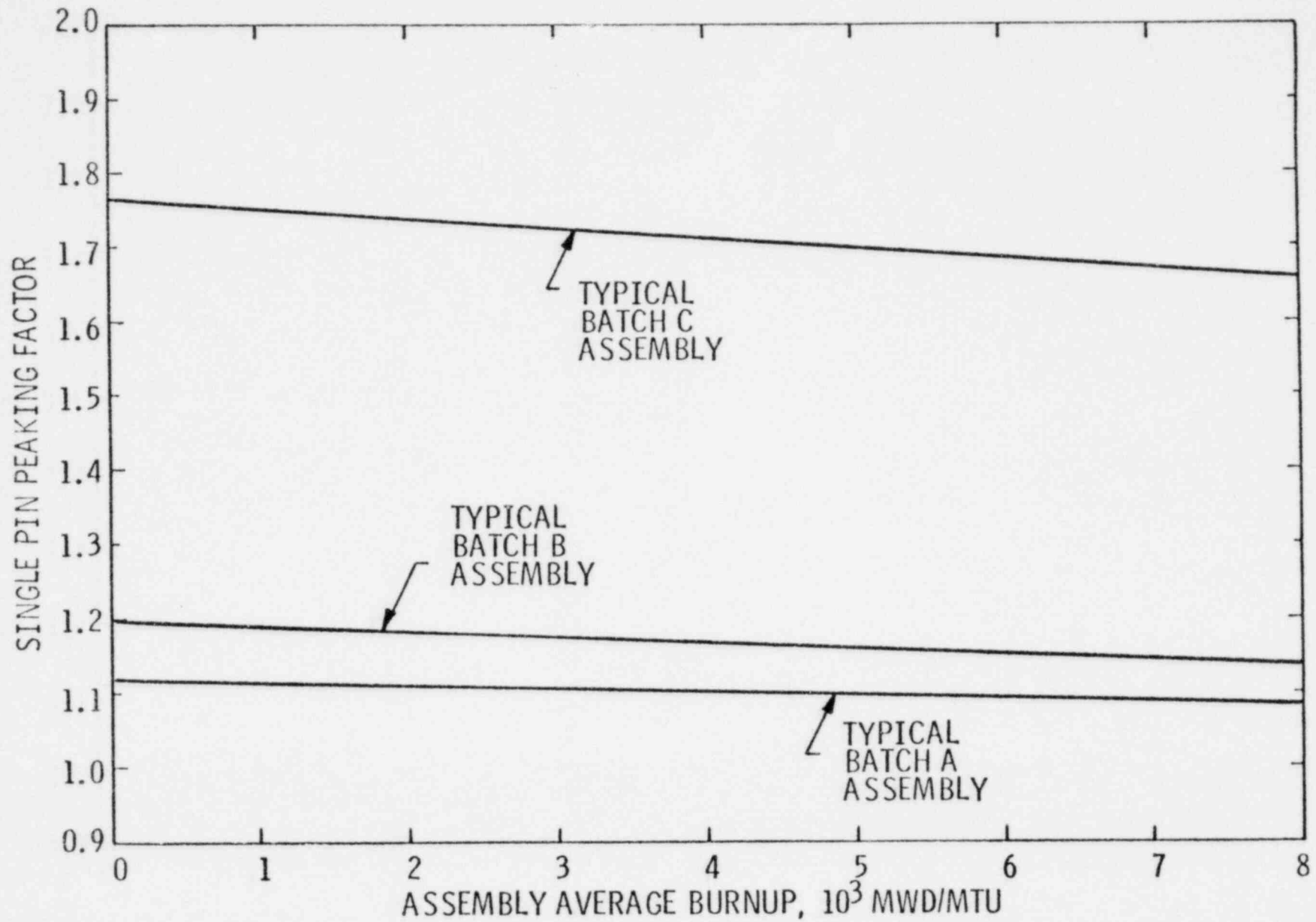
Figure 2-3
TYPICAL AVERAGE COUPLING COEFFICIENT BEHAVIOR
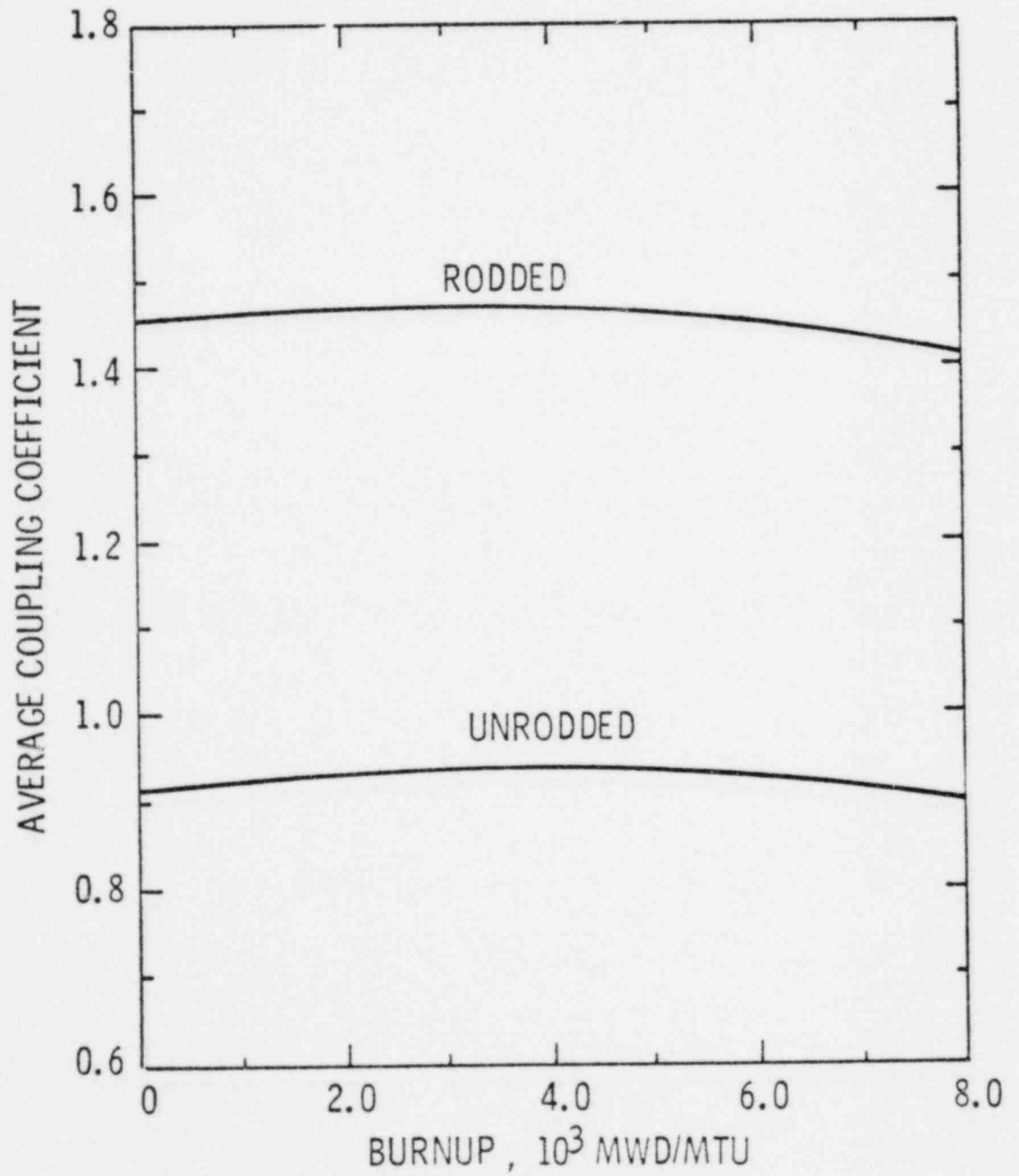
Figure 2-4
RADIAL TILT FUNCTION g(r)

$$\frac{J_1(\alpha_{01}\frac{r}{R})}{J_0(\alpha_{11}\frac{r}{R})}$$

$$\frac{\varphi_1}{\varphi_0 \cos\theta} = g(r)$$

g(r)

RADIUS, ASSEMBLY PITCH

II.2.11
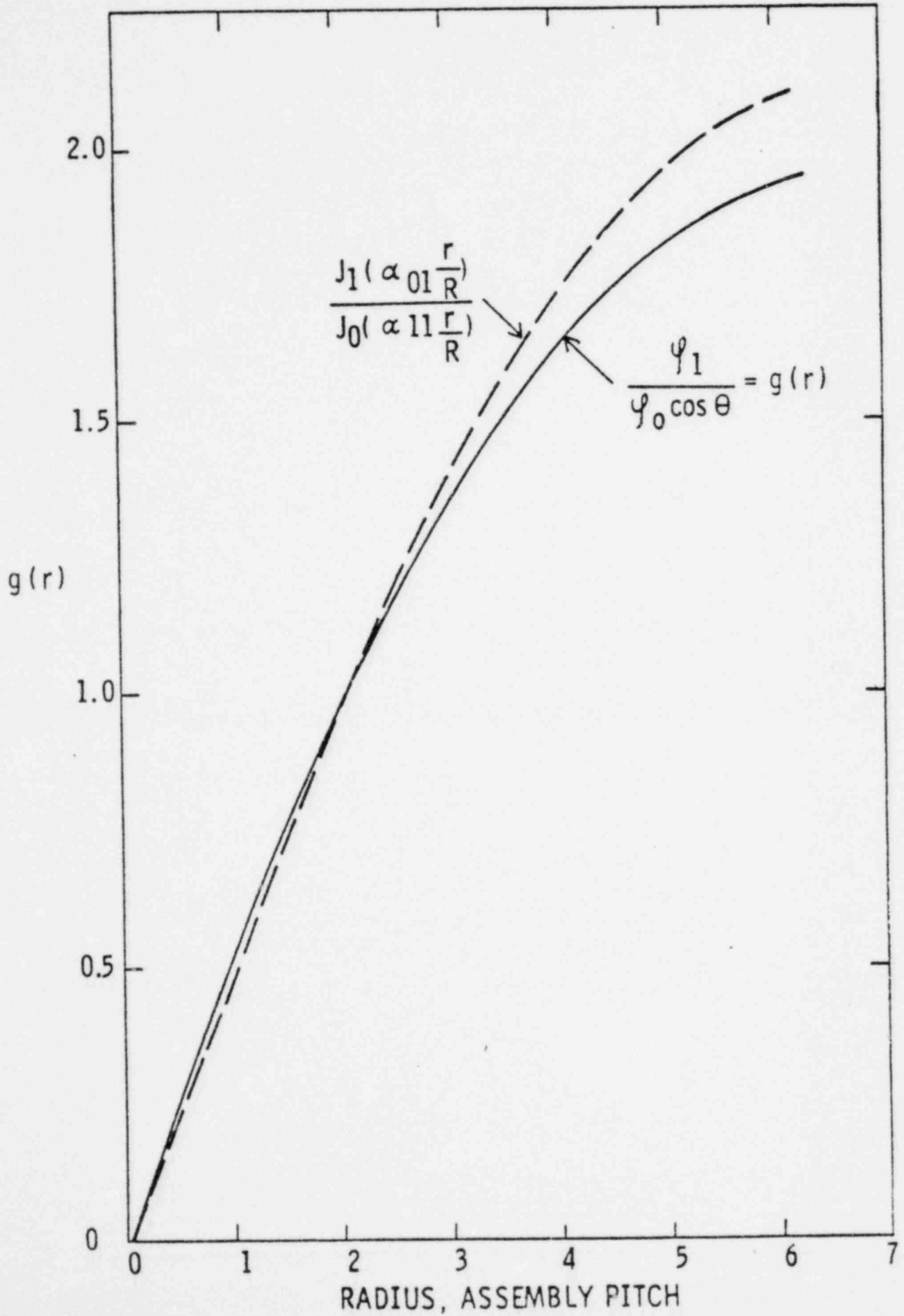
Figure 2-5

GENERATION AND QUALITY ASSURANCE OF INCA LIBRARIES

II.3   SYNTHESIS UNCERTAINTIES

3.0   INTRODUCTION

3.0.1   Description of Methods

The uncertainties to be attributed to the INCA software system are evaluated
by separate analyses of (1) assembly or box power synthesis errors and (2)
pin peaking synthesis errors consisting of INCA system synthesis errors and
basic pin/box calculational errors.

Box power synthesis errors arise in the process of extrapolating to uninstru-
mented locations axially and radially.

Pin power synthesis errors arise because the pin power is not measured
directly but is inferred from the use of calculated pin/box factors (cf. II.2).
Uncertainties in the pin/box factors are due to:

a)   The calculative process itself.
b)   The reconstruction of the calculated pin/box factors by INCA/CECOR.

In this chapter, the terminology used refers to these two sources of uncertainty
as the pin peaking calculational uncertainty and the pin peaking synthesis
error, respectively.

3.0.1.1   Box Power Uncertainty Analysis

The analysis of box power synthesis uncertainties is based upon comparisons
of reference three-dimensional diffusion theory calculations against INCA
system synthesis calculations, [

]

The analysis has been done for the first three cycles of Calvert Cliffs (CC) Unit 1, using three-dimensional core-follow calculations performed with the two-group ROCS code (References 3.1 and 3.2) as a source for the true power distribution [

              ] The box power distribution synthesis errors were thus determined by comparison of the ROCS reference calculations and the CECOR synthesis calculations for the three reactor cycles. [

        ] The core layout and maneuver structure in the ROCS reference calculation and the CECOR synthesis models are described in Section 3.1.1.

Estimates have been made at each timepoint for (1) box power synthesis uncertainty in power sharing ($\sigma_{S_{Fr}}$) by comparing ROCS and CECOR values of
[   ]
(2) the overall box power synthesis uncertainty ($\mu_{S_{Fq}}$, $\sigma_{S_{Fq}}$) by comparing ROCS and CECOR values of [

              ] (3) the planar peak box power synthesis uncertainty ($\mu_{S_{Fxy}}$, $\sigma_{S_{Fxy}}$) by comparing ROCS and CECOR values of [

          ] The calculational and statistical models used in the box power uncertainty analysis are described in Section 3.1.2.

3.0.1.2   Pin Peaking Uncertainty Analysis

The component of pin peaking uncertainty attributed to synthesis error ($\mu_{S_{Fp}}$, $\sigma_{S_{Fp}}$) is estimated using [

              ] for existing reload core models. [

                                        ] These differences form a conservative basis for estimating the pin peaking synthesis error,
[

              ]

The analysis of the pin peaking synthesis uncertainty has been made using
[   ] calculations performed with the PDQ
code (Reference 3.3) for several C-E reload cores, including Calvert Cliffs
Unit 2 Cycle 2, St. Lucie Unit 1 Cycle 2, Millstone Unit 2 Cycle 2, and
Calvert Cliffs Unit 1 Cycle 4. Descriptions of the reactor configurations
and PDQ models used for the pin peaking synthesis analysis are given in
Section 3.2.1. The calculational and statistical models are described in
Section 3.2.2.

The basic pin peak calculation uncertainty (μ_{CF_p}, σ_{CF_p}) has been determined
with the use of data from two series of critical experiments which simulate
typical C-E MARK V fuel assembly designs:

(1) Combustion Engineering Sponsored Critical Experiments (C-E Criticals)
     performed at the Westinghouse Reactor Evaluation Center (WREC);

(2) KRITZ Experiments, sponsored jointly by C-E and KWU and performed at
     the KRITZ critical facility of AB Atomenergi, Sweden.

The experiments are described in detail in Section 3.3.1. The calculational
method and statistical model used in evaluating the pin-peaking calculational
uncertainty are described in Sections 3.3.2 and 3.3.3.

II.3.3

3.0.2 Summary of Results

The estimates of box power synthesis uncertainty for the parameters F_r, F_q and F_{xy}, as well as the number of degrees of m edom in the sample estimates, are summarized in Table 3.I. The results are described in Section 3.1.3.

The estimate of pin peaking or Fp synthesis error is included in Table 3.I, and results are described in Section 3.2.3. Similarly, the estimate of basic F_p calculational uncertainty is included in Table 3.I, and results are described in Section 3.3.4.

3.1 BOX POWER SYNTHESIS UNCERTAINTIES

3.1.1 Description of Calculation Models

3.1.1.1 ROCS Reference Models

The three-dimensional ROCS models and calculations used in the box power distribution synthesis analysis were based on the core layouts and operating histories for the first three cycles of Calvert Cliffs (CC) Unit 1, as described in Chapter 3 of Part I. The operating histories for these three cycles are typical of other 217 assembly C-E reactors, and include operations with reduced power and partial insertion of the lead rod bank (Rod Bank 5). The ROCS calculations were performed using quarter-core geometry with 24 axial planes. The quarter-core models used are consistent with the full-core layout and loading patterns for Cycles 1 through 3 as shown in Figures 3-1 through 3-3, respectively. These figures also show the box locations for Rod Bank 5 and the 45 in-core detector strings. The ROCS maneuver structures for the three cycles, including rod insertions, are given in Tables 3.II through 3.IV. The 3-D ROCS calculation results are identical to those described in Chapter 3 of Part I.

3.1.1.2 CECOR Synthesis Models

The CECOR models used for the box power synthesis calculations use full-core geometry corresponding to the layouts in Figures 3-1 through 3-3 for Cycles 1 through 3 of Calvert Cliffs Unit 1. The axial geometries of the ROCS and CECOR models, including the four detector levels, are shown in Figure 3-4.

The maneuver structures used in the CECOR models are identical to the ROCS maneuver structures in Tables 3.II through 3.IV. [

]

[   ] Test signals were not used in the CECOR calculations for instruments
which were failed according to the operating history. Thus the error
analysis includes the effect of failed detectors on the full-core solution.
The failed instruments for each CECOR model timepoint are given in Tables
3.V through 3.VII for Cycles 1 through 3 of Calvert Cliffs Unit 1.

[

                                                    ] INCA library polynomial fits
of coefficient values as a function of local burnup were then produced for
each cycle according to the formalism described in Section 2.1.

Axial synthesis boundary conditions used in the CECOR calculations were
obtained by using the results of design three-dimensional ROCS depletion
calculations [   ] for Cycles 1 through
3 of Calvert Cliffs Unit 1.

3.1.1.3   Summary of Calculation Models

The CECOR calculations used in the box power synthesis uncertainty analysis
were modeled consistently from the reference three-dimensional ROCS core-
follow calculations for Cycles 1 through 3 of Calvert Cliffs Unit 1, using
the geometries, maneuver structures, INCA coefficient libraries, failed
instruments, and axial boundary conditions described above. The BOC exposure
distributions used for the CECOR depletion calculations for Cycles 2 and 3
were obtained by shuffling EOC exposures from the previous cycles, according
to INCA system procedures.

3.1.2 Statistical Model for Calculation of Box Power Synthesis Uncertainties

3.1.2.1 Definitions

N_F Number of boxes or assemblies in full core; $=217$

K Number of Axial planes in ROCS core model; $=24$

K_L

K_U

N_{LU}

J Number of axial nodes in CECOR core model; $=51$

h_k Thickness of plane k of ROCS core model

h_c Uniform mesh thickness between CECOR axial nodes

H Total core height;

$$= \sum_{k=1}^{K} h_k = (J-1)h_c$$

P_{ik}^R Calculated value of power for box i of ROCS plane k from the ROCS reference calculation

P_{ij}^C Calculated value of power per axial mesh thickness h_c for box i at axial node j from the CECOR syntheis calculation

P_{ik}^C Calculated value of summed axial power for box i corresponding to ROCS plane k from the CECOR synthesis calculation;

$$= \sum_{j \varepsilon k} P_{ij}^C$$

P_i^R Calculated value of axially integrated power for box i from the ROCS reference calculation, obtained by summing;

$$= \sum_{k=1}^{K} P_{ik}^R$$

P_i^C Calculated value of axially integrated power for box i from the CECOR reference calculation, obtained by the trapezodial rule;

$$= \sum_{j=1}^{J} P_{ij}^C - 1/2 \ (P_{i1}^C + P_{iJ}^C)$$

P_k^R Calculated value of power for ROCS plane k from the ROCS reference calculation;

$$= \sum_{i=1}^{N_F} P_{ik}^R$$

P_k^C Calculated value of power corresponding to ROCS plane k from the CECOR synthesis calculation;

$$= \sum_{i=1}^{N_F} P_{ik}^C$$

$$\left[\right]$$

σ_S The standard deviation of box power differences between truth and synthesis calculation.

μ_S The bias of box power differences between truth and synthesis calculation

S_S Sample standard deviation of box power differences between truth and synthesis calculation.

$\bar{D}_S$ Sample bias of box power differences between truth and synthesis calculation.

M_ℓ Number of data points for a sample ℓ.

N_{TOT} Total sample size.

N_{DEG} Total number of degrees of freedom.

Estimates of the one-sided upper tolerance limit are given by $\bar{D}_S + kS_S$, where $\bar{D}_S$ and S_S are the sample bias and standard deviation, respectively, and k is the probability/confidence factor for the sample.

3.1.2.2 F_r Uncertainty: $S_{S_{Fr}}$

For the F_r box power synthesis uncertainty the box to core-average values of axially integrated assembly powers from the CECOR and ROCS calculations are compared for all 217 full core boxes. The normalization is:

$$\sum_{i=1}^{N_F} P_i^C = \sum_{i=1}^{N_F} P_i^R = P \qquad (3.1)$$

where P is the total core power.

3.1.2.3　$\underline{F_q}$ Uncertainty:　$S_{S_{Fq}}$, $\bar{D}_{S_{Fq}}$

3.1.2.4 $\underline{F}_{xy}$ Uncertainty: $S_{S_{Fxy}}$, $\underline{\bar{D}}_{S_{Fxy}}$

3.1.2.5   Summary of Sample Variances and Biases

The sample variances and biases given by Equations 3.4, 3.6, 3.7, 3.9 and
3.10 are estimates of the variances and biases attributed to the synthesis
errors for box power F_r, F_q and F_{xy}.

3.1.2.6   Procedure for Pooling Estimates for the Variance and Bias

The estimates for the variances and biases discussed above are applicable
for comparisons at each timepoint. Pooling over the timepoints is accomplished
by calculating the bias $\bar{D}$ and variance S^2 for the entire set of sample
comparison cases, $\ell = 1, \ldots, L$, using the definitions:

$$\bar{D} = \sum_{\ell=1}^{L} \sum_{i=1}^{M_\ell} D_{\ell i} \Big/ \sum_{i=1}^{L} M_\ell$$

$$= \sum_{\ell=1}^{L} M_\ell \bar{D}_\ell \Big/ \sum_{\ell=1}^{L} M_\ell \tag{3.11}$$

$$S^2 = \sum_{\ell=1}^{L} \sum_{i=1}^{M_\ell} (D_{\ell i} - \bar{D})^2 \Big/ \sum_{\ell=1}^{L} (M_\ell - 1) \tag{3.12}$$

where $D_{\ell i}$ is the difference for data point i of sample ℓ, $\bar{D}_\ell$ is the bias
for sample ℓ, and M_ℓ is the number of data points for sample ℓ.

In cases where the sample bias values are identically zero for the whole
data set, then $\bar{D}$ is zero and the expression for the pooled variance reduces
to:

$$S^2 = \sum_{\ell=1}^{L} \sum_{i=1}^{M_\ell} D_{\ell i}^2 \Big/ \sum_{\ell=1}^{L} (M_\ell - 1) \tag{3.13}$$

or equivalently, using the sample variances S_ℓ^2:

$$S^2 = \sum_{\ell=1}^{L} (M_\ell - 1) S_\ell^2 \bigg/ \sum_{\ell=1}^{L} (M_\ell - 1) \qquad (3.14)$$

3.1.2.7 Procedure for Computing One-Sided Tolerance Limits

For a normal distribution, the one-sided tolerance limit, when needed, is obtained from the total sample size and number of degrees of freedom using Reference 3.11. For pooled data sets the total sample size is defined by

$$N_{TOT} = \sum_{\ell=1}^{L} M_{\ell} \qquad (3.15)$$

where M_{ℓ} is the number of data points in sample ℓ, and the total number of degrees of freedom is defined by

$$N_{DEG} = \sum_{\ell=1}^{L} (M_{\ell} - 1) \qquad (3.16)$$

For worst-case data sets, the sample numbers for size and degrees of freedom are used, i.e.,

$$N_{TOT} = M_{\ell} \qquad (3.17)$$

$$N_{DEG} = M_{\ell} - 1 \qquad (3.18)$$

for data set ℓ.

GENERAL PROCEDURE FOR JUSTIFYING AND CONFIRMING POOLABILITY

[

]

3.1.3 Evaluation of Box Power Synthesis Uncertainties

The method of estimating the variance σ_S^2 and bias μ_S to be attributed to box power distribution synthesis uncertainties has been described in detail in Section 3.1.2. The data for the quantities of interest are summarized below for each reactor.

3.1.3.1 Calvert Cliffs Unit 1 Cycle 1

Table 3.VIIIa gives the ROCS-CECOR timepoint comparison results for the quantities F_r, F_q and F_{xy}. Typical maps showing F_r and F_q comparison data are shown for the timepoints:

(1)   500 MW /T near BOC in Figures 3-5a and 3-5b;

(2)   10,000 MWD/T near MOC in Figures 3-5c and 3-5d;

(3)   16,000 MWD/T near EOC in Figures 3-5e and 3-5f.

For these respective timepoints, comparison plots of the F_{xy} data are shown in Figures 3-5g through 3-5i, and core-average axial power shape comparisons are shown in Figures 3-5j through 3-5ℓ. The comparisons at 16,000 MWD/T reflect the 18% insertion of Rod Bank 5 as indicated by the maneuver structure in Table 3.II. A comparison of assembly burnup values for 16,000 MWD/T near EOC is shown in Figure 3-5m. The results of time pooling for the three quantities are given in Table 3.VIIIb.

3.1.3.2   Calvert Cliffs Unit 1 Cycle 2

Table 3.IXa gives the ROCS-CECOR timepoint comparison results for the
quantities F_r, F_q and F_{xy}. Typical maps showing F_r and F_q comparison data
are shown for the timepoints:

(1)   325 MWD/T near BOC in Figures 3-6a and 3-6b;

(2) 4192 MWD/T near MOC in Figures 3-6c and 3-6d;

(3) 8330 MWD/T near EOC in Figures 3-6e and 3-6f.

For these respective timepoints, comparison plots of the F_{xy} data are shown
in Figures 3-6g through 3-6i, and core average axial power shape comparisons
are shown in Figures 3-6j through 3-6ℓ. A comparison of assembly burnup
values for 8330 MWD/T near EOC is shown in Figure 3-6m. the results of
time pooling for the three quantities are given in Table 3.IXb.

[

] The results of
normality testing for the F_q, F_r and F_{xy} data from Cycle ? are summarized
in Table 3.IXd. These results show that the F_q data pass the D-prime test
at the 5% significance level, while both the F_r and F_{xy} data fail the D-prime test at the 5% significance level.

3.1.3.3 Calvert Cliffs Unit 1 Cycle 3

Table 3.Xa gives the ROCS-CECOR timepoint comparison results for the quantities
F_r, F_q and F_{xy}. Typical maps showing F_r and F_q comparison data are shown
for the timepoints:

(1)   495 MWD/T near BOC in Figures 3-7a and 3-7b;

(2)   801 MWD/T in Figures 3-7c and 3-7d;

(3)   5994 MWD/T near MOC in Figures 3-7e and 3-7f;

(4)   8578 MWD/T near EOC in Figures 3-7g and 3-7h.

For these respective timepoints, comparison plots of the F_{xy} data are shown in Figures 3-7i through 3-7ℓ, and core average axial power shape comparisons are shown in Figures 3-7m through 3-7p. The comparisons at 801 MWD/T reflect the 50% insertion of Rod Bank 5 as indicated by the maneuver structure in Table 3.IV. A comparison of assembly burnup values for 8578 MWD/T near EOC is shown in Figure 3-7q. The results of timepoint pooling for the three quantities are given in Table 3.Xb.

3.1.3.4   Summary of Core Box Power Synthesis Errors

The standard deviation and bias of the uncertainty in F_r, F_q and F_{xy} assigned for each reactor cycle are summarized in Table 3.XI. [

]

The results of pooling the date in Table 3.XI for Cycles 1,2, and 3 are given in Table 3.XII along with results of the Bartlett and Normal Deviate Tests. [

]

The F_r distribution fails the normality test at 5% significance, although the data points are contained within a normal distribution shape, as shown by Figure 3-9. [

]

The F_{xy} distribution shown in Figure 3-10 also fails the normality test at 5% significance. [

]

The overall box power distribution synthesis uncertainties to be applied for all cycles and reactors are taken from the [   ] values in Table 3.XI

as discussed above. Since this table gives the sample biases and standard
deviations [

                                              ] for F_r, F_q and F_{xy}.

[

                                                              ] In addition,
the 95%/95% probability/confidence limits on the basic assembly power
distribution synthesis uncertainties are given in Table 3.I.

3.2   PIN PEAKING SYNTHESIS UNCERTAINTY

3.2.1   Description of Pin Peaking Models

The estimate of pin peaking synthesis uncertainty is based upon two-
dimensional quarter-core PDQ calculations for the following reactors:

(1) Calvert Cliffs (CC) Unit 2 Cycle 2
(2) St. Lucie (SL) Unit 1 Cycle 2
(3) Millstone (ML) Unit 1 Cycle 2
(4) Calvert Cliffs (CC) Unit 1 Cycle 4

The full-core layouts and loading patterns for these reactors are shown in
Figures 3-11 through 3-14, respectively. The calculations were based on
consistent design PDQ models [

                                                      ] Since INCA

coefficient libraries are generated [

                                    ]

3.2.2   Statistical Model for Calculation of Pin Peaking Synthesis Uncertainty

3.2.2.1   Definitions

N_Q Number of boxes or assemblies in quarter-core; =62

F_{pi}^T Calculated value of pin/box factor [
                ] in the PDQ model

F_{pi}^M Calculated value of pin/box factor [
                ] in the PDQ model

D_{pi} Difference [
                                                    ]

$\sigma_{S_{Fp}}$ The standard deviation of pin peaking differences between truth
                and synthesis calculation

$\mu_{S_{Fp}}$ The bias of pin peaking differences corresponding to truth minus
                synthesis calculation

$S_{S_{Fp}}$ Sample standard deviation of pin peaking differences [
                ]

$\bar{D}_{S_{Fp}}$ Sample bias of pin peaking differences [   ]

Estimates of the one-sided tolerance limit are given by $\bar{D}_{S_{Fp}} + kS_{S_{Fp}}$,

where $S_{S_{Fp}}$ and $\bar{D}_{S_{Fp}}$ are the sample standard deviation and bias, respectively,

and k is the sample probability/confidence factor.

3.2.2.2 F_p Synthesis Uncertainty: $S_{S_{Fp}}$, $\bar{D}_{S_{Fp}}$

For the pin peaking synthesis uncertainty [
                                    ] PDQ calculations are compared for
all quarter core boxes with no normalization. The differences which correspond
to truth minus synthesis are given as:

$$D_{pi} = F_{pi}{}^T - F_{pi}{}^M \qquad\qquad i = 1, \ldots, N_Q \qquad\qquad (3.19)$$

$$\bar{D}_{S_{Fp}} = \frac{1}{N_Q} \sum_{i=1}^{N_Q} D_{pi} \qquad\qquad (3.20)$$

The bias is in general non-zero. The sample variance of the difference is then:

$$S_{S_{Fp}}{}^2 = \frac{1}{N_Q - 1} \sum_{i=1}^{N_Q} (D_{pi} - \bar{D}_{S_{Fp}})^2 \qquad\qquad (3.21)$$

The sample variance and bias given by Equations 3.20 and 3.21 are estimates of the variance and bias attributed to synthesis errors for F_p in the INCA/CECOR system.

3.2.2.3   Procedure for Pooling Estimates for the Variance and Bias

The procedures and criteria for pooling the data are as described in Section 3.1.2.6.

3.2.2.4   Procedure for Computing One-Sided Tolerance Limit

The methods of obtaining the probability/confidence factor, one-sided tolerance limit and degrees of freedom are as described in Section 3.1.2.7.

3.2.3 Evaluation of Pin Peaking Synthesis Uncertainty

The method of estimating the variance σ^2_{SFp} and bias μ_{SFp} to be attributed to pin peaking synthesis uncertainty has been described in detail in Section 3.2.2. The data for pin peaking synthesis errors are summarized below for each reload cycle.

3.2.3.1 Calvert Cliffs Unit 2 Cycle 2

Figure 3-15 shows a map comparing the PDQ [   ] calculation values of assembly pin peaking [   ]. The sample bias and standard deviation are given in Table 3.XIII.

3.2.3.2 St. Lucie Unit 1 Cycle 2

Figure 3-16 shows a map comparing the PDQ [   ] calculation values of assembly pin peaking [   ]. The sample bias and standard deviation are given in Table 3.XIII.

3.2.3.3 Millstone Unit 2 Cycle 2

Figure 3-17 shows a map comparing the PDQ [   ] calculation values of assembly pin peaking [   ]. The sample bias and standard deviation are given in Table 3.XIII.

3.2.3.4 Calvert Cliffs Unit 1 Cycle 4

Figure 3-18 shows a map comparing the PDQ [   ] calculation values of assembly pin peaking [   ]. The sample bias and standard deviation are given in Table 3.XIII.

3.2.3.5 Summary of Pin Peaking Synthesis Errors

The results of pooling the data for the four reactor reload cycles are included in Table 3.XIII along with the results of the Bartlett and Normal Deviate Tests. Both tests are satisfied, and so pooling of the data is not rejected on this basis.

Table 3.XIV summarizes the results of tests for normality for the individual reactor and pooled data sets. The results show that the data for each reactor passes the D-prime test at the 5% significance level or better. The pooled data set fails the D-prime test at the 5% significance level, but passes at the 4.5% significance level, and so is considered marginal.
[

]

The overall INCA system pin peaking synthesis uncertainty to be applied for all reload cycles is taken from the pooled values in Table 3.XIII as discussed above. [

] Table 3.I quotes the pin peaking synthesis uncertainty in units of percent of average pin/box value. In addition, Table 3.I gives the associated number of degrees of freedom and the 95%/95% probability/ confidence limit on the basic pin peaking synthesis uncertainty.

3.3 PIN PEAKING CALCULATIVE UNCERTAINTY

The INCA system determines the maximum pin power in a given fuel assembly by employing the pin/box power factor as described in II.2. The pin/box factor, also called F_p, is defined for a given axial elevation as the ratio between peak and average power within a given assembly.

Since neither F_p nor local pin power can be measured directly, the synthesis process must rely on calculated values for F_p. This section describes the calculative method and the uncertainty that pertains to it.

3.3.1 Description of Critical Experiments

To provide data applicable to the evaluation of the uncertainty in the calculated pin/box factor, F_p, three series of critical experiments have been performed which simulate typical C-E fuel assembly designs. Each of these is described briefly below.

3.3.1.1 Combustion Engineering Sponsored Critical Experiments (C-E Criticals)

A series of critical experiments were performed for Combustion Engineering by Westinghouse Corporation at the Westinghouse Reactor Eva' :ion Center (WREC) employing the CRX reactor. The experimental program consisted of approximately 70 critical configurations of fuel rods. The basic core configuration was a 30x30 square, fuel rod array of Zr-4 clad UO_2 fuel having an enrichment of 2.72 w/o U-235. Fuel rods were removed to create internal water holes or channels to accommodate control rods or to simulate control rod channels and water gaps representative of C-E assembly designs (primarily the MARK V 14x14 design).

The majority of the experiments employed a lattice pitch of [   ] inches with several experiments repeated with a lattice pitch of [   ] inches. These values of [   ] and [   ] inches, together with the fuel pellet

dimensions and enrichment and the rod diameter, resulted in hydrogen to fuel ratios representative of the MARK V design at room and at operating temperatures, respectively.

The fuel rod assemblies were fully reflected with H_2O on the four sides. The experiments were conducted at room temperature. Both borated and unborated cores were employed. A given configuration was made critical by adjusting the water height. The reactivity worths of incremental water height changes were made to provide a means of interpolating to exact criticality. Axial bucklings were obtained by fitting measured activities along a rod to a cosine function.

Power distribution measurements were made by measuring the gross fission product gamma activities of selected irradiated fuel rods and relating these values to the relative power in the rods. Low background or pre-scanned fuel rods were used in the experiments to minimize corrections to the data after irradiation.

The fission rate measurement system employed two separate scintillation counters. Each consisted of a NaI (1-3/4 x 2 inch) crystal optically coupled to a photomultiplier tube with its associated counting electronics (amplifiers, discriminators, scalers). One detector unit, termed the monitor channel, was used to measure the gross γ-activity of a single monitor rod which had been irradiated in the experiment. The information from this measurement was used to account for the decrease of the fission product activity with time, since the rods selected for measurement were analyzed sequentially. The monitor channel was used to set the count time interval for each rod measurement by counting to a preset number of counts (usually 20,000). The other detector system, termed the data channel, was used to measure the gross γ-activity of the rods selected for measurement. The data channel was housed in a lead container with 6 to 12 inch walls. A 1/2 inch high slot in the lead permitted a half-inch length of fuel rod to be scanned. The fuel rod being analyzed was placed in a mechanism which allowed it to be moved axially. The rod was stopped at each axial position

to be scanned. The housing for the monitor channel was similar except that the monitor rod position was fixe. Both scalers in the counting channels were started simultaneously and the data channel stopped when the preset count in the monitor rod had been reached. See Figure 3-20 for a block schematic of the system.

The detectors were set to measure the γ-activity above 0.5 MeV. The discriminator settings were calibrated daily with a ^{22}Na γ-source. The ^{22}Na source emits two photons, a 0.510 MeV and a 1.28 MeV γ-ray. The discriminator voltage was set to detect gross γ-activity with energies above 0.5 MeV. Since both detectors were calibrated with the same source and only the relative count rates from the two detectors were used, the difference between the source spectrum and the fission product gamma spectrum is not a pertinent factor.

In order to minimize the effect of instrument drift, one of the irradiated rods from the experiment was chosen as a "reference". The reference rod was counted at the start of a measurement set, after every five or six rods during the measurement period and again at the end of the period. The data from the reference rod measurements were plotted as a function of time and then fitted by a least square method to a straight line. The data from the measurements of the other fuel rods were normalized (as required) to this reference line to correct for instrument drift.

Each experiment in which fission rate measurements were made was performed only once and in each experiment each selected rod was measured only once (except for the reference rod). Overall uncertainties in the measured values were determined by comparing values from symmetric rod locations. These uncertainties would include both small contributions due to discriminator settings, instrumentation drift and counting statistics (<0.3% based on accumulated counts >100,000) and contributions due to rod misalignments during the irradiation and during the subsequent measurements.

Experiments Analyzed

For this analysis, the experimental configurations which contained large water holes (unrodded) and for which power distributions were measured were selected for inclusion. These are designated C-E #12, C-E #32, C-E #43, C-E #53, and C-E #56. Pertinent core parameters are contained in Table 3.XV. Core layouts with the fuel rods selected for power measurements designated by numbers are shown in Figs. 3-21 through 3-23. The gamma activity for each of the numbered rods was measured at selected points along the rod (representing the axial power distribution). The activities for each rod were summed to provide a total activity which is proportional to the total power in the rod.

<div align="center">

TABLE 3.XV

C-E CRITICALS

</div>

Lattice	Core Configuration Fuel Rod Array	Fuel Cell Pitch (Inch)	No. of Fuel Rods	Temp. of Core	Soluble Boron Conc. PPM	No. of Control Rod Channels

3.3.1.2 KRITZ Experiments

A program of critical experiments, sponsored jointly by Combustion Engineering and KWU, was performed at the KRITZ critical facility of AB Atomenergi, Studsvik, Sweden. The program consisted of analyzing a number of core configurations of interest to C-E and KWU. Both UO_2 and mixed-oxide cores

were included. The C-E configurations were representative of the MARK V
assembly (14x14 with 5 large control rod channels). A basic cell pitch of
[   ] inches was used for all lattices.

A description of the fuel rods, both UO_2 and mixed-oxide, is given in Table
3.XVI. The cores are relatively large both in cross sectional area and
height. Each core contained about 1450 rods (265 cm in length). The core
was reflected with water on the four sides and the bottom. Soluble boron
was employed for gross reactivity control.

Core criticality was obtained by adjusting the water height. The water
temperature was raised by passing the moderator through a 500 kw electric
heater outside the core and circulating the water until the desired equilibrium
temperature was reached. Once the experiment is started, the water is not
circulated. Temperature measurements were made at 3 axial positions to
insure equilibrium conditions were reached. In the higher temperature
experiments, some cooldown occurred during the experiment. Its effect on
reactivity was accounted for by adjusting the reported soluble boron
concentration. The small amount of cooldown did not affect the power
distribution.

The axial buckling was inferred by fitting data from axial gamma scans of
the irradiated rods to a cosine function. Copper wire activation measurements
were also employed to determine axial bucklings.

Fission rate measurements were made in selected fuel rods by a gamma scan
technique. The fuel rod to be measured was placed vertically between two
NaI scintillation detectors (See Figure 3-24). The rod was scanned downward
and upward over a distance of 11 cm around the center. The scan speed was
about 0.9 mm/sec. The rod was also rotated slowly during the scan at about
3 rpm.

The gross fission product γ-activity above 0.6 MeV was measured. The 0.6
MeV threshold corresponds to a minimum in the fission gamma spectrum as

well as to an energy region where the natural background activity of the rods is relatively flat. Calibrations were performed to establish the discriminator settings. Since the same detectors were used to measure all rods, intercalibration between the detectors was not a pertinent factor.

In each measurement set, a reference rod was measured at regular intervals (about every 40 minutes) during the period. As appropriate for the type of rod being measured, a UO_2, a 2.0% Pu or a 3.2% Pu rod was selected. The measurement data from the reference rods were corrected for background (both room and rod) and for instrument dead time and the results fitted to equations of the form $At^{-\alpha}$ (one for each type rod). The count data for the rods measured to determine power distribution were then referenced to the values from the fitted equations. In this way, the values for each rod were corrected for fission product decay and any instrument drift that might have occurred.

The rod background was minimized by using either fresh rods, or, in two instances, several previously irradiated rods with well characterized backgrounds. The activities of the latter were below 10% of the activities after re-irradiation. The measured backgrounds of the fresh and irradiated rods were ∼40 cps and <130 cps, respectively with a room background of ∼8 cps included.

Instrument dead time corrections were less than 0.6%. Any error in this correction was further compensated because the fission rate distributions were expressed as a ratio to a selected rod.

Each experiment was performed once. Each rod in a particular experiment was measured once (except for the reference rods).

Measurement uncertainties are derived from comparisons of fission rate values in symmetric locations in the core. The C-E experiments in KRITZ contained relatively few symmetric location points. However, in the KWU sponsored KRITZ experiments, a number of symmetric measurements were made.
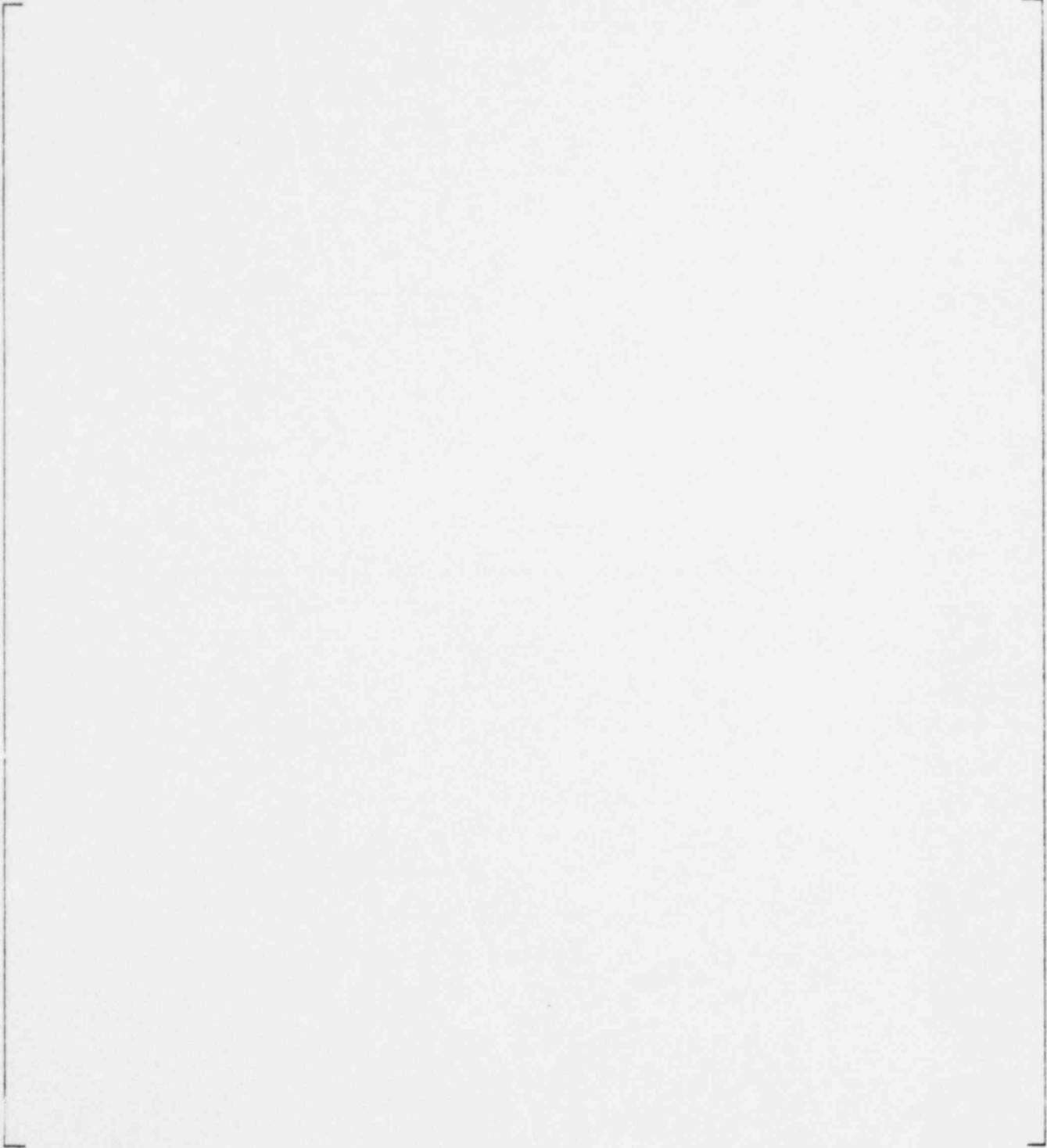
These have been used together with the C-E KRITZ data to establish an overall measurement uncertainty. This approach is justified since the fuel and the experimental arrangements are identical except for the size and locations of the water holes. The fission rate measurement technique is identical and the procedure of rotating the rods during measurements essentially eliminates uncertainties due to water hole induced flux gradient differences for the two types of arrangements.

Experiments Analyzed

U-WH2 Experiment - The experiment was performed at 229°C (445°F). The core configuration is shown in Figure 3-25.

Pu-WH2 Experiment - Experiments were performed at 24.6°C (76°F) and 231°C (448°F). The core configurations are shown in Figure 3-26.

TABLE 3.XVI
FUEL SPECIFICATION (KRITZ EXPERIMENTS)

3.3.1.3   BNWL Critical Experiments

Combustion Engineering, Inc. sponsored a series of critical experiments
performed by the Battelle Northwest Laboratory at the Plutonium Recycle
Criticality Facility (PRCF). The experimental program included a number of
UO_2 and mixed-oxide fueled configurations of interest to C-E. Unshimmed,
shimmed and control rodded configurations were included in the program.
The basic lattice consisted of a central 14x14 fuel pin arrangement, which
simulated the C-E MARK V assembly design, surrounded by a driver region of
UO_2 fuel rods. The configuration of the central region (in one lattice the
driver region was also modified) was varied to investigate mixed-oxide
assembly designs. Power distributions were measured in all cores. The
fuel rod specifications are given in Figure 3-27.

The fuel rods were arranged in a spacer grid with a basic cell pitch of
[   ] inches. All experiments were conducted at about 20°C (68°F).

The basic procedure for a given configuration was to assembly the array and
adjust the concentration of boron in the moderator to achieve criticality
with a very small excess reactivity when fully reflected and with the
control rods fully withdrawn. The majority of the irradiations were performed
while on a very slowly rising reactor period with control rods withdrawn
and an effectively infinite reflector at all boundaries. In all cases, the
excess reactivity of the fully reflected array was determined.

The relative power distribution was determined from measurements of the
gross fission product gamma activity in each of the selected fuel rods in
the array. Each fuel rod selected for measurement was counted on a dual
channel counting system as illustrated in Figure 3-28. This system auto-
matically corrected for fission product decay during the measurement period.

The fission rate measurement technique was very similar to the one employed
for the C-E Critical experiments. The system employed two matching counting
systems--one measured the rods of interest (called the traverse system),
and another provided a means of correcting the measurements for radioactive

decay during counting (called the decay system). A fuel rod of similar exposure history to those being measured was placed in the decay system at the start of the measurement and left there for the duration of the measurements. The decay system was electronically arranged to stop the traverse system after a preset number of counts has been obtained from the decay rods, thereby correcting for decay. Both systems were matched according to gain and energy discrimination. An integral counting method was used; only gammas with energies greater than 0.470 MeV were counted.

The fuel rods were rotated at about 20 RPM about their longitudinal axis in the traverse system during the counting periods in order to average the circumferential fuel rod activity. The decay rod was not rotated.

The collimator aperture of the traverse system was rectangular, 0.375 inches x 0.75 inches, such that a 0.375 inch long axial segment of the fuel rod was scanned at each point.

Each rod was counted at its axial mid-plane to obtain the rod-to-rod power distribution within the array. Two rods in each array were traversed in two-inch intervals to obtain the axial power shapes.

A reference rod was selected from each experiment and counted at selected intervals throughout each measurement period. The data from these measurements were used to correct for the decrease in fission product γ-activity with time and any drift in the electronics of the counting systems.

The background γ-activity for each fuel rod was determined prior to re-irradiation during an experiment. The background levels of the fuel rods were considerably higher than those for the rods in the C-E Criticals and the KRITZ experiments, since the rods were used in several experiments.

The count data from the measurements on the reference rods were corrected for background and instrument dead time and fitted to a linear function with time. The count data from each fuel rod measurement was also corrected for background and dead time and was normalized to the count rate from the

reference rod at the appropriate time interval. This procedure essentially eliminated the effects of any instrument drift and also corrected for gross fission product decay with time.

Experiments Analyzed

GPL-88 - This is a UO_2 core with a central 14x14 fuel rod region with 5 large (C-E) water holes. The outer region is composed of UO_2 fuel rods with no water holes. See Figure 3-29 for a schematic of the core layout.

GPL-92 - The core layout is identical to GPL-88 except that borated glass absorbers (shims) occupy the positions shown in Figure 3-30.

3.3.2 Statistical Model for Calculation of F_p Uncertainty

3.3.2.1 Definitions

C_j^ℓ = calculated value at position j of experiment no. ℓ, $j=1,\ldots,M_\ell$, $\ell=1,\ldots,L$.

M_{ij}^ℓ = measured value at symmetric positions i of rod j, measurement no. ℓ, $i=1,\ldots,N$.

M_j^ℓ = averaged measured value at position j of experiment no. ℓ, $j=1,\ldots,M_\ell$.

T_j^ℓ = true value of power at position j of experiment no. ℓ, $j=1,\ldots,M_\ell$.

ξ_j^ℓ = random error of the calculation for position j.

CB_j^ℓ = systematic error (bias) of the calcu,ation for position j.

δ_{ij}^ℓ = random error of measurement M_{ij}^ℓ

δ_j^ℓ = random error of M_j^ℓ.

MB_j^ℓ = systematic error (bias) of the measurement for position j.

It is assumed that the random errors are normally distributed, and independent, i.e.,

$$\xi_j^\ell \sim N(0,\sigma_{C\ell}^2); \quad \delta_j^\ell \sim N(0,\sigma_{M\ell}^2); \quad \delta_{ij}^\ell \sim N(0,\tau_\ell^2); \qquad (3.22)$$

where,

$$\sigma_{M\ell}^2 = \frac{\tau_\ell^2}{N}, \qquad (3.23)$$

is the measurement variance associated with M_j^ℓ which is obtained by folding N measurements of symmetrically located pins.

The following relations between calculation, truth and measurement hold:

$$C_j^\ell = T_j^\ell + CB_j^\ell + \xi_j^\ell \tag{3.24}$$

$$M_{ij}^\ell = T_j^\ell + MB_j^\ell + \delta_{ij}^\ell \tag{3.25}$$

$$M_j^\ell = T_j^\ell + MB_j^\ell + \delta_j^\ell \tag{3.26}$$

The difference between calculation and measurement is:

$$D_j^\ell = C_j^\ell - M_j^\ell = DB_j^\ell + \xi_j^\ell - \delta_j^\ell \tag{3.27}$$

$$DB_j^\ell = CB_j^\ell - MB_j^\ell \tag{3.28}$$

$$D_j^\ell = \text{observed difference.}$$

$$DB_j^\ell = \text{true difference.}$$

One also has the relations,

$$\bar{D}_\ell = \frac{1}{M_\ell} \sum_{j=1}^{M_\ell} D_j^\ell = \overline{DB}_\ell + \bar{\xi}_\ell - \bar{\delta}_\ell \tag{3.29}$$

$$\bar{\xi}_\ell = \frac{1}{M_\ell} \sum_{j=1}^{M_\ell} \xi_j^\ell \sim N(0, \frac{\sigma_{C\ell}^2}{M_\ell}) \tag{3.30}$$

$$\bar{\delta}_\ell = \frac{1}{M_\ell} \sum_{j=1}^{M_\ell} \delta_j^\ell \sim N(0, \frac{\sigma_{M\ell}^2}{M_\ell}) \tag{3.31}$$

Consider the relationship between $\sigma_{C\ell}^2$, $\sigma_{M\ell}^2$ and $\sigma_{D\ell}^2$. Let $E(x)$ be the expected value and $D^2(x)$ the variance of any random variable x.

From Eqns. (3.22), (3.27) we have

$$E(D_j^\ell) = E(DB_j^\ell) = DB_j^\ell \tag{3.32}$$

$$D^2(D_j^\ell) = D^2(\xi_j^\ell) + D^2(\delta_j^\ell) = \sigma_{C\ell}^2 + \sigma_{M\ell}^2 = \sigma_{D\ell}^2 \tag{3.33}$$

This follows because ξ and δ are independent variables. Eq. (3.33) defines $\sigma_{D\ell}$. By rearranging (3.33) we have the basic relation for $\sigma_{C\ell}$, namely

$$\boxed{\sigma_{C\ell}^2 = \sigma_{D\ell}^2 - \sigma_{M\ell}^2} \tag{3.34}$$

3.3.2.2   The Sample Variance for the Difference Between Calculation and Measurement

The sample variance for the difference between calculation and measurement is,

[

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II.3.42
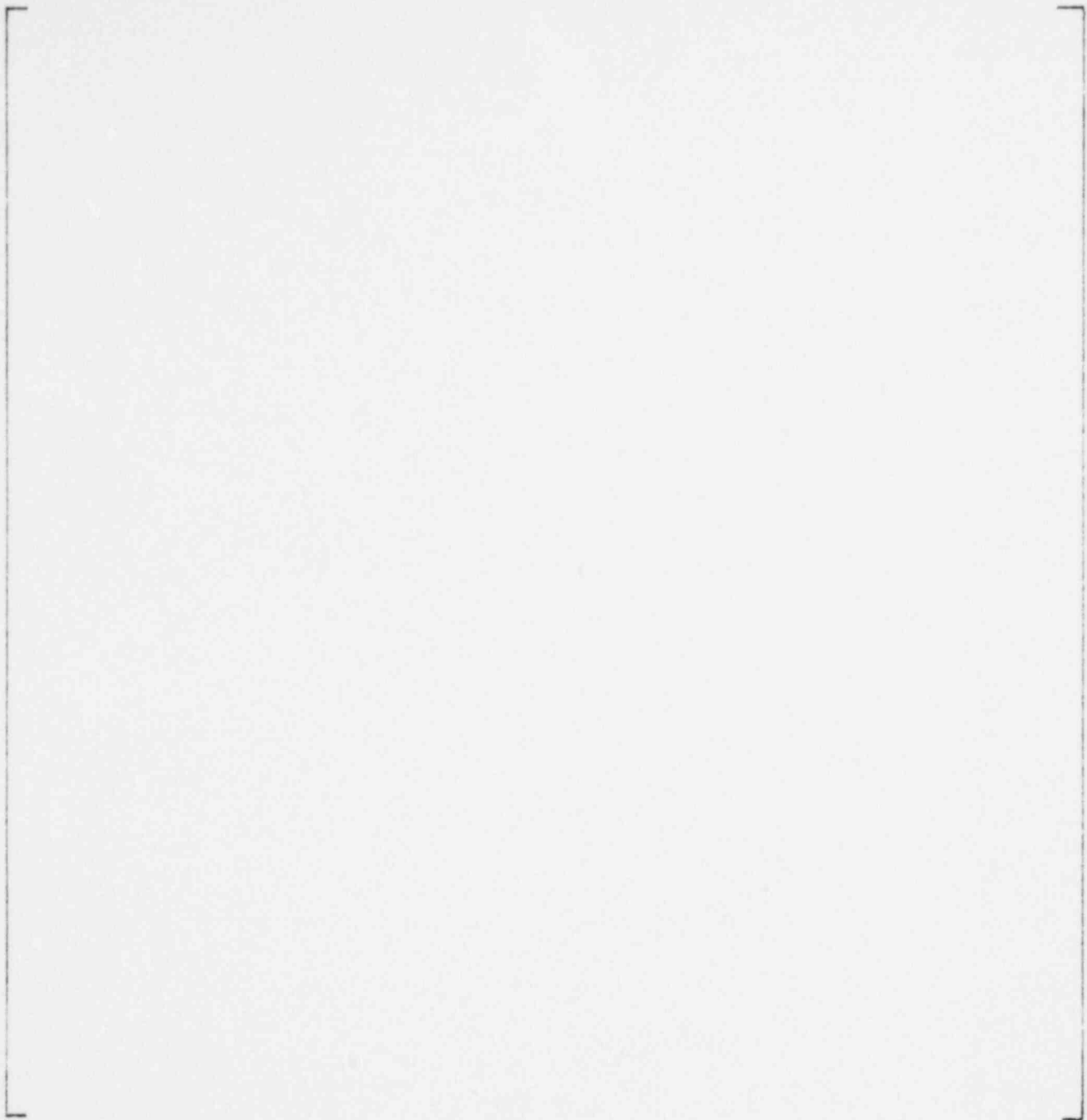
3.3.2.3   The Measurement Uncertainty

3.3.2.4   <u>An Estimate of $\sigma_{C\ell}^2$</u>

3.3.2.5 <u>The Variance of $S_{C\ell}^2$</u>
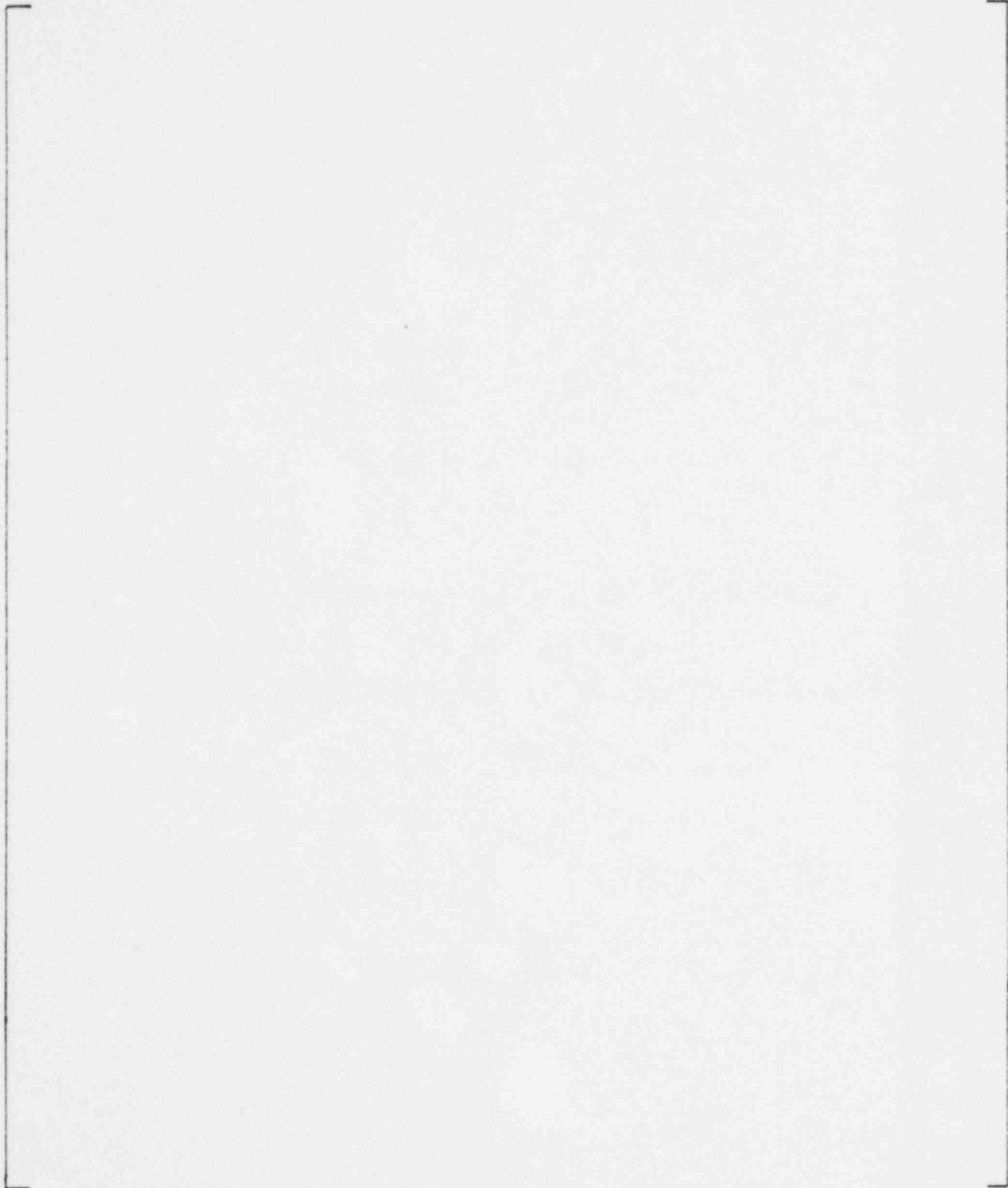
3.3.2.6 The Number of Degrees of Freedom

To obtain a tolerance limit, one treats $S_{C\ell}^2$ as though it was proportional to a chi-square distributed random variable with f degrees of freedom and finds the constant of proportionality, and f, by equating the means and variances. One gets:

$$f_C = \frac{2E^2(S_C^2)}{D^2(S_C^2)} \tag{3.59}$$

3.3.2.7 Procedure for Pooling Estimates

3.3.3   Calculational Method

3.3.3.1   Design Method

The design method for generating in-core instrument system data employs the PDQ code in either four or two neutron energy groups and the assignment of one mesh volume per fuel rod with its associated water.

3.3.3.2   Method of Incorporating Transport Results Into the Design Method

The design procedure is extended by integral transport theory in a multigroup formulation modeling the details of the assembly geometry without homogenization and accounting for all relevant spectrum interaction effects between fuel and other components of the assembly such as burnable absorbers, control rods or water holes. The following is a summary of the method.

The transport calculations are done with the DIT code (Refs. 3.4, 3.5) and adjustments are made in such a way that the entire PDQ calculation, including edits, provides pin/box factors no smaller than those from direct DIT calculations when applied to an individual assembly. This is achieved by applying a combination of multipliers to the PDQ edited fine mesh power distribution and fitting of PDQ diffusion parameters. The combination is determined by DIT and PDQ assembly calculations covering each type of fuel and the entire lifetime of the fuel in the core. It can be shown, Appendix 3.1, that this approach leads to an uncertainty, σ_C, that is identical to that of DIT.

3.3.3.3   Pin/Box Factor and Pin Power Distribution Calculations for Comparison with Measurement

To make direct comparisons between calculated results using DIT and the Critical Experiments described above, the latter are taken for the centrally located assembly in the core where effects of the global distribution are a minimum. The experimental results are then reduced to remove the global

component using PDQ calculations for the core and for the central assembly. The experimental results thus obtained are compared directly to DIT calculations. The method for removing the global distribution introduces an additional uncertainty in the experimental values. The size of this uncertainty is negligible and has been investigated in detail. This small uncertainty component is automatically retained in the final estimate of the uncertainty for the calculational method since it will be part of $S_{D\ell}$.

3.3.4   Statistical Error and Bias Evaluation

The evaluation of the calculational uncertainty for local pin peaking must
be based upon comparisons with experiments for those pins that may have the
peak value. Estimates based on the entire set of measured pins within an
assembly are not sufficient since they do not provide the bias for peak
pins. Furthermore, the statistical error (estimate of standard deviation)
observed in comparing measurement and calculation is not necessarily the
same for peak pins as for the entire population of fuel pins.

This evaluation is, therefore, based upon comparisons of peak location
only. In the C-E design these locations are always next to CEA water holes
or other positions where fuel has been replaced by mainly moderating material.
When performing the comparisons, both measurements and calculations are
normalized to unit average power (fission rate) for the assembly (the
majority of cases) or for those pins that were measured when the measurements
were done for less than all pins (KRITZ). Biases and standard deviations
are expressed in percent of peak power.

3.3.4.1   Geometry

The calculation of local pin peak by transport theory methods is undertaken
in assembly geometry with all symmetries in the design and in the boundary
conditions accounted for. Thus, the 1/8 assembly geometry is the unit of
interest.

In all the experiments, multiple measurements were done for pins located
symmetrically in the core. The purpose of doing duplicate measurements is
to provide estimates of the effect of any asymmetries in the experimental
situation. Prior to comparison with calculated results, this information
is utilized to reduce the experimental uncertainty by folding the measurements
into 1/8 core as reflected by Equation (3.23). Figures 3-31 to 3-38 show the
comparisons between measurements and calculation.

3.3.4.2   The Bias, $\bar{D}$

The primary information from the comparison of measurements and calculations consists of the bias, $\bar{D}_\ell$ and the sample standard deviation $S_{D\ell}$ with notation as explained in 3.3.2.1.

For the entire set of experiments, Table 3.XVII and Figure 3-39 show the observed values of $\bar{D}_\ell$.

TABLE 3.XVII

The Bias: Calculation - Measurement

Table 3.XVII shows that the bias is of the order of 1% with the calculation overestimating peak power. Although small, this calculational error is expected on theoretical grounds and it is appropriate therefore that it appears in the bias instead of being a contribution to the variance. Figure 3-39 shows that the bias has a definite trend with the wetness of these lattices. Indicated on the Figure is the location of C-E 14x14 and 16x16 fuel assembly designs. The majority of the experiments cluster around this location while the two BNWL experiments have very high wetnesses

atypical of the designs. These two lattices have, therefore, been removed from the analysis. There is an indication that the two Pu lattices depart slightly from the trend and the cold lattice (with essentially zero bias) is atypical of operating conditions. The hot lattice is also atypical of the U fuel cycles without Pu recycle since the enrichment is as high as 3%. These two lattices have nonetheless been retained in the analysis. Excluding them would only change the average bias from [   ] an entirely insignificant amount. Credit has not been taken for the best fit through all points of Figure 3-39 showing a bias of approximately [   ] at C-E fuel design operating conditions. Using the higher bias would be a credit since transport effects are incorporated in PDQ as described by 3.3.3.2. The credit would be small: about 0.3% of peak power. In conclusion, therefore, the DIT calculational bias is taken as:

[   ]

3.3.4.3 The Random Component of Observed Differences Between Calculation and Measurement, σ_D

The method of estimating σ_D was described in 3.3.2.2. Table 3.XVIII shows the results for all lattices except the BNWL lattices which were excluded as described in 3.3.4.2.

TABLE 3.XVIII

The Standard Deviation From Comparisons

of Calculations and Measurement

The last line in the table shows the pooled estimate calculated as described
in 3.3.2.7. The justification for pooling the individual sample variances
is as follows.

(1) The physical situation encountered by the calculational method is
     very similar for all these experiments. This is particularly
     true for the C-E criticals which have wetness ratios identical to
     conditions for C-E operating cores. Figures 3-31 to 3-35 show
     that the magnitude of the peaking at the water holes is very
     nearly the same for all these cases. Hence it is physically
     unrealistic to expect different calculational errors for these
     cases which constitute the major part of the data base. Since
     the calculational error is dominant in σ_D it is therefore physically
     unrealistic to expect the sample values to reflect an inhomogeneous
     data base. Statistical testing confirms this expectation.

(2) The distribution of observed differences was subjected to a
normality test (Reference 3.9) which shows that it is not unreason-
able to assume that the differences are normally distributed.
The hypothesis that individual $S_{D\ell}$ are based on samples from one
parent population with the single standard deviation σ_D, was
subjected to the Bartlett tests (References 3.6 and 3.7). The
calculated test statistic is

In conclusion the pooled estimate of the standard deviation of the difference between calculation and measurement is

$$\sigma_D \cong S_D = [\qquad]$$

3.3.4.4 The Measurement Uncertainty, σ_M

As described in 3.3.2.3, the measurement uncertainty, including effects due to counting statistics, counting geometry, fuel inhomogeneity and asymmetries in the core configuration, is obtained by comparing symmetrically located measurements. The resulting measurement uncertainty is shown in Table 3.XX along with the appropriate number of points measured using the notation of 3.3.2.3.

The distributions of measurement errors for individual experiments have been subjected to tests for normality according to ANSI N15.5-1974 (Reference 3.9). The tests show that it is not unreasonable to assume that the measurement

errors are normally distributed. Figure 3-40 shows a typical distribution for the C-E criticals. The ε_{ij} used in the figure is consistent with the definition in Eq. (3.43).

TABLE 3.XX

The Measurement Uncertainty in
Critical Experiments

The justifications for pooling the individual measurement uncertainties are as follows:

In conclusion, the pooled estimate of the measurement uncertainty is

$$\sigma_M \cong S_M = [\qquad]$$

3.3.4.5 The Calculational Uncertainty, σ_C

The calculational uncertainty, σ_C is related to the measurement and difference uncertainty by Eq. (3.34):

$$\sigma_C^2 = \sigma_D^2 - \sigma_M^2$$

Since it has been shown that the individual case estimates of σ_D and σ_M (i.e., $S_{D\ell}$ and $S_{M\ell}$) can be pooled, Eq. (3.64) can be used to form the pooled estimate of σ_C:

$$\sigma_C^2 \cong S_C^2 = S_D^2 - S_M^2 \tag{3.64}$$

This results in

[

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3.3.4.6 Summary

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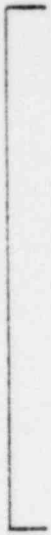
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APPENDIX 3.1

TRANSPORT THEORY ADJUSTMENTS IN THE DESIGN PDQ MODEL

Transport theory adjustments are made by a combination of fitted diffusion constants in PDQ and correction factors on the PDQ edited power distributions. This combination is determined by doing comparable DIT and PDQ assembly calculations covering the life of the fuel. The transport theory adjusted PDQ is such that it gives pin/box factors no smaller than DIT (adjusted for its bias as determined in 3.3.4.2) throughout the cycle. Therefore, the resulting bias in PDQ is always zero.

TABLE 3.I
Summary of Synthesis Uncertainties

Box Power[+]	$\bar{D}$	S	Number of Degrees of Freedom	k95/95	$\bar{D} + kS$
F_r			216		
F_{xy}			260		
F_q			216		
Pin Peaking[++]					
F_p (S)			244		
F_p (C)			27		

+   Quoted in percent of peak box value.

++   Quoted in percent of average pin to box value.

TABLE 3.II
Calvert Cliffs Unit 1 Cycle 1

ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	20%	0%	
01	100	50%	0%	
02	500	80%	0%	*
03	850	100%	0%	*
04	1000	100%	0%	*
05	2000	100%	0%	*
06	3000	100%	0%	*
07	4000	100%	0%	*
08	5000	100%	0%	*
09	6000	100%	0%	*
10	7000	100%	0%	*
11	8000	100%	0%	*
12	9000	100%	0%	*
13	10000	100%	0%	*
14	11000	100%	0%	*
15	12000	100%	0%	*
16	13000	100%	0%	*
17	14000	100%	0%	*
18	15000	100%	0%	*
19	15500	100%	0%	*
20	16000	95%	18%	*
21	16500	68%	18%	*
22	16670	57%	18%	*

[†] Lead Bank

TABLE 3.III
Calvert Cliffs Unit 1 Cycle 2

ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	49%	0%	
01	75	70%	0%	*
02	150	80%	0%	*
03	200	90%	0%	*
04	325	100%	0%	*
05	990	100%	0%	*
06	1436	100%	0%	*
07	1746	100%	0%	*
08	2087	100%	0%	*
09	2722	100%	0%	*
10	3341	100%	0%	*
11	3970	100%	0%	*
12	4192	100%	0%	*
13	5056	102%	0%	*
14	6000	101%	0%	*
15	6446	103%	0%	*
16	7000	103%	0%	*
17	7360	103%	0%	*
18	7600	90%	0%	*
19	8280	90%	3.2%	*
20	8330	90%	3.2%	*

[†] Lead Bank

TABLE 3.IV
Calvert Cliffs Unit 1 Cycle 3

ROCS Maneuver Structure

Man #	Bu	Power	Rods[†]	Comparisons
00	0	27%	50%	
01	177	84%	0%	*
02	495	82%	0%	*
03	801	57%	50%	*
04	1202	91%	0%	*
05	1611	93%	0%	*
06	2021	99%	0%	*
07	2238	99%	15.8%	*
08	2582	93%	0%	*
09	3011	94%	0%	*
10	3811	95%	0%	*
11	4626	95%	0%	*
12	5434	94%	0%	*
13	5849	97%	7.2%	*
14	5994	96%	0%	*
15	6442	94%	0%	*
16	6547	94%	0%	*
17	6658	94%	0%	*
18	6869	0%	0%	
19	6869	95%	0%	*
20	7147	95%	0%	*
21	7327	87%	6.7%	*
22	7554	96%	6.7%	*
23	7738	96%	6.7%	*
24	7964	100%	6.7%	*
25	8149	95%	6.7%	*
26	8578	100%	8.2%	*
27	8969	100%	0%	*
28	9440	100%	0%	*

[†] Lead Bank

TABLE 3.V

Calvert Cliffs Unit 1 Cycle 1
CECOR MANEUVER STRUCTURE AND FAILED DETECTORS

Burnup	Power Level	Rod+ Insertion	Failed Detectors Level 1	Level 2	Level 3	Level 4
0	20%	0%	None	None	None	None
100	50%	0%	None	None	None	None
500	80%	0%	None	None	None	None
850	100%	0%	None	None	23	None
1000	100%	0%	None	None	23	None
2000	100%	0%	None	None	23	None
3000	100%	0%	20	None	23	None
4000	100%	0%	20	None	23	None
5000	100%	0%	20	None	23	None
6000	100%	0%	20	None	23	None
7000	100%	0%	20	None	23	None
8000	100%	0%	20	None	23	None
9000	100%	0%	20	None	23	35
10000	100%	0%	20	None	23	35
11000	100%	0%	20	None	23	35
12000	100%	0%	20	None	23	35
13000	100%	0%	20	None	23	35
14000	100%	0%	20,26	None	23	35, 8
15000	100%	0%	20,26	None	23	35, 8
15500	100%	0%	20,26	None	23	35, 8
16000	95%	18%	20,26	35	23	35, 8
16500	68%	18%	20,26	35	23	35, 8
16700	57%	18%	20,26	35	23	35, 8

+ Lead Bank

TABLE 3.VI

Calvert Cliffs Unit 1 Cycle 2
CECOR MANEUVER STRUCTURE AND FAILED DETECTORS

Burnup	Power Level	Rod+ Insertion	Failed Detectors Level 1	Level 2	Level 3	Level 4
0	49%	0%	3,14,15,25,44,1,7	3,14,15,18,25,31,1,7,44	3,14,15,25,44,1,7	3,14,15,25,44,1,7
75	70%	0%	"	"	"	"
150	80%	0%	"	"	"	"
200	90%	0%	"	"	"	"
325	100%	0%	"	"	"	"
990	100%	0%	"	"	"	"
1436	100%	0%	"	"	"	"
1746	100%	0%	"	"	"	"
2087	100%	0%	"	"	"	"
2722	100%	0%	"	"	"	3,14,15,25,30,44,1,7
3341	100%	0%	"	3,14,15,18,25,31,43, 44,1,7	"	3,14,15,25,30,33, 44,1,7
3970	100%	0%	"		"	
4192	100%	0%	"	3,14,15,18,24,25,31, 43,44,1,7	"	"
5056	102%	0%	"		"	"
6000	101%	0%	"	"	"	2,3,14,15,25,30, 33,44,1,7
6446	103%	0%	"	"	"	
7000	103%	0%	"	"	"	"
7360	103%	0%	"	3,14,15,18,24,25,31, 42,43,1,7,44	3,14,15,25,29,44, 1,7	"
7600	90%	0%	"			"
8280	90%	3.2%	"	"	"	"
8330	90%	3.2%	"	"	"	"

+Lead Bank

II.3.69

TABLE 3.VII

Calvert Cliffs Unit 1 Cycle 3
CECOR MANEUVER STRUCTURE AND FAILED DETECTORS

II.3.70

Burnup	Power Level	Rod+ Insertion	Failed Detectors Level 1	Level 2	Level 3	Level 4
0	27%	0%	4,5,6,16,19,22,23,33	4,6,23,33,35,42	3,4,5,6,16,19,23,33	4,5,6,23,33
177	84%	0%	"	"	"	"
495	82%	0%	"	"	"	"
801	57%	50%	"	"	"	"
1202	91%	0%	"	"	"	"
1611	93%	0%	"	"	"	"
2021	99%	0%	"	4,6,23,33,34,35,42	"	4,5,6,23,33,34
2238	99%	15.8%	"	"	"	"
2582	93%	0%	"	"	"	"
3011	94%	0%	"	"	"	"
3811	95%	0%	4,5,6,16,19,21,22,23,33	"	3,4,5,6,16,19,23,33.34	"
4626	95%	0%	"	"	"	"
5434	94%	0%	"	"	"	4,5,6,23,33,34,35
5849	97%	7.2%	"	"	"	"
5994	96%	0%	"	"	"	"
6442	94%	0%	4,5,6,16,19,21,22,23,33,34	"	"	"
6547	94%	0%	"	"	"	4,5,6,20,23,33,34,45
6658	94%	0%	"	"	"	"
6869	95%	0%	"	"	3,4,5,6,8,16,19,23,33,34	"
7174	95%	0%	"	"	"	"
7327	87%	6.7%	"	"	"	"
7554	96%	6.7%	"	"	3,4,5,6,8,16,19,21,23,33,34	"
7738	96%	6.7%	"	"	"	"
7964	100%	6.7%	"	"	"	"
8149	95%	6.7%	"	"	"	"
8578	100%	8.2%	"	"	"	"
8969	100%	0%	"	"	"	"
9440	100%	0%	"	"	"	"

+ Lead Bank

TABLE 3.VIIIa
Calvert Cliffs Unit 1 Cycle 1

BIAS AND STANDARD DEVIATION OF DIFFERENCE BETWEEN ROCS AND CECOR CALCULATIONS

Burnup (MWD/T)	F_q			F_r			F_{xy}		
	$\bar{D}_S$	S_S	N_F	$\bar{D}_S$	S_S	N_F	$\bar{D}_S$	S_S	N_{LU}
500			217			217			14
850			217			217			14
1000			217			217			14
2000			217			217			14
3000			217			217			14
4000			217			217			14
5000			217			217			14
6000			217			217			14
7000			217			217			14
8000			217			217			14
9000			217			217			14
10000			217			217			14
11000			217			217			14
12000			217			217			14
13000			217			217			14
14000			217			217			14
15000			217			217			14
15500			217			217			14
16000			217			217			14
16500			217			217			14
16700			217			217			14

+Worst-case Value

TABLE 3.VIIIb
Calvert Cliffs Unit 1 Cycle 1

RESULTS OF BOX POWER DATA POOLING AND
BARTLETT AND NORMAL DEVIATE TESTS

Pooled Time Point and Test Results*

	$\bar{D}_S$	S_S	N_{DEG}	Bartlett Fcal(20,∞)	Normal Deviate Pcal($\bar{D}\ell_1, \bar{D}\ell_2$)
F_q					
F_r					
F_{xy}					

ower Synthesis Results

	$\bar{D}_S$	S_S	N_{DEG}
F_q^+			
F_r^+			
F_{xy}^+			

TABLE 3.IXa
Calvert Cliffs Unit 1 Cycle 2

BIAS AND STANDARD DEVIATION OF DIFFERENCE BETWEEN ROCS AND CECOR CALCULATIONS

Burnup (MWD/T)	F_q			F_r			F_{xy}		
	$\bar{D}_S$	S_S	N_F	$\bar{D}_S$	S_S	N_F	$\bar{D}_S$	S_S	N_{LU}
75			217			217			14
150			217			217			14
200			217			217			14
325			217			217			14
990			217			217			14
1436			217			217			14
1746			217			217			14
2087			217			217			14
2722			217			217			14
3341			217			217			14
3970			217			217			14
4192			217			217			14
5056			217			217			14
6000			217			217			14
6446			217			217			14
7000			217			217			14
7360			217			217			14
7600			217			217			14
8280			217			217			14
8330			217			217			14

+ Worst-case Value

TABLE 3.IXb

Calvert Cliffs Unit 1 Cycle 2

RESULTS OF BOX POWER DATA POOLING AND
BARTLETT AND NORMAL DEVIATE TESTS

Pooled Time Point and Test Results*

	$\bar{D}_S$	S_S	N_{DEG}	Bartlett $Fcal(19,\infty)$	Normal Deviate $Pcal(\bar{D}\ell_1, \bar{D}\ell_2)$
F_q					
F_r					
F_{xy}					

Box Power Synthesis Results

	$\bar{D}_S$	S_S	N_{DEG}
F_q^+			
F_r^+			
F_{xy}^{++}			

TABLE 3.IXc
Calvert Cliffs Unit 1 Cycle 2

NORMALITY TEST RESULTS [   ]

Burnup (MWD/T)	N_{TOT}	S_S	[

[   ]

TABLE 3.IXd

Calvert Cliffs Unit 1 Cycle 2

NORMALITY TEST RESULTS [   ]

	N_{TOT}	$\bar{D}_S$	S_S	D-Prime Test	
				D'	$\alpha(\%)$
F_q					
F_r^+					
F_{xy}^+					

[   ]

TABLE 3.Xa

Calvert Cliffs Unit 1 Cycle 3

BIAS AND STANDARD DEVIATION OF DIFFERENCE BETWEEN ROCS AND CECOR CALCULATIONS

Burnup	F_q			F_r			F_{xy}		
(MWD/T)	$\bar{D}_S$	S_S	N_F	$\bar{D}_S$	S_S	N_F	$\bar{D}_S$	S_S	N_{LU}
495			217			217			14
801			217			217			14
1202			217			217			14
1611			217			217			14
2021			217			217			14
2238			217			217			14
2582			217			217			14
3011			217			217			14
3811			217			217			14
4626			217			217			14
5435			217			217			14
5849			217			217			14
5994			217			217			14
6442			217			217			14
6547			217			217			14
6658			217			217			14
6869			217			217			14
7147			217			217			14
7327			217			217			14
7554			217			217			14
7738			217			217			14
7964			217			217			14
8149			217			217			14
8578			217			217			14
8969			217			217			14
9440			217			217			14

+ Worst-case Value

TABLE 3.Xb
Calvert Cliffs Unit 1 Cycle 3

RESULTS OF BOX POWER DATA POOLING AND
BARTLETT AND NORMAL DEVIATE TESTS

Pooled Time Point and Test Results*

	$\bar{D}_S$	S_S	N_{DEG}	Bartlett $F_{cal}(26,\infty)$	Normal Deviate $P_{cal}(\bar{D}\ell_1, \bar{D}\ell_2)$
F_q					
F_r					
F_{xy}					

Box Power Synthesis Results

	$\bar{D}_S$	S_S	N_{DEG}
$F_q{}^+$			
$F_r{}^+$			
$F_{xy}{}^{++}$			

TABLE 3.XI
Calvert Cliffs Unit 1

SUMMARY OF BOX POWER SYNTHESIS ERROR BIAS AND
STANDARD DEVIATION RESULTS FOR CYCLES 1, 2 AND 3

Quantity	Cycle	$\bar{D}_S$	S_S	N_{DEG}
F_q	1			
	2+			
	3			
F_r	1			
	2+			
	3			
F_{xy}	1			
	2+			
	3			

[   ]

TABLE 3.XII

Calvert Cliffs Unit 1

RESULTS OF POOLING SYNTHESIS ERRORS FOR CYCLES 1, 2, 3

$\bar{D}_S$ S_S N_{DEG}

F_q^+

F_r^+

F_{xy}^+

TABLE 3.XIII

Bias and Standard Deviation of Difference for [

] PDQ Calculations for Pin Peaking, And Results of Data Pooling

Reactor	Cycle	Burnup (MWD/T)	$\overline{D}_{S_{F_p}}$	$S_{S_{F_p}}$	N_{DEG}
Calvert Cliffs Unit 2	2				61
St. Lucie Unit 1	2				61
Millstone Unit 2	2				61
Calvert Cliffs Unit 1	4				61
Pooled Result**					244

TABLE 3.XIV

Normality Test Results for Pin-Peaking Synthesis Error Data

Reactor	Cycle	N_{TOT}	$S_{S_{Fp}}$	[	]
Calvert Cliffs Unit 2	2	62			
St. Lucie Unit 1	2	62			
Millstone Unit 2	2	62			
Calvert Cliffs Unit 1	4	62			
Pooled Data		248			

Figure 3-1
LOADING & INSTRUMENT PATTERN
CALVERT CLIFFS UNIT 1 CYCLE 1

BATCH ROX

INSTR.

| C | 1 | C | 2 | C | 3 | C | 4 |

| C | S | C | 6 | C+ | 7 | C+ | 8 | B | 9 | C+ | 10 | C+ | 11 | C | 12 | C | 13 |
| | | | | | | | | | | | | | | | | 1 |

| C | 14 | C. | 15 | B | 16 | A | 17 | B | 18 | A | 19 | B | 20 | A | 21 | B | 22 | C. | 23 | C | 24 |
| | 2 | | | 3 | | | | | ✕ | | | | | | | | |

| C | 25 | C. | 26 | B | 27 | A | 28 | B | 29 | A | 30 | B | 31 | A | 32 | B | 33 | A | 34 | B | 35 | C. | 36 | C | 37 |
| | | ✕ | | | | | | | | 4 | | | 5 | | | | ✕ | | 6 |

| C | 38 | C. | 39 | B | 40 | A | 41 | B | 42 | A | 43 | B | 44 | A | 45 | B | 46 | A | 47 | B | 48 | A | 49 | B | 50 | C. | 51 | C | 52 |
| 7 | | 8 | | 9 | | | | | | | | | | 10 | | | |

| C | 53 | B | 54 | A | 55 | B | 56 | A | 57 | BX | 58 | A | 59 | B | 60 | A | 61 | B | 62 | A | 63 | B | 64 | A | 65 | B | 66 | C | 67 |
| | | | | | | | | 11 | | | 12 | | | | 1 |

| C+ | 68 | A | 69 | B | 70 | A | 71 | B | 72 | A | 73 | B | 74 | A | 75 | B | 76 | A | 77 | B | 78 | A | 79 | B | 80 | A | 81 | C+ | 82 |
| C | 83 | 14 | | 15 | | | 16 | | | | | | | | | 17 | | C | 84 |

| C+ | 85 | B | 86 | A | 87 | B | 88 | A | 89 | B | 90 | A | 91 | B | 92 | A | 93 | B | 94 | A | 95 | B | 96 | A | 97 | B | 98 | C+ | 99 |
| C | 100 | | | | | 18 | | | | | | | | 19 | | | C | 101 |
| 20 |

| B | 102 | A | 103 | B | 104 | A | 105 | B | 106 | A | 107 | B | 108 | A | 109 | B | 110 | A | 111 | B | 112 | A | 113 | B | 114 | A | 115 | B | 116 |
| C | 117 | ✕ | 21 | | 22 | | | | ✕ | 23 | | 24 | | | 25 | ✕ | 26 | C | 118 |

| C+ | 119 | B | 120 | A | 121 | B | 122 | A | 123 | B | 124 | A | 125 | B | 126 | A | 127 | B | 128 | A | 129 | B | 130 | A | 131 | B | 132 | C+ | 133 |
| C | 134 | 27 | | | | | | | | | | | | | C | 135 |

| C+ | 136 | A | 137 | B | 138 | A | 139 | BX | 140 | A | 141 | B | 142 | A | 143 | B | 144 | A | 145 | BX | 146 | A | 147 | B | 148 | A | 149 | C+ | 150 |
| 28 | | | | | | | 29 | | | | 30 | | 31 |

| C | 151 | B | 152 | A | 153 | B | 154 | A | 155 | B | 156 | A | 157 | B | 158 | A | 159 | B | 160 | A | 161 | B | 162 | A | 163 | B | 164 | C | 165 |
| 32 | | | | | 33 | 34 | | | 35 | | |

| C | 166 | C. | 167 | B | 168 | A | 169 | B | 170 | A | 171 | B | 172 | A | 173 | B | 174 | A | 175 | B | 176 | A | 177 | B | 178 | C. | 179 | C | 180 |
| 36 | | | | | 37 | | | 38 | | | 39 |

| C | 181 | C. | 182 | B | 183 | A | 184 | B | 185 | A | 186 | B | 187 | A | 188 | B | 189 | A | 190 | B | 191 | C. | 192 | C | 193 |
| 40 | ✕ | | | 41 | | 42 | | | | ✕ |

| C | 194 | C. | 195 | B | 196 | A | 197 | B | 198 | A | 199 | B | 200 | A | 201 | B | 202 | C. | 203 | C | 204 |
| | | | | | ✕ | | | 43 | | 44 |

| C | 205 | C | 206 | C+ | 207 | C+ | 208 | B | 209 | C+ | 210 | C+ | 211 | C | 212 | C | 213 |
| 45 |

| C | 214 | C | 215 | C | 216 | C | 217 |

- BX INDICATES TEST ASSEMBLY

✕ INDICATES ROD BANK 5 LOCATIONS

II.3.83

Figure 3-2
LOADING & INSTRUMENT PATTERN
CALVERT CLIFFS UNIT 1 CYCLE 2

BATCH BOX

INSTR.

D 1	D 2	D 3	D 4

D 5	D 6	D 7	C 8	B 9	C 10	D 11	D 12	D 13
								1

D 14	D 15	C+ 16	B 17	B 18	D 19 ✕	B 20	B 21	C+ 22	D 23	D 24
2		3								

D 25	C 26 ✕	B 27	B 28	D 29	B 30	B 31	B 32	D 33	B 34	B 35	C 36 ✕	D 37
						4		5				6

D 38	D 39	B 40	D 41	B 42	B 43	C. 44	C 45	C. 46	B 47	B 48	D 49	B 50	D 51	D 52
7		8	9								10			

D 53	C+ 54	B 55	B 56	BX 57	C 58	C 59	C. 60	C 61	C 62	B 63	B 64	B 65	C+ 66	D 67
							11		12				13	

D 68	B 69	D 70	B 71	C 72	B 73	C+ 74	C 75	C+ 76	B 77	C 78	B 79	D 80	B 81	D 82
14	15				16								17	

D 83	C 85	B 86	B 87	C. 88	C 89	C+ 90	B 91	C 92	B 93	C+ 94	C 95	C. 96	B 97	B 98	C 99	D 84
						18						19				

D 100	B 102	D 103 ✕	B 104	C 105	C. 106	C 107	C 108	B 109 ✕	C 110	C 111	C. 112	C 113	B 114	D 115 ✕	B 116	D 101
20		21		22				23		24			25		26	

D 117	C 119	B 120	B 121	C. 122	C 123	C+ 124	B 125	C 126	B 127	C+ 128	C 129	C. 130	B 131	B 132	C 133	D 118
D 134		27														D 135

D 136	B 137	D 138	B 139	C 140	B 141	C+ 142	C 143	C+ 144	B 145	C 146	B 147	D 148	B 149	D 150	31
28								29				30			

D 151	C+ 152	B 153	B 154	B 155	C 156	C 157	C. 158	C 159	C 160	BX 161	B 162	B 163	C+ 164	D 165
	32					33	34				35			

D 166	D 167	B 168	D 169	B 170	B 171	C. 172	C 173	C. 174	B 175	B 176	D 177	B 178	D 179	D 180
			36					37			38			39

D 181	C 182 ✕	B 183	B 184	D 185	B 186	B 187	B 188	D 189	B 190	B 191	C 192 ✕	D 193
40				41		42						

D 194	D 195	C+ 196	B 197	B 198	D 199 ✕	B 200	B 201	C+ 202	D 203	D 204
								43		44

D 205	D 206	D 207	C 208	B 209	C 210	D 211	D 212	D 213
45								

D 214	D 215	D 216	D 217

● BX INDICATES TEST ASSEMBLY

✕ INDICATES ROD BANK 5 LOCATIONS

II.3.84

Figure 3-3
LOADING & INSTRUMENT PATTERN
CALVERT CLIFFS UNIT 1 CYCLE 3

BATCH BOX

INSTR.

| E | 1 | E | 2 | E | 3 | E | 4 |

| E | 5 | E | 6 | E | 7 | D | 8 | C | 9 | D | 10 | E | 11 | E | 12 | E | 13 |
1

| E | 14 | D | 15 | A | 16 | D | 17 | A | 18 | C | 19 | A | 20 | D | 21 | A | 22 | D | 23 | E | 24 |
2   3   ✕

| E | 25 | E | 26 | A | 27 | E | 28 | D | 29 | D | 30 | D | 31 | D | 32 | D | 33 | E | 34 | A | 35 | E | 36 | E | 37 |
✕   4   5   ✕   6

| E | 38 | D | 39 | A | 40 | E | 41 | A | 42 | C | 43 | D | 44 | C | 45 | D | 46 | C | 47 | A | 48 | E | 49 | A | 50 | D | 51 | E | 52 |
7   8   9   10

| E | 53 | A | 54 | E | 55 | A | 56 | D | 57 | D | 58 | C | 59 | D | 60 | C | 61 | D | 62 | D | 63 | A | 64 | E | 65 | A | 66 | E | 67 |
11   12   13

| E | 68 | D | 69 | D | 70 | C | 71 | D | 72 | A | 73 | E | 74 | C | 75 | E | 76 | A | 77 | D | 78 | C | 79 | D | 80 | D | 81 | E | 82 |
| E | 83 | 14   15   16   17 | E | 84 |

| D | 85 | A | 86 | D | 87 | D | 88 | C | 89 | E | 90 | A | 91 | D | 92 | A | 93 | E | 94 | C | 95 | D | 96 | D | 97 | A | 98 | D | 99 |
| E | 100 | 18   19 | E | 101 |
20

| C | 102 | C | 103 | D | 104 | C | 105 | D | 106 | C | 107 | D | 108 | BX 109 | D | 110 | C | 111 | D | 112 | C | 113 | D | 114 | C | 115 | C | 116 |
| E | 117 | ✕   21   22   ✕   23   24   25   ✕   26 | E | 118 |

| D | 119 | A | 120 | D | 121 | D | 122 | C | 123 | E | 124 | A | 125 | D | 126 | A | 127 | E | 128 | C | 129 | D | 130 | D | 131 | A | 132 | D | 133 |
| E | 134 | 27 | E | 135 |

| E | 136 | D | 137 | D | 138 | C | 139 | D | 140 | A | 141 | E | 142 | C | 143 | E | 144 | A | 145 | D | 146 | C | 147 | D | 148 | D | 149 | E | 150 |
28   29   30 | 31 |

| E | 151 | A | 152 | E | 153 | A | 154 | D | 155 | D | 156 | C | 157 | D | 158 | C | 159 | D | 160 | D | 161 | A | 162 | E | 163 | A | 164 | E | 165 |
32   33   34   35

| E | 166 | D | 167 | A | 168 | E | 169 | A | 170 | C | 171 | D | 172 | C | 173 | D | 174 | C | 175 | A | 176 | E | 177 | A | 178 | D | 179 | E | 180 |
36   37   38   39

| E | 181 | E | 182 | A | 183 | E | 184 | D | 185 | D | 186 | D | 187 | D | 188 | D | 189 | E | 190 | A | 191 | E | 192 | E | 193 |
40   ✕   41   42   ✕

| E | 194 | D | 195 | A | 196 | D | 197 | A | 198 | C | 199 | A | 200 | D | 201 | A | 202 | D | 203 | E | 204 |
✕   43   44

| E | 205 | E | 206 | E | 207 | D | 208 | C | 209 | D | 210 | E | 211 | E | 212 | E | 213 |
45

| E | 214 | E | 215 | E | 216 | E | 217 |

• BX INDICATES TEST ASSEMBLY

✕ INDICATES ROD BANK 5 LOCATIONS

II.3.85

Figure 3-4
CALVERT CLIFFS UNIT 1
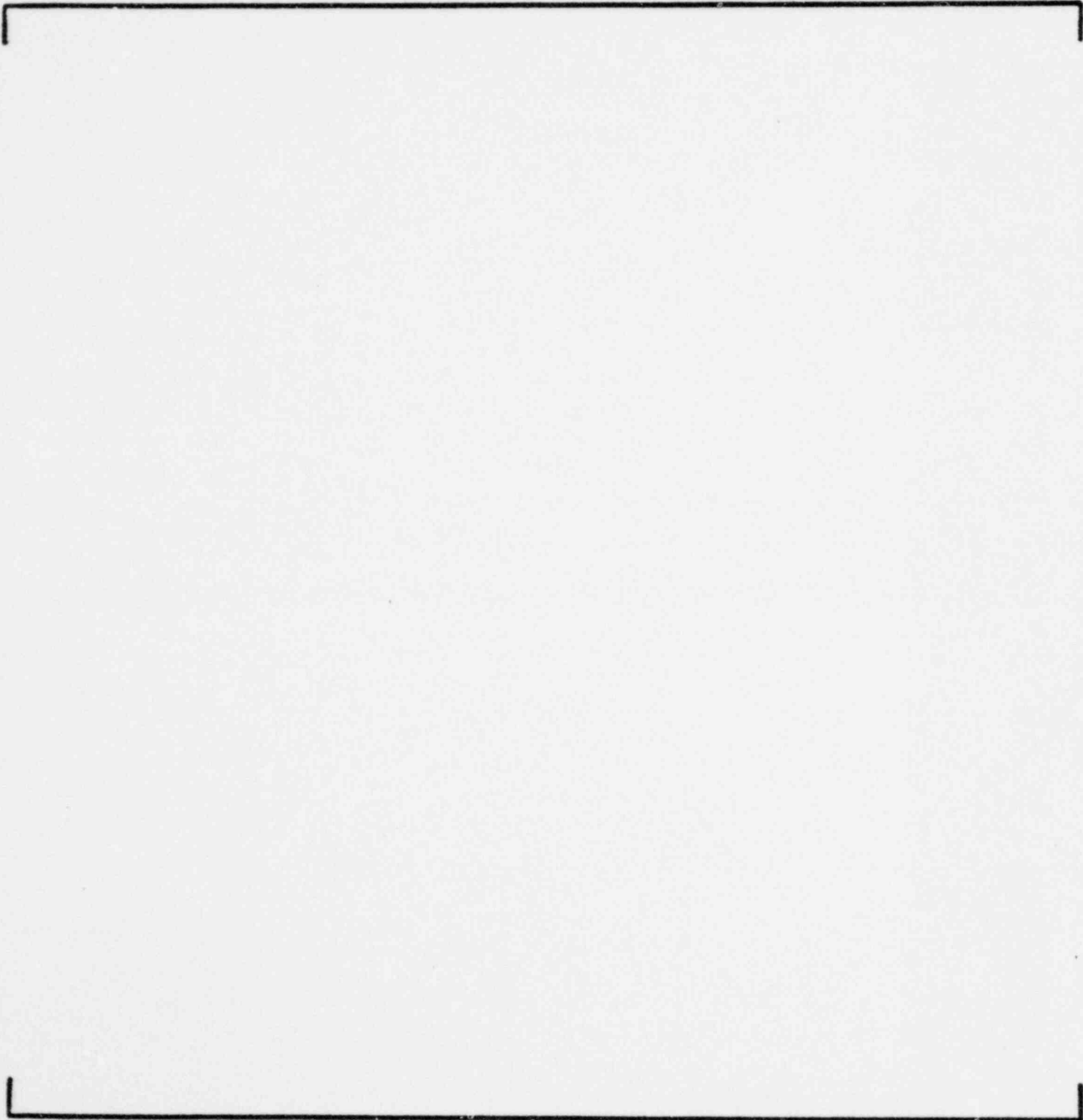AXIAL GEOMETRIES FOR ROCS AND CECOR MODELS
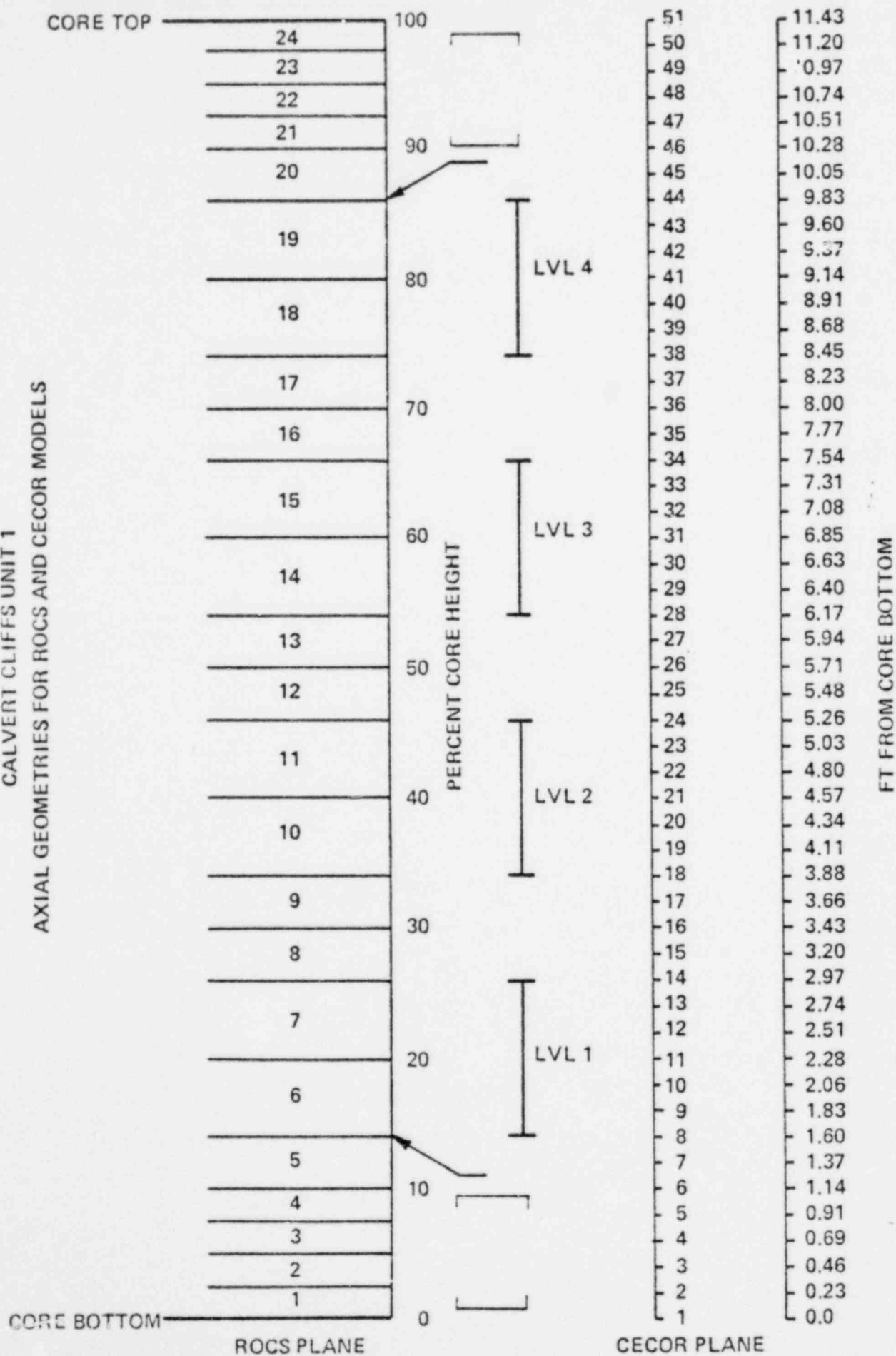
Figure 3-5b
CALVERT CLIFFS UNIT 1 CYCLE 1
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
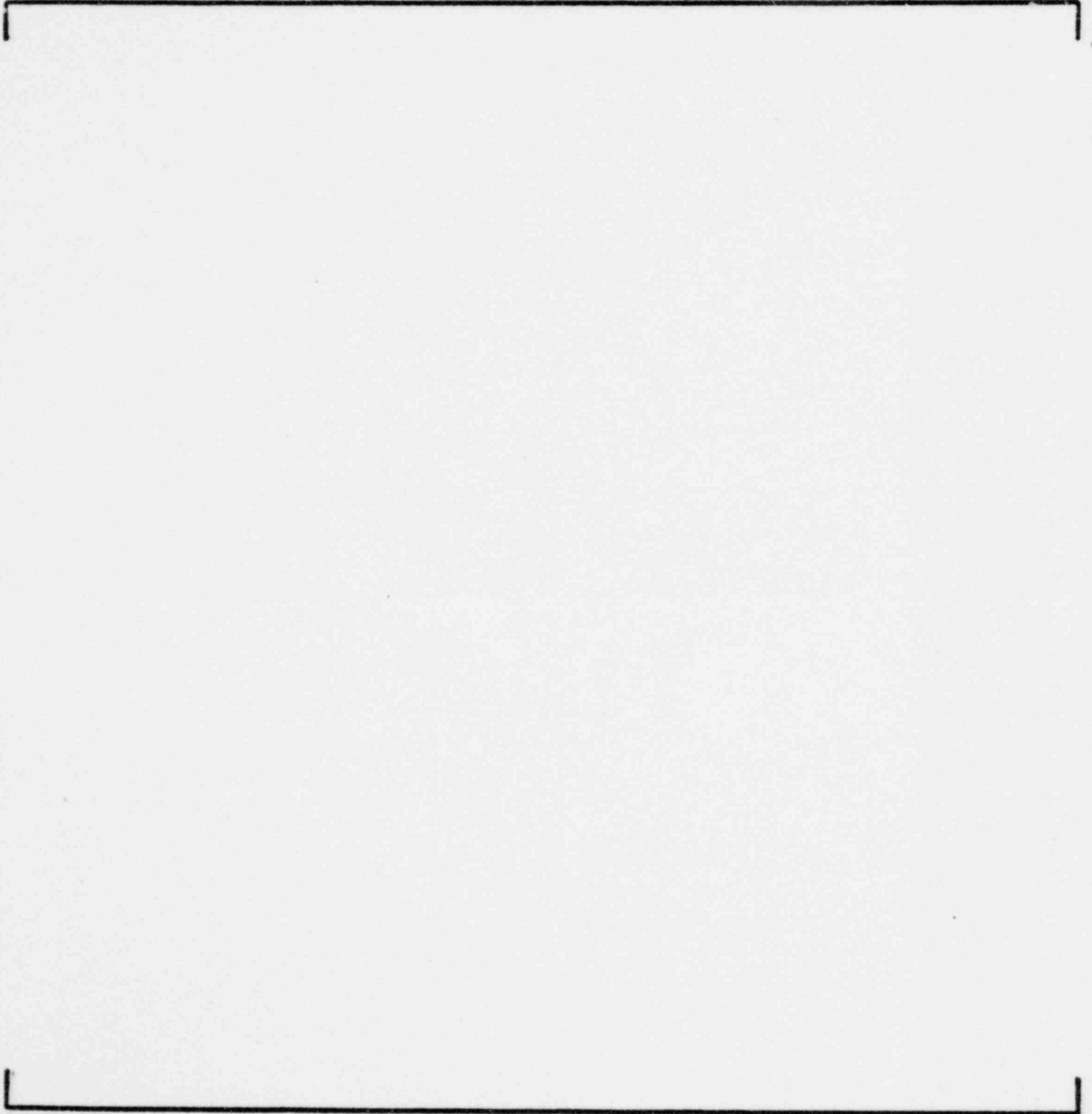500 MWD/T
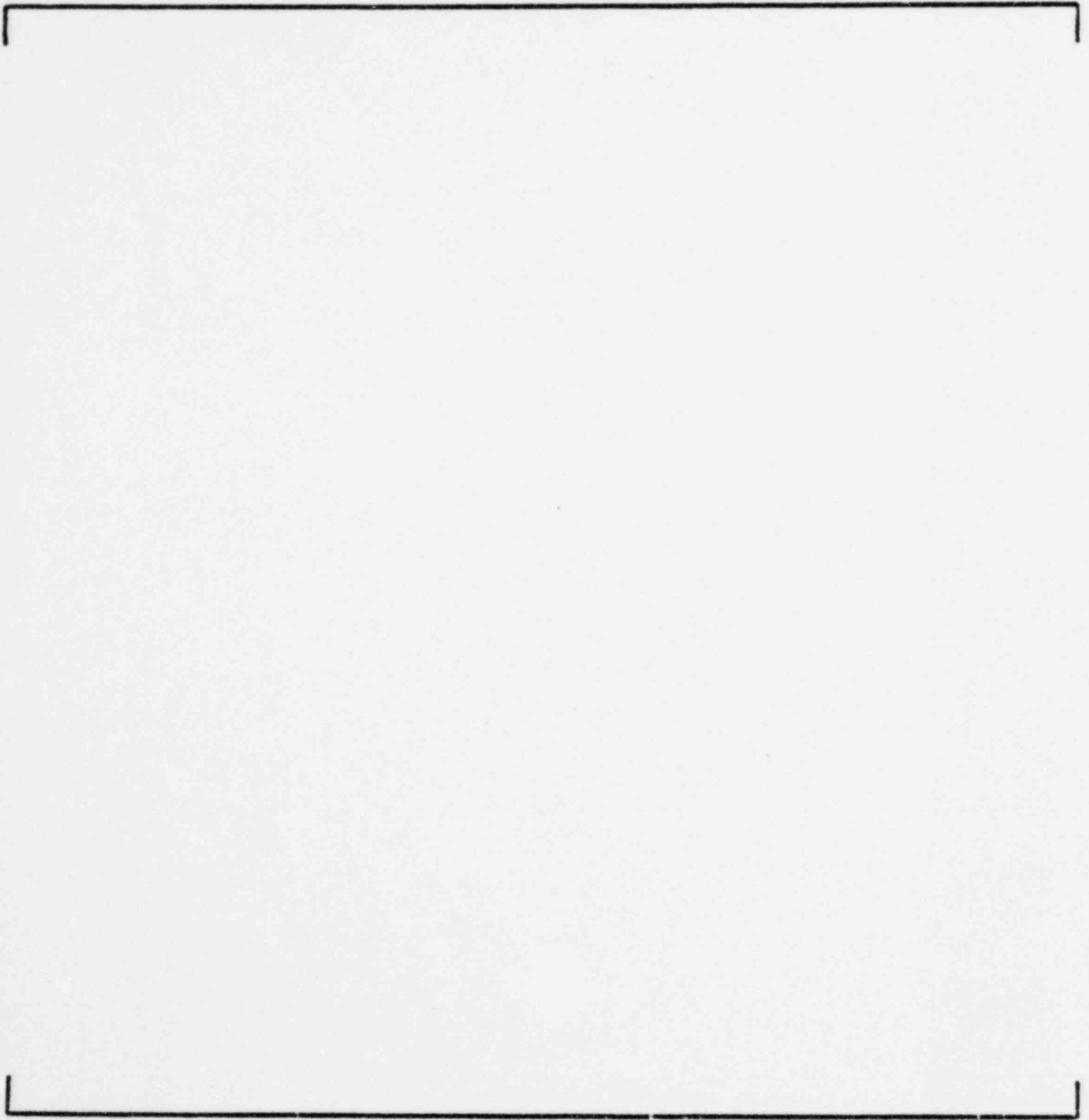
Figure 3-5c
CALVERT CLIFFS UNIT 1 CYCLE 1
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
10,000 MWD/T
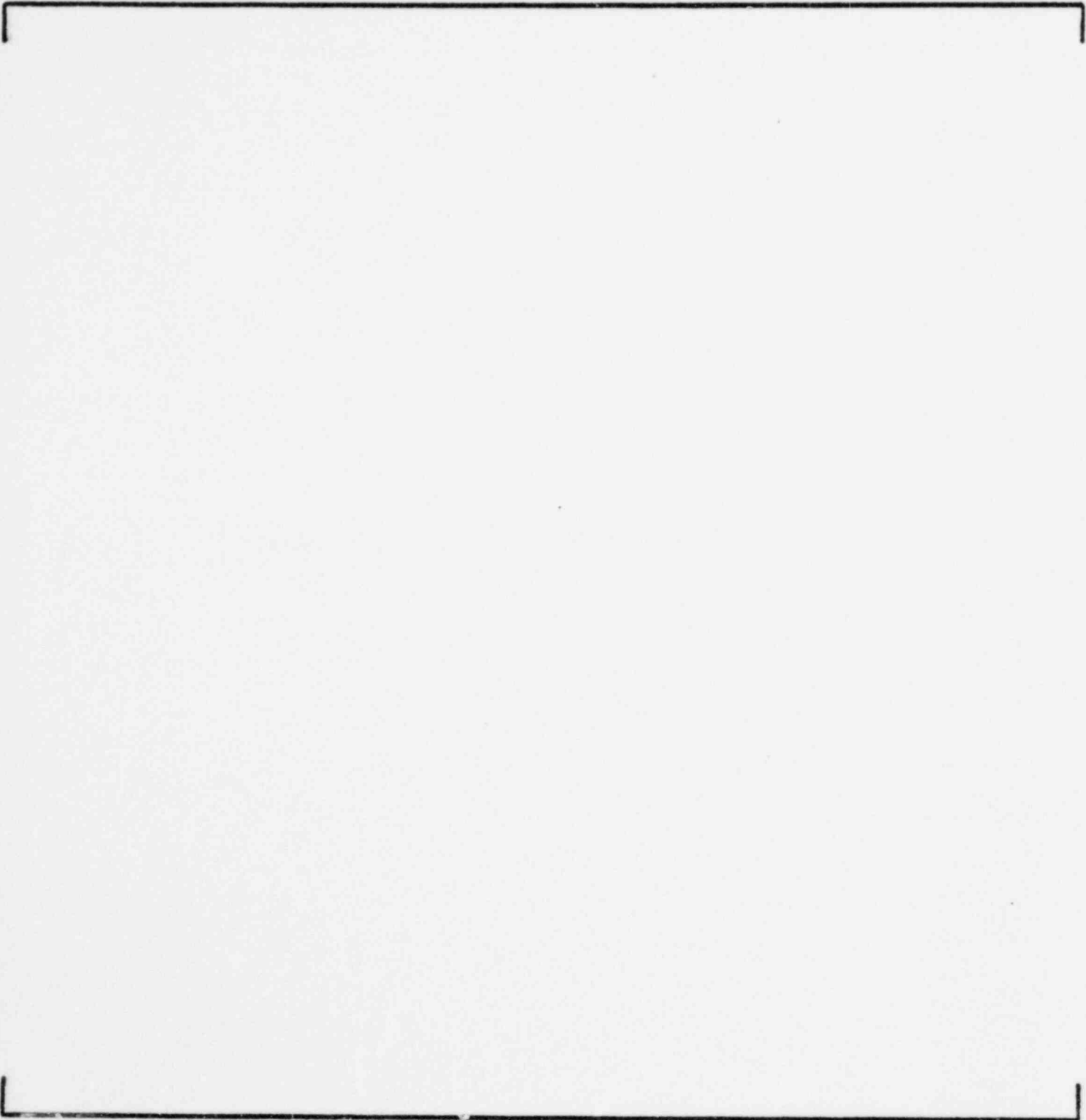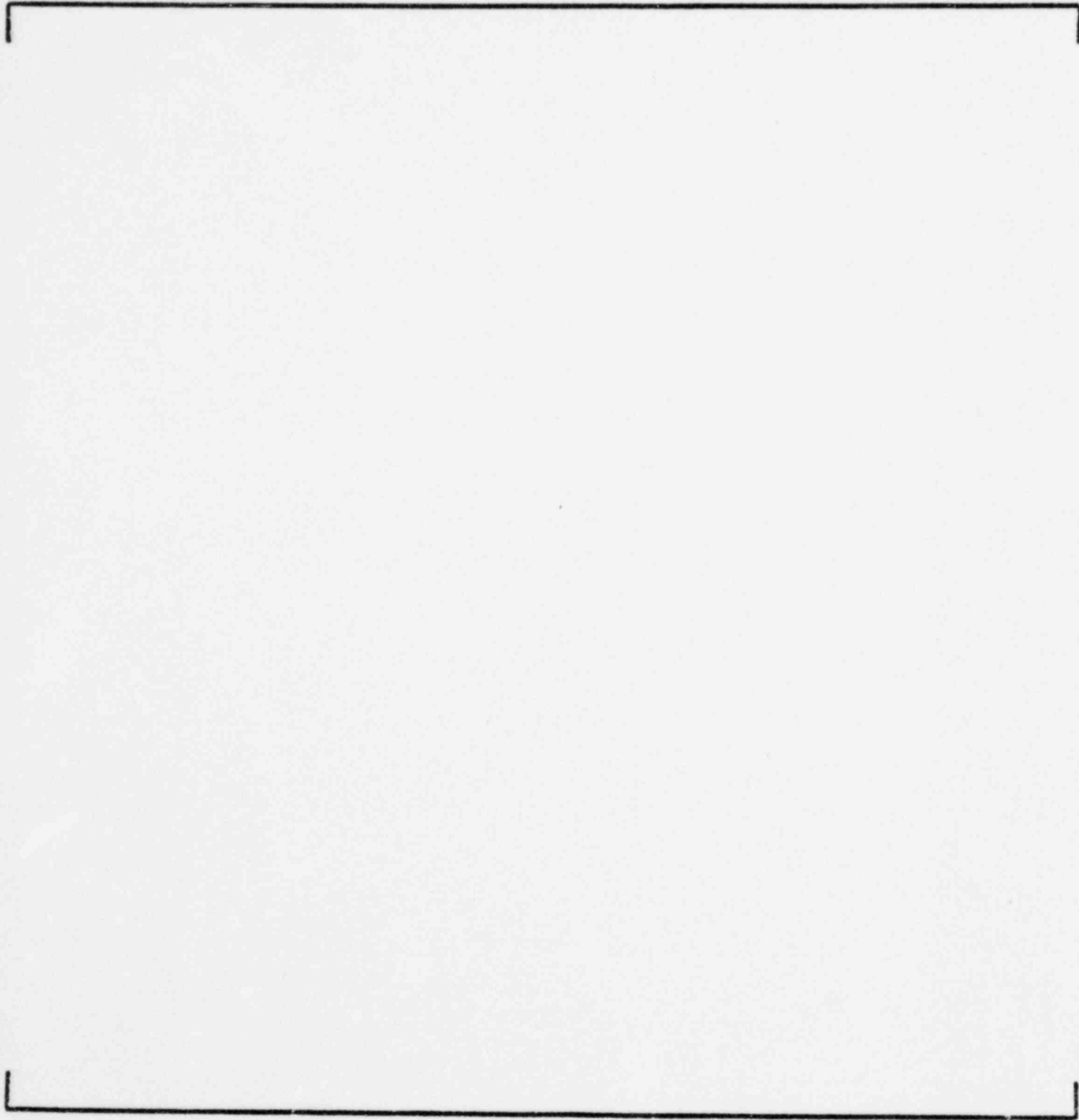
Figure 3-5e
CALVERT CLIFFS UNIT 1 CYCLE 1
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
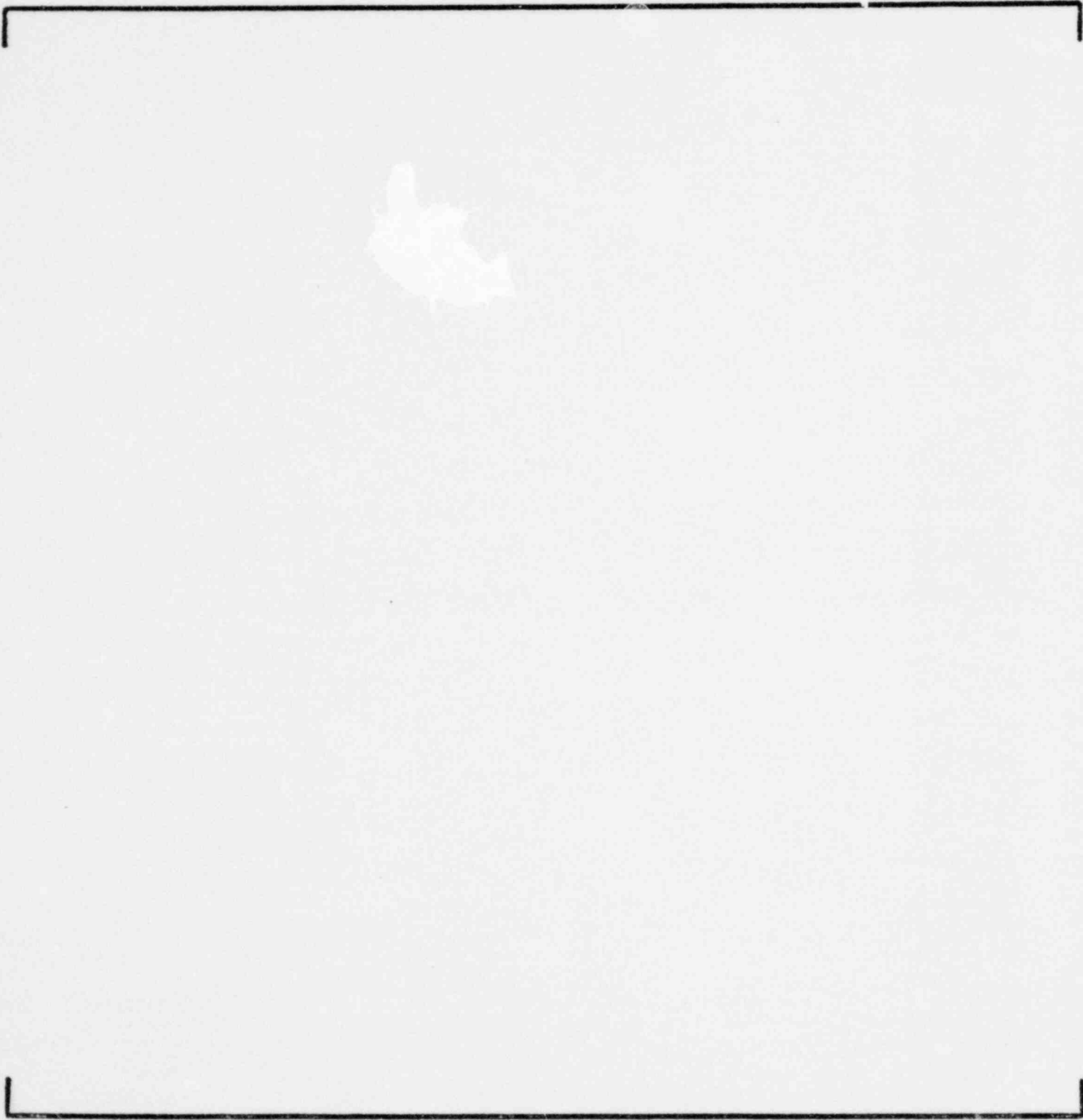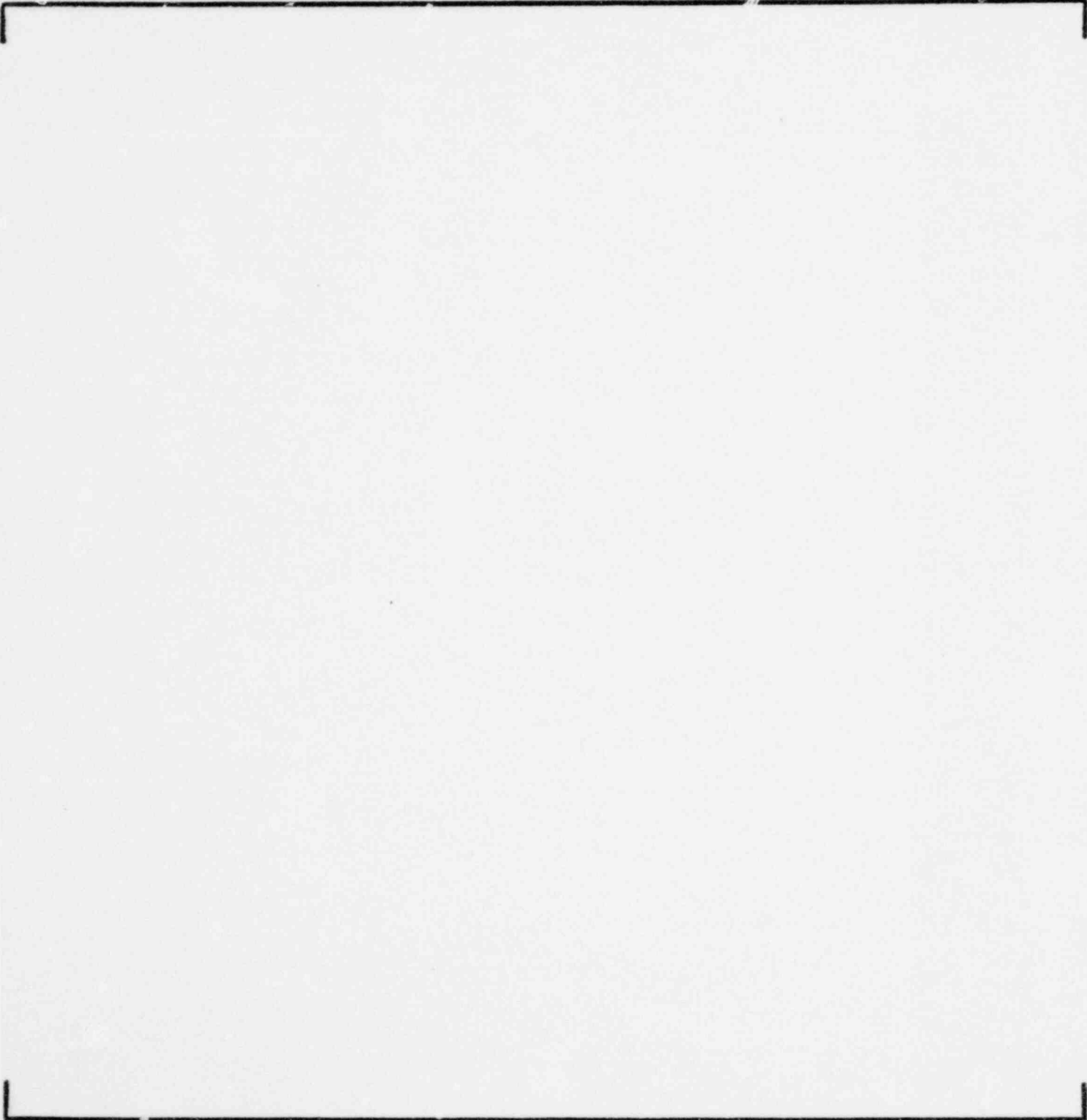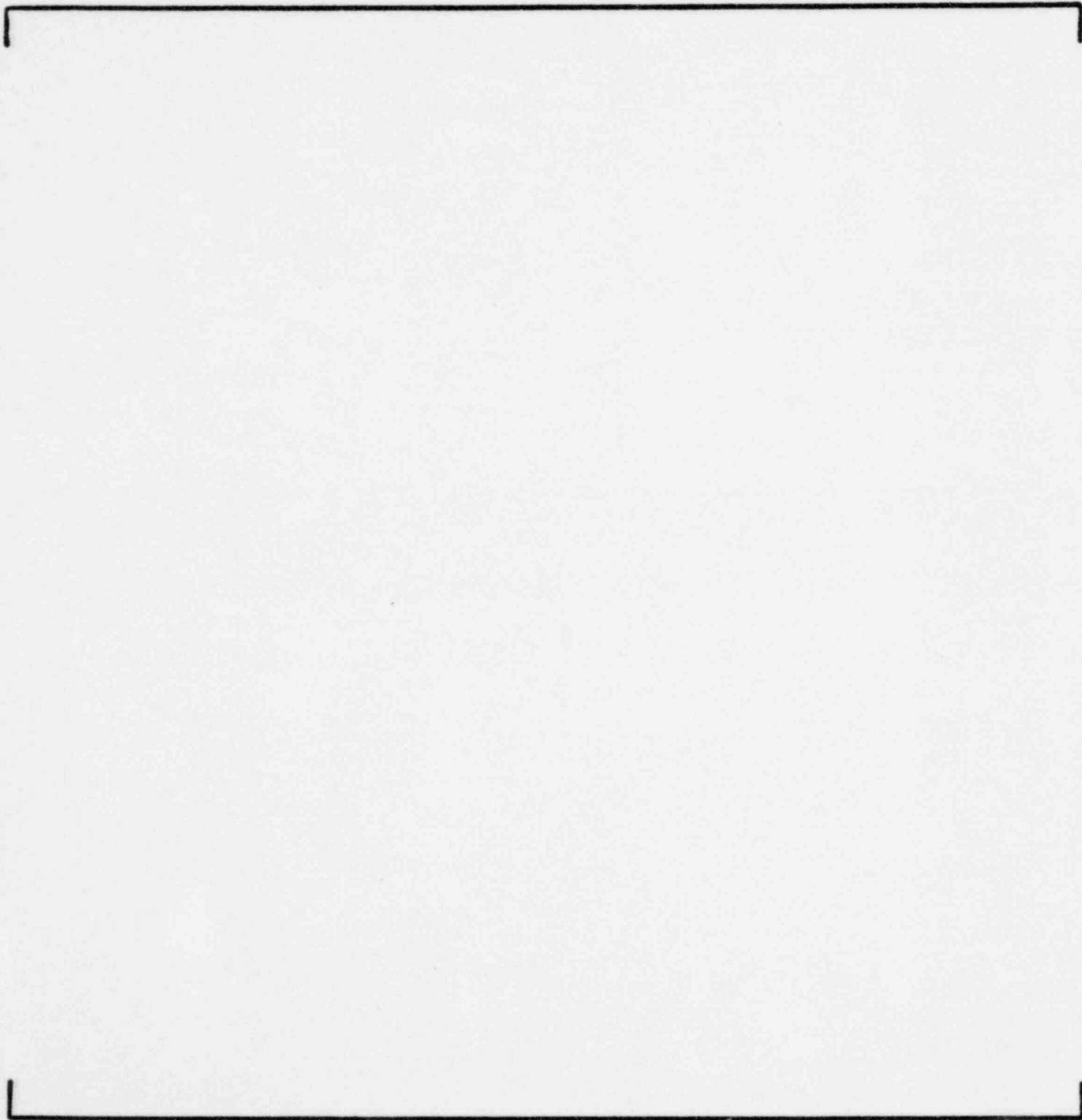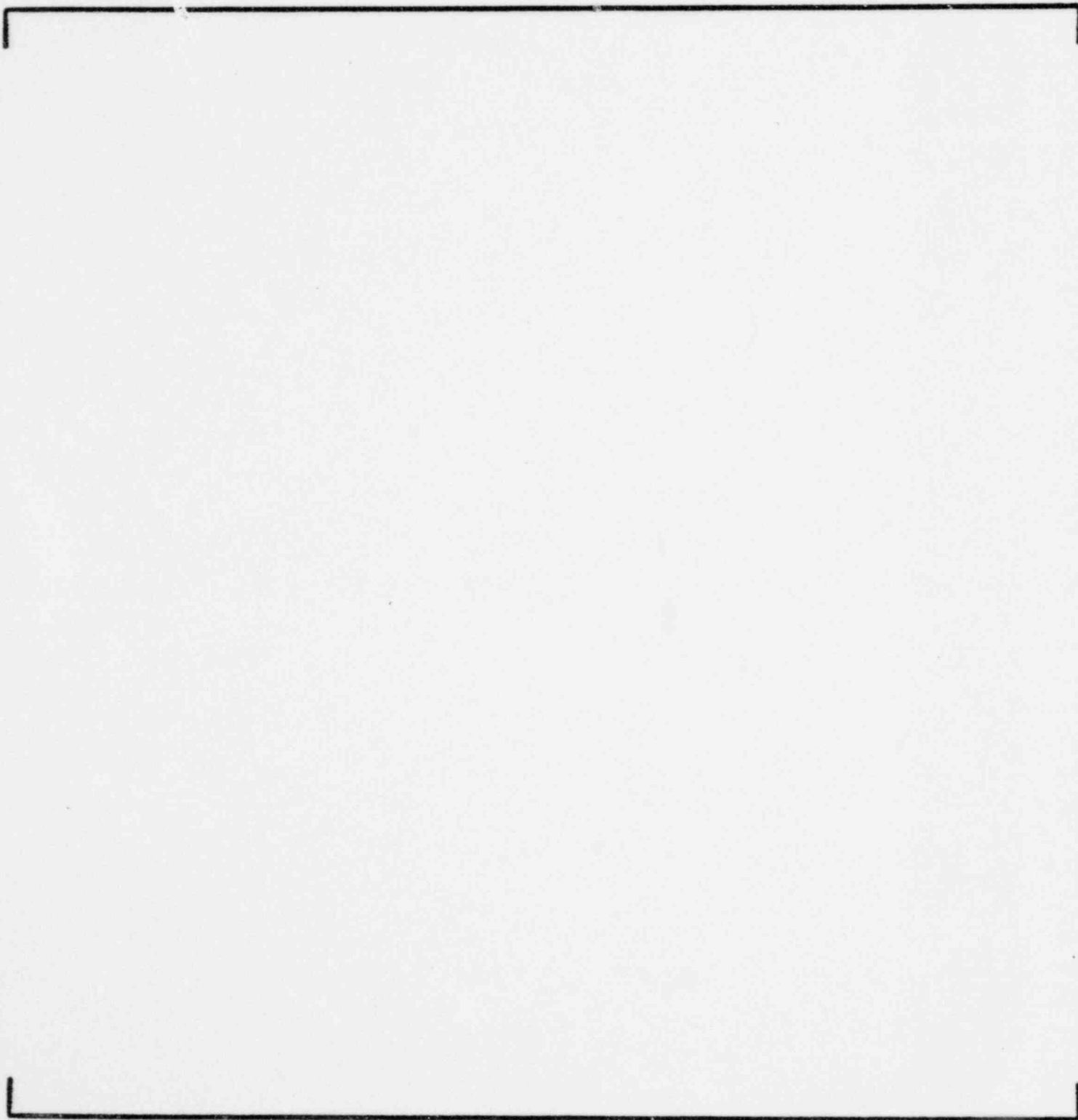16,000 MWD/T (18% ROD BANK 5 INSERTION)
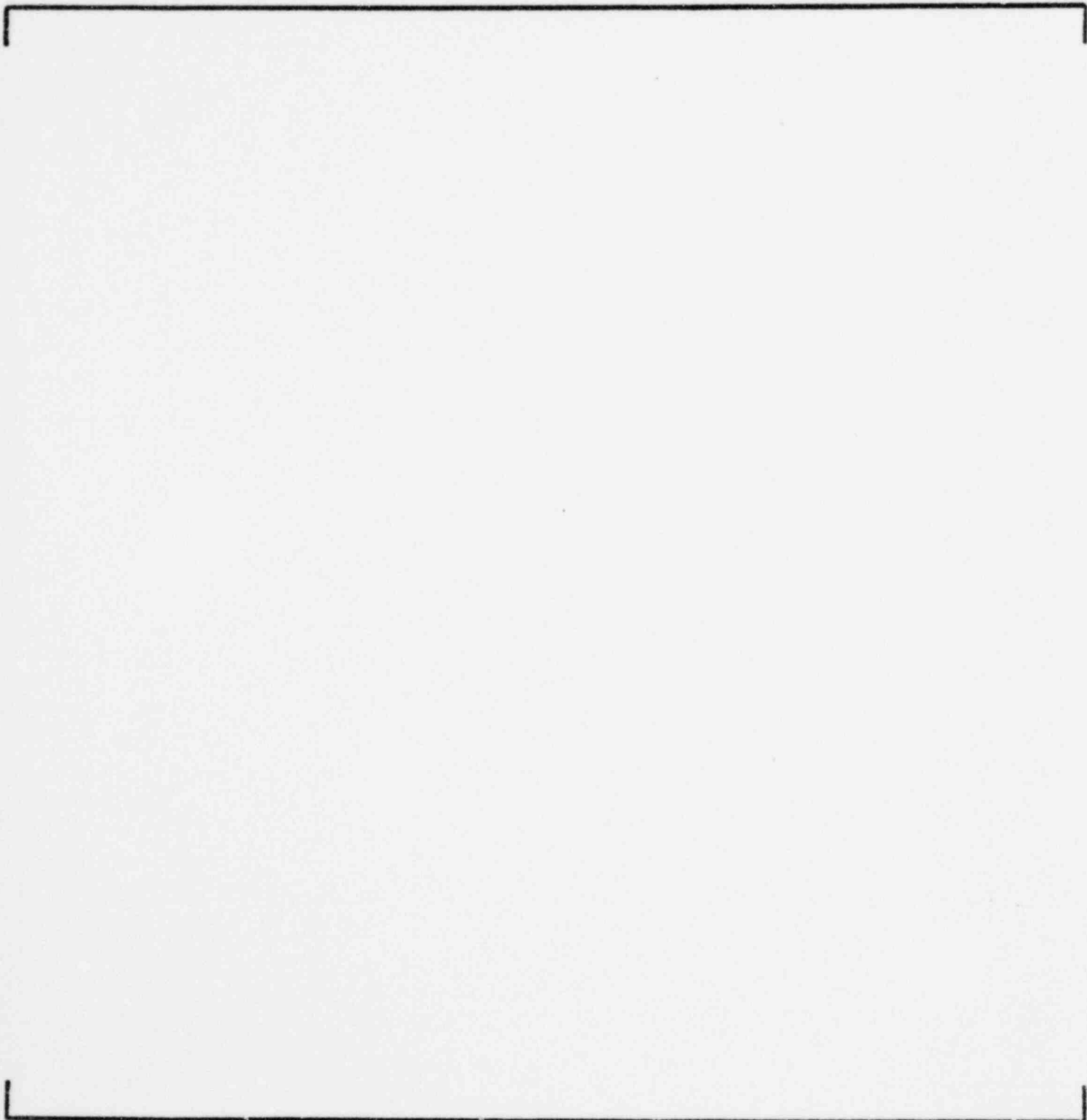
Figure 3-5f
CALVERT CLIFFS UNIT 1 CYCLE 1
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
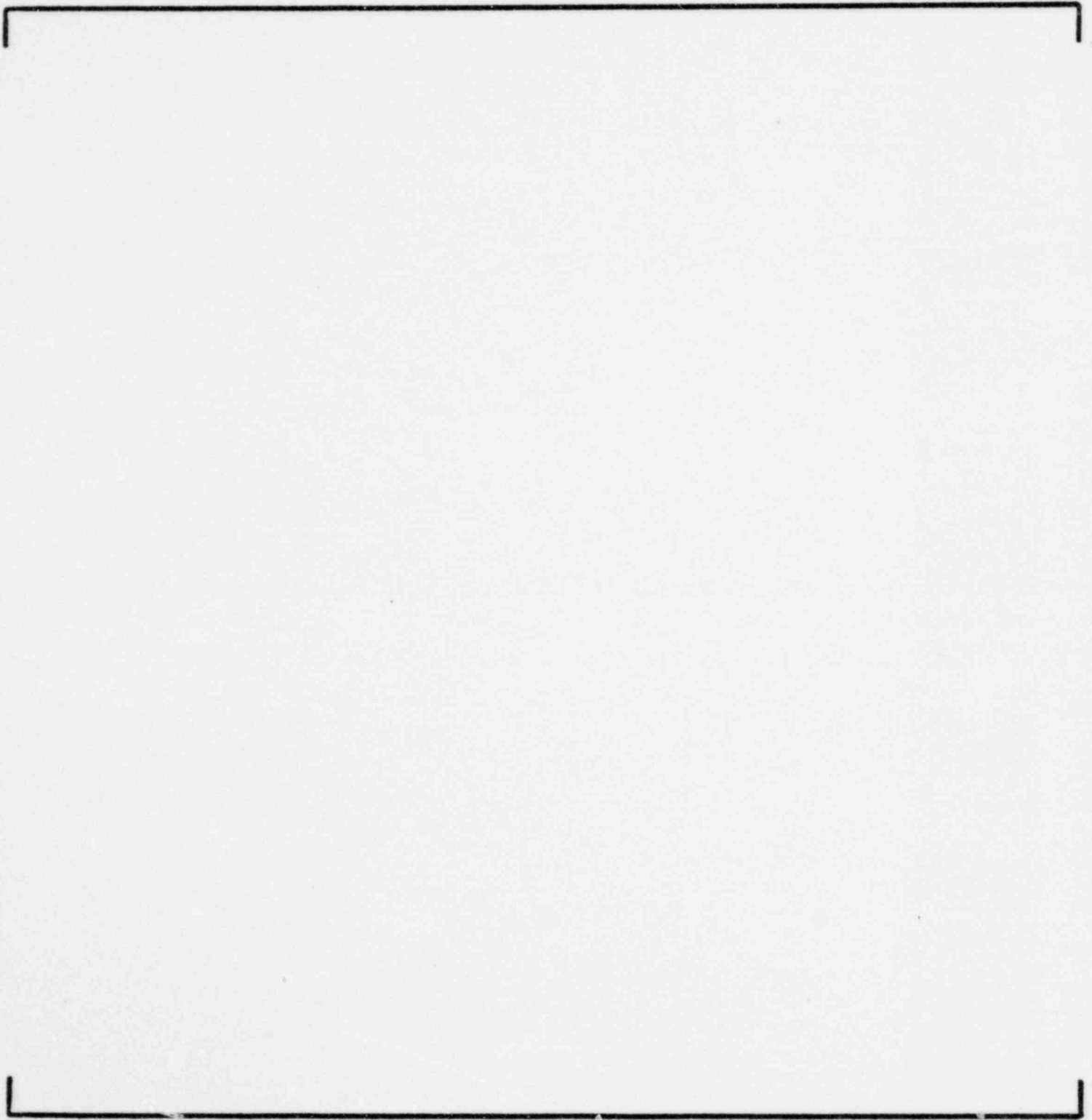16,000 MWD/T (13% ROD BANK 5 INSERTION)

Figure 3-5g
CALVERT CLIFFS UNIT 1 CYCLE 1
COMPARISON OF ROCS AND CECOR PLANAR PEAK TO PLANE AVERAGE BOX POWERS
500 MWD/T

II.3.93

II.3.94

Figure 3-5i
CALVERT CLIFFS UNIT 1 CYCLE 1
COMPARISON OF ROCS AND CECOR PLANAR PEAK TO PLANE AVERAGE BOX POWERS
16,000 MWD/T (18% ROD BANK 5 INSERTION)

II.3.95

Figure 3-5j
CALVERT CLIFFS UNIT 1 CYCLE 1
COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES
500 MWD/T

Figure 3-5k

CALVERT CLIFFS UNIT 1 CYCLE 1

COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES

10,000 MWD/T

Figure 3-51

CALVERT CLIFFS UNIT 1 CYCLE 1

COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES

16,000 MWD/T (18% ROD BANK 5 INSERTION)

II.3.98

Figure 3-5 m
CALVERT CLIFFS UNIT 1 CYCLE 1
COMPARISON OF ROCS (R) AND CECOR (C) ASSEMBLY BURNUP
16000 MWD/T
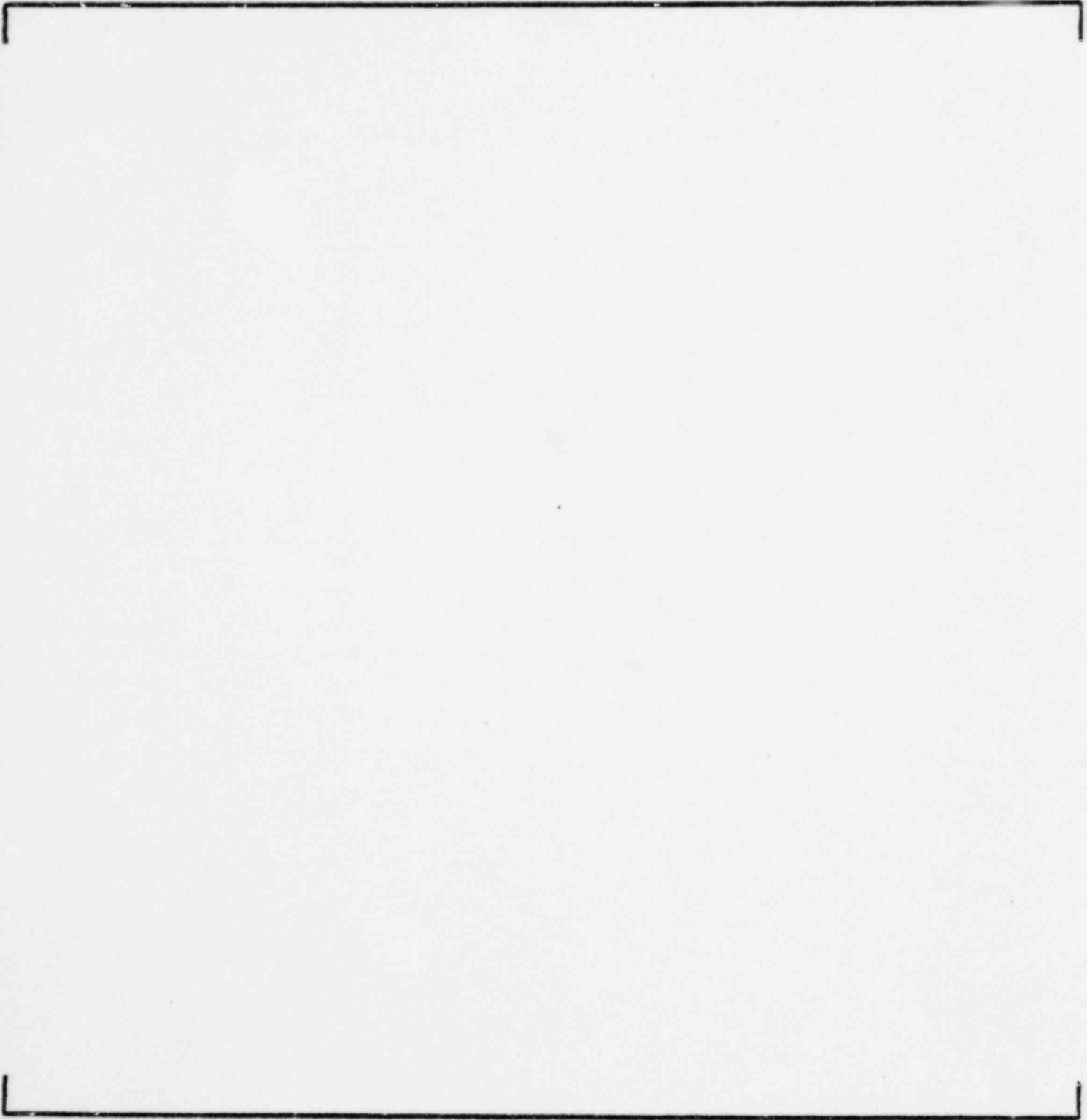
Figure 3-6a
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
325 MWD/T

Figure 3-6b
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
325 MWD/T
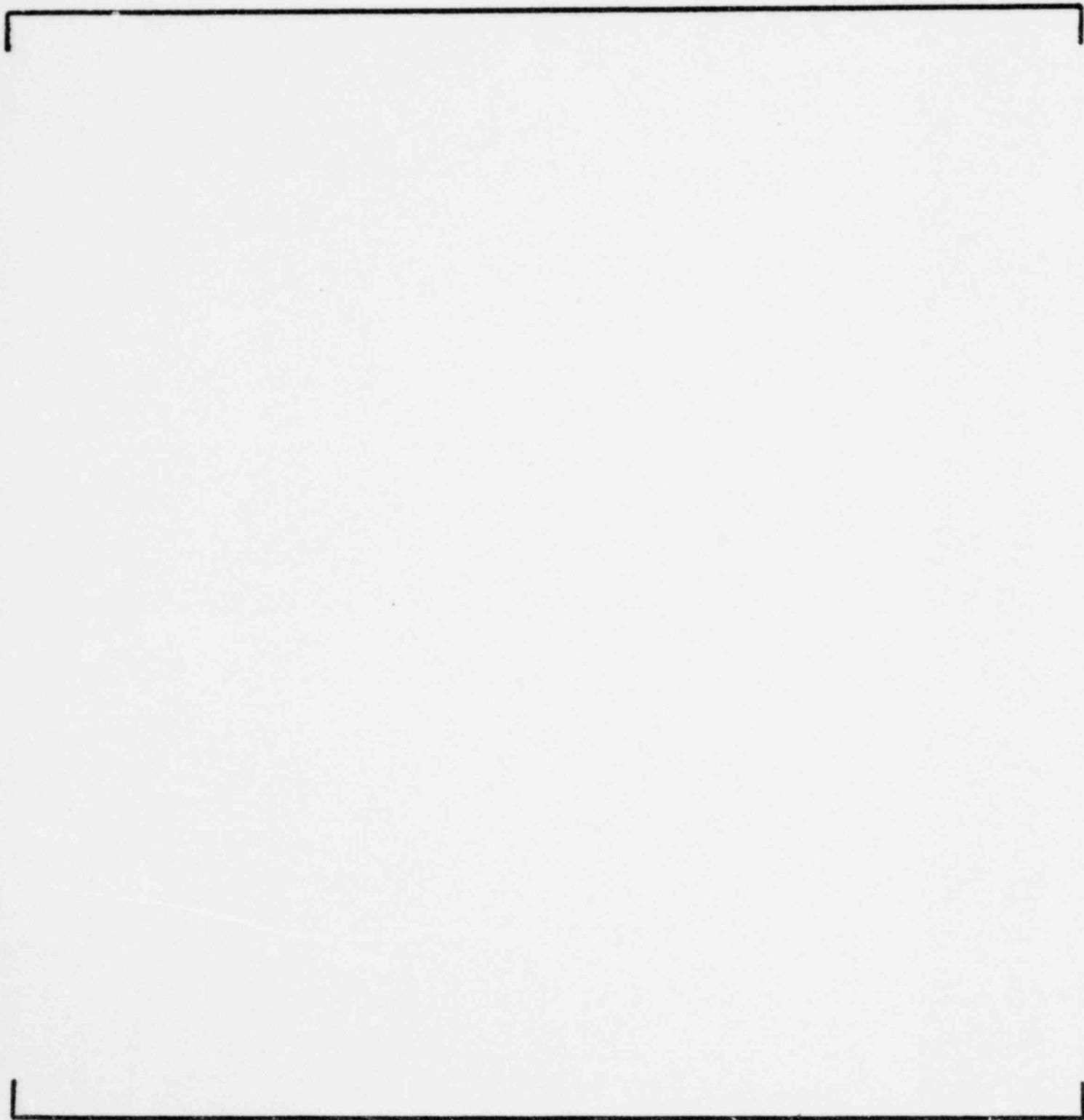
Figure 3-6c
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
4192 MWD/T
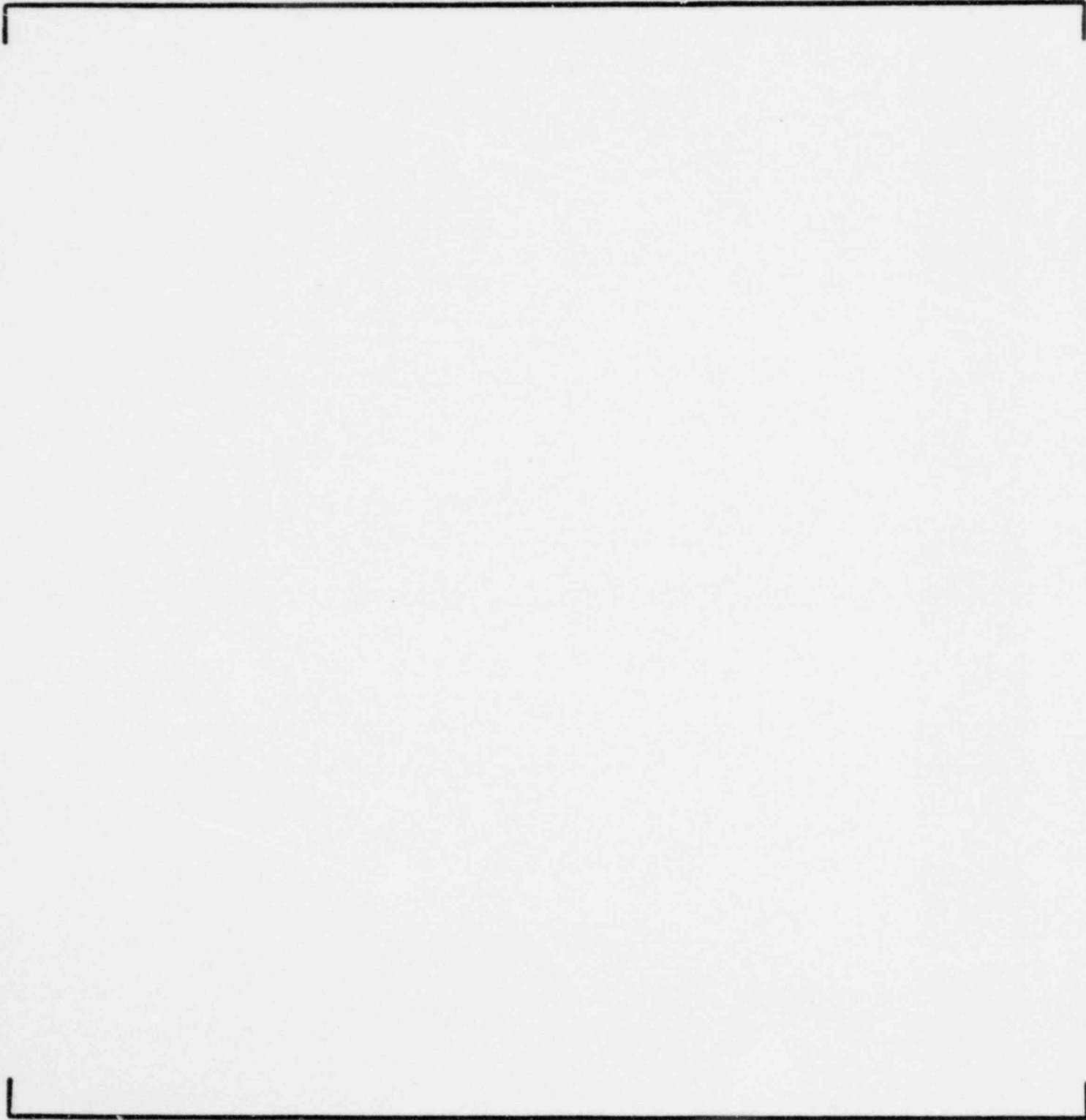
Figure 3-6d
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
4192 MWD/T
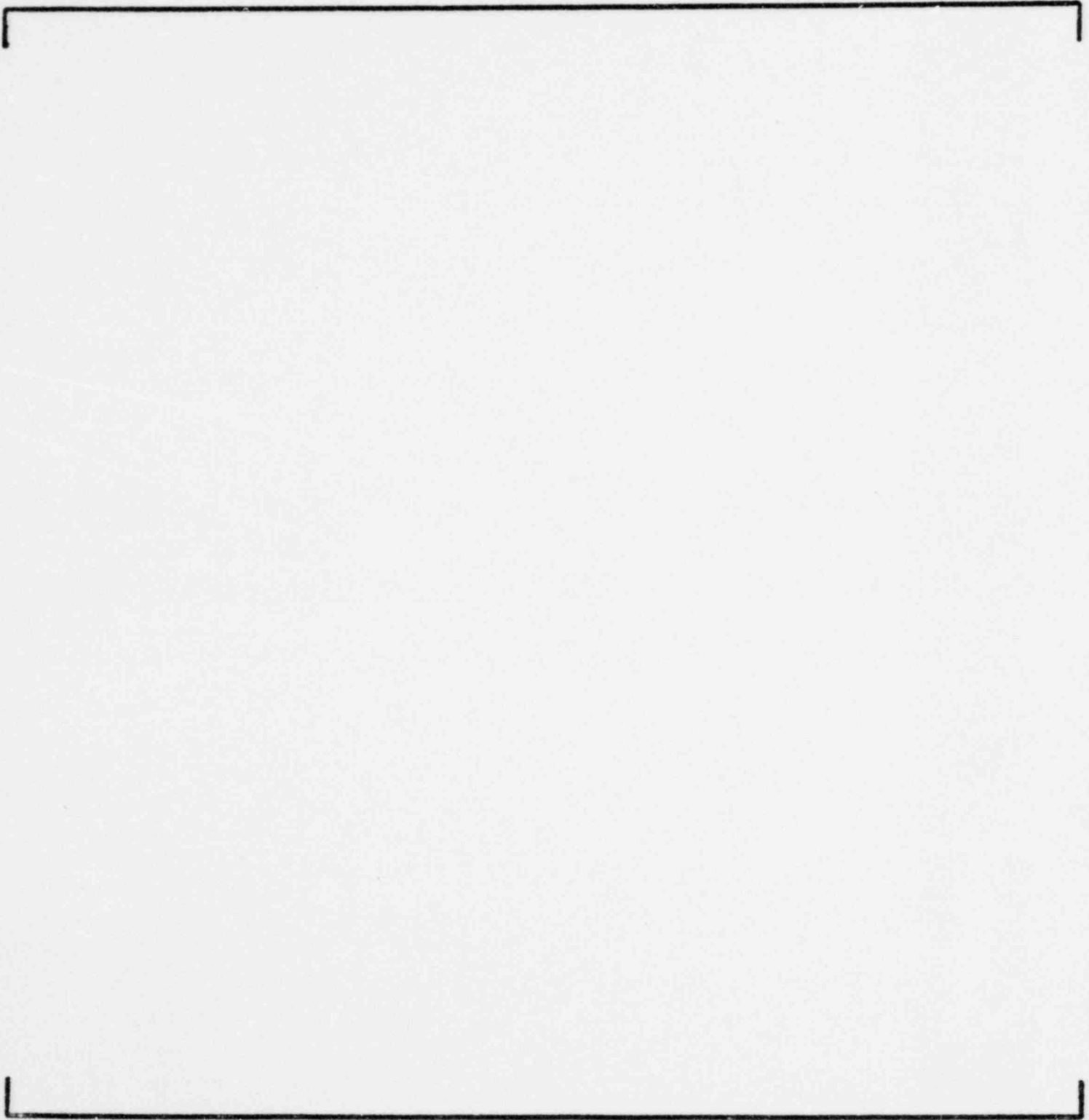
Figure 3-6e
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
8330 MWD/T

Figure 3-6f
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
8330 MWD/T
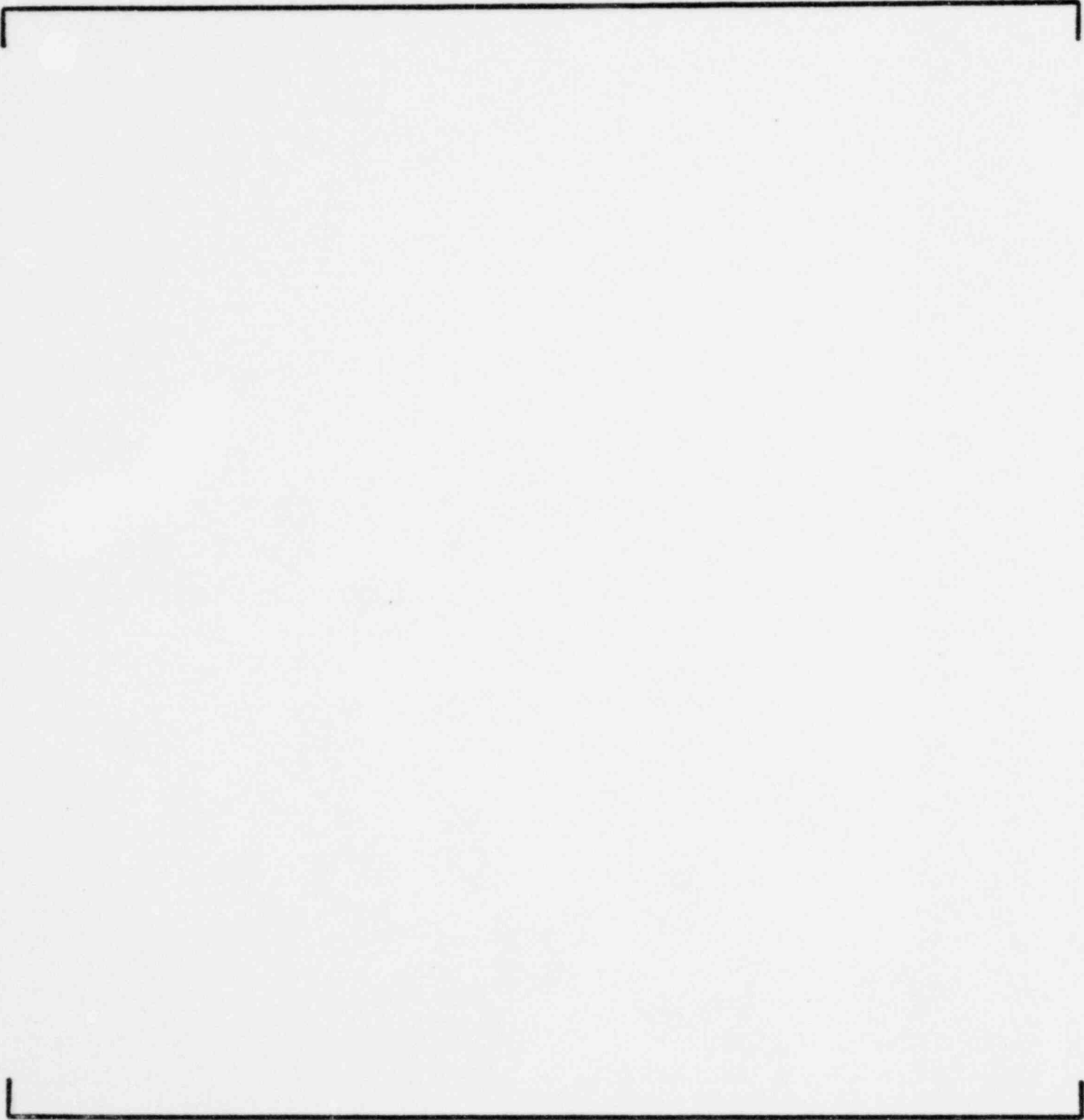
Figure 3-6g
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS AND CECOR PLANAR PEAK TO PLANE AVERAGE BOX POWERS
325 MWD/T

Figure 3-6i
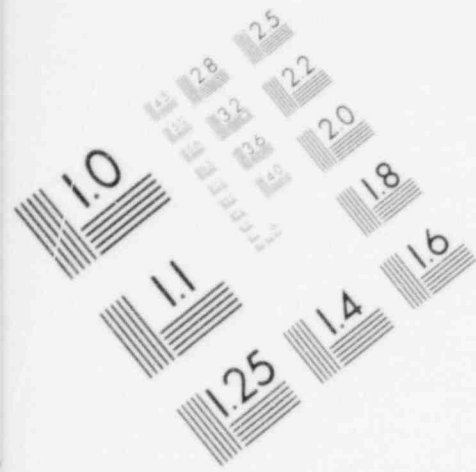CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS AND CECOR PLANAR PEAK TO PLANE AVERAGE BOX POWERS
8330 MWD/T

II.3.108

Figure 3-6j
CALVERT CLIFFS UNIT 1 CYCLE 2
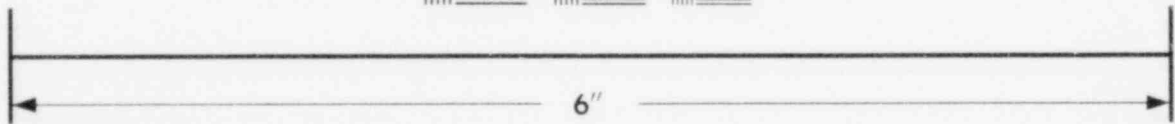COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES
325 MWD/T

Figure 3-6k
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES
4192 MWD/T

Figure 3-6l
CALVERT CLIFFS UNIT 1 CYCLE 2
COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES
8330 MWD/T

Figure 3-7a
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
495 MWD/T

Figure 3-7b
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
495 MWD/T

Figure 3-7c
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
801 MWD/T (50% ROD BANK 5 INSERTION)

Figure 3-7d
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
801 MWD/T (50% ROD BANK 5 INSERTION)
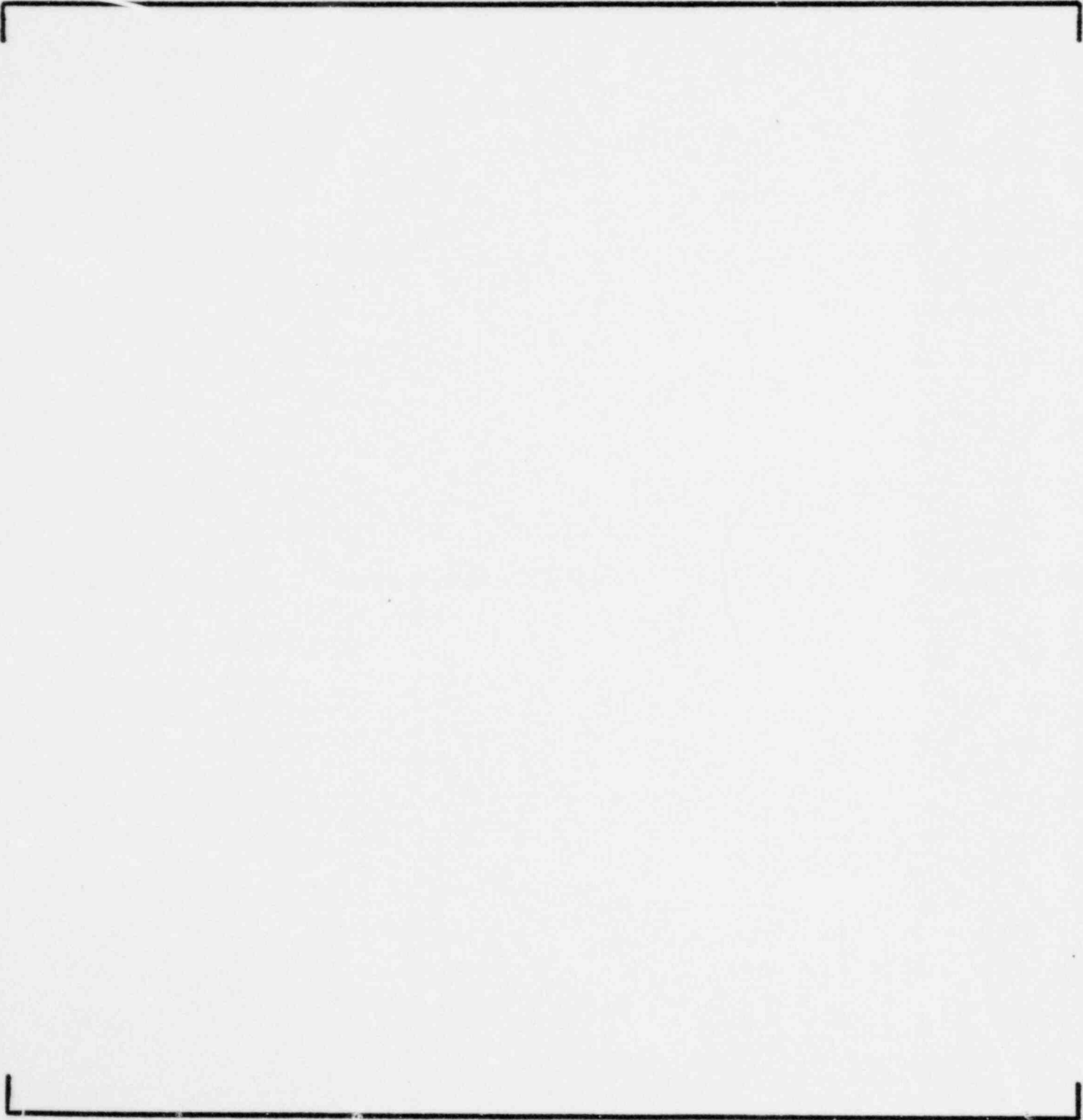
Figure 3-7e
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
5994 MWD/T

Figure 3-7f
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
5994 MWD/T

Figure 3-7g
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS (R) AND CECOR (C) BOX POWER FRACTIONS
8578 MWD/T

Figure 3-7h
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS (R) AND CECOR (C) BOX PEAK TO CORE AVERAGE POWER
8578 MWD/T

Figure 3-71

CALVERT CLIFFS UNIT 1 CYCLE 3

COMPARISON OF ROCS AND CECOR PLANAR PEAK TO PLANE AVERAGE BOX POWERS

495 MWD/T

Figure 3-7j
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARSION OF ROCS AND CECOR PLANAR PEAK TO PLANE AVERAGE BOX POWERS
801 MWD/T (50% ROD BANK 5 INSERTION)

II.3.122

Figure 3-71
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS AND CECOR PLANAR PEAK TO PLANE AVERAGE BOX POWERS
8578 MWD/T
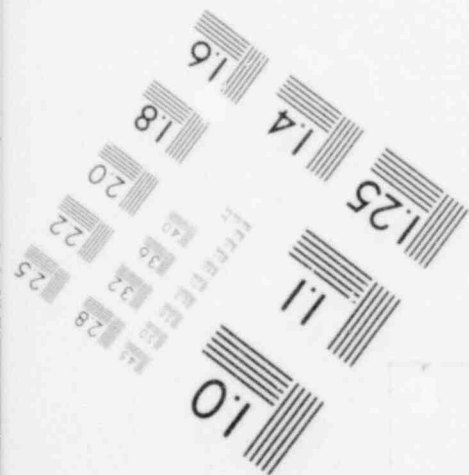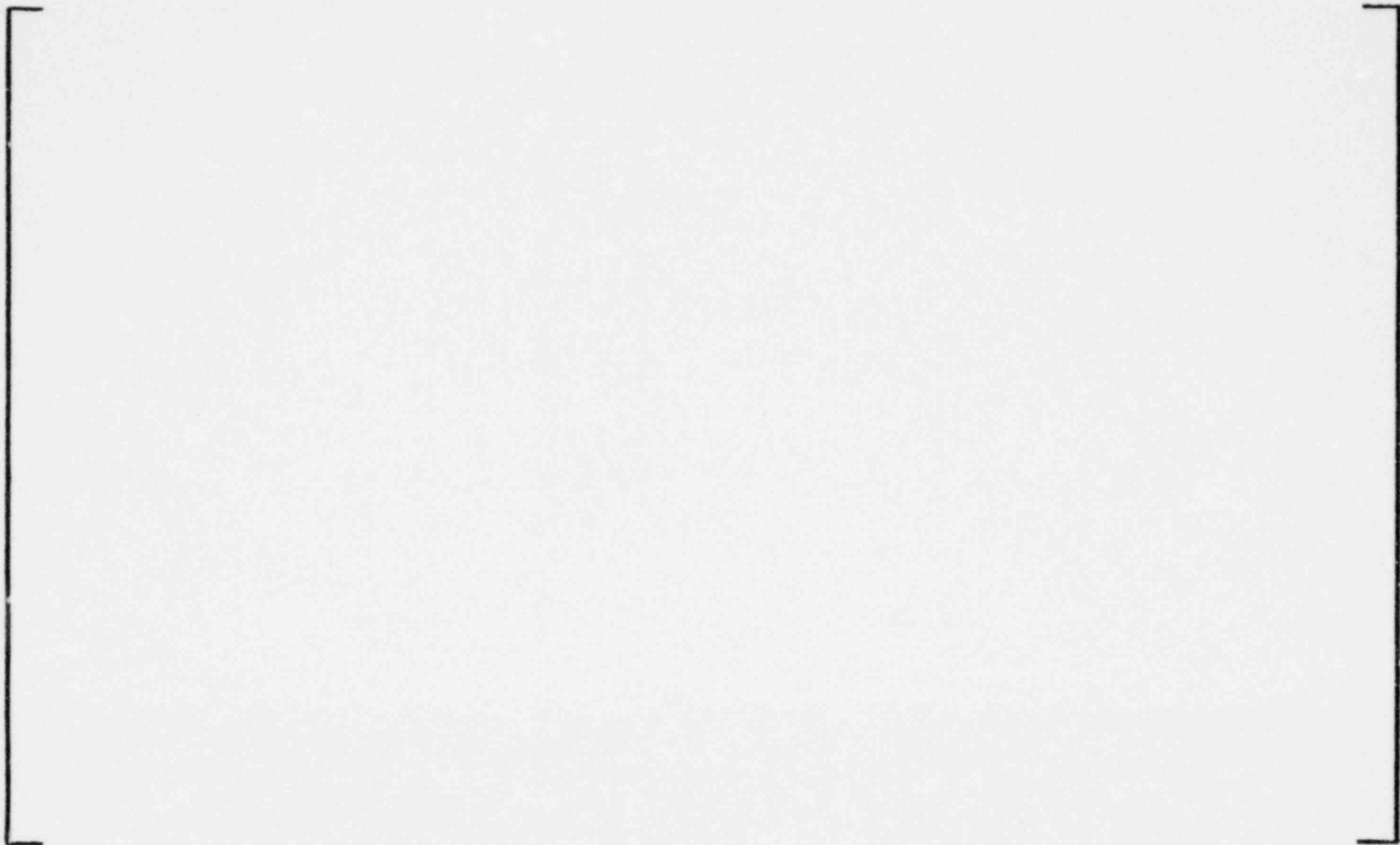
Figure 3-7m
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES
495 MWD/T

Figure 3-7n
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES
801 MWD/T (50% ROD BANK 5 INSERTION)
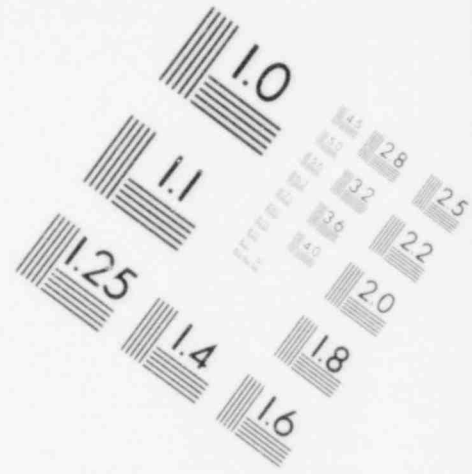
IMAGE EVALUATION
TEST TARGET (MT-3)
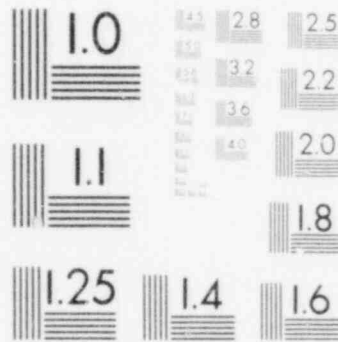
MICROCOPY RESOLUTION TEST CHART
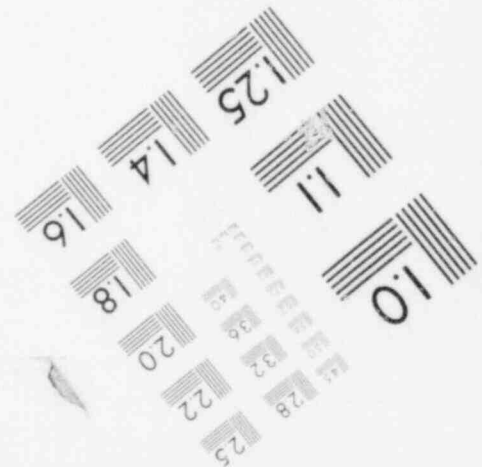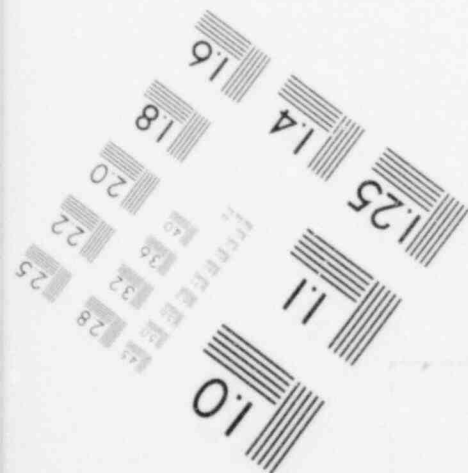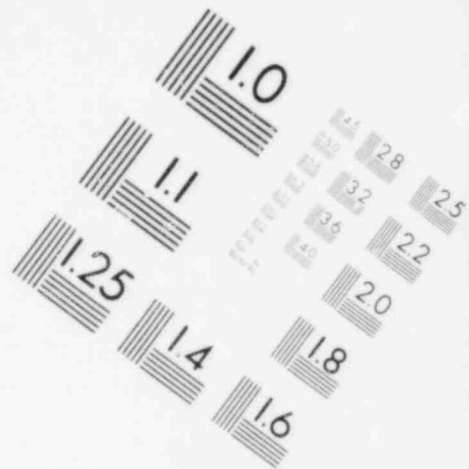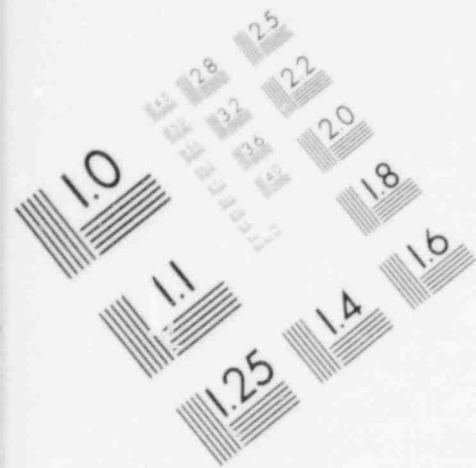
IMAGE EVALUATION
TEST TARGET (MT-3)
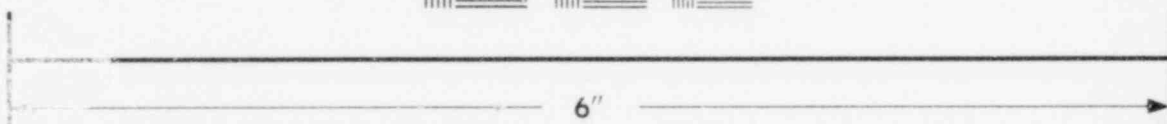
MICROCOPY RESOLUTION TEST CHART
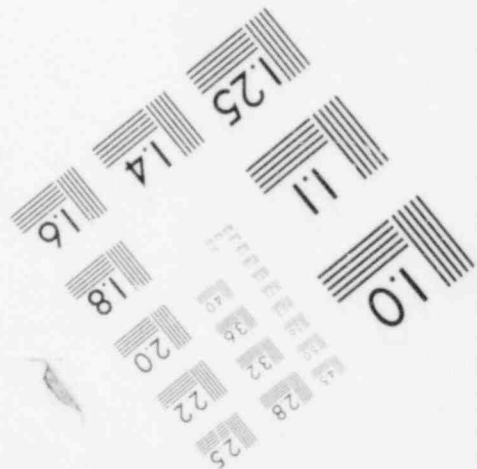
Figure 3-7o
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES
5994 MWD/T

Figure 3-7p
CALVERT CLIFFS UNIT 1 CYCLE 3
COMPARISON OF ROCS AND CECOR CORE AVERAGE AXIAL SHAPES
8578 MWD/T

II.3.128
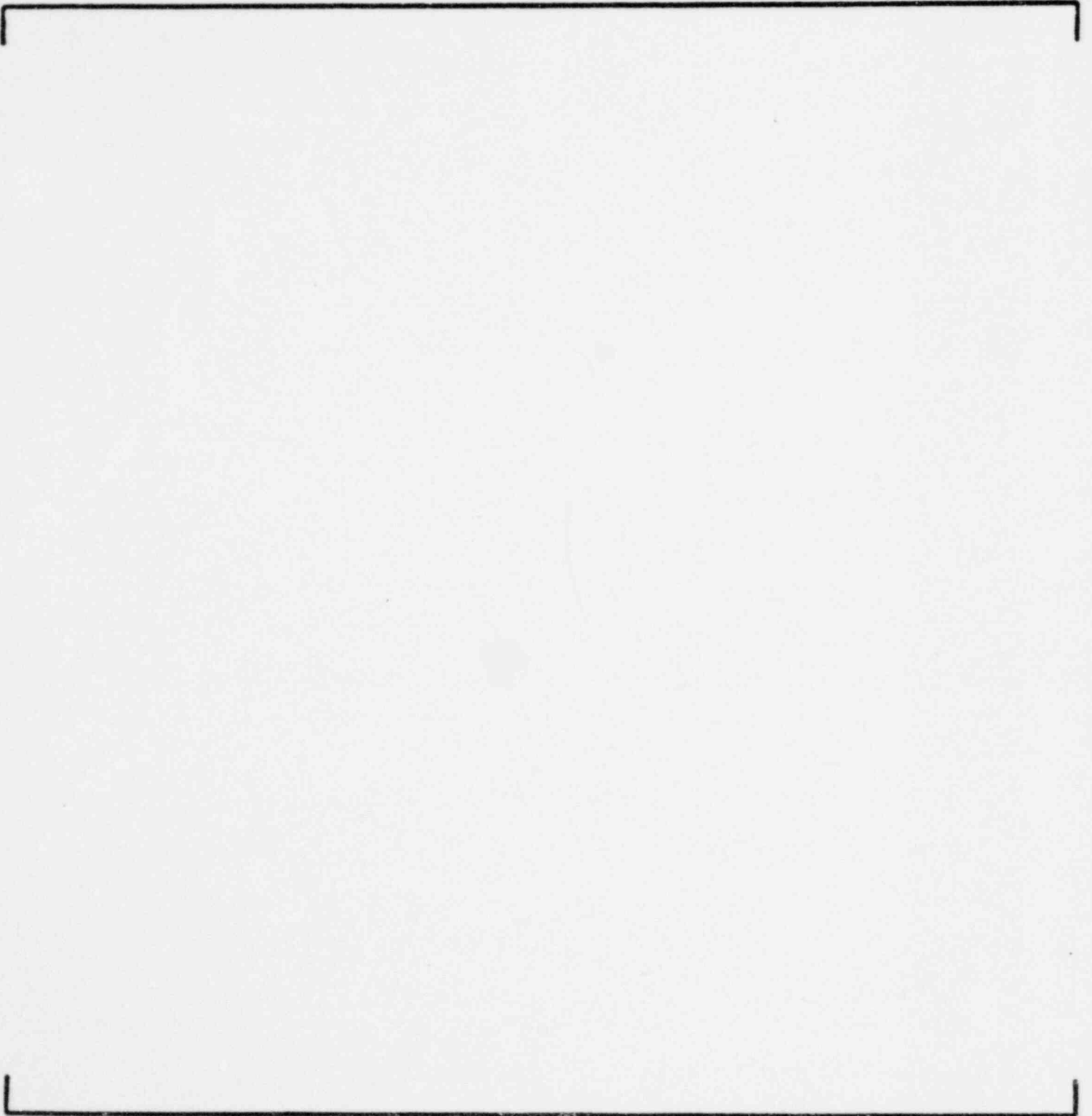
Figure 3-8
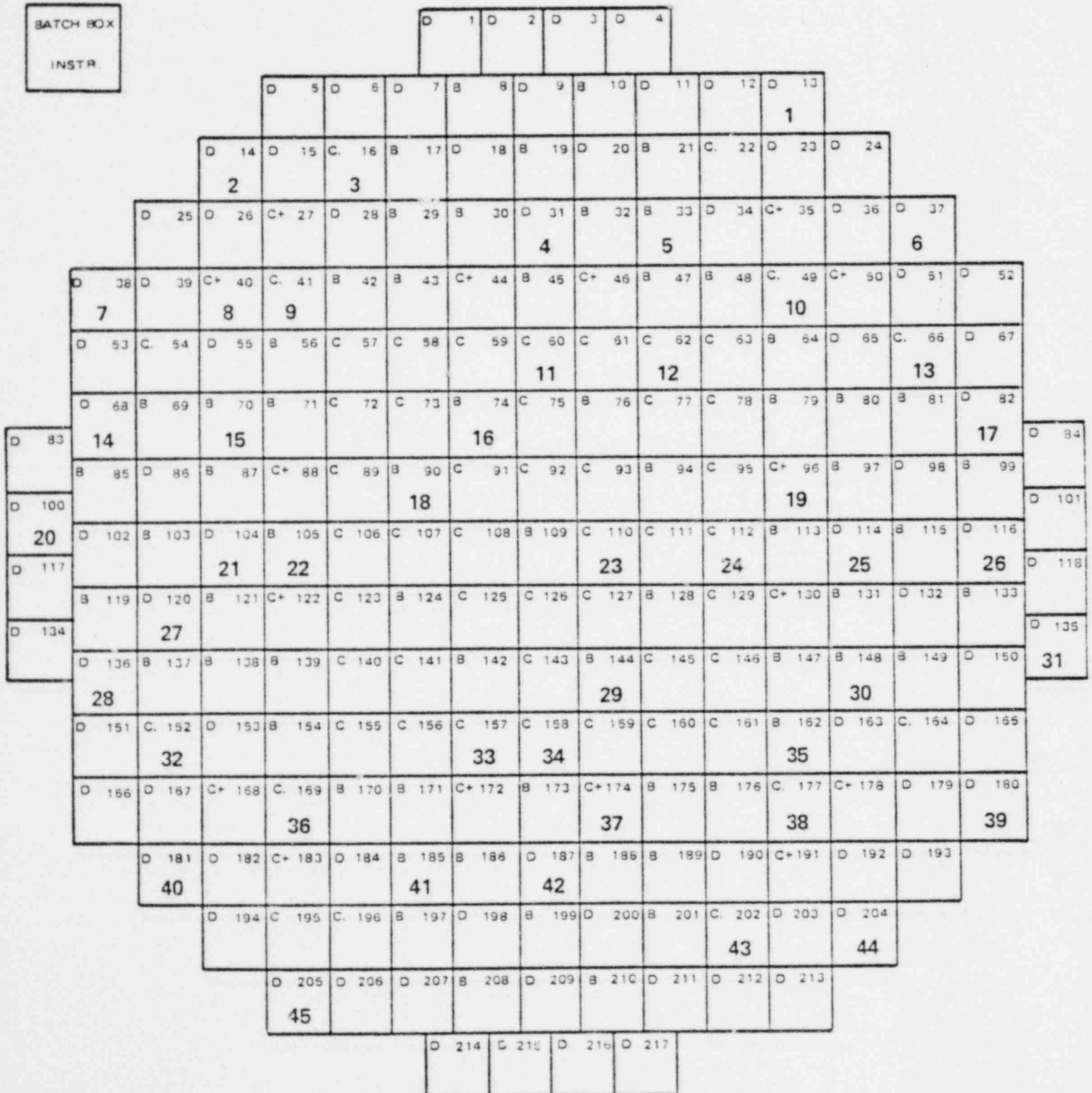DISTRIBUTION OF DEVIATIONS IN Fq BOX SYNTHESIS
CALVERT CLIFFS UNIT 1 CYCLE 2

Figure 3-9
DISTRIBUTION OF DEVIATIONS IN Fr BOX SYNTHESIS
CALVERT CLIFFS UNIT 1 CYCLE 2

II.3.131

Figure 3-10
DISTRIBUTION OF DEVIATIONS IN Fxy BOX SYNTHESIS
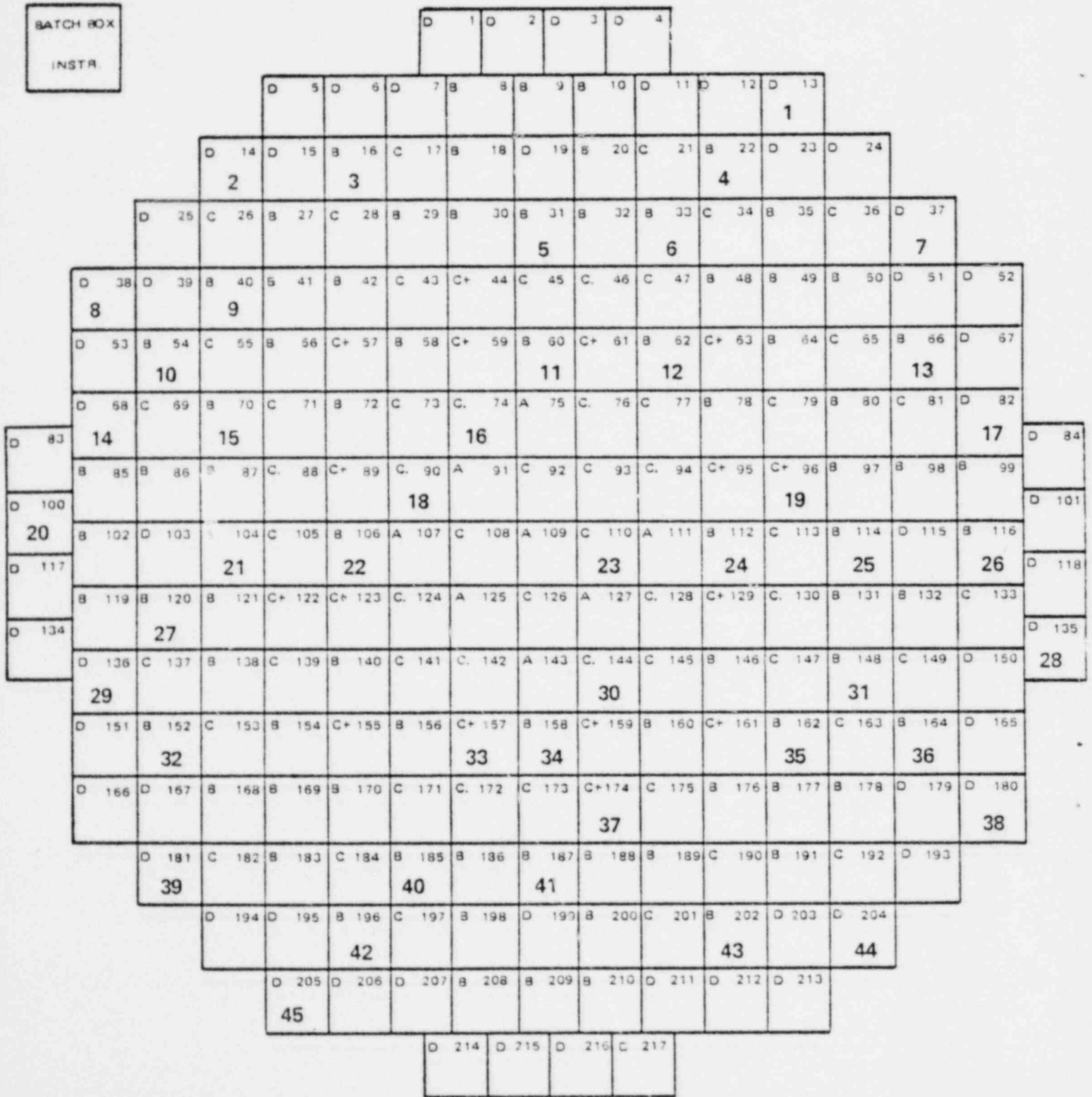CALVERT CLIFFS UNIT 1 CYCLE 2

II.3.132

BATCH BOX

INSTR.

Figure 3-12
LOADING & INSTRUMENT PATTERN
ST. LUCIE CYCLE 2

BATCH BOX

INSTR.

| D 1 | D 2 | D 3 | D 4 |

| D 5 | D 6 | D 7 | B 8 | B 9 | B 10 | D 11 | D 12 | D 13 |
1

| D 14 | D 15 | B 16 | C 17 | B 18 | D 19 | B 20 | C 21 | B 22 | D 23 | D 24 |
2   3   4

| D 25 | C 26 | B 27 | C 28 | B 29 | B 30 | B 31 | B 32 | B 33 | C 34 | B 35 | C 36 | D 37 |
5   6   7

| D 38 | D 39 | B 40 | B 41 | B 42 | C 43 | C+ 44 | C 45 | C. 46 | C 47 | B 48 | B 49 | B 50 | D 51 | D 52 |
8   9

| D 53 | B 54 | C 55 | B 56 | C+ 57 | B 58 | C+ 59 | B 60 | C+ 61 | B 62 | C+ 63 | B 64 | C 65 | B 66 | D 67 |
10   11   12   13

| D 68 | C 69 | B 70 | C 71 | B 72 | C 73 | C. 74 | A 75 | C. 76 | C 77 | B 78 | C 79 | B 80 | C 81 | D 82 |
14   15   16   17

| D 83 | B 85 | B 86 | B 87 | C. 88 | C+ 89 | C. 90 | A 91 | C 92 | C 93 | C. 94 | C+ 95 | C+ 96 | B 97 | B 98 | B 99 | D 84 |
18   19

| D 100 | B 102 | D 103 | 104 | C 105 | B 106 | A 107 | C 108 | A 109 | C 110 | A 111 | B 112 | C 113 | B 114 | D 115 | B 116 | D 101 |
20   21   22   23   24   25   26

| D 117 | B 119 | B 120 | B 121 | C+ 122 | C+ 123 | C. 124 | A 125 | C 126 | A 127 | C. 128 | C+ 129 | C. 130 | B 131 | B 132 | C 133 | D 118 |
27

| D 134 | D 136 | C 137 | B 138 | C 139 | B 140 | C 141 | C. 142 | A 143 | C. 144 | C 145 | B 146 | C 147 | B 148 | C 149 | D 150 | D 135 |
29   30   31   28

| D 151 | B 152 | C 153 | B 154 | C+ 155 | B 156 | C+ 157 | B 158 | C+ 159 | B 160 | C+ 161 | B 162 | C 163 | B 164 | D 165 |
32   33   34   35   36

| D 166 | D 167 | B 168 | B 169 | B 170 | C 171 | C. 172 | C 173 | C+ 174 | C 175 | B 176 | B 177 | B 178 | D 179 | D 180 |
37   38

| D 181 | C 182 | B 183 | C 184 | B 185 | B 186 | B 187 | B 188 | B 189 | C 190 | B 191 | C 192 | D 193 |
39   40   41

| D 194 | D 195 | B 196 | C 197 | B 198 | D 199 | B 200 | C 201 | B 202 | D 203 | D 204 |
42   43   44

| D 205 | D 206 | D 207 | B 208 | B 209 | B 210 | D 211 | D 212 | D 213 |
45

| D 214 | D 215 | D 216 | C 217 |

II.3.134

Figure 3-13
LOADING & INSTRUMENT PATTERN
MILLSTONE II CYCLE 2

BATCH BOX
INSTR.

D 1	D 2	D 3	D 4							

D 5	D 6	D 7	C 8	B 9	C 10	D 11	D 12	D 13
							44	

D 14	D 15	C+ 16	B 17	B 18	D 19	B 20	B 21	C+ 22	D 23	D 24
42		43						29		

D 25	C 26	B 27	B 28	D 29	B 30	B 31	B 32	D 33	B 34	B 35	C 36	D 37
						27		28				45

D 38	D 39	B 40	D 41	B 42	B 43	C. 44	C 45	C. 46	B 47	B 48	D 49	B 50	D 51	D 52
41		25												

D 53	C+ 54	B 55	B 56	B 57	C 58	C 59	C. 60	C 61	C 62	B 63	B 64	B 65	C+ 66	D 67
	26						8		9				30	

D 68	B 69	D 70	B 71	C 72	B 73	C+ 74	B 75	C+ 76	B 77	C 78	B 79	D 80	B 81	D 82
40		24				7							31	

D 83	C 85	B 86	B 87	C. 88	C 89	C+ 90	C 91	C 92	C 93	C+ 94	C 95	C. 96	B 97	B 98	C 99	D 84
D 100					6							11				D 101

| 39 | B 102 | D 103 | B 104 | C 105 | C. 106 | B 107 | C 108 | B 109 | C 110 | B 111 | C. 112 | C 113 | B 114 | D 115 | B 116 | |
| D 117 | | 23 | | 5 | | | | | 1 | | 10 | | 12 | | 32 | D 118 |

C 119	B 120	B 121	C. 122	C 123	C+ 124	C 125	C 126	C 127	C+ 128	C 129	C. 130	B 131	B 132	C 133
D 134	22													D 135

D 136	B 137	D 138	B 139	C 140	B 141	C+ 142	B 143	C+ 144	B 145	C 146	B 147	D 148	B 149	D 150	33
21								2				13			

D 151	C+ 152	B 153	B 154	B 155	C 156	C 157	C. 158	C 159	C 160	B 161	B 162	B 163	C+ 164	D 165
20						4	3				14		15	

D 166	D 167	B 168	D 169	B 170	B 171	C. 172	C 173	C. 174	B 175	B 176	D 177	B 178	D 179	D 180
								16						34

D 181	C 182	B 183	B 184	D 185	B 186	B 187	B 188	D 189	B 190	B 191	C 192	D 193
38				18		17						

D 194	D 195	C+ 196	B 197	B 198	D 199	B 200	B 201	C+ 202	D 203	D 204
		19								35

D 205	D 206	D 207	C 208	B 209	C 210	D 211	D 212	D 213
37							36	

D 214	D 215	D 216	D 217

Figure 3-14
LOADING & INSTRUMENT PATTERN
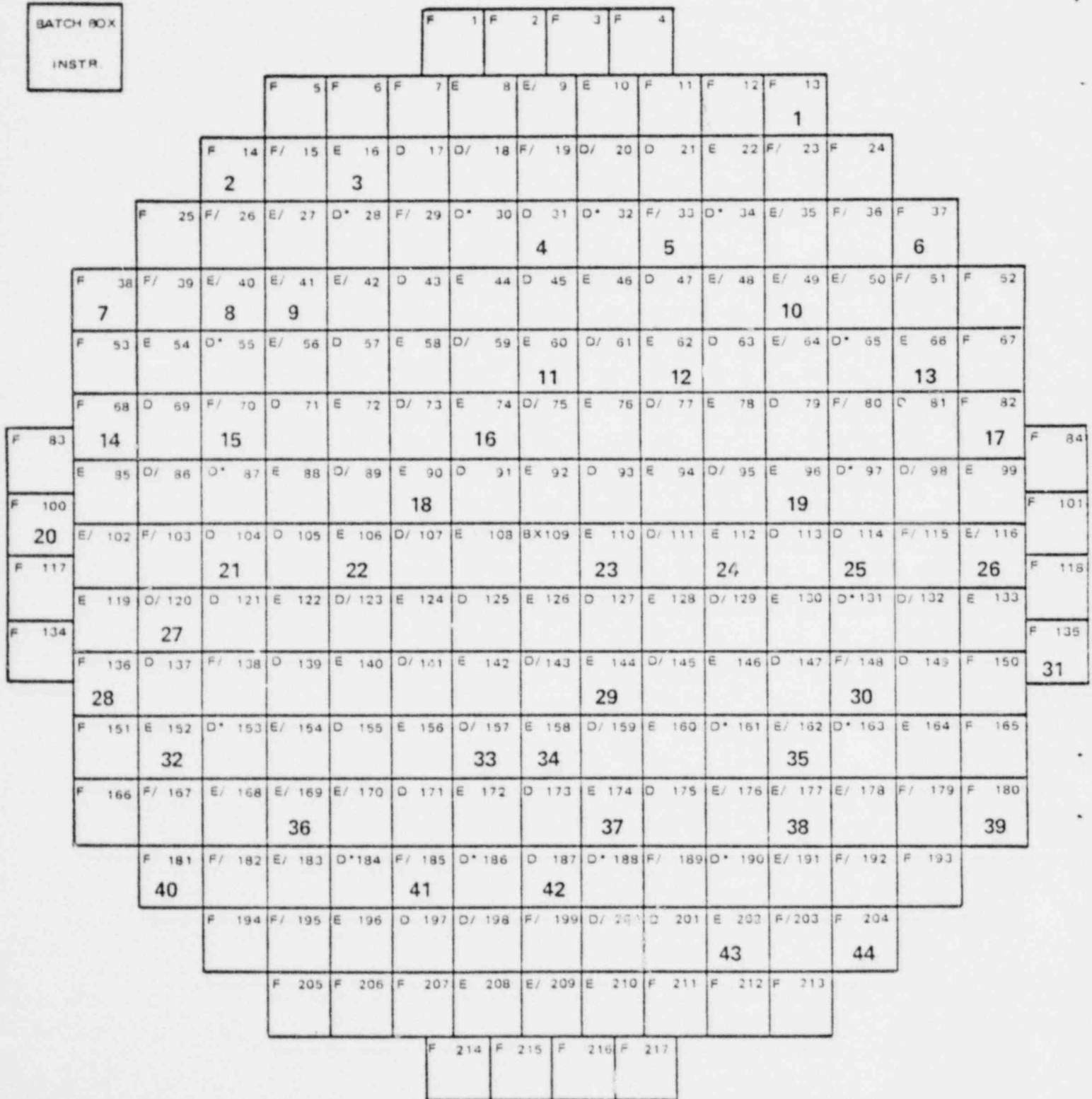## CALVERT CLIFFS UNIT 1 CYCLE 4

Figure 3-15
CALVERT CLIFFS UNIT 2 CYCLE 2
COMPARISON OF [   ] PDQ PEAK PIN TO BOX AVERAGE PIN POWER
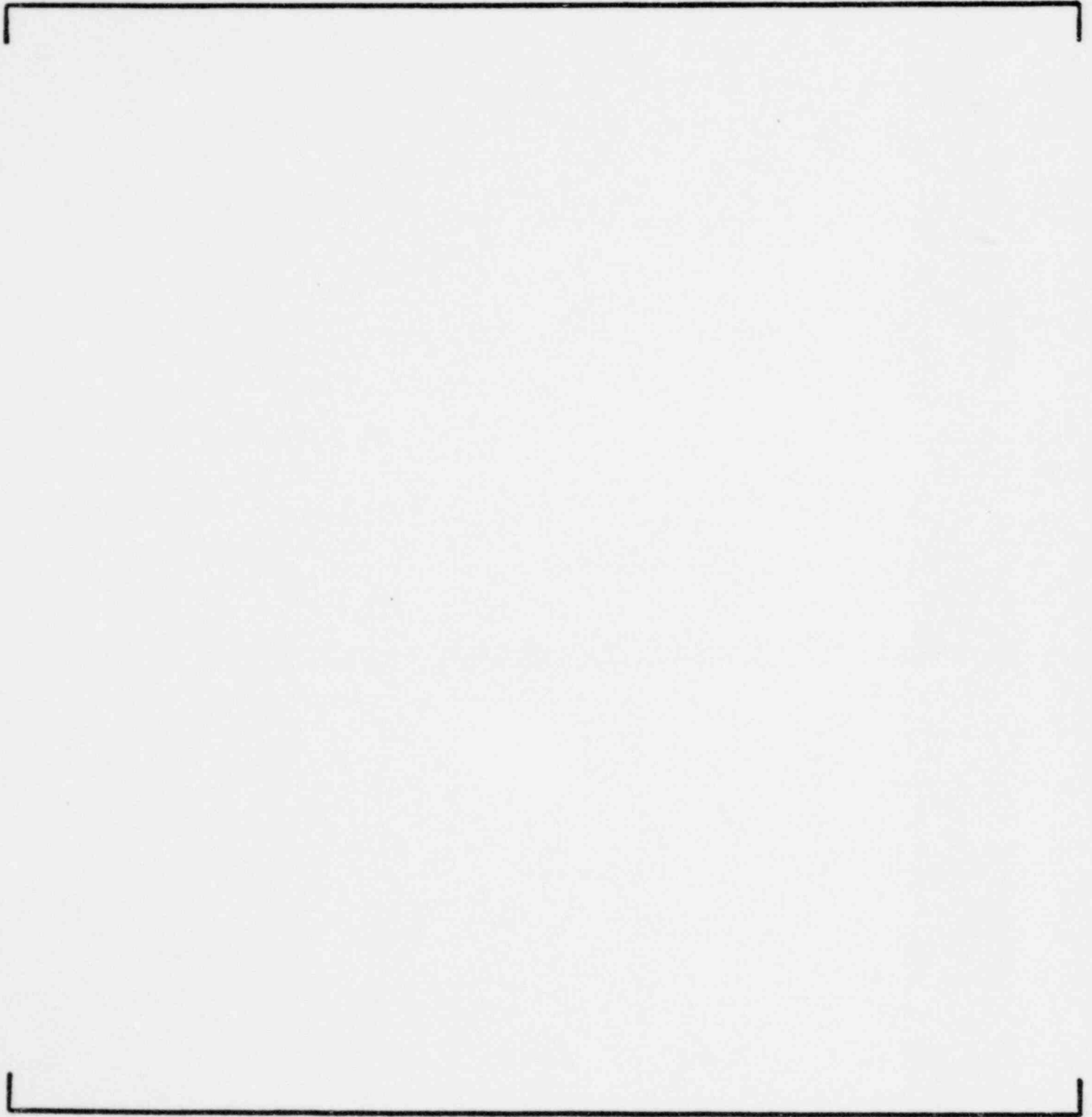
Figure 3-16
ST. LUCIE UNIT 1 CYCLE 2
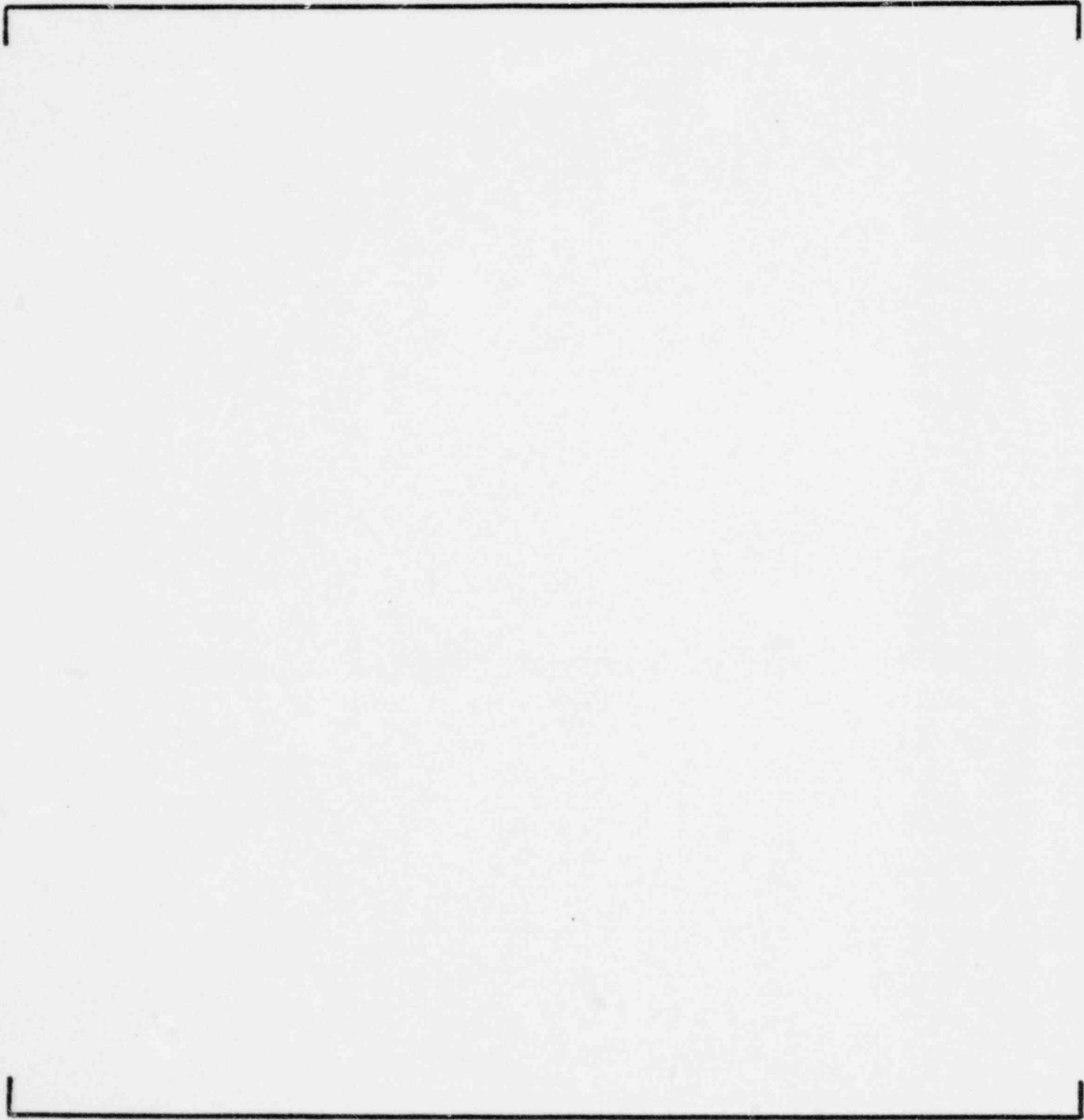COMPARISON OF [   ] PDQ PEAK PIN TO BOX AVERAGE PIN POWER

Figure 3-17

MILLSTONE UNIT 2 CYCLE 2

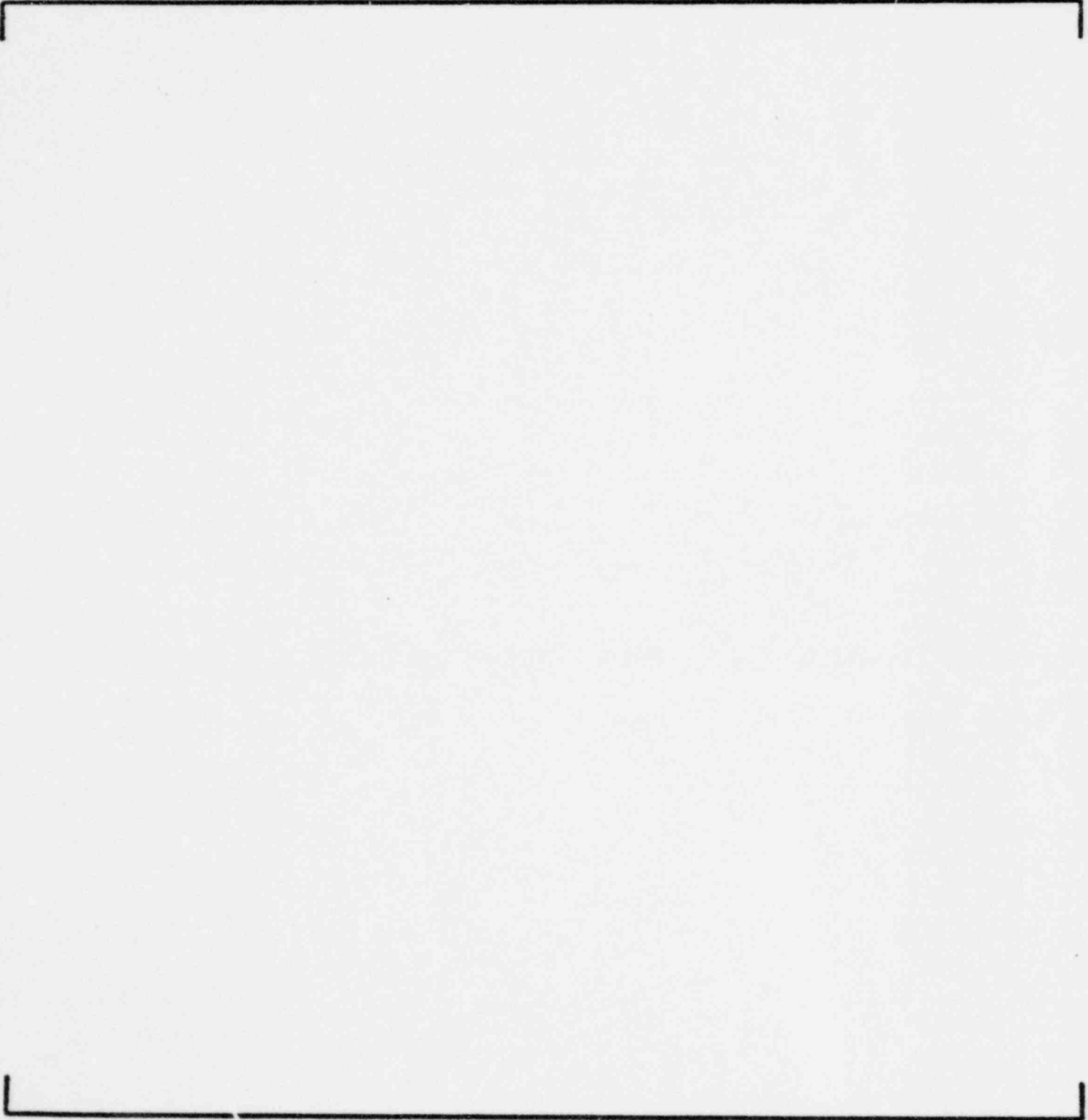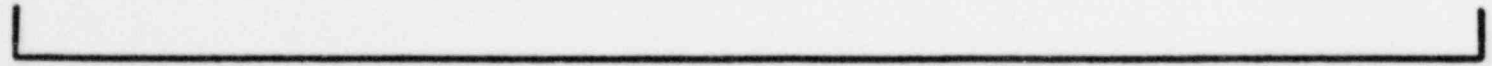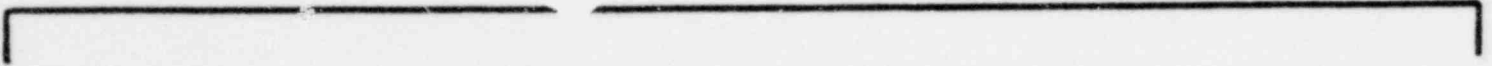COMPARISON OF [   ] PDQ PIN PEAK TO BOX AVERAGE PIN POWER

Figure 3-18
CALVERT CLIFFS UNIT 1 CYCLE 4
COMPARISON OF [   ] PDQ PIN PEAK TO BOX AVERAGE PIN POWER

Figure 3-19

DISTRIBUTION OF DEVIATIONS IN Fρ SYNTHESIS
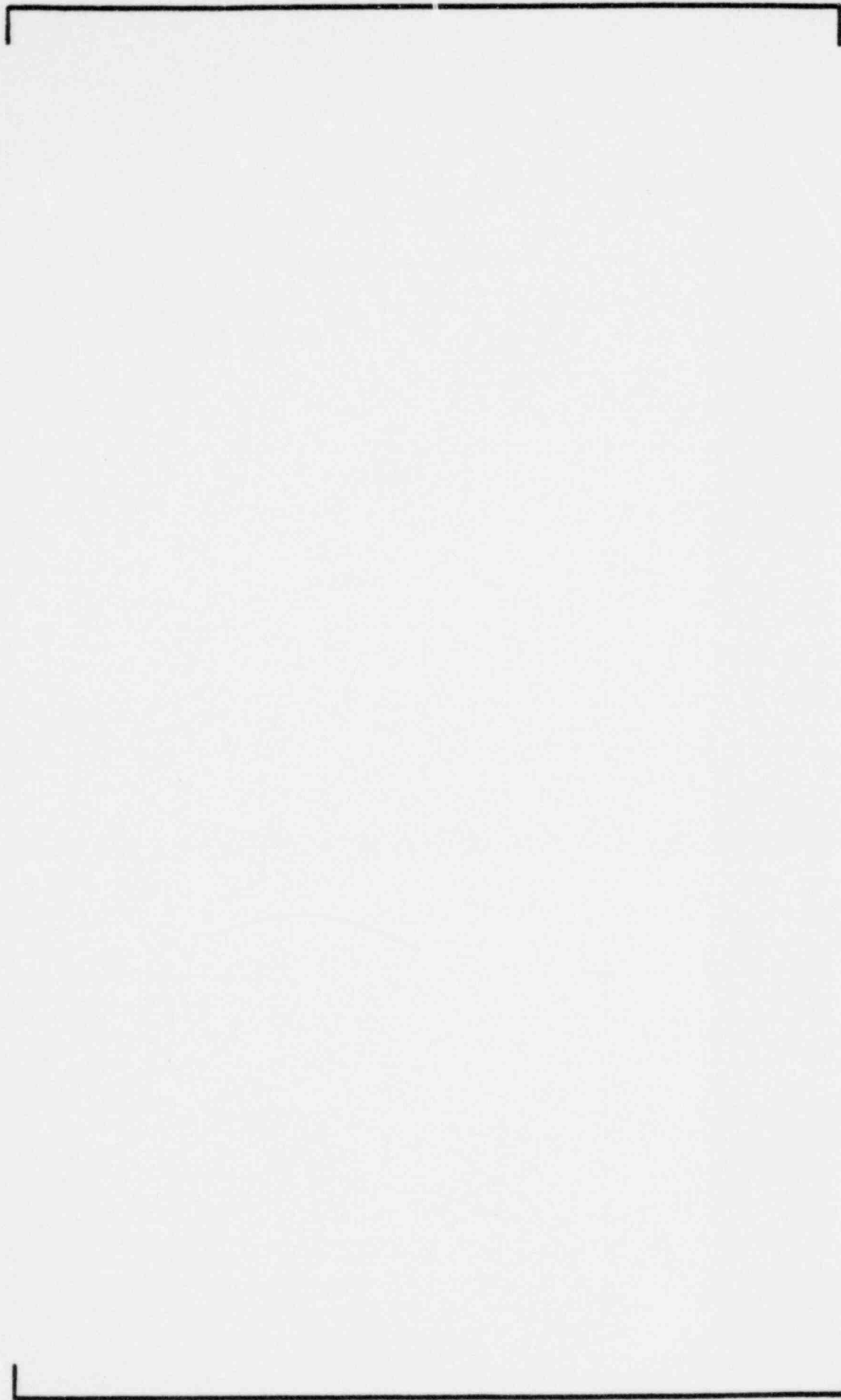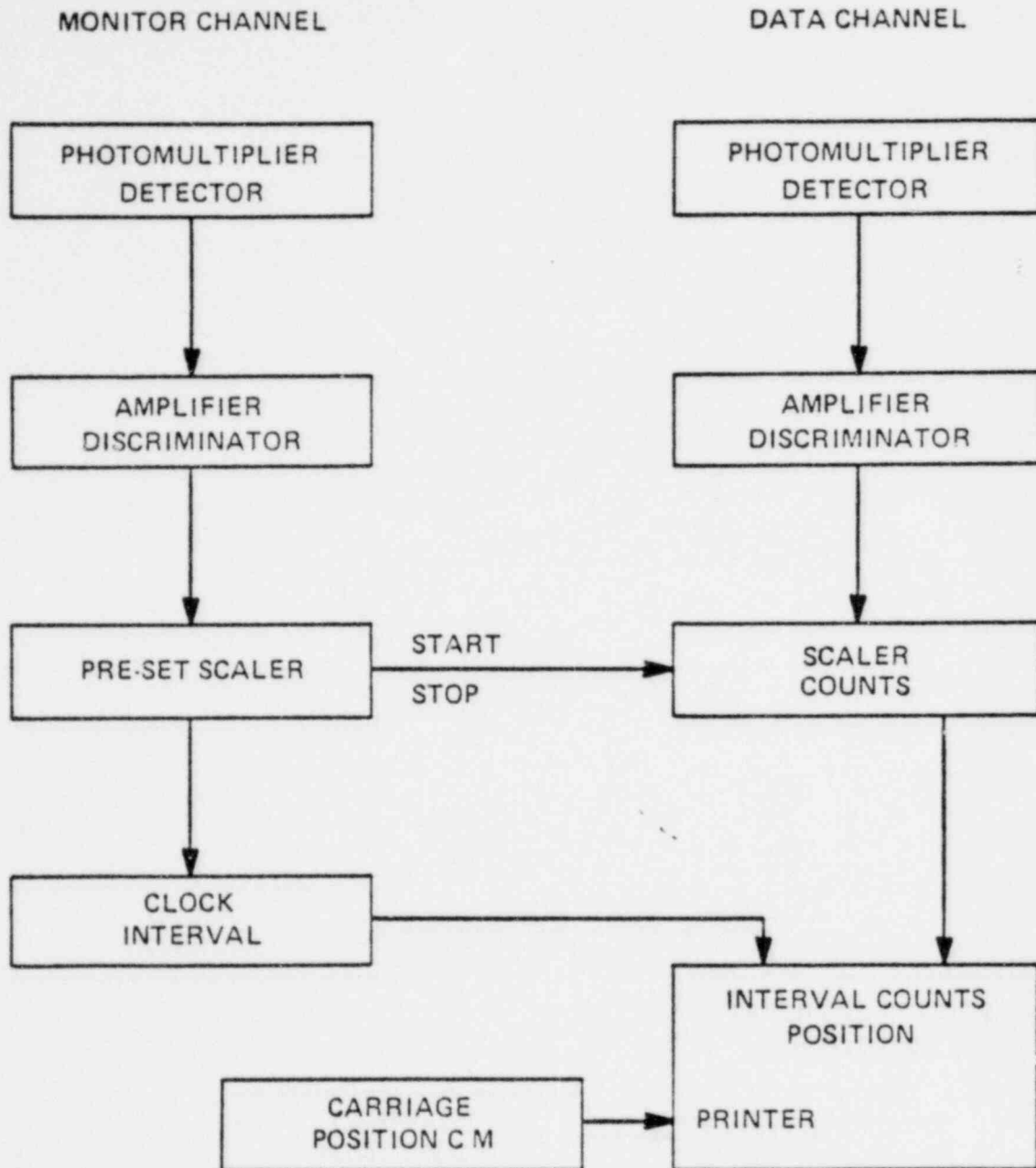
Figure 3-20

BLOCK DIAGRAM OF
SEMI-AUTOMATIC FUEL ROD SCANNER
FOR C-E CRITICALS
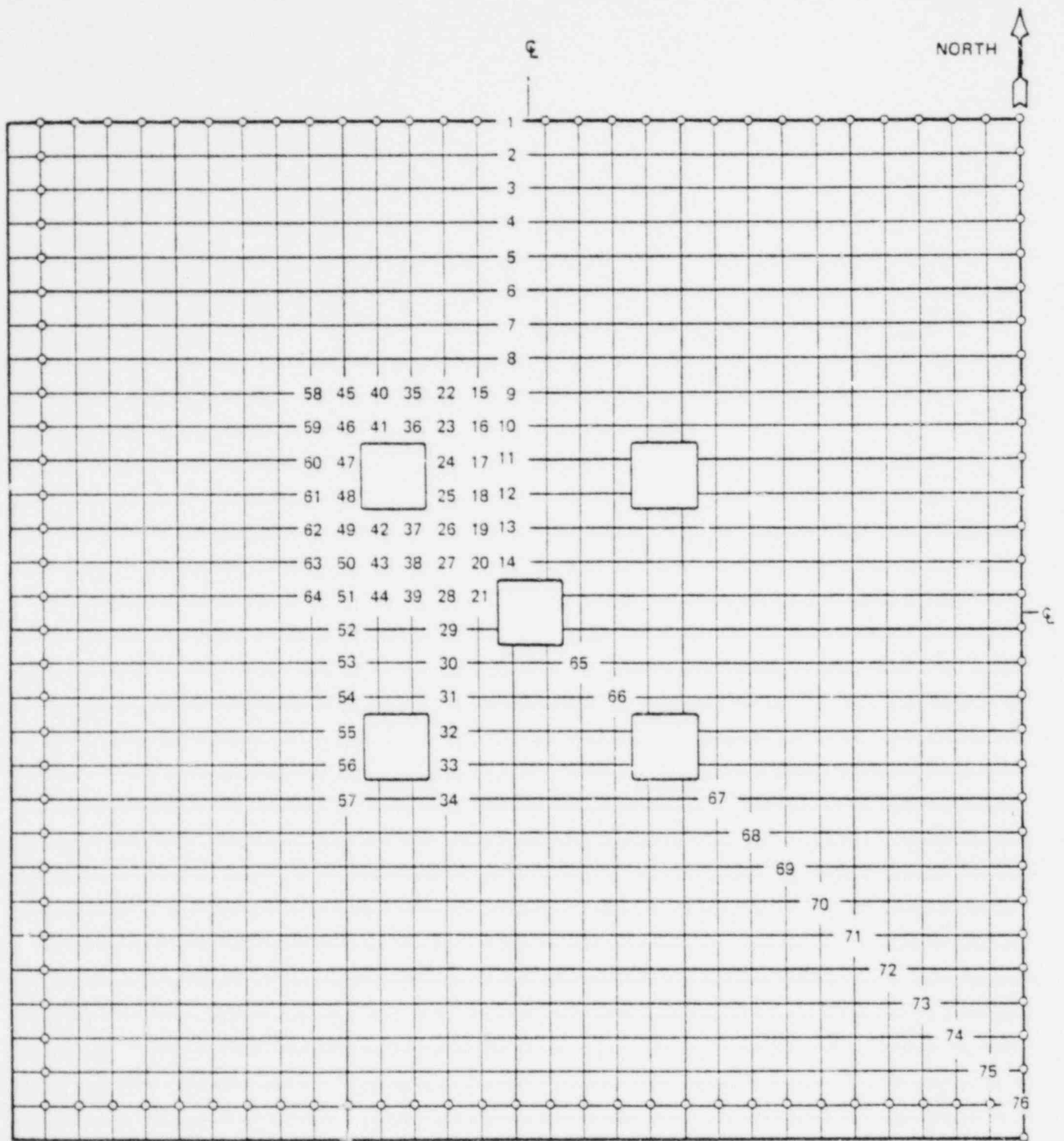
Figure 3-21

NUMBERING SYSTEM FOR POWER SCAN AND BUCKLING MEASUREMENTS

CE No. 12
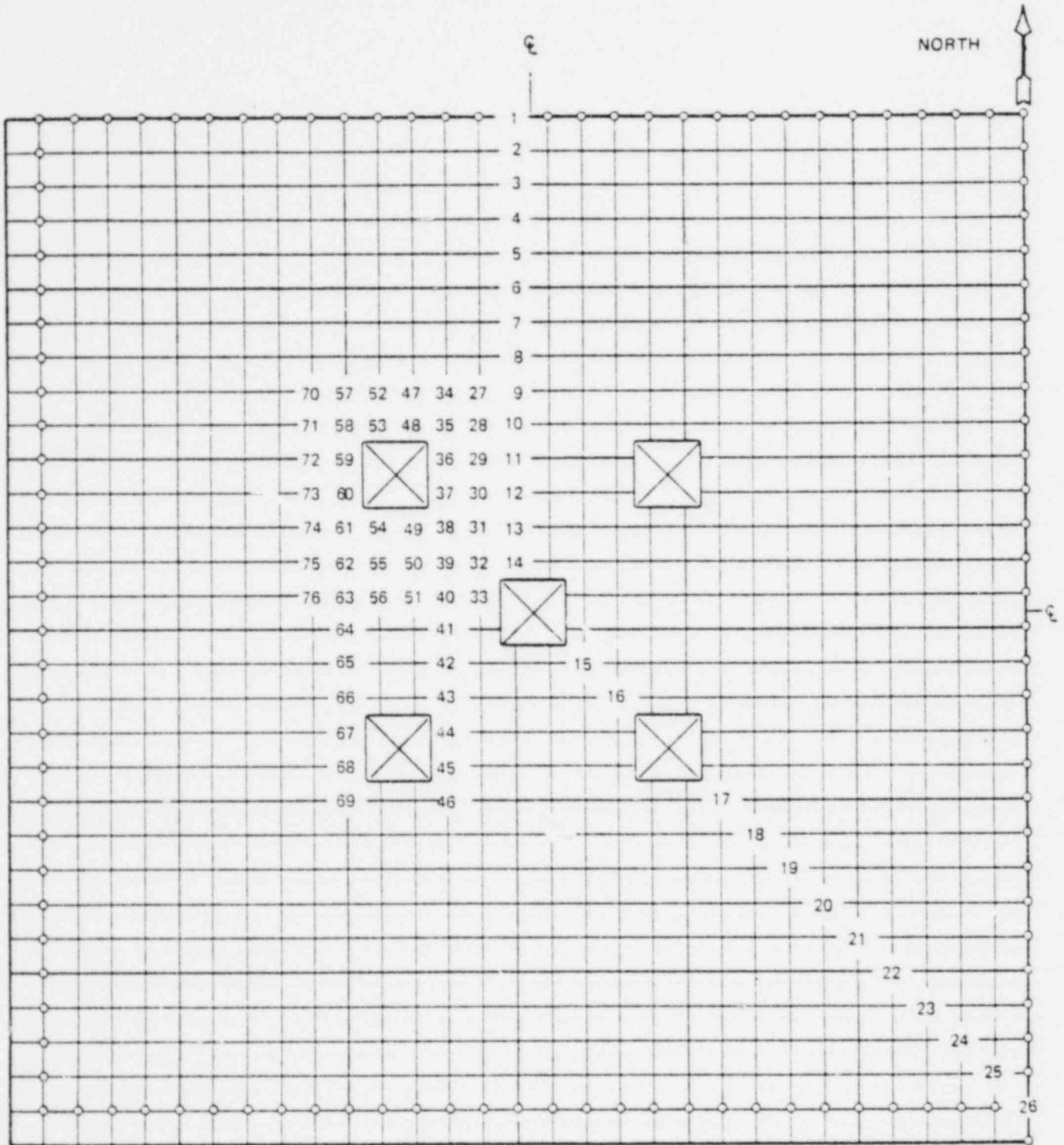
Figure 3-22

NUMBERING SYSTEM FOR POWER SCAN AND BUCKLING MEASUREMENTS

CE No. 43
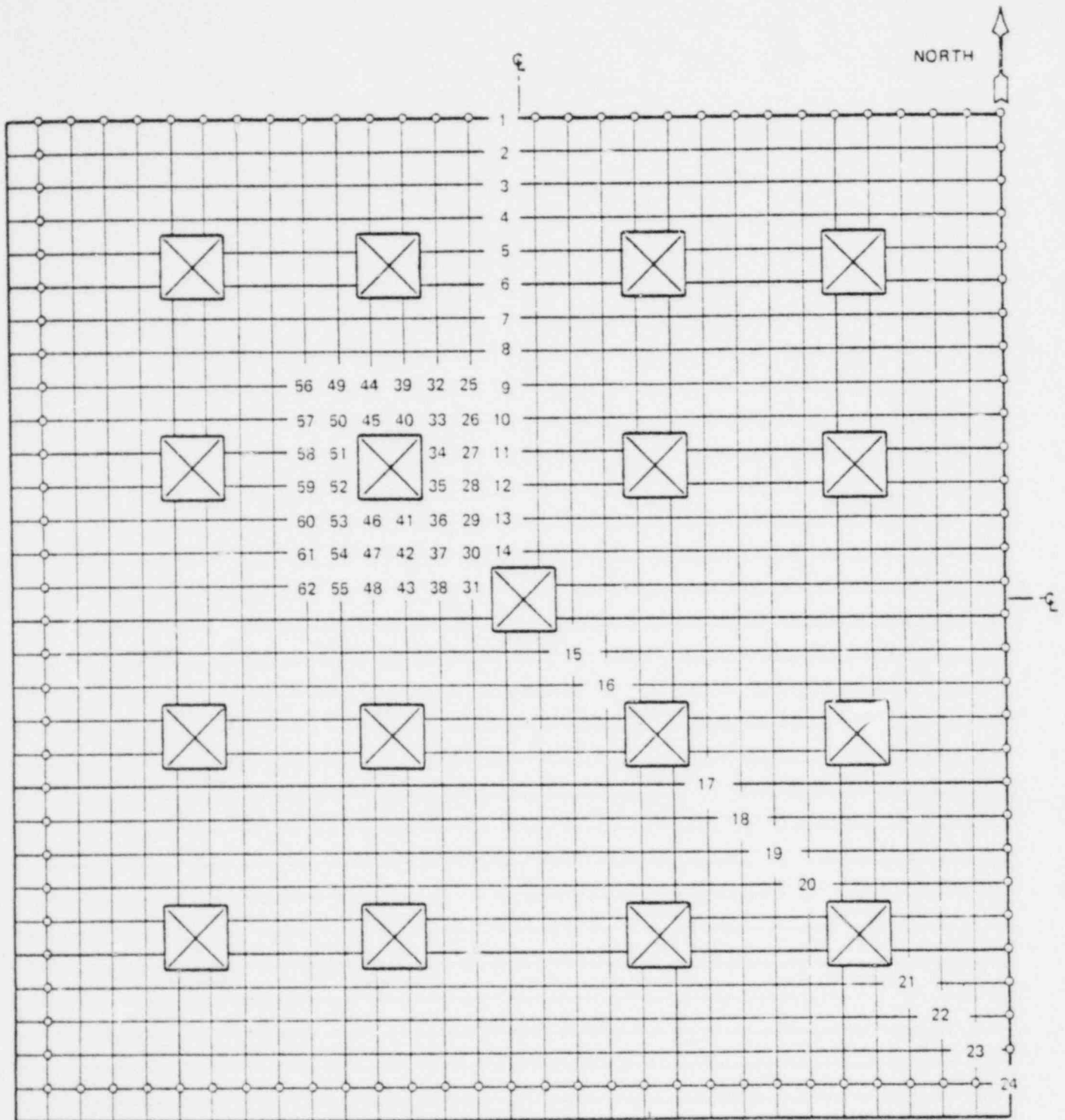
Figure 3-23

NUMBERING SYSTEM FOR POWER SCAN AND BUCKLING MEASUREMENTS
CE No. 32, 53, 56
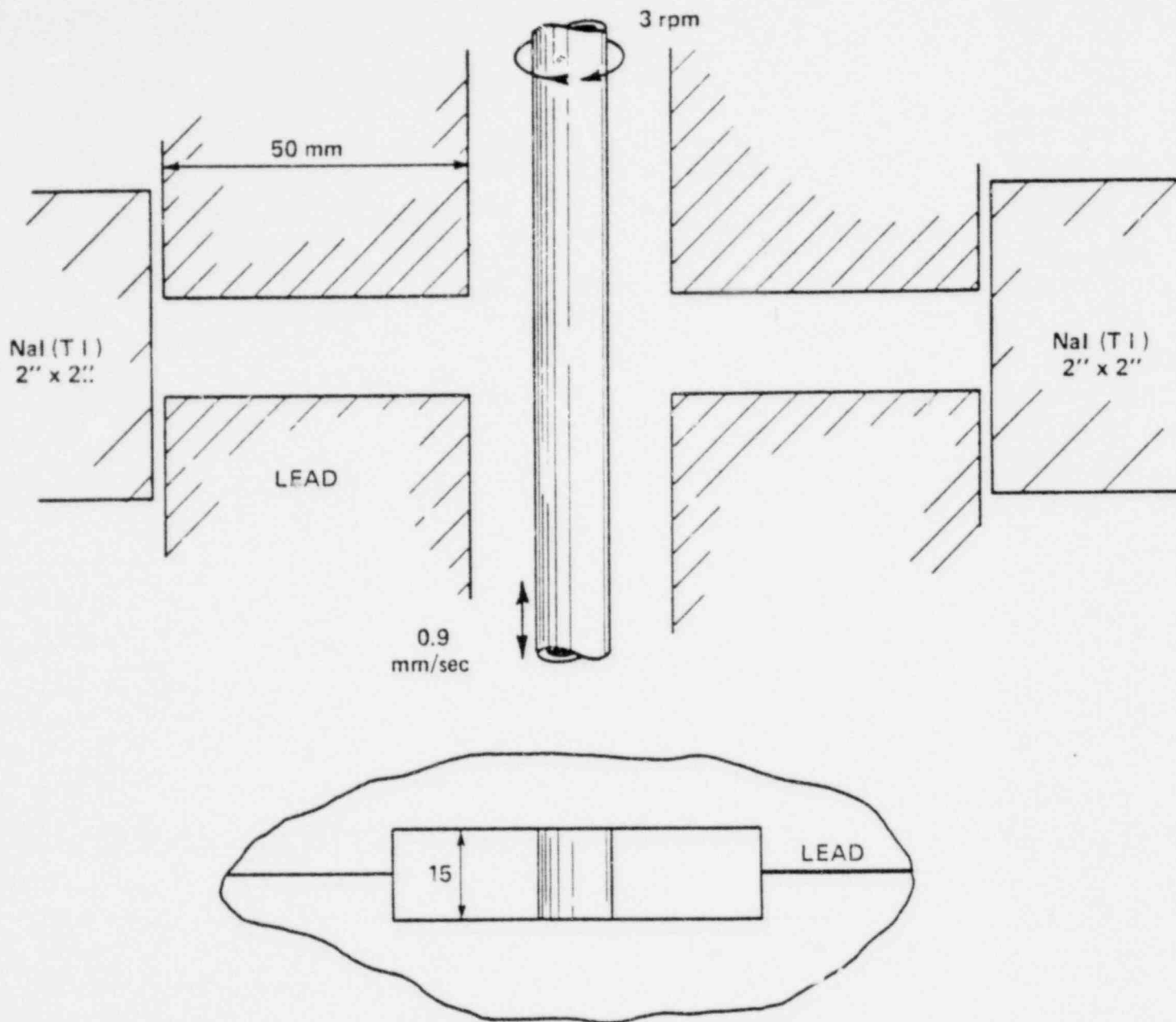
Figure 3-24

ARRANGEMENT FOR THE GAMMA SCANNING

KRITZ EXPERIMENTS

Figure 3-25
KRITZ U-WH2 CORE LAYOUT

ROD FOR FISSION RATE
MEASUREMENT
*) NOT AT 245°C
**) NOT AT 20°C

WATER HOLE
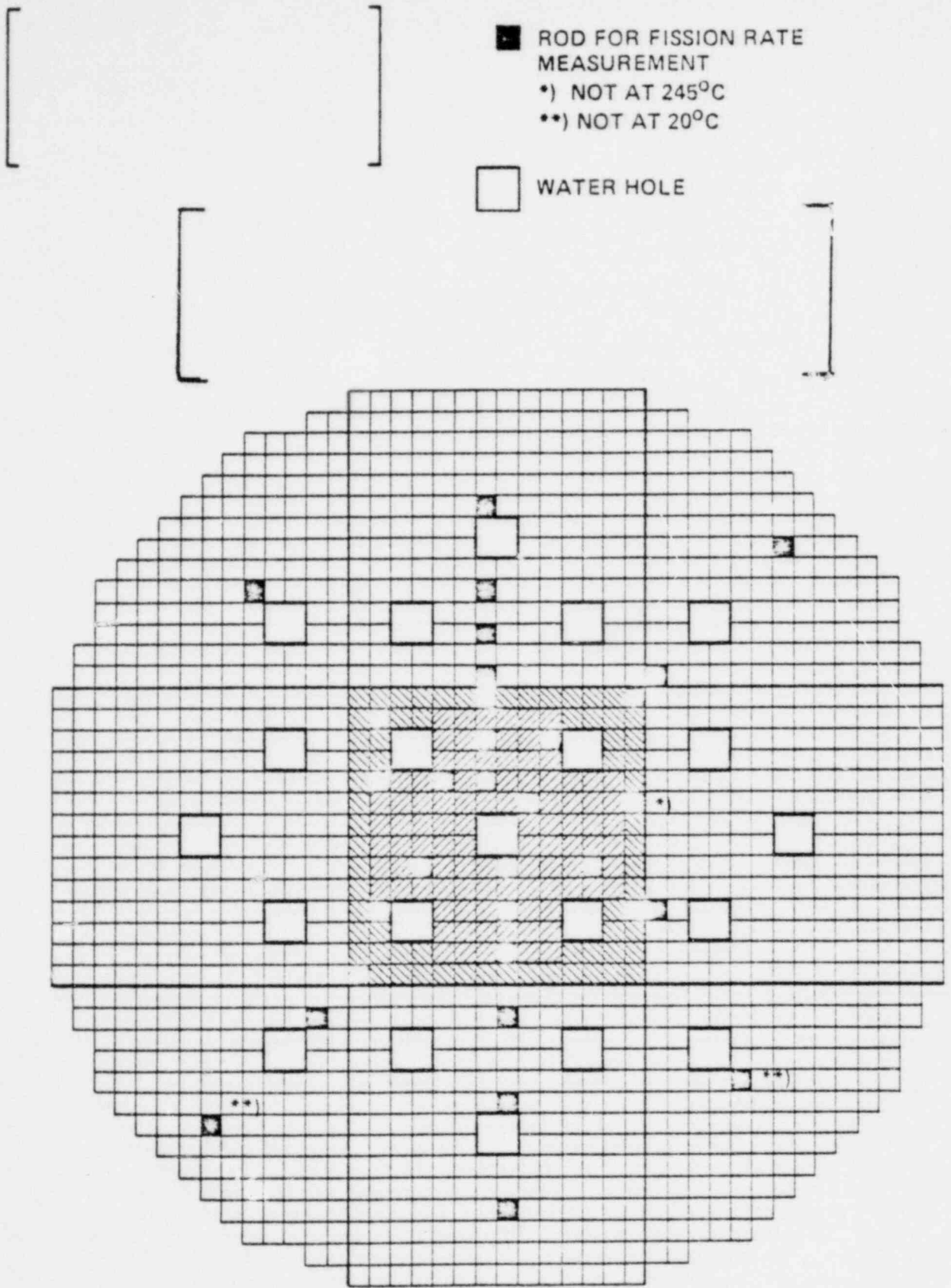
Figure 3-26
KRITZ
LATTICE Pu - WH2

II.3.148

FUEL SPECIFICATIONS: 2.35% ENRICHED UO$_2$

FUEL RODS

1. ROD DIMENSIONS

CLAD: 0.500 OD x 0.030" WALL

FUEL: 0.44" DIA

0.500" DIA

2.0"

36.0"

38.5"
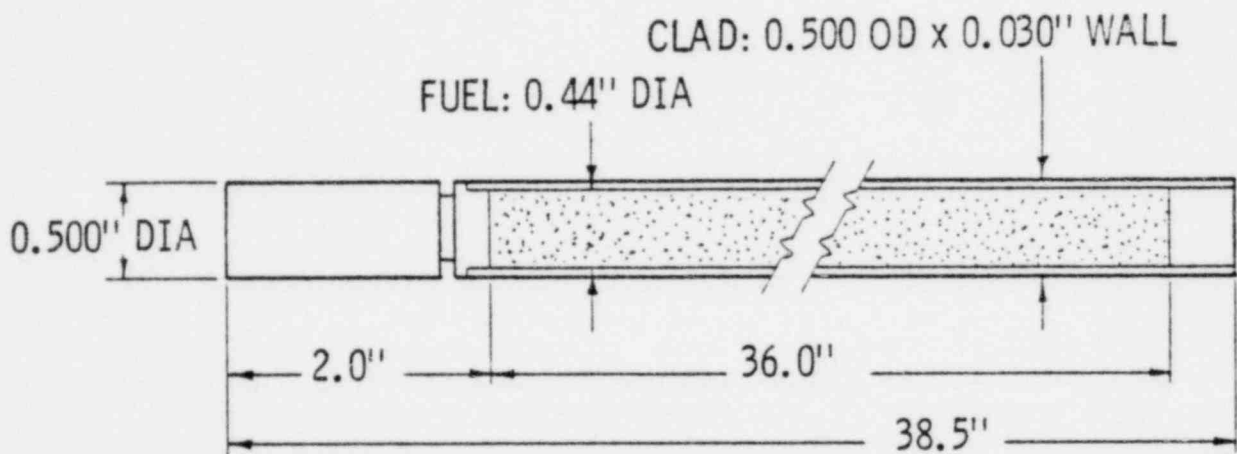
2. CLADDING: 6061 ALUMINUM TUBING

3. TOTAL WEIGHT OF LOADED FUEL RODS: 917 gm (AVERAGE)

FUEL LOADING

1. FUEL MIXTURE VIBRATIONALLY COMPACTED
2. 825 gm OF UO$_2$ POWDER/ROD, 726 gm OF U/ROD, 17.08 gm OF U-235/ROD
3. ENRICHMENT - 2.35 $\pm$ 0.05 w/o U-235
4. FUEL DENSITY - 9.20 gm/cm^3 (84% THEORETICAL DENSITY)
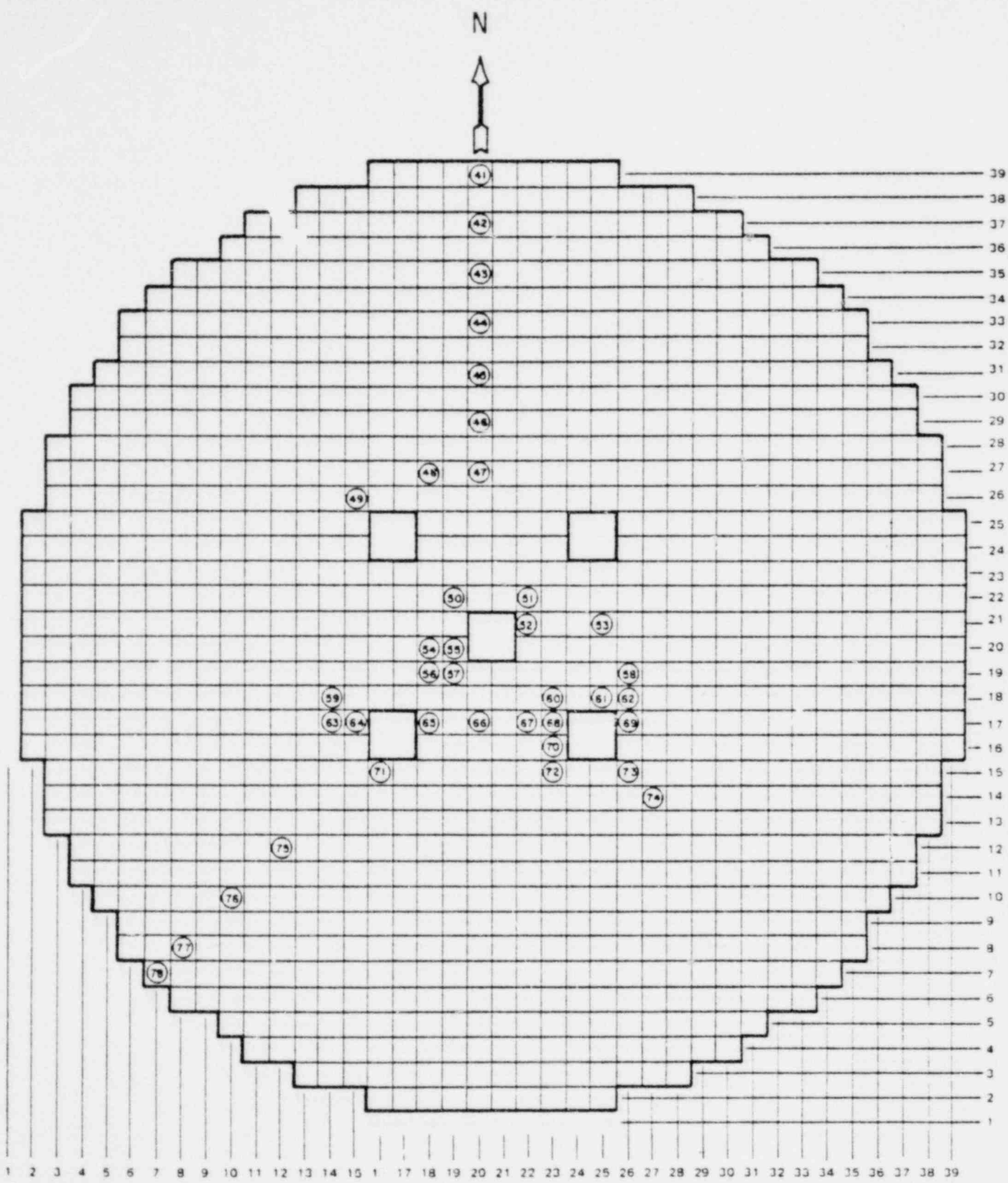
Figure 3-27
BNWL FUEL DESCRIPTION
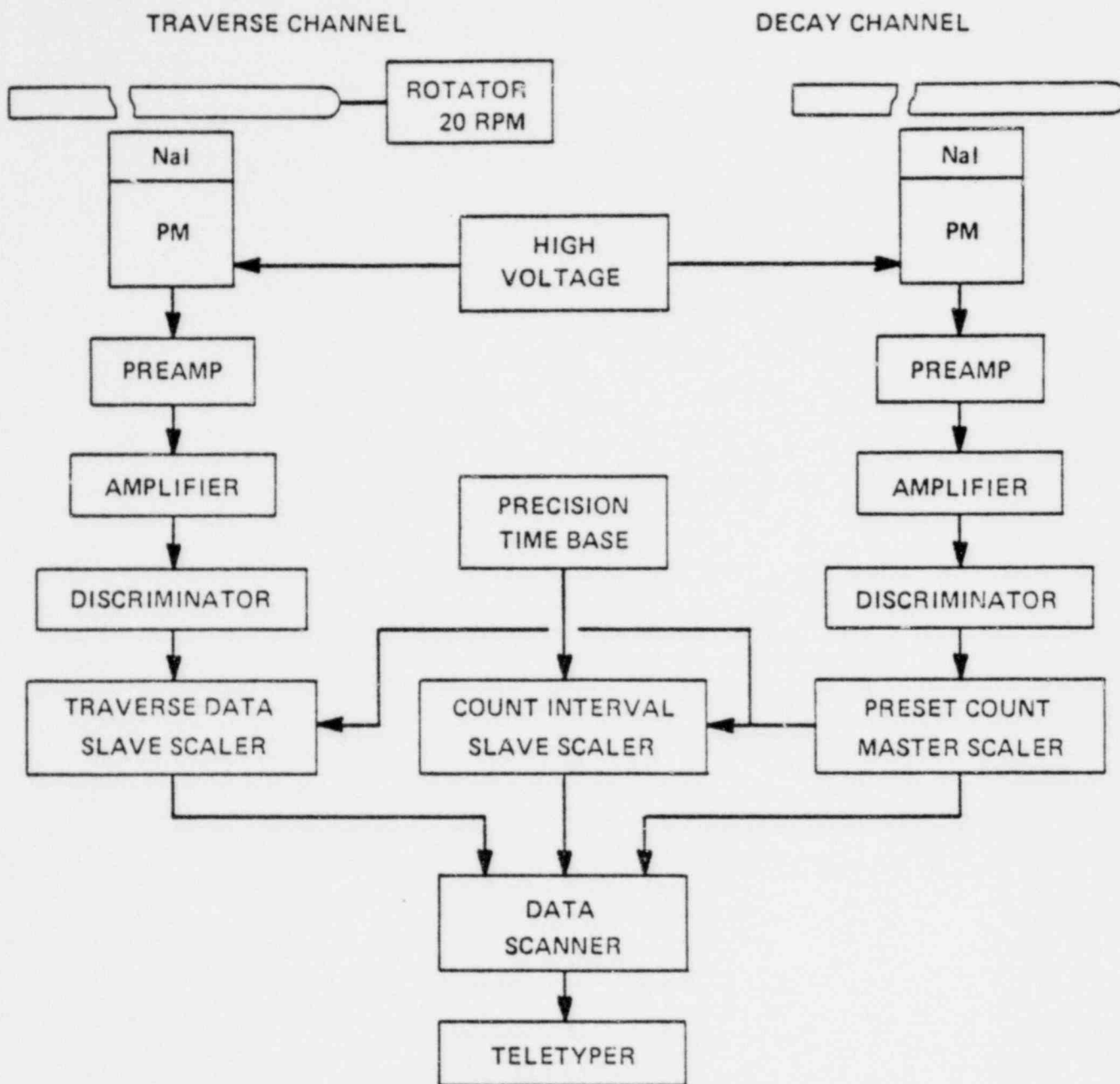
Figure 3-28

DUAL CHANNEL GAMMA SCANNING SYSTEM

BNWL EXPERIMENTS

N

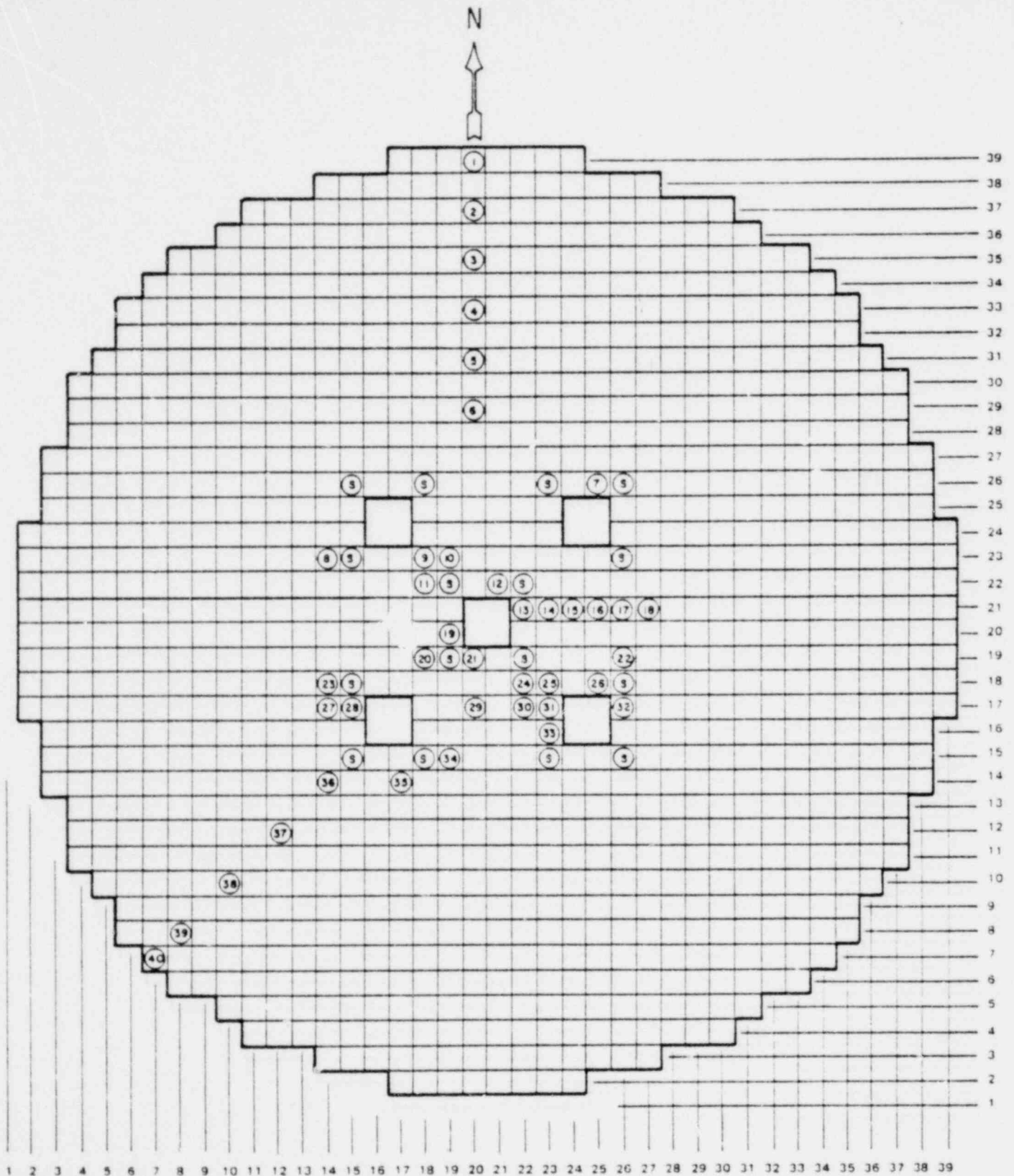UO$_2$·2.35% ^{235}U CORE W/WATER HOLES. BNWL GPL-88

Figure 3-29

Figure 3-30

UO$_2$·2.35% ^{235}U CORE W/WATER HOLES AND KG·33 GLASS SHIMS·
BNWL GPL·92

II.3.152

$$\% \text{ DIFF} = \frac{\text{DIT} - \text{MEAS}}{\text{DIT}} \times 100$$
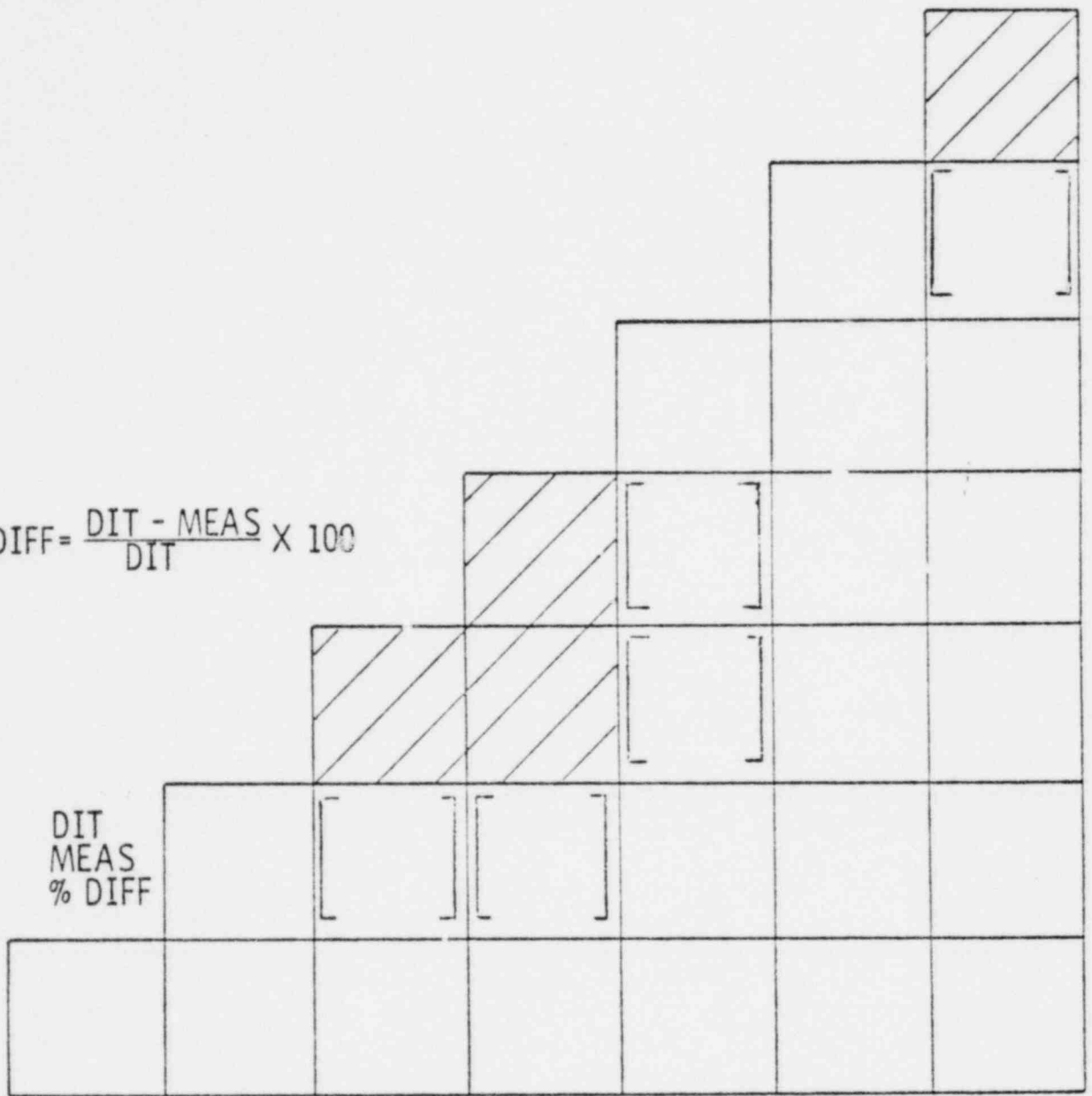
DIT
MEAS
% DIFF

Figure 3-31
DIT (K=1) vs MEASURED PIN POWERS
CE No. 12

$$\% \text{ DIFF} = \frac{\text{DIT} - \text{MEAS}}{\text{DIT}} \times 100$$

DIT
MEAS
% DIFF

Figure 3-32
DIT (K=1) vs MEASURED PIN POWERS
CE No. 32

$$\% \text{ DIFF} = \frac{\text{DIT} - \text{MEAS}}{\text{DIT}} \times 100$$

DIT
MEAS
% DIFF

Figure 3-33
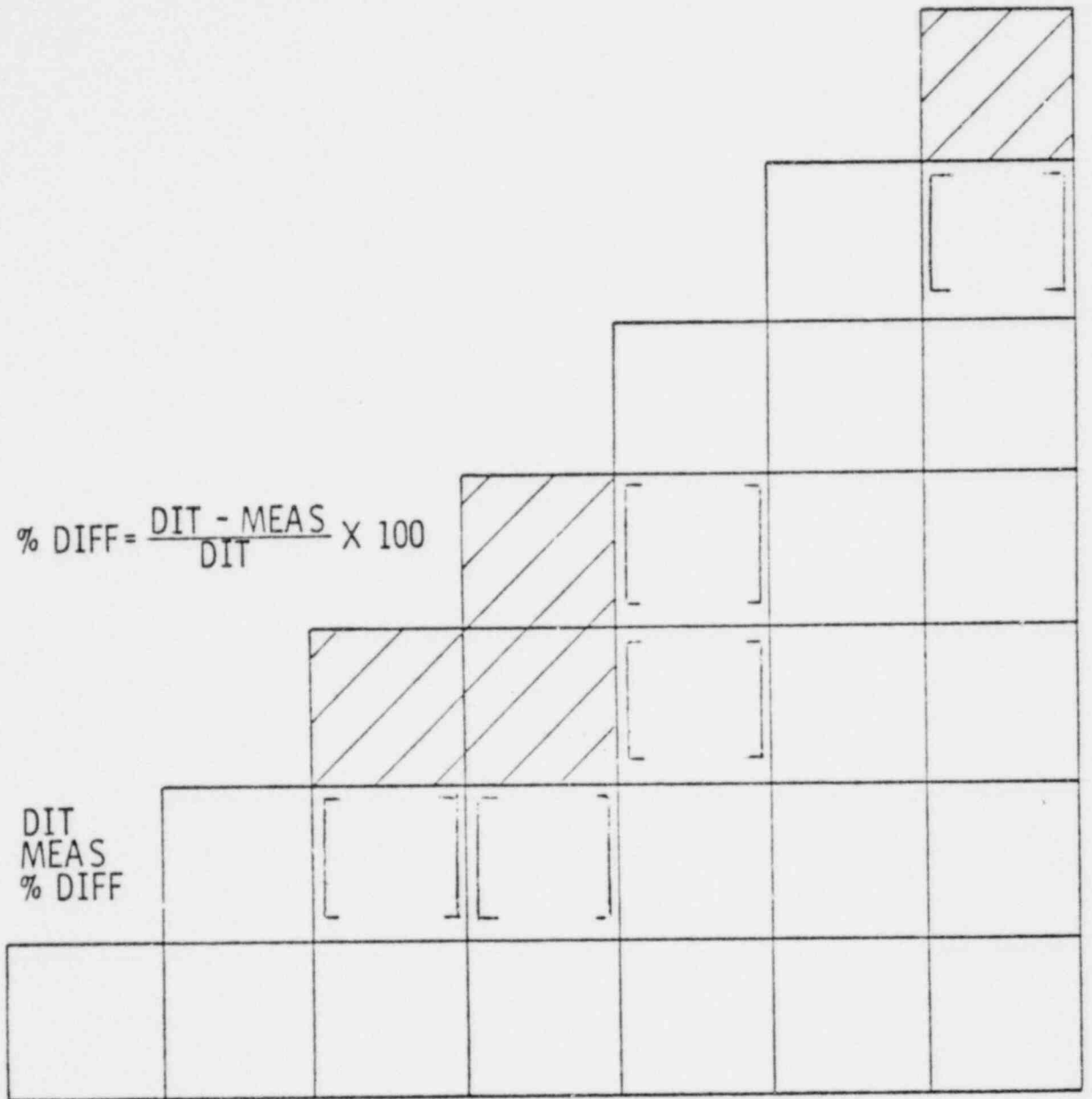DIT (K=1) vs MEASURED PIN POWERS
CE No. 43

$$\% \text{ DIFF} = \frac{\text{DIT} - \text{MEAS}}{\text{DIT}} \times 100$$

DIT
MEAS
% DIFF
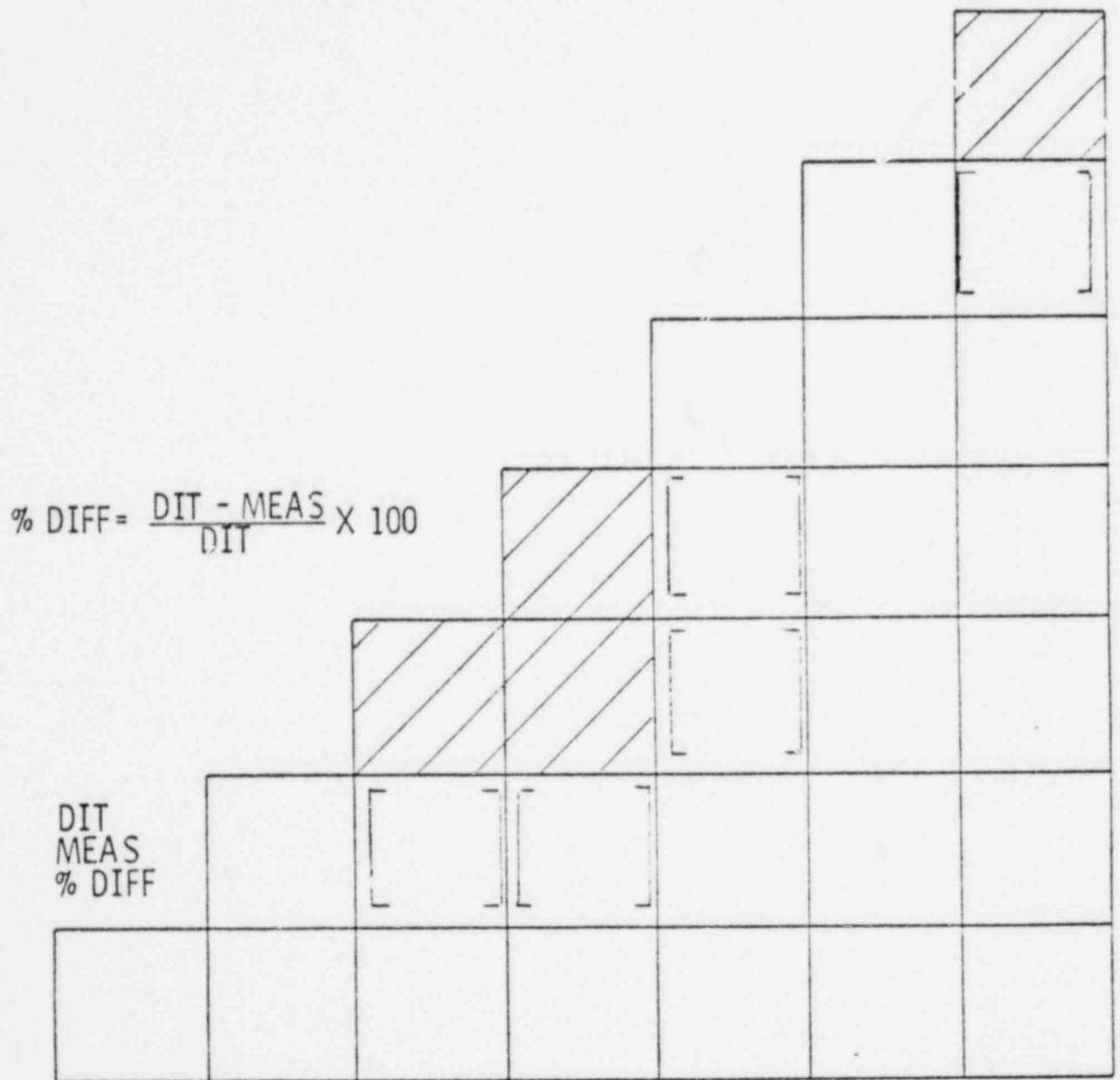
Figure 3-34
DIT (K=1) vs MEASURED PIN POWERS
CE No. 53 CORE

$$\% \text{ DIFF} = \frac{\text{DIT} - \text{MEAS}}{\text{DIT}} \times 100$$

DIT
MEAS
% DIFF
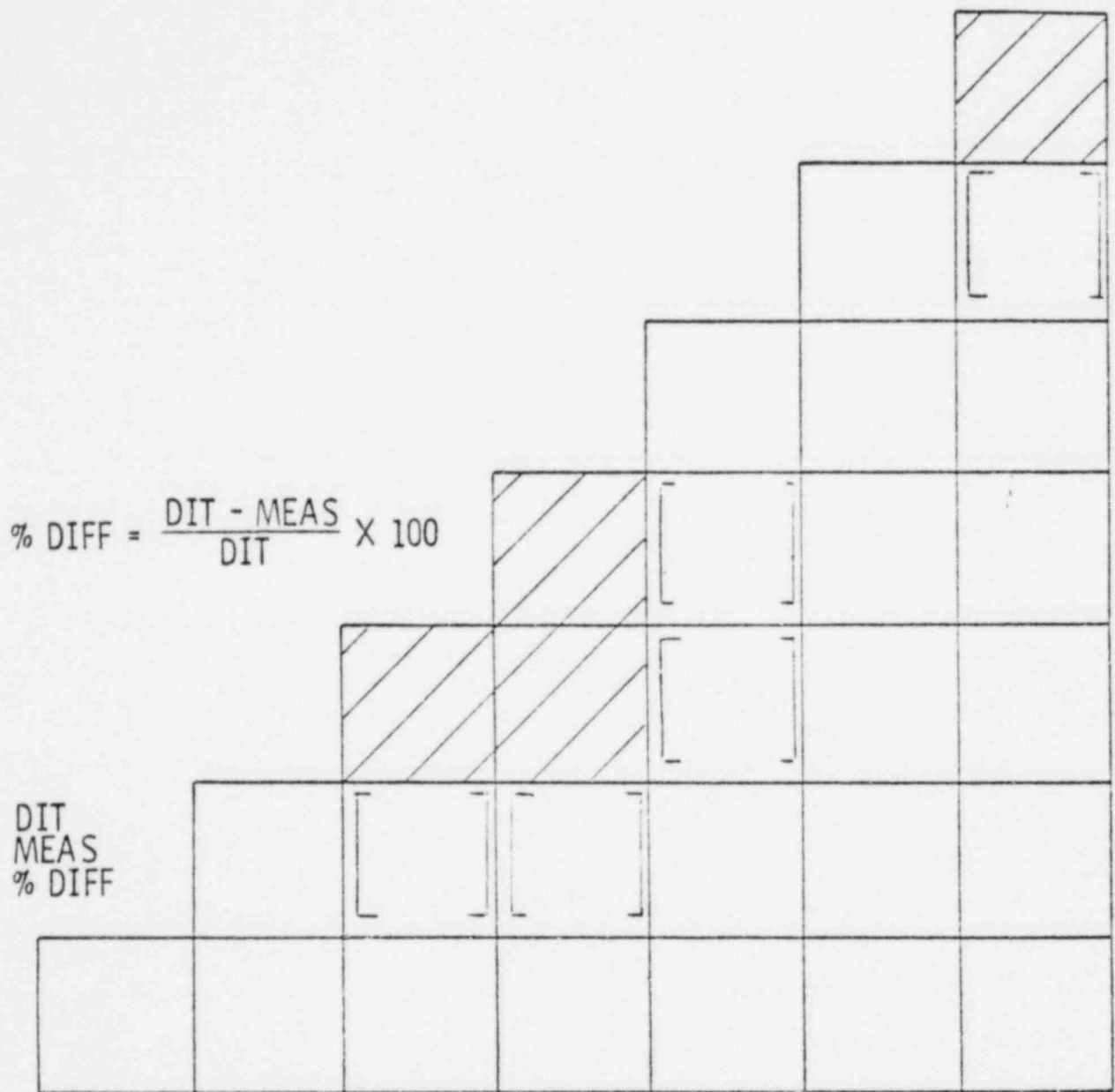
Figure 3-35

DIT (K=1) vs MEASURED PIN POWERS

CE No. 56 CORE

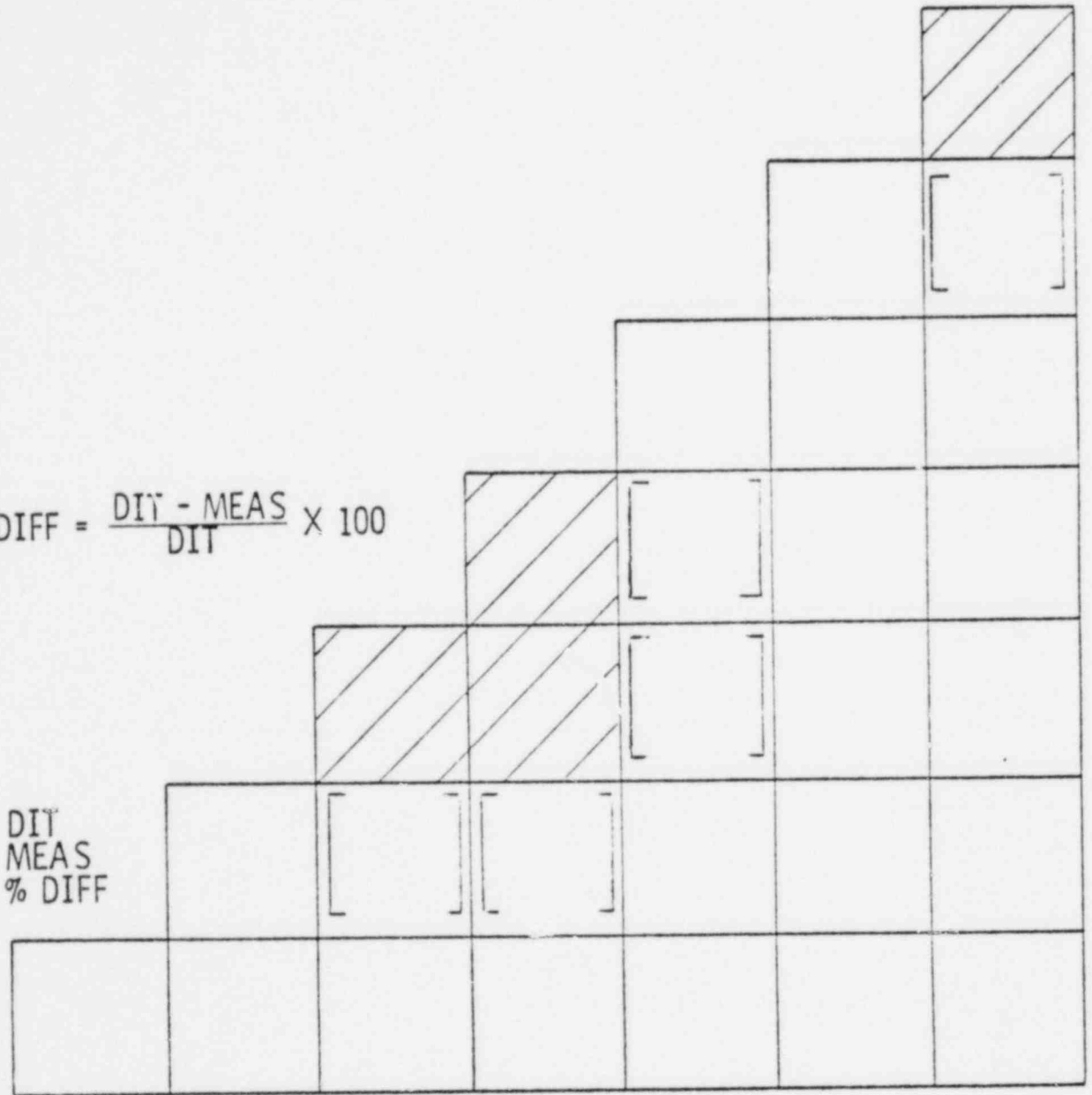$$\% \text{ DIFF} = \frac{\text{DIT} - \text{MEAS}}{\text{DIT}} \times 100$$

DIT
MEAS
% DIFF

Figure 3-36
DIT (K=1) vs MEASURED PIN POWERS
KRITZ U-WH2 CORE

$$\% \text{ DIFF} = \frac{\text{DIT} - \text{MEAS}}{\text{DIT}} \times 100$$

DIT
MEAS
% DIFF

Figure 3-37
DIT (K=1) vs MEASURED PIN POWERS
KRITZ Pu-WH2 CORE (COLD)

$$\% \text{ DIFF} = \frac{\text{DIT} - \text{MEAS}}{\text{DIT}} \times 100$$

DIT
MEAS
% DIFF

Figure 3-38
DIT (K=1) vs MEASURED PIN POWERS
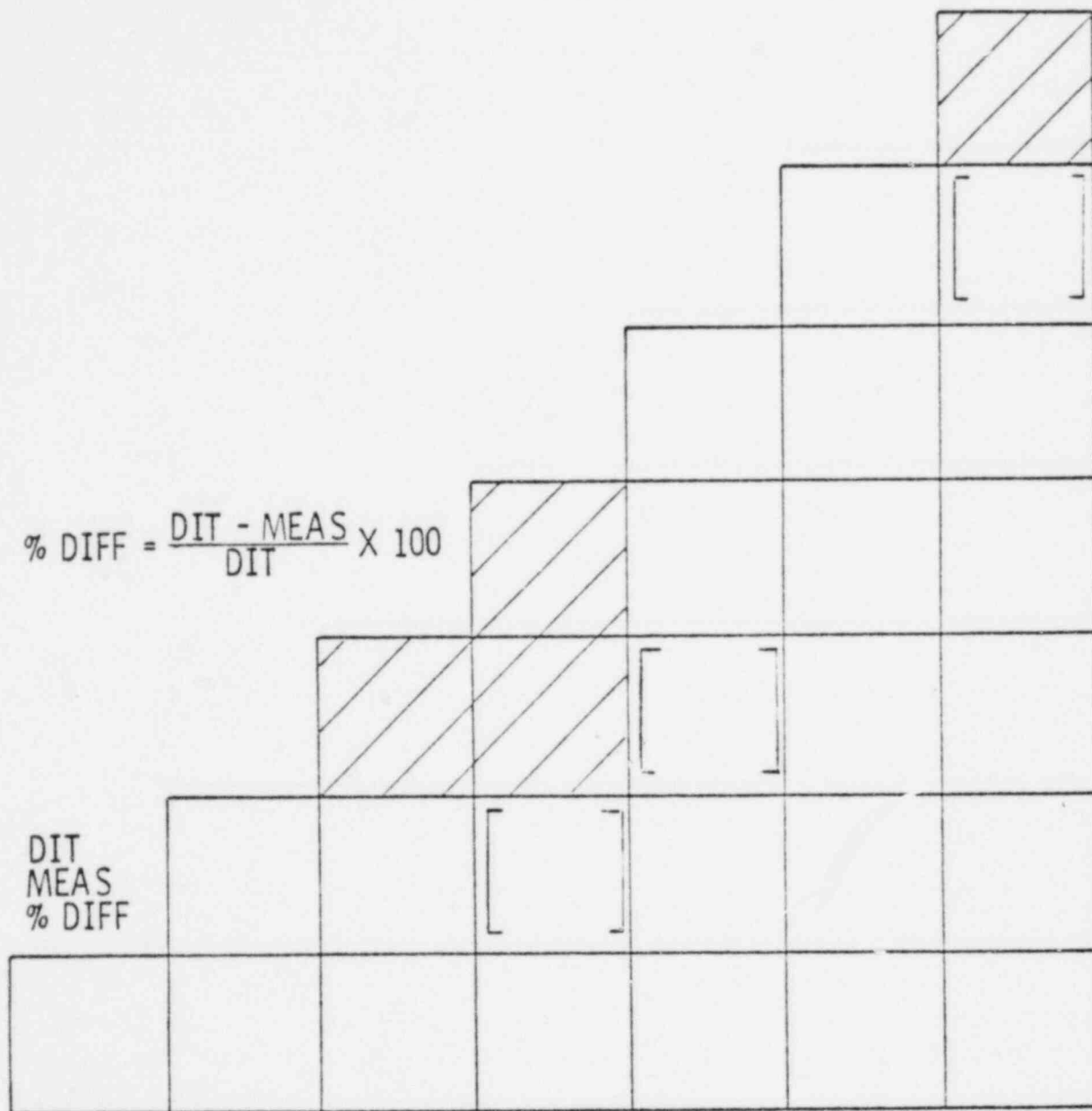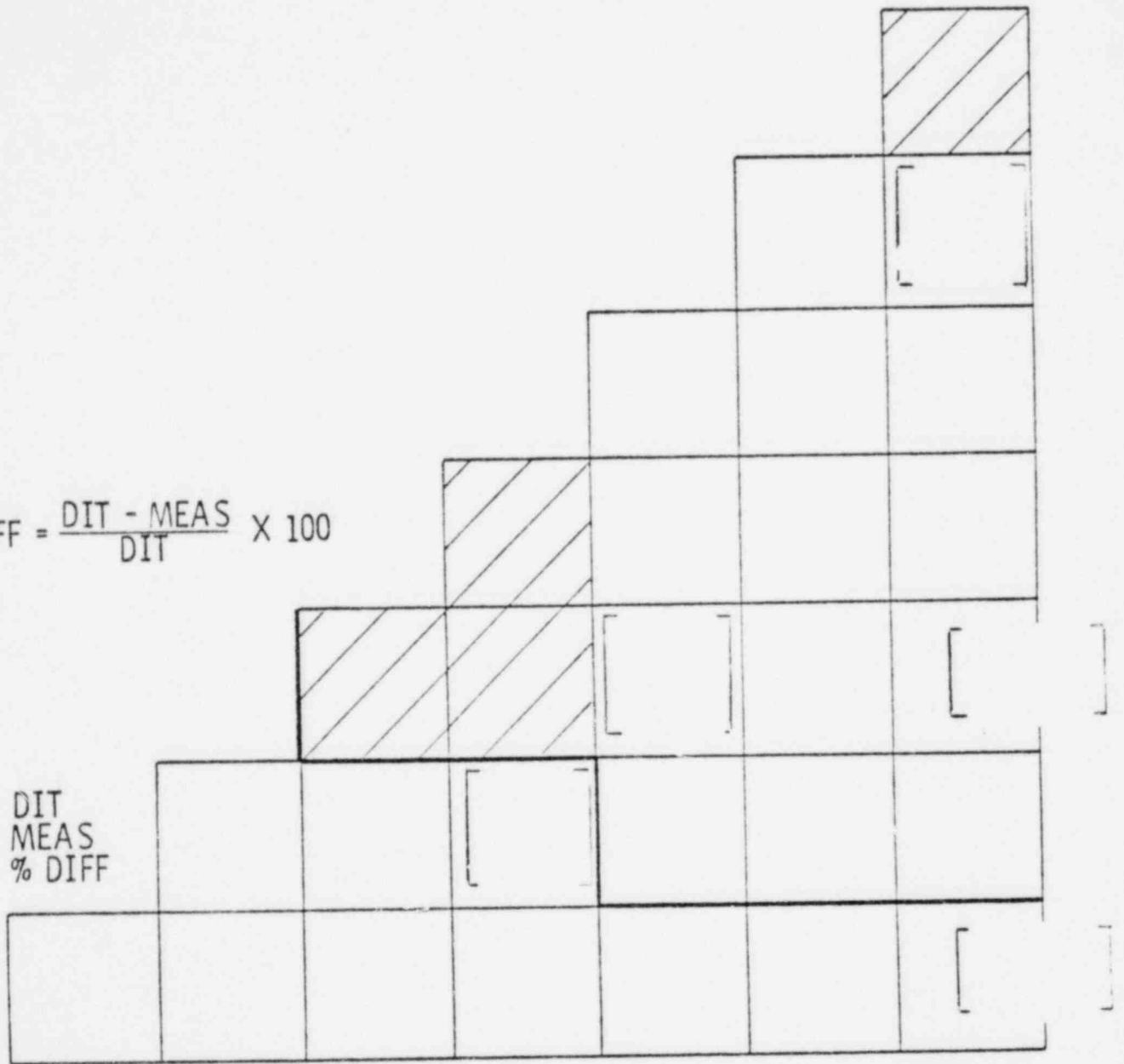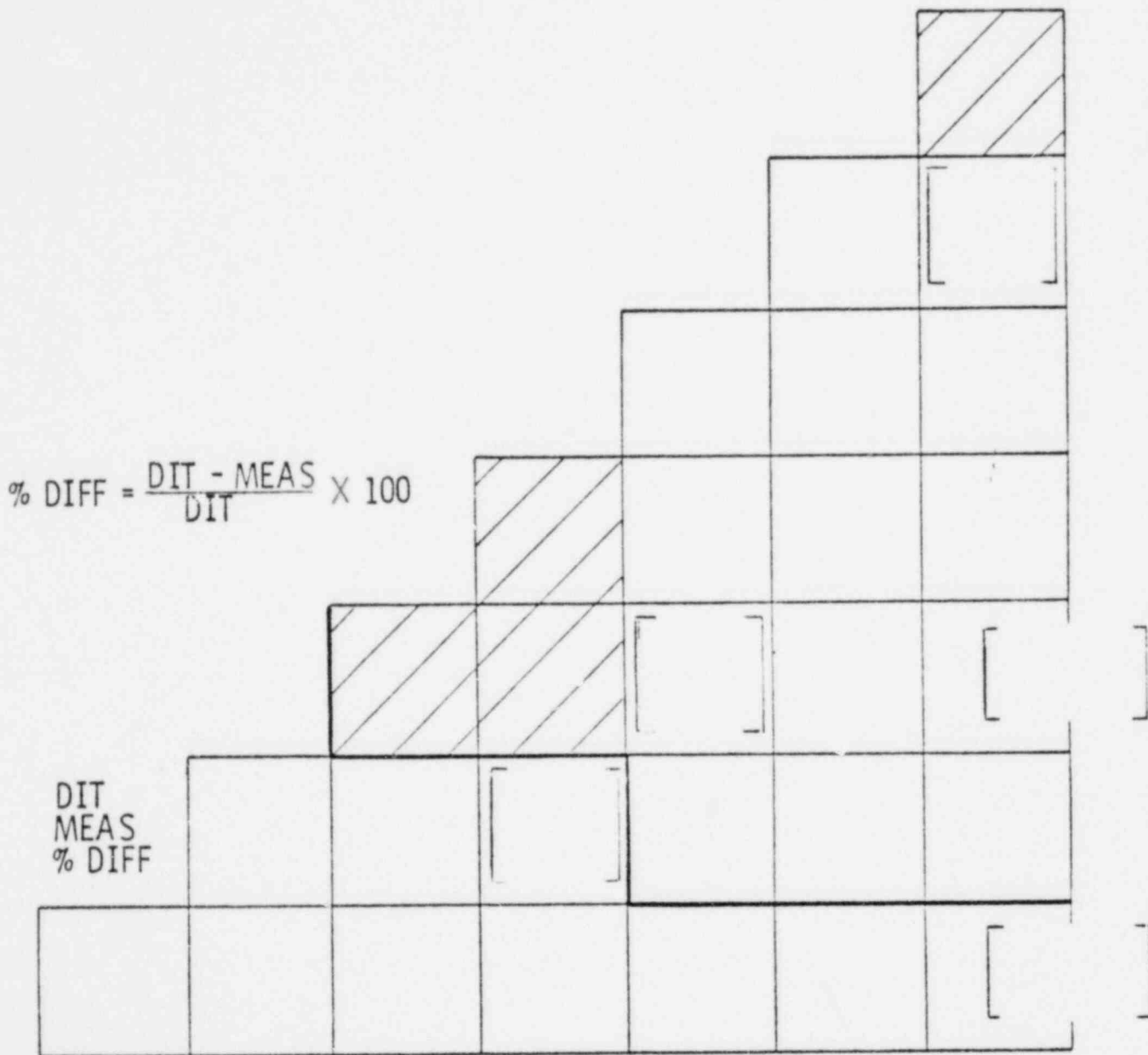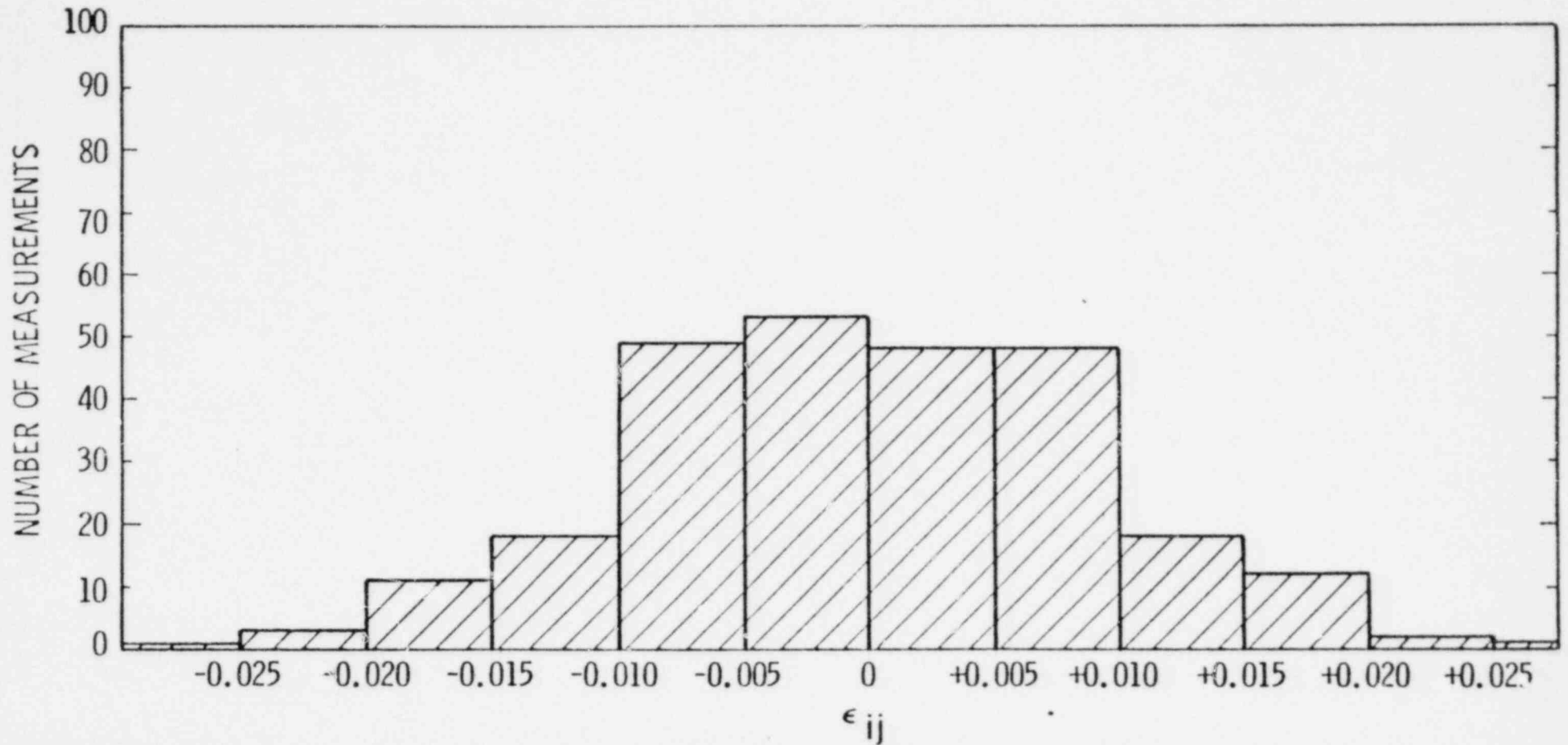KRITZ Pu-WH2 (HOT)

Figure 3-39

COMPARISON OF MEASURED/DIT BIAS AS A FUNCTION OF
HYDROGEN/URANIUM ATOM RATIO

Figure 3-40

SUMMARY OF RUNS 12, 32, 43, 53, 56
DISTRIBUTION OF ϵ_{ij}

EVALUATION OF UNCERTAINTY
IN THE NUCLEAR POWER PEAKING
MEASURED BY THE SELF-POWERED, FIXED IN-CORE
DETECTOR SYSTEM

PART III
COMBINED UNCERTAINTIES

III.1   COMBINED MF   REMENT AND SYNTHESIS UNCERTAINTIES

1.0   INTRODUCTION

The individual contributors of measurement and synthesis uncertainties to
the overall uncertainty are:
-The box power measu. ement uncertainty,   (Chapter I.3)
-The box power synthesis uncertainty,   (Chapter II.3.1)
-The pin/box synthesis uncertainty,   (Chapter II.3.2)
-The pin/box calculational uncertainty.   (Chapter II.3.3)
Numerical estimates for the respective component variances, tolerance
limits and the corresponding number of degrees of freedom, f, were derived
in the individual chapters refereced.   Table 1.I lists these quantities
for each of the three peaking factors F_q, F_r, and F_{xy}.   The units used in
the table are relative units, (%).

1.1   STATISTICAL MODEL

A one-sided lower tolerance limit for the random error in pin peaking
measured by INCA/CECOR is to be established for each of the three peaking
factors, F_q, F_r and F_{xy}.   Table 1.I contains separate estimates of the mean
error and variance for box peaking (F_{qBOX}, F_{rBOX}, F_{xyBOX}) and for pin/box
factors (F_p).   The pin peaking factors are related to F_{BOX} and F_p by:

$$F_q = F_{qBOX} \cdot F_p \tag{1.1}$$

$$F_r = F_{rBOX} \cdot F_p \tag{1.2}$$

$$F_{xy} = F_{xyBOX} \cdot F_p \tag{1.3}$$

One task of the statistical model is therefore to combine the uncertainties
of box peaking and pin/box factors in order to obtain the overall uncertainty.
This will be described in 1.1.3.

Each of the two factors on the right hand side of Eqs. (1.1 - 1.3) are associated with two independent components of the random error. The uncertainty in the pin/box factors has two components designated "calculation" and "synthesis" in Table 1.I. The model for combining these two components is described in 1.1.1. Each box peaking factor, F_{qBOX}, F_{rBOX} and F_{xyBOX} is associated with two independent components of the random error, viz., the measurement error and the synthesis error. The statistical model for combining these two is described in 1.1.2.

1.1.1   Combination of the Pin/Box Synthesis and Calculative Uncertainty

Since local pin peaking cannot be measured directly, box power is converted to peak pin power through the use of calculated pin/box factors, F_p, as reflected by Equations 1.1 - 1.3 and described in detail in II.1. The calculation is associated with a random error, $\delta F_p(C)$. The mean and variance of this error were established in II.3.3. The calculations on which F_p are based are incorporated in the CECOR and INCA libraries as described in II.2. This process gives rise to a synthesis error, $\delta F_p(S)$, which is in addition to the calculational error. The total error in the INCA/CECOR pin/box factor is therefore:

[   ]

[
            ] Since the sample means and variances of Table 1.I are either
unbiased or conservatively biased estimates, Eqs. (1.5) and (1.6) may be
used also for sample means and variances, i.e.:

[   ]

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\text{(1.7)}$$

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\text{(1.8)}$$

These relations are used in 1.1.3 to obtain the overall uncertainty.

1.1.2   Combination of Box Synthesis and Measurement Uncertainties

For each one of the box power peaking factors, Table 1.I contains an estimate
of the mean and the variance of the associated random error. This error
originates from the synthesis process and from the measurement itself. In
order to obtain the overall box power peaking uncertainty these two components
must be combined. The nature of the combination depends on the analytical
relationship between measurement and synthesis errors. This relationship
is implicit in the analytical methods for performing the radial coupling
and the axial expansion as described in II.1. It can be shown that the
combined error is of the form

[   ]

$$\left[\right] \tag{1.10}$$

$$\tag{1.11}$$

where $(\mu_{BOX}, \sigma_{BOX})$ characterizes the uncertainty in INCA box power and (μ_{BS}, σ_{BS}), (μ_{BM}, σ_{BM}) are the box synthesis and measurement uncertainties, respectively.

Since μ_{BM} is identical to zero Eq. (1.10) reduces to

$$\mu_{BOX} = \mu_{BS} \tag{1.12}$$

[

] Eq. (1.11)

can conservatively be replaced by:

$$\sigma_{BOX}{}^2 \leq \sigma_{BS}{}^2 + \sigma_{BM}{}^2 \tag{1.13}$$

Eqs. (1.12) and (1.13) show that the component means and variances combine additively. [

$$\left[\right]$$

1.1.3   Combination of Box Peaking and Pin/Box Factor Uncertainties

The box peaking factor uncertainty is characterized by (μ_{BOX}, s_{BOX}) and estimated by the method described in 1.1.2. The pin/box factor uncertainty

is characterized by (μ_p, σ_p) estimated by the method described in 1.1.1. The overall uncertainty for pin peaking will be characterized by (μ, σ) and the method for estimating it is described in this section.

Eqs. (1.1 - 1.3) show the single analytical relationship between the box peaking and the pin/box factors. It follows from these relationships that the random errors are related by:

If the relative units of Table 1.I are used, Eqs. (1.17) and (1.18) are therefore equivalent to

$$\mu = \mu_{BOX} + \mu_p \qquad (1.19)$$

$$\sigma^2 = \sigma_{BOX}^2 + \sigma_p^2 \qquad (1.20)$$

Rewriting Eqs. (1.19) and (1.20) in terms of individual components and using sample means and variances from (1.7), (1.8), (1.14) and (1.15) yields the final form for the overall, combined uncertainty:

$$\mu \cong \bar{D} = \bar{D}_{BS} + \bar{D}_{pC} + \bar{D}_{pS} \tag{1.21}$$

$$\sigma^2 \leq S^2 = S_{BS}^2 + S_{BM}^2 + S_{pC}^2 + S_{pS}^2 \tag{1.22}$$

1.1.4   Determination of a Tolerance Limit for the Combined Uncertainty

$\bar{D}$ and S from Eqs. (1.21) and (1.22) are estimates of the true distribution characteristics μ and σ and are therefore themselves subject to random errors. A one-sided, lower tolerance limit is constructed such that the INCA power distribution measurement uncertainty can be estimated on a 95%/95% probability/confidence level.

Table 1.I lists, for each individual component, the individual 95%/95% probability/confidence limits and the associated number of degrees of freedom (d.f.) as determined in the appropriate section of this report. The component d.f.'s will be used to construct the overall tolerance limit. Accordingly, each sample variance is assumed to be proportional to a chi-square distributed variable with the number of d.f. given in Table 1.I. Justification for these assumptions are given in the appropriate section of this report. [

                                                                    ] Finally, for all
other cases normality tests did not refute assumptions of normal distributions. Hence in all cases the assumption of chi-square distributed sample variances is justified.

Expressing each sample variance in Eq. (1.22) as proportional to a χ^2-distribution gives:

$$\frac{\sigma^2 \chi_f^2}{f} = \frac{\sigma_{BS}^2 \chi_{fBS}^2}{f_{BS}} + \frac{\sigma_{BM}^2 \chi_{fBM}^2}{f_{BM}} + \frac{\sigma_{pC}^2 \chi_{fpC}^2}{f_{pC}} + \frac{\sigma_{pS}^2 \chi_{fpS}^2}{f_{pS}} \tag{1.23}$$

Taking the variance of both sides in (1.23) yields the following relationship

$$\frac{\sigma^4}{f} = \frac{\sigma_{BS}^4}{f_{BS}} + \frac{\sigma_{BM}^4}{f_{BM}} + \frac{\sigma_{pC}^4}{f_{pC}} + \frac{\sigma_{pS}^4}{f_{pS}} \tag{1.24}$$

Finally, estimating the population variances by the sample variances yields the following relationship:

$$\frac{S^4}{f} = \frac{S_{BS}^4}{f_{BS}} + \frac{S_{BM}^4}{f_{BM}} + \frac{S_{pC}^4}{f_{pC}} + \frac{S_{pS}^4}{f_{pS}} \tag{1.25}$$

The overall number of d.f. is determined from (1.25) and the 95%/95% probability/confidence multiplier, $k_{95/95}$, is determined by Reference 1.1. The lower one-sided tolerance limit for the deviation between INCA/CECOR and the true power is then determined by:

$$\bar{D} - k_{95/95} S \tag{1.26}$$

1.2 NUMERICAL RESULTS FOR THE OVERALL INCA/CECOR MEASUREMENT UNCERTAINTY

Following the method described in 1.1 using the data from Table 1.I, the following numerical estimates result for each one of the uncertainties associated with F_q, F_r and F_{xy}.

The lower, one-sided tolerance limits of the overall uncertainty for core peaking factors measured by INCA/CECOR:

	$\bar{D}(\%)$	$S(\%)$	f	k	$\bar{D} - kS(\%)$
F_q					-6.24
F_r					-6.04
F_{xy}					-5.29

Thus the overall measurement uncertainty is such that there is a 95% probability that at least 95% of the true F_q, F_{xy}, and F_r values will be less than the values inferred from INCA/CECOR measurement plus 6.2, 5.3 and 6.0% respectively.

These uncertainties are to be used in conjunction with Technical Specification limits on F_q, F_{xy} and F_r to establish appropriate LCO and LSSS limits for plant operation and safety analysis.

1.3   REFERENCES

  1.1   "Factors for One-Sided Tolerance Limits and for Variables Sampling
          Plans," Sandia Corporation Monograph, SCR-607, 1963, Table 2.4.

Table 1.I

Summary of Measurement and Synthesis
Uncertainty Components+
For INCA/CECOR Core Peaking Factors

Parameter	Uncertainty Component	$\bar{D}$ (%)	S (%)	f	$\bar{D} - kS$ (%)
F_q	Box (meas)				
	(synth)				
	Pin (calc)				
	(synth)				
F_r	Box (meas)				
	(synth)				
	Pin (calc)				
	(synth)				
F_{xy}	Box (meas)				
	(synth)				
	Pin (calc)				
	(synth)				

+Note that the statistics in this table use the convention that deviations
 correspond to INCA/CECOR measurement minus truth. In Chapters I.3 and II.3
 the reverse sign convention is used.