NOV 18 1986

MASTER

HNPF

HALLAM NUCLEAR POWER FACILITY

PREOPERATIONAL TEST COMPLETION REPORT

WET EXCESS FUEL LOADING

AI-PC-710

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

HALLAM NUCLEAR POWER FACILITY

Post Critical Test Procedure

AI-PC-710

Wet Excess Fuel Loading

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:
A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.
As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Test Procedure Submitted for Approval 6/30/61 James E. Rhone
Date Atomic International

Test Procedure Reviewed 9/6/62 DE Simpson
Date Atomic Energy
Commission

Test Approved for Performance 8/25/62 James E. Rhone
Date Atomic International

Test Completed 10/14/62 James E. Rhone
Date Atomic International

Test Approved for Performance 8/25/62 RC Buntam
Date Atomic Energy
Commission

Test Completed 10/14/62 RC Buntam
Date Atomic Energy
Commission

HALLAM NUCLEAR POWER FACILITY
POST CRITICAL TEST COMPLETION REPORT,
WET EXCESS FUEL LOADING TEST.

AI-PC-710

Test and Analysis

by

J. R. ROHLFS

Evaluation

by

J. M. ZETTERBAUM

A T O M I C S I N T E R N A T I O N A L
A DIVISION OF NORTH AMERICAN AVIATION, INC.
P. O. Box 309 Canoga Park, California

CONTENTS

	Page
I. Purpose of Test	1
II. Discussion of Test Performance	1
A. Summary	1
B. Fuel Loading	8
C. Counting Procedure	15
D. Control Rod Calibration	17
E. Control Rod Manipulation	18
III. Analysis and Presentation of Results	20
A. General	20
B. Count Rate Data	30
C. 53 Element Loading	30
D. 56 Element Loading	32
E. 62 Element Loading	33
F. 68 Element Loading	33
G. 74 Element Loading	39
H. 83 Element Loading	40
I. 92 Element Loading	48
J. 101 Element Loading	50
K. 110 Element Loading	51
L. 125 Element Loading	61
M. 140 Element Loading	70
N. Removal of Fixed Rods	79
O. 140 Element Loading - Fixed Rods Removed	82
P. Conclusions	84
IV. Compliance With Test Completion Criteria	86
V. Evaluation	88
A. Introduction	88
B. Determination of Excess Reactivity	88
C. Summary	95

TABLES

	Page
I. Summary of Wet Excess Fuel Loading Data	3
II. Wet Excess Fuel Loading Sequence	9
III. Sequence of Rod Withdrawal	13
IV. Control Rod Positions	20
V. Rod Movements Required by Source Separation	22
VI. Rod Worths at the 68 Element Loading	35
VII. Comparison of Relative Rod Worths at the Calculated Critical Loading of 50 Elements and the 68 Element Loading . .	35
VIII. Sodium Worth Data - 68 Element Loading	36
XI. Rod Worths at the 83 Element Loading	44
X. Relative Rod Worths at Wet Critical, 68 Element, and 83 Element Loadings.	44
XI. Sodium Worth Data 83 Element Loading	45
XII. Rod Worths at the 83 Element Loading - Reactor Drained. .	47
XIII. Sodium Worth Data 110 Element Loading	54
XIV. Rod Worths at the 110 Element Loading - Reactor Drained .	55
XV. Gang Worths at the 110 Element Loading - Reactor Drained	58
XVI. Control Rod Positions During 120 Element Draining Test. .	62
XVII. Rod Worths at the 125 Element Loading - Reactor Drained and Fixed Rods Installed	67
XVIII. Sodium Worth Data 140 Element Loading	73
XIX. Estimate of Excess Reactivity - 140 Element Loading . . .	95

FIGURES

710-	1.	K _{eff} -1 vs B ² x 10 ⁶	4
710-	2.	Reactor Loading Face Shield Core Component and Process Channel	19
710-	3.	K _{eff} -1 vs Factor Proportional to Radial Buckling.	24
710-	4.	Per Cent Excess Reactivity vs Number of Fuel Elements. .	25
710-	5.	Approximate Gang 5 Integral Worth Curve Based on Worth of Successive Loading Increments	27

FIGURES (Continued)

	Page
710- 6. All Rods Banked Critical Position <u>vs</u> Number of Fuel Elements	29
710- 7. Inverse Count Rate ($\bar{I}$) <u>vs</u> Number of Fuel Elements.	31
710- 8. Sodium Worth <u>vs</u> Elevation of Sodium	38
710- 9. Approximate Gang 4 Integral Worth Curve Based on Worth of Successive Loading Increments	40
710-10. Gang 5 Integral Worth Curve at 83 Elements (Calibration with all other rods banked; the bank moving from 86.0" to 66.6" wet and 43.9" to 34.9" dry).	42
710-11. Sodium Worth <u>vs</u> Elevation of Sodium	46
710-12. Analysis of Rod Worths at the 83 Element Loading - Reactor Drained	49
710-13. Approximate Gang 3 Integral Worth Curve Based on Worth of Successive Loading Increments	52
710-14. Sodium Worth <u>vs</u> Elevation of Sodium	56
710-15. Gang 5 Worth Curve, 110 Element Loading, Dry Core . . .	57
710-16. CR-15 Worth Curve, 110 Element Loading, Dry Core . . .	59
710-17. Gang 5 Integral Worth Curve to 80" at 125 Elements - Reactor Drained	64
710-18. Sodium Worth at 125 Element Loading.	65
710-19. Integral Worth Curves for CR-15, -17, and -19 at 125 Element Loading, Reactor Drained and Fixed Rods Installed	69
710-20. Gang 3 Worth Curve, 140 Fuel Elements	72
710-21. "Split" Gang 1, Integral Rod Worths at 140 Element Loading, Reactor Drained	76
710-22. Gangs 1 and 2 Integral Worth Curves at the 140 Element Loading, Dry Core.	78
710-23. K_{eff} <u>vs</u> Number of Fuel Elements at 140 Fuel Element Loading.	89

HALLAM NUCLEAR POWER FACILITY
POST CRITICAL TEST COMPLETION REPORT
WET EXCESS FUEL LOADING TEST, AI-PC-710

I. PURPOSE OF TEST

The purpose of this test was to present the sequence to be followed for installing an operational loading of fuel in the HNPF sodium filled reactor. As a result of the fuel loading experiment, values for the following reactor parameters could be established:

- 1) The excess reactivity composing the operational loading of fuel.
- 2) The shutdown margin available to the reactor.
- 3) The total worth of the control rods in the reactor.
- 4) The reactivity worth of the sodium in the reactor.
- 5) The reactivity effect of moving the source element from the normal core position to a peripheral channel in a partially loaded core, and inserting a fuel element in the original source position.

II. DISCUSSION OF TEST PERFORMANCE

A. SUMMARY

Fuel loading commenced with a 53 element core which had been loaded previously as part of the Wet Critical Test, AI-P-1158. A total of eighty-seven additional elements were installed in the core in ten increments consisting of 3, 6, 6, 6, 9, 9, 9, 9, 15, and 15 elements, respectively, making the total core loading 140 fuel elements.

After each fuel loading increment, it was determined that the reactor would not go critical with the two most reactive control rods withdrawn. This was accomplished by fully withdrawing the two rods estimated to have the greatest reactivity worth, CR-1 (gang 5) and CR-6, and observing the sub-critical behavior of the neutron flux.

The reactivity worth of each incremental loading of fuel was measured by calibrating control rods. The control rod travel necessary to compensate for each fuel addition was calibrated by the differential period technique. The total excess reactivity for each fuel loading was taken as the sum of the individual reactivity increments for previous loadings. A summary of the wet excess fuel loading data is presented in Table I.

It can be shown that:

$$1 - k_{\text{eff}} \approx M^2 B^2 - (K_{\infty} - 1),$$

where $B^2 = \left(\frac{\pi}{H}\right)^2 + \left(\frac{2.405}{R - \delta}\right)^2$ = geometric buckling,

H = height of reactor with axial reflector savings,

δ = radial reflector saving,

R = effective core radius = $\sqrt{\frac{NA}{\pi}}$,

where N = number of fuel elements loaded and

A = cross sectional area associated with each fuel element.

For N < 95, A = 870 cm²

For N > 95, $R = \sqrt{\frac{95 \times 870}{\pi} + \frac{(N - 95)A}{\pi}}$ where A = 724 cm²

The change in the expression for R at N = 95 is due to the fact that there is one control rod for every 5 elements up to element 95, but no additional control rods for fuel elements in excess of 95.

Therefore, a plot of $1 - k_{\text{eff}}$ vs B^2 should approximate a straight line, with a slope equal to the migration area, M^2 , and a y-intercept equal to $(k_{\infty} - 1)$. In such a plot of the dry critical loading, M^2 was within 8 percent of its calculated value.

The experimentally determined reactivity vs fuel loading is plotted in Figure 710-1 as $k_{\text{eff}} - 1$ vs B^2 , where

$$\rho = (k_{\text{eff}} - 1)/k_{\text{eff}}$$

This plot departs from a straight line relationship, particularly near the full core loading of 140 elements. Two factors contribute to this departure,

TABLE I
SUMMARY OF WET EXCESS FUEL LOADING DATA

No. of FE Incore	Critical Control Rod Gang Position (inches) ***					All Rods Banked (inches)	No. of FE Loaded	Excess Loaded (cents)	Excess Loaded (%)	Total Excess (cents)	Total Excess (%)	Shut- down Margin
	1	2	3	4	5							
53	out	out	out	out	129.1	139.8	0	14.909	0.103	14.909	0.103	
56	out	out	out	out	90.6		3	69.636	0.483	84.545	0.586	
62	out	out	out	out	49.95	97.7	6	138.848	0.962	223.393	1.548	
68	out	out	out	115.0	in	84.8	6	146.561	1.016	369.954	2.564	
69	out	out	66.7	66.7	out	74.6	1					
74	out	out	out	84.6	in	76.6	5	107.804	0.707	477.758	3.311	
83	out	out	out	57.3	in	68.6	9	150.719	1.044	628.477	4.355	
83*	33.95	out	33.95	33.95	33.95	38.7	0					
92	out	out	out	34.75	in	62.65	9	141.769	0.982	770.246	5.338	
101	out	out	111.3	in	in	58.45	9	134.03	0.929	904.276	6.267	
110	out	out	76.9	in	in	54.45	9	96.488	0.669	1000.764	6.935	
110*	15.1	100.0	15.1	15.1	15.1	32.0	0					3.64
125	out	out	32.0	in	in	50.6	15	191.299	1.326	1192.063	8.261	
125*	121.6	in	in	in	in	29.0	0					2.45
125+	out	in	64.0	in	in	41.75	0	-147.19	-1.02	1044.873	7.241	3.47
125++	out	out	95.5	in	in	77.8	0					
140++	out	120.5	in	in	in	65.95	15	212.703	1.474	1257.576	8.715	
140+	109.6	in	in	in	in	35.9	0					3.1
140**	69.45	out	12	12	12	45.05	0					2.1

* drained

+ drained with fixed rods

++ fixed rods installed

** fixed rods removed

*** in = 0 inches

out = 156 inches

Figure 710-1. K_{eff}^{-1} vs $B^2 \times 10^6$

(1) direct summation of incremental reactivities overestimates total reactivity due to decrease in worth of the early fuel increments as the core size increases, and (2) as core loading increased the control rods near the center of the core were inserted to compensate for the excess reactivity. This shifted the neutron flux radially outward and increased the apparent worth of peripheral fuel elements.

Also plotted on Figure 710-1 is a multigroup calculation of $1 - k_{\text{eff}}$ vs B^2 . This plot is essentially linear, and at the smaller core loadings, where the corrections to the measured values are small, agrees fairly well with the experimental points. At a fuel loading of 140 elements, the calculated k_{eff} is 1.069, giving an excess reactivity of 6.5%. Because of the good agreement of the calculated excess reactivity with the measurements for the first few loading increments, it is believed that the excess reactivity in the 140 element core is about 6.5%.

Core shutdown margin and sodium worth were measured by a number of core sodium draining tests. Such tests, in which the reactor was drained of sodium and various reactivity measurements were made, were performed at the 68, 83, 110, 125, and 140 element loadings. At the 125 element core loading it was estimated that additional control rods would be required in the 140 element core to maintain the desired shutdown margin of $2\% \Delta k/k$ in the drained reactor. (It was later shown that the shutdown margin was underestimated at the 125 element loading). Therefore, three fixed poison columns were added near the core center to increase shutdown margin.

After 140 elements had been loaded, the shutdown margin was measured by three methods;

- a) inter-comparison of control rods (dry core)
- b) calibration of "split" gang 1 rods (dry core), and
- c) period calibration of gang 1 as a bank in the wet core and extrapolating to dry core.

These methods gave the shutdown margin as 2.49%, 3.15%, and 3.20%, respectively.

Method (a) consisted of measuring the total worth of the control rods in gang 1 by comparing each rod individually with gang 3, which was calibrated by period measurements, and summing the results for the 6 rods of gang 1.

It was determined that this method of measuring the shutdown margin gave too low a value, due to the radial tilting of the flux when one rod of gang 1 was inserted. Method (b) consisted of calibrating 3 rods of gang 1 moving downward with the other three (every other one to maintain radial symmetry) moving upward. The two halves of gang 1 were not worth exactly the same, due to shadowing within the gang itself. The total gang worth was taken as twice that of the half-gang with lower worth, or less than the sum of the two components. Method (c) was accomplished with gangs 3, 4, and 5, near the core center, fully withdrawn to minimize radial flux peaking. Gang 2 was used to compensate for the changed position of gang 1 during the period measurements.

Methods (b) and (c) are considered to be more accurate determinations of the shutdown margin, which in the dry, 140 element core with three fixed poison columns is $3.2\% \Delta k/k$.

It was estimated that the three fixed control rods could be removed from the core with ample shutdown margin remaining. Therefore, the fixed rods were removed from the reactor, and their worth was measured to be 0.9% in a dry core (see discussion on rod calibrations, below). Therefore, the shutdown margin was reduced to 2.3% , still greater than the desired 2% at the test temperature of 350 F . Subsequent temperature coefficient measurements indicate that the shutdown margin at operating temperatures will be $\sim 2.0\%$ in the dry core.

Measurement of the worth of the three fixed poison columns was made both upon insertion in the 125 element, dry core, and upon removal from the 140 element, wet core. The fixed rods increased the shutdown margin in the 125 element dry core, by 1.02% , so this represents the worth of these rods in this core.

At the 140 fuel element loading, the poison column worth upon removal was measured by noting the change in critical position of gang 1 before and after the poison column removal. Gang 1 had been calibrated again after the poison columns were removed. As expected, the worth of gang 1 decreased when the poison columns were removed, due to the shifting of reactor flux. Two values were thus obtained for poison column worth; 0.87% and 0.75% .

It is to be expected that poison column worth would be less in the 140 element wet core than in the 125 element dry core for two reasons. First, control rod worth is approximately proportional to the lattice migration area. The dry core migration area has been experimentally determined to be 485 cm^2 , and that for the wet core 435 cm^2 . Second, control rod worth is inversely proportional to the square of core radius. Therefore, the predicted worth of poison columns in the 140 element wet core, based on the measured value in the 125 element dry core, is $1.02 \times \frac{435}{485} \times \frac{125}{140} = 0.82\%$. This agrees with the above measured poison column worth. Again correcting the poison column worth by the migration area ratio, their worth in the 140 element dry core is between 0.83% and 0.96%.

Critical rod configurations at the 140 element loading showed that the insertion of gang 2 rods, from full out to full in, is adequate to compensate for draining the reactor of sodium. Gang 2 is worth 4% in the wet core and 4.4% in the dry core.

Gang 3 was used to compensate for the actual draining of sodium during the test at the 140 element loading. A dry core calibration of gang 3 shows the sodium to be worth 4.13%. The calibration was performed in the least perturbed state that could be arranged; gangs 2, 4, and 5 inserted and gang 1 being inserted as gang 3 was withdrawn. These measurements of sodium worth are somewhat less than the calculated worth of $5.4\% \Delta k/k$.

The best approximation to total control rod worth is the summation of the other measured values; namely excess reactivity (6.5%), sodium worth (4.1%), and shutdown margin (2.3%), or 12.9%. The shutdown margin and sodium worth are for a dry core, so the estimate of rod worth in a wet core is 12.2%. This compares with the theoretically calculated total rod worth of $14\% \Delta k/k$ and a total rod worth of $11\% \Delta k/k$ calculated from previous dry core measurements.

The neutron source relocation experiment was performed at the 68 element loading. The source was moved from its normal position near the core center to the periphery of the then active core and a fuel element was placed in the normal source position. The reactivity change due to this movement was determined from differences in critical control rod positions.

A fuel element in the source position was determined to be worth 122 cents with gang 5 withdrawn, and 69 cents with gang 5 inserted. During measurements, gangs 1 and 2 were full out and gangs 3 and 4 were at approximately 70 inches. The source was returned to its normal position following these measurements.

The major objectives of the wet excess loading test have been achieved and the measured core parameters are in reasonable agreement with calculations made prior to the loading.

B. FUEL LOADING

The Operations Manager was notified of the intention to start the test and his permission obtained. During the testing the Shift Leader was cognizant of the test status at all times, and his approval was required for all plant operations. The test was performed round-the-clock, seven days a week, with the Responsible Test Engineer directing the overall performance. Shift coordination of the test was by the Shift Test Engineer and the Shift Leader.

Testing under AI-PC-710 began immediately after the wet criticality test had been completed. (Refer to HNPF Test Completion Report, AI-P-1158, Wet Critical Test, for a discussion of reactor conditions at the start of this test.) Fuel was loaded into the reactor according to the sequence shown in Table II. The table also lists the specific core channel into which each particular fuel element (as designated by fuel accountability numbers) was inserted. The first loading increment was three elements. Only 3.6 w/o U^{235} 10M elements were loaded into the reactor, except for one element. A 3.45 w/o U^{235} element was the 42nd element loaded as a part of the wet critical test.

After an increment of fuel had been loaded, the count rate of each of the three incore nuclear instrument (ICNI) channels were recorded with all control rods inserted. The numerical average of the three count rates was used to calculate the inverse of the average count rate ($\bar{I}$). This inverse

TABLE II
WET EXCESS FUEL LOADING SEQUENCE

Loading Sequence	Core Position	Fuel Element Number	Shield Plug Number	Type of Fuel
(First Increment)				
54 **	C- 49	MF- 60	RP- 46	R *
55	C- 61	MF-105	RP- 91	R
56	C- 73	MF- 32	RP-157	R
(Second Increment)				
57	C- 57	MF- 33	RP-167	R
58	C- 69	MF-162	RP-162	R
59	C- 45	MF-154	RP-208	R
60	C- 93	MF-155	RP-147	R
61	C-109	MF-156	RP-117	R
62	C- 77	MF- 84	RP-150	R
(Third Increment)				
63	C- 95	MF- 85	RP-171	R
64	C-111	MF- 86	RP- 69	R
65	C- 79	MF- 87	RP-140	R
66	C- 97	MF- 88	RP-176	R
67	C-113	MF- 83	RP- 89	R
68	C- 81	MF- 90	RP-187	R
(Fourth Increment)				
69	C-104	MF- 95	RP-113	R
70	C- 91	MF- 91	RP-161	R
71	C-107	MF- 92	RP-216	R
72	C- 75	MF- 93	RP- 58	R
73	C- 88	MF- 94	RP- 31	R
74	C-120	MF- 96	RP- 49	R

* Regular fuel element.

** First 53 elements were loaded as part of AI-P-1158, Wet Criticality Test.

TABLE II (continued)

Loading Sequence	Core Position	Fuel Element Number	Shield Plug Number	Type of Fuel
(Fifth Increment)				
75	C-100	MF-161	RP-139	R-P *
76	C-116	MF- 97	RP-131	R
77	C- 84	MF- 98	RP- 81	R
78	C-101	MF-108	RP-152	R
79	C-117	MF- 99	RP- 59	R
80	C- 85	MF-100	RP-173	R
81	C-103	MF-101	RP-172	R
82	C-119	MF-102	RP-169	R
83	C- 87	MF-103	RP-122	R
(Sixth Increment)				
84	C- 76	MF-151	RP-206	R-P
85	C- 92	MF-104	RP- 66	R
86	C-108	MF-106	RP-106	R
87	C-112	MF- 89	RP-125	R
88	C- 80	MF-107	RP-168	R
89	C- 96	MF- 19	RP- 17	R-P-T*
90	C-147	MF-120	RP- 90	R
91	C-167	MF-121	RP- 80	R
92	C-127	MF-121	RP- 99	R
(Seventh Increment)				
93	C- 90	MF-111	RP- 70	R
94	C-106	MF-112	RP- 84	R
95	C- 74	MF-113	RP- 88	R
96	C- 89	MF-114	RP- 82	R
97	C-105	MF-115	RP- 86	R
98	C-121	MF-116	RP- 61	R
99	C- 99	MF-117	RP- 94	R
100	C-115	MF-118	RP- 75	R
101	C- 83	MF-119	RP- 62	R
(Eighth Increment)				
102	C- 98	MF-109	RP- 86	R
103	C-114	MF-157	RP-170	R-P
104	C- 82	MF-110	RP-108	R
105	C-145	MF-122	RP- 95	R
106	C-165	MF-124	RP- 64	R
107	C-125	MF-125	RP- 68	R
108	C-149	MF-126	RP- 78	R
109	C-169	MF-127	RP- 38	R
110	C-129	MF-128	RP-136	R

* R - Regular fuel element

* T - Thermocoupled fuel element (in-fuel T/C's)

* P - Premeasured fuel slugs

TABLE II (continued)

Loading Sequence	Core Position	Fuel Element Number	Shield Plug Number	Type of Fuel
(Ninth Increment)				
111	C-138	MF-129	RP-105	R *
112	C-158	MF-130	RP-164	R
113	C-170	MF-131	RP- 65	R
114	C-156	MF-132	RP-153	R
115	C-176	MF-133	RP-111	R
116	C-136	MF-134	RP-143	R
117	C-146	MF-135	RP-175	R
118	C-166	MF-136	RP-185	R
119	C-126	MF-137	RP-120	R
120	C-148	MF-138	RP- 92	R
121	C-168	MF-139	RP-102	R
122	C-128	MF-140	RP- 76	R
123	C-143	MF-141	RP- 96	R
124	C-163	MF- 59	RP- 73	R
125 **	C-123	MF- 43	RP- 37	R

* R - Regular fuel element

** After the 125th element had been loaded, three fixed control rods were installed in the core, to ensure adequate shutdown margin would be available at the operational loading. To allow loading of the fixed control rods in the desired core positions, the following fuel element moves were required:

Fuel Element No.	From	To
a) MF- 4	C- 8	C- 10
b) MF- 71	C- 10	C-178
c) MF-153	C- 5	C- 13
d) MF- 69	C- 13	C-131
e) MF- 64	C- 11	C-154

TABLE II (continued)

Loading Sequence	Core Position	Fuel Element Number	Shield Plug Number	Type of Fuel
	(Tenth Increment)			
126	C-151	MF-160	RP-103	R-P *
127	C-171	MF-159	RP-126	R-P
128	C-174	MF- 57	RP-215	R
129	C-134	MF- 67	RP-212	R
130	C-140	MF- 56	RP- 43	R
131	C-160	MF- 75	RP- 63	R
132	C-180	MF- 79	RP- 55	R
133	C-150	MF- 82	RP-100	R
134	C-130	MF-150	RP-142	R-P
135	C-144	MF-147	RP-190	R
136	C-164	MF- 73	RP- 41	R
137	C-124	MF- 38	RP- 21	R
138	C-137	MF- 74	RP- 87	R
139	C-157	MF-148	RP-123	R
140 **	C-177	MF- 76	RP- 74	R

* R - Regular fuel element

* P - Premeasured fuel slugs

** Fifteen more fuel elements were loaded (loading sequence 126 to 140), bringing the reactor to an operational loading of 140 fuel elements.

Measurements made following completion of the operational loading determined that the three fixed control rods were not required to allow adequate shutdown margin. Basis for the decision to remove the fixed rods is discussed in section III. O, (Conclusions), of this report.

Following removal of the fixed rods, the fuel elements in core positions C-137, C-157 and C-177 were moved to core positions C-8, C-11 and C-5, respectively.

count rate was plotted on a graph of inverse count rate vs fuel elements loaded from which an extrapolated critical loading (with all rods inserted) was obtained by extrapolating to $\bar{I}$ equals zero.

After each fuel addition and prior to withdrawing control rods, the control rod positions for criticality were predicted with limits which required cessation, review, evaluation and approval by the Test Engineer.

To comply with technical specifications and prove that the core could not go critical by withdrawing any two rods, CR-1 (gang 5) and CR-6 were fully withdrawn first. For this control rod configuration, the inverse of the average count rate ($\bar{I}$) was determined and plotted vs N. An extrapolation of this plot to $\bar{I}$ equals zero indicated the loading at which the core might be expected to become critical with these two control rods withdrawn. Control rods CR-1 and CR-6 were then fully inserted and rod withdrawal followed the sequence shown in Table III, until the core was brought critical.

TABLE III
SEQUENCE OF ROD WITHDRAWAL

Step	0% Withdrawn	50% Withdrawn	100% Withdrawn
A	Gangs 1, 2, 3, 4, 5		
B	Gangs 1, 2, 3, CR-9 and CR-12		Gang 5, CR-6
C	Gangs 4, 5	Gangs 1, 2, 3	
D		Gangs 1, 2, 3, 4, 5	
E		Gangs 4, 5	Gangs 1, 2, 3
F		Gang 5	Gangs 1, 2, 3, 4
G	Gangs 1, 2, 3, 4, 5		

The reactivity worth of an addition of fuel was considered equal to the reactivity corresponding to the difference in the critical positions of the control rods before and after adding the fuel increment. The excess reactivity worth of the fuel increment loaded was determined by calibrating this section of control rod(s) by the differential period technique. After determining the reactivity worth of a fuel loading increment, total excess reactivity (ρ_{ex}) was plotted vs the total number of fuel elements loaded (N).

The excess reactivity loaded was determined by summing the incremental worths of each loading. The last two points on this plot were extrapolated linearly to determine how many fuel elements could be loaded (1% reactivity or less) in the next increment.

It was recognized that the summing of the incremental worths, to determine total excess in the reactor, was not proper and that corrections had to be made for core size and arrangement. However, summing the values was a conservative approach and the corrections, which were necessarily theoretical, could be made at any subsequent time. Therefore, the method of summation was utilized in developing a value for the total excess loading in the reactor during the performance of the test.

The criticality extrapolations were utilized to load ten increments of 3, 6, 6, 6, 9, 9, 9, 9, 15 and 15 fuel elements, respectively. Table II also lists the individual elements that were loaded during each increment, including the core channels occupied. Reactor symmetry was achieved with each loading increment, at least to the extent of loading an equal number of elements into each 120 degree sector of the reactor.

After the fuel loading had been completed, dummy elements were placed in the unoccupied core channels to complete the core loading. The reactivity change due to addition of the dummy elements was also measured.

In addition, sodium draining experiments were performed at fuel loadings of 68, 83, 110, 125 and 140 fuel elements, to experimentally determine reactor shutdown margin and worth of sodium.

A source relocation test was performed as part of AI-PC-710. Following the reactor sodium draining test at 68 elements, the neutron source was moved from its normal position (C-4) to the periphery of the then active core (C-104) and a fuel element was placed in core position C-4. The reactivity was determined from differences in critical control rod positions. Following this, the source was returned to C-4 and the fuel loading continued.

C. COUNTING PROCEDURE

Indicated in the detailed, step-by-step procedure were certain counting rate statistical accuracies, such as 0.5%, 1%, 2%. The statistical accuracy in percent was found from the following formula:

$$\frac{1}{\sqrt{\text{total counts}}} \times 100 = 1\% \text{ statistical accuracy}$$

Thus, for a statistical accuracy of:

0.5%, 4×10^4 counts are required.

1%, 10^4 counts are required.

2%, 2.5×10^3 counts are required.

5%, 400 counts are required.

A 1% statistical accuracy was obtained for most measurements used in obtaining the inverse count rate.

The counting rates on the incore and source range instruments were determined at specified times during the loading procedure.

1. Sub-critical

After each addition of fuel with all rods inserted, the inverse of the average count rate ($\bar{I}$) of the three fission chambers was determined and plotted vs the number of fuel elements (N). Extrapolations of $\bar{I}$ to zero indicated the number of fuel elements required to attain criticality with all rods in and, thus, provided an indication of the shutdown capabilities of the control rods.

2. Period

The reactor was made super-critical after each loading of excess fuel, to obtain positive periods and, consequently, to determine the excess reactivity of each loading of excess fuel. The periods were determined using scalers with automatic printouts.

With counting rates of 1.36×10^5 cpm or greater, resolution time errors (0.5%) are introduced and count rates must be corrected using:

$$C_a = \frac{C_m}{1 - \tau C_m}$$

where,

C_a = adjusted or corrected count rate

C_m = measured count rate

τ = resolution time of the circuitry
(3.67×10^{-8} minute)

Periods were initiated from equilibrium count rates of about 500 cpm. The fission chambers were positioned at approximately eight feet above the core centerline to allow sufficient range for flux increases to provide adequate information for accurately determining reactor periods. (Refer to Test Completion Report AI-P-1158, Wet Critical Test, for a discussion of the chamber re-positioning and of the incore nuclear instrumentation in general.) The ICNI printout recorded the total count for 10-sec intervals. The approximate period was found from the following expression:

$$T = \frac{t_d}{\ln 2} = \frac{t_d}{0.693} = 1.443 t_d \quad (1)$$

where,

T = reactor period

t_d = doubling time

The period is related to the reactivity change by the inhour equation:

$$\rho = \frac{\lambda}{(T) k_{eff}} + \sum_{i=1}^m \frac{\beta_i}{1 + \tau_i T} \quad (2)$$

where,

ρ = reactivity

k_{eff} = effective multiplication factor

λ = neutron lifetime

m = number of delayed neutron groups

β_i = delayed neutron fraction for i^{th} group

T = reactor period

λ_i = the decay constant for the i^{th} group

A tabulated list of reactivity (in cents vs period) is available in Part D, Volume IV of the Operations Manual. This list was used to convert ratio of total counts during an asymptotic period directly to reactivity without first calculating the period and without plotting. Reactivity in cents (ρ cents) is related to reactivity in $\%$ $\frac{\Delta k}{k}$ as follows:

$$\rho \text{ cents} \times (.00693) = \frac{\Delta k}{k} \text{ percent}$$

Data for calculating periods were obtained at flux levels where nuclear heating does not yet exist (point A).

D. CONTROL ROD CALIBRATION

Control rod increments were calibrated by the differential period technique, as the core was loaded toward the operational loading, to determine the worth of each incremental fuel loading.

An example best explains the technique. With 56 fuel elements in the core, the control rod positions at criticality, with the neutron flux at or above point B (the minimum critical flux level) were; gangs 1, 2, 3 and 4 fully withdrawn and gang 5 at 88.1 inches (X_1). With 62 fuel elements and the neutron flux at or above point B, the control rod positions at criticality were; gangs 1, 2, 3, and 4 fully withdrawn and gang 5 at 48.55 inches (X_2). Thus, the total reactivity change resulting from the addition of the 57th, 58th, 59th, 60th, 61st and 62nd fuel elements was equivalent to the reactivity worth of gang 5 from X_2 to X_1 (ΔX). To find the reactivity associated with these six fuel elements it was necessary to calibrate gang 5 from X_2 to X_1 (ΔX).

First gang 5 was withdrawn from 48.55 to 52.0 inches, which produced a period of approximately 80 seconds. The reactivity associated with an 80 second period is 11.4 cents. Thus, the reactivity worth of gang 5 from 48.55 to 52.0 inches is 11.4 cents. The flux level was then brought to approximately point B again with gang 5 about one-half inch below its position, (about 51.5

inches). To accomplish this, gang 2 had to be inserted. Gang 5 was then withdrawn to 52.0 inches again and a long (590 sec) period obtained. After this period was measured, the flux was dropped below point B again, and a short (41 sec) period obtained by pulling gang 5 to approximately 56.5 inches. The reactivity associated with a 590 second period is 2.0 cents; with a 41 second period 18.2 cents. Thus, the reactivity worth of gang 5 from 52.0 inches to 56.5 inches is 16.2 cents (18.2 minus 2.0). The reactivity worth of gang 5 from 48.55 inches to 56.5 inches is 29.6 cents (18.2 plus 11.4). This long and then short period technique was continued until the desired portion of gang 5 was calibrated (from 48.55 to 88.1 inches in this example), and the reactivity worth of the fuel increment determined. This is the differential period technique of determining reactivity. For a detailed explanation of how period data are reduced to reactivities by the "Ratio Method", see HNPF Operations Manual NAA-SR-7500, Volume IV, Section D.

E. CONTROL ROD MANIPULATION

The control rods are grouped in five gangs consisting of 6, 6, 3, 3, and 1 rod in gangs 1, 2, 3, 4, and 5, respectively. Table IV lists the respective gang core position. Figure 710-2 shows a cross-sectional view of the reactor indicating the positions of the core components and process channels.

As the reactor loading progressed to the operational loading, the number of control rods that could be withdrawn without making the reactor supercritical decreased. The required ICNI data which could not be attained under the prevailing conditions were therefore eliminated and the plots discontinued. The two-rod, "no-critical" requirement and associated graph were available throughout the test, however, and a minimum of this plot and the "rods in" plot were maintained.

The control rods were operated as shown in Table III (preceding). The inverse average count rate ($\bar{I}$) was determined and plotted for steps A, B, and C. One plot was maintained for each of these control rod configurations. $\bar{I}$ vs the total number of fuel elements loaded (N).

NORTH

NOTE: Core positions prefixed by "C" have removable plugs in loading face shield

M-3 is the instrumented moderator can

LEGEND

- Control Rod
- ⊙ Source
- ⊠ Sodium Level Measuring Element
- ⊡ Sodium Temperature Measuring Element
- ⊙ Reflector Filler
- ⊕ In-Core Fission Chambers

Figure 710-2. Reactor Loading Face Shield Core Component and Process Channel.

TABLE IV
CONTROL ROD POSITIONS

Gang No.	Rod No.	Core Position
1	14	C- 78
	15	C- 86
	16	C- 94
	17	C-102
	18	C-110
	19	C-118
2	5	C- 38
	7	C- 44
	8	C- 50
	10	C- 56
	11	C- 62
	13	C- 68
3	2	C- 20
	3	C- 28
	4	C- 36
4	6	C- 16
	9	C- 24
	12	C- 32
5	1	C- 1

III. ANALYSIS AND PRESENTATION OF RESULTS

A. GENERAL

Several aspects of the wet excess fuel loading test required consideration throughout the analysis of the test. Among these is the source separation utilized during the loading increment calibrations (mentioned previously as a part of II. B). This and other items are discussed here from a qualitative standpoint to alleviate repetition during the subsequent description of analyses performed and results determined. A summary of conclusions resulting from analysis of all the test data obtained in Part III. P, Conclusions.

1. Source Separation

The ICNI channels respond with a count rate of approximately 6×10^5 cpm at criticality, when the chambers are positioned to give adequate indication of neutron population when the reactor is shutdown (15 - 25 cpm). The upper limit of the instruments is 1×10^7 cpm with an automatic scram at 9×10^6 cpm and an alarm at 7.5×10^6 cpm. Thus, the allowable range for period measurements was just slightly over one decade on the instruments with the instruments positioned as described above. It was, therefore, desirable to withdraw the antimony capsule portion of the source from within the beryllium sleeve to decrease the count rate at criticality. With the source separated, periods could be run from approximately 500 cpm (Point "B", minimum critical flux level) to 120,000 cpm (Point "A" beginning of nuclear heating, as indicated on the ICNI). This represents approximately 2.5 decades of range, which is sufficient for period measurements. Reactor shutdown required re-insertion of the source, of course, to give indication of the neutron population with rods inserted.

As the source was separated (at criticality), it was necessary to withdraw control rods to compensate for the manipulation, prior to 110 fuel elements. Subsequent to the 110 element loading, it was necessary to insert control rods to compensate for source separation. This phenomenon is felt to be due to the relative importance of the source neutrons becoming less significant than the poison effect of the source holder element, as the loading progressed and/or due to the axial flux peaking which resulted from the manner in which the reactor was loaded. Certainly, the importance of the center region of the reactor was decreased as fuel elements were loaded. With a small loading of elements in the reactor, the positive reactivity due to the source neutrons was relatively significant. It was, therefore, necessary to withdraw rods to insert reactivity in order to hold the reactor level constant with the source separated. The relative contribution of the source neutrons decreased to being equal to the poison removal effect somewhere between the 101 and 110 fuel element loadings. Thereafter, their contribution relative to the total reactor was less and it became necessary to insert

rods to hold the reactor critical, thus compensating for the removal of the poison contained in the source holder element.

The determination of the worth of each loading increment was determined from the "source-in" to "source-in" critical position. Table V lists the rod movements required to maintain criticality at the various fuel loadings upon separation of the source.

TABLE V
ROD MOVEMENTS REQUIRED BY SOURCE SEPARATION

No. of Elements Loaded	Critical Rod Gang	Position With Source Together	Position With Source Separated	*Required Rod Movement
53	5	129.1	122.0	-7.1
56	5	90.6	88.1	-2.5
62	5	49.95	48.55	-1.40
68	4	115.0	113.3	-1.7
74	4	84.6	84.0	-0.6
83	4	57.3	57.2	-0.1
92	4	34.75	34.4	-0.35
101	3	111.3	110.85	-0.45
110	3	76.9	76.95	+0.05
125	3	32.0	33.7	+1.7
140 (1)	2	120.5	121.3	+0.8
140 (2)	1	73.85	73.95	+0.1

* Plus indicates rod withdrawal

Minus indicates rod insertion

(1) Fixed rods in core.

(2) Fixed rods out of core

2. Temperature Corrections

The bulk sodium temperature in the primary heat transfer system was maintained at $350\text{ F} \pm 5\text{ F}$ during the test performance. On limited occasions, the spread increased to $\pm 10\text{ F}$, but was always corrected shortly thereafter. No corrections were required of the counting data obtained to compensate for these variations because of the following considerations: The temperature coefficient associated with the clean, initially loaded core is calculated to be 0.34 cents per degree F ($2.13 \times 10^{-5} \frac{\Delta k}{k}$ per degree F

measured in the dry zero power experiments, plus 0.59×10^{-5} added for sodium). Hence, the temperature swings previously described could be worth only ± 3.4 cents in the worst case (± 10 F). Further, it is quite reasonable to assume that, due to the length of time involved in the loading operations, the positive and negative quantities of these small variations would be equal.

Subsequent to this test, the temperature coefficient was measured as a part of the post critical testing program and was determined to be only about 0.1 cent per degree F. This lessened the errors imposed by the temperature variations described above.

3. Summing of Measured Excess Reactivities

The original method for determining total excess reactivity in the reactor was to sum arithmetically the reactivity values determined for each loading increment. This method was utilized throughout the loading, but with increasingly less reliability as the test progressed. Analysis of the data verified that this method introduced two errors. One was due to flux perturbations created by the insertion of the central control rods as the loading progressed. This tended to peak the flux at the outside of the core, thus, the measured (apparent) worth of each additional excess loading increment was greater than expected. The second error resulted from the enlarging of the active core as fuel was loaded, thus reducing the actual worth of each loading increment as succeeding increments were loaded.

A plot of k_{eff} vs the factor proportional to radial buckling demonstrated that the errors were cumulative. The first six loading increments determined a straight line for this plot, as was expected. Figure 710-3 shows how the summed reactivities continually diverged from the expected straight line values after the sixth loading increment. Reading the k_{eff} for 140 fuel elements on the expected curve and transposing to excess reactivity gives the expected value as 7.55 percent. Figure 710-4 shows the originally calculated excess reactivity vs number of fuel elements curve and the summed excess reactivities that were measured.

Plots of the incremental rod calibrations performed to measure the excess in each loading increment were maintained throughout the test.

Figure 710-3. K_{eff}^{-1} vs Factor Proportional to Radial Buckling

Figure 710-4. Per Cent Excess Reactivity vs Number of Fuel Elements

These graphs had the familiar rod integral worth curve shape when the incremental rod calibrations were connected. To recall, a specific reactor loading had an associated critical rod position on one gang of rods. Addition of fuel resulted in a new critical position. The rods were then calibrated over the change in critical rod position and the excess reactivity determined was the worth of the fuel elements loaded. Thus, the total gang was calibrated from 156 inches (full out) to zero inches (full in). Making a single plot of the increments, such as in Figure 710-5, develops an approximate rod integral worth curve. It was known throughout the test that such plots were not accurate. It is improper to sum the rod incremental worths since they were obtained with different core configurations.

4. Flux Shapes and Rod Configurations

Data obtained by various techniques during the test, with respect to rod worths and sodium worth, were not consistent. As the reactor loading approached the operational loading of 140 fuel elements, it was obvious that the choice of rod configurations for determining sodium and rod worths was very crucial, and that slight variations had large effects on the measured values.

Shadowing of control rods was definitely occurring and affecting test results. The insertion of any three adjacent gang 1 and gang 2 rods resulted in a decreased worth of those rods and an increased worth of the rods across the reactor. The conclusion drawn from these results was that rod calibrations by intercomparison was not meaningful.

At the 83, 110, 125, and 140 element loadings, all rods were banked for measurement in an attempt to develop a two region reactor which was compatible with theoretical calculations. Resulting flux distortions required such significant corrections that no real validity could be attached to the values derived. A description of some of the analyses performed on data obtained under these conditions is contained in sections III. H, K, and L. The all rods banked configuration did, however, develop qualitative information with respect to shutdown margin. A plot of this configuration vs number of fuel elements in the drained reactor was an excellent indication

Figure 710-5. Approximate Gang 5 Integral Worth Curve Based on Worth of Successive Loading Increments.

of shutdown margin in terms of inches of rod yet to be utilized, and also of the trend the shutdown margin was following as the loading progressed. Figure 710-6 shows the banked rod configuration data obtained for both the drained and filled reactor.

It became evident as the test progressed that both radial and axial flux distortions were being created by the various rod configurations. The flux can best be described as "quite mobile" and defies accurate measurement. This does not create any problem for the operating reactor, as the control rods will be positioned to develop minimum flux distortions and undergo little movement. The flux peaking and depressions that result from rod manipulations are an unfortunate circumstance that arises when rods are necessarily manipulated in attempted experiments.

The major conclusions drawn from analysis of the above situations are that:

- 1) The control rods must be operated as gangs (split gangs in the case of gangs 1 and 2, as long as adjacent rods are oppositely positioned) for both normal power operation and experimental measurements.
- 2) Meaningful rod calibrations can be performed but only with concentrically adjacent banks serving as the compensating rods.
- 3) All rod worth determinations must include a description of all non-involved rod positions, to allow evaluation of control rod shadowing in the configuration utilized for calibration.

Sodium worth could not be accurately determined until the operational loading of 140 fuel elements was reached. Accurate rod gang calibrations could be performed at this time which were required for determining the incremental worth of the sodium as it was drained. The maximum reactivity worth that can be associated with the sodium is 4.2 percent, the minimum 3.6 percent. Attempts to measure sodium worth prior to the full core loading resulted in inconsistent results, as will be discussed in the 68, 83, 110 and 125 element loading descriptions.

Figure 710-6. All Rods Banked Critical Position vs Number of Fuel Elements

B. COUNT RATE DATA

One plot of average inverse count rate vs fuel elements loaded for each of the following control rod configurations was maintained during the loading, as required by the test procedure.

- 1) All rods in
- 2) CR-1 and CR-6 withdrawn
- 3) All rods 50% withdrawn

Plot number 3) had to be discontinued at the 68 element loading, as positioning all rods at 50% withdrawn resulted in a positive reactor period.

CR-1 and CR-6 were completely withdrawn following the loading of each fuel increment, verifying that the reactor could not be made critical on the two most reactive rods, thus complying with HNPF Technical Specifications. Figure 710-7 displays the control curves developed by the count rate data obtained. No analysis of this information was made, other than that required to utilize the curves to denote proper fuel loading progress.

C. 53 ELEMENT LOADING

Initial criticality was attained in the sodium filled reactor at the 53 element loading with all rods withdrawn, except gang 4, which was at 134.0 inches. (Refer to test completion report AI-P-1158, Wet Critical Test.) The critical rod configuration was shifted to gang 5 controlling at 129.1 inches with gang 4 withdrawn, to initiate wet excess fuel loading test measurements.

Gang 5 was withdrawn to full out (156.0 inches) and a reactor period of 55.16 seconds was measured. This period corresponds to a reactivity of 14.909 cents. It was thus established that the 53 element loading contained an excess reactivity of 14.909 cents or 0.1035 percent. This was the first point plotted on the following loading curves:

$K_{\text{eff}} - 1$ vs factor proportional to radial buckling (Figure 710-3)

Percent ρ_{ex} vs number of fuel elements (Figure 710-4)

Figure 710-7. Inverse Count Rate ($\bar{I}$) vs Number of Fuel Elements

K_{eff} was determined by the following relationship:

$$K_{\text{eff}} = \frac{1}{1 - \rho_{\text{ex}} (\%)}$$

The buckling factor was derived from the following:

$$\beta_n = \frac{10^5}{(R + S)^2}$$

where,

$$S = 22 \text{ cm}$$

$$R = \sqrt{NA/\pi}$$

$$N = \text{Number of fuel elements}$$

$$A = 870 \text{ cm}^2$$

NOTE

For loading above 95 fuel elements, the value for "A" changes to 725 cm^2 as discussed in Part II. A.

D. 56 ELEMENT LOADING

The loading of the 54th, 55th, and 56th elements resulted in a change in gang 5 critical position from 129.1 inches to 90.6 inches. The calibration of this increment of rod determined that these three fuel elements were worth 69.636 cents in reactivity. The addition of this amount and the previously measured 14.909 cents established the total excess reactivity in the reactor at the 56 element loading as 84.545 cents. This point was plotted on the excess loading curve and allowed the first extrapolation to determine the number of fuel elements that could be loaded in the next increment. The criterion of linearly extrapolating the last two measured points to one percent greater than the last point, to determine the maximum number of fuel elements to be loaded in the next increment, was used throughout the test. In this instance, the extrapolation showed six more fuel elements could be loaded (Figure 710-4).

Extrapolation of the two excess loading curve points in the negative direction (to the excess equals zero point) also gives a better definition of where minimum criticality would have occurred. This extrapolation indicated that criticality would have occurred with all rods withdrawn at 52.4 fuel elements.

The first approximation of sodium worth was made at this time. Excess reactivity in the reactor at this loading was 84.545 cents, as a result of loading 3.6 fuel elements in addition to those required for minimum criticality. This gives a worth of approximately 0.16 percent for each of the elements loaded. Wet criticality was achieved with 21 more fuel elements in the reactor than were required for dry criticality. The first excess loading was immediately adjacent to the wet criticality elements. Hence, the worths of the elements must be similar. Thus, the 21 additional elements represent approximately 3.4 percent reactivity. This value, it was found later, was somewhat low, but represented a good initial value for sodium worth. Final sodium worth determined at the 140 element loading was approximately four percent.

E. 62 ELEMENT LOADING

Calibration of gang 5 from 49.95 inches to 90.6 inches was required to determine the excess reactivity associated with the six elements loaded to bring total reactor loading to 62 fuel elements. The excess reactivity measured was 138.848 cents, or 1.548 percent. This point was plotted on Figure 710-4, the one percent extrapolation made, and the next loading determined to be six elements.

F. 68 ELEMENT LOADING

1. Excess Reactivity Determination

Critical rod positions for the 68 fuel element reactor loading were: gang 5 full in, gang 4 at 115.0 inches, and gangs 1, 2, and 3 full out. The loading of the six elements in the third increment was therefore equivalent in worth to gang 5 from 49.95 inches to full in and gang 4 from 156.0 inches to

115.0 inches. These sections of rods were calibrated by the differential period technique, again compensating with gang 2. The excess reactivity measured was 146.561 cents (1.016 percent). Total reactivity in the reactor was 369.954 cents. As shown in Figure 710-4, the summed excess reactivities were beginning to deviate slightly from the calculated loading curves. Some effort was expended at this time on determining the proper correction factors to apply to the excess reactivity determinations (as discussed previously in Part III. A. 4). The next loading was again extrapolated to be six fuel elements. It was decided that the 68 element loading was the appropriate place to perform the source relocation test and the first sodium draining experiment.

2. Sodium Draining Test

The first sodium draining test was initiated at the 68 element reactor loading. The first step of the procedure, which required a calibration of gang 5 in the wet core, was waived in favor of the approximate worth curve developed by summing the fuel loading increments (Figure 710-5). The final section of the curve had been supplied by this loading and it was felt that the information contained in the worth curve would not be significantly changed by the calibration data. This line of thinking was later proven to be in error.

Intercomparison of gangs 1 and 2, and of each rod in gangs 3 and 4, with the "calibrated" gang 5 in the wet core gave the rod worth results as shown in Table VI. The measured 1781 cents is equivalent to 12.34 percent.

The apparent discrepancy in the worth of the individual gang 3 and gang 4 rods can be attributed to the poison effect of the source element. The three rods which are lower than the average 187 ± 2 cents rod worth are that amount lower corresponding to their position relative to the source. CR-12 is the closest and sees a worth of 29 cents less. CR-3 and CR-4 are further away from the source element and see a lesser deviation (20 cents) from the average. Considering the source element, the measured rod worths are in excellent agreement with each other.

TABLE VI
ROD WORTHS AT THE 68 ELEMENT LOADING

Gang	Control Rod	Individual Worths	Gang Worths	Relative Worths
5	CR-1	323 cents	323 cents	1.0
4	CR-6 CR-9 CR-12	185 cents 186 cents 158 cents	529 cents	1.64
3	CR-2 CR-3 CR-4	189 cents 168 cents 166 cents	523 cents	1.62
2	All 6 rods	302 cents	302 cents	0.93
1	All 6 rods	104 cents	1104 cents	0.32
Total Rod Worth			1781 cents	

Table VII compares the relative worths of the rods at the 68 element loading and the predicted values for a wet critical reactor of 50 elements. The existing difference is probably due to the difference in reactor size. In the 68 element reactor, fuel is closer to gangs 1 and 2, thus, increasing the flux in that region. Thereby, the relative worth of gangs 1 and 2 is increased at the expense of gangs 3, 4, and 5.

TABLE VII
COMPARISON OF RELATIVE ROD WORTHS AT THE CALCULATED
CRITICAL LOADING OF 50 ELEMENTS AND THE 68 ELEMENT LOADING

Gang	Predicted Relative Worths at 50 Elements	Measured Relative Worths at 68 Elements
5	1.0	1.0
4	1.7	1.64
3	1.7	1.62
2	0.6	0.93
1	0.2	0.32

Critical rod positions at the start of the reactor draining were: gangs 1, 2, 4 and 5 full out, and gang 3 at 58.4 inches. As poison was removed from the reactor by the sodium draining, gang 5 was inserted to maintain criticality. The draining was stopped at numerous levels and the gang 5 critical position obtained precisely. The worth of the sodium drained at any of these levels was considered to be equivalent to the change in critical position of gang 5. Gang 5 incremental worth was obtained from Figure 710-5; the worth curve developed from the summation of the loading increments. Table VIII lists the sodium levels at which the critical rod position was obtained precisely, gang 5 position, incremental gang 5 and/or sodium worth, and total worth to that level.

TABLE VIII
SODIUM WORTH DATA - 68 ELEMENT LOADING

Sodium Level	Elev (ft. - in.)	Gang 5 Position (inches)	Increment Worth (cents)	Total Worth (cents)
6' above mod cans	1425' - 0"	156.0	0	0
3' above mod cans	1422' - 0"	152.7	1	1
Top of mod cans	1419' - 0"	140.7	4.5	5.5
Top of active core	1417' - 0"	135.0	4	9.5
Core $\mathbb{C}$ plus 5' - 4"	1415' - 7"	128.5	5.5	15
Core $\mathbb{C}$ plus 4' - 0"	1414' - 3"	109.0	26	41
Core $\mathbb{C}$ plus 2' - 8"	1412' - 11"	85.35	56	97
Core $\mathbb{C}$ plus 1' - 3"	1411' - 6"	55.3	107	204
Active core centerline	1410' - 3"	0 *	137	341

* Gang 4 also inserted to 133" to maintain critical

The test was prematurely terminated due to operational difficulties, when the sodium level was at the core centerline. Figure 710-8 is the sodium worth curve obtained using the results of this initial draining test.

3. Source Relocation Test

The following critical control rod configurations were obtained prior to relocating the source:

<u>Case I</u>		<u>Case II</u>	
Gang 1	out	Gang 1	out
Gang 2	out	Gang 2	out
Gang 3	77.7 inches	Gang 3	123.9 inches
Gang 4	77.7 inches	Gang 4	123.9 inches
Gang 5	out	Gang 5	in

The reactor was shutdown and the source moved to core position C-104. C-104 was a core position just outside the fueled part of the partially loaded reactor. A fuel element was inserted in the source core position (C-4), bringing the total reactor loading to 69 fuel elements. Criticality was then achieved with the following rod configurations:

<u>Case I</u>		<u>Case II</u>		<u>Case III</u>	
Gang 1	out	Gang 1	out	Gang 1	out
Gang 2	out	Gang 2	out	Gang 2	out
Gang 3	66.7 inches	Gang 3	104.7 inches	Gang 3	77.7 inches
Gang 4	66.7 inches	Gang 4	104.7 inches	Gang 4	77.7 inches
Gang 5	out	Gang 5	in	Gang 5	56.05 inches

Comparison of Case I before and after the source and fuel element exchange shows that with gang 5 out, the exchange required the insertion of gangs 3 and 4 a distance of 11 inches to maintain criticality. Case II demonstrates that the required rod movement was 19.2 inches with gang 5 in. The worth of gangs 3 and 4 at 120 inches is, of course, considerably less than at 70

Figure 710-8. Sodium Worth vs Elevation of Sodium

inches. Comparison of the "before" Case I and Case III shows that the manipulation required the insertion of gang 5 from 156.0 inches to 56.05 inches or a distance of 99.95 inches.

Gangs 3 and 4 were calibrated from 66.7 inches to 77.7 inches with gang 5 out and compensating with gang 1. The reactivity change associated with this calibration was 122.368 cents. Gangs 3 and 4 were calibrated from 104.7 inches to 123.9 inches with gang 5 in, again compensating with gang 1. The worth of the source-fuel element manipulation was determined to be 69.648 cents by this measurement. It was concluded that the decrease in apparent worth of the fuel element installed in C-4 was due to the shadowing effect of gang 5 when it is inserted.

Utilizing Figure 710-5 to obtain the worth of the gang 5 position change, as recorded in Case III and the "before" Case I, the manipulation was worth 201 cents. This was the first definite indication that the gang 5 worth curve obtained by summing the worth of the fuel loading increments was not valid. It was not unexpected, as core size had increased appreciably from the starting point of 53 fuel elements. Reviewing the dry excess testing data showed the gang 5 worth to be even greater in the smaller dry core (3.8 percent @ 42 fuel elements).

G. 74 ELEMENT LOADING

Loading of the reactor from 68 to 74 elements resulted in an excess reactivity contribution of 107.804 cents, measured by calibrating gang 4 from 84.6 inches to 115 inches, (the amount of rod insertion required to compensate for loading the six elements). Gang 5 was fully inserted during the calibration, gangs 1 and 3 withdrawn, and gang 2 compensating. Calibration of this loading increment allowed continuation of Figure 710-9, which was initiated the previous loading, when it was necessary to insert gang 4 to 115 inches to maintain criticality.

The excess reactivity determined for this loading was plotted on the excess loading graphs Figures 710-3 and -4. The procedural one percent extrapolation indicated nine fuel elements could be loaded as the next

Figure 710-9. Approximate Gang 4 Integral Worth Curve Based on Worth of Successive Loading Increments.

increment. This point caused the first significant "break" in the linear loading curve (Figure 710-4) and demonstrated that the loading was progressing similarly to that calculated. The buckling plot (Figure 710-3) continued on the same curve.

H. 83 ELEMENT LOADING

1. Excess Reactivity Measurements

Gang 4 critical position changed from 84.6 inches to 57.3 inches with the increase to 83 fuel elements in the reactor (gangs 1, 2, 3, out; gang 5 fully inserted). Calibration of this section of gang 4 determined the excess reactivity increase to be 150.719 cents, bringing the total excess reactivity to 628.471 cents (4.36 percent). Gang 2 was used to compensate during the calibration. The one percent extrapolation showed that nine more elements could be loaded (Figure 710-4).

2. Sodium Drain Test

Gang 5 was calibrated by the differential period technique and an intercomparison with all other rods was performed prior to draining the reactor at the 83 element loading. Total worth of gang 5 was 224.63 cents. All other rods were banked during the calibration and period compensation was accomplished by the total bank. Figure 710-10 shows the integral worth curve developed for gang 5.

The choice of all rods banked as the compensating gang was based on attempting to develop a two-region core which would lend itself to analytical calculations and determination of correction factors. It was subsequently determined that the all rods banked configuration resulted in significant axial flux peaking under the bank and depression above the bank. Also, the bank moved from 86.0 inches to 66.6 inches as compensation during the calibration of gang 5. Developing proper correction factors was thus made very difficult. Repeating the "measuring with banked rods" technique at the 110 element loading ultimately resulted in shifting the criteria for loading fuel. Dry core shutdown margin measurements were utilized to govern

Figure 710-10. Gang 5 Integral Worth Curve at 83 Elements (Calibration with all other rods banked; the bank moving from 86.0" to 66.6" wet and 43.9" to 34.9" dry)

loading progress, as opposed to determination of rod worths and excess reactivity in the reactor. This shift of emphasis will be discussed in more detail at the 110 fuel element loading.

Table IX lists the data from intercomparison of each of the rods with calibrated gang 5 prior to draining. The difference in the worths of the individual gang 3 and gang 4 rods is again attributed to the source element. The consistency in the deviation between the 68 and 83 element loadings substantiates the original theory of the source element creating the disturbance. The variation in gang 1 rod worths is due to CR-15, -17, and -19 being surrounded by more fuel than the partially covered rods CR-14, -16, and -18.

Total gang worths and relative worths are listed in Table X. The 68 element loading relative worths and predicted wet critical relative worths are also listed to allow comparison.

Sodium draining was started with the reactor critical and all rods at 65.0 inches, except gang 2, which was fully withdrawn to act as safety rods. The removal of poison (sodium) from the reactor was compensated for by the insertion of gang 5. When gang 5 reached nearly full in, the draining was stopped and gang 5 was again withdrawn to the all rods banked position (except gang 2), inserting the bank to maintain criticality. Sodium incremental worths were determined according to gang 5 position at the various sodium levels. Total worth was obtained by summing the increments. Final bank position was 33.95 inches, except gang 2 which was still full out. Table XI lists the draining results.

Following the draining of sodium, all rods (including the gang 2 safeties) were banked at 38.7 inches to maintain criticality. Gang 5 was then re-calibrated to determine what effect draining the sodium had on its worth. Similarly, intercomparisons were made with all the other rods. The all rods banked technique was employed in these measurements, with the bank being at 38.7 inches initially.

The worth of gang 5 in the dry core was determined to be 293.2 cents, appreciably higher than that of the wet core. Figure 710-10 shows both the wet and dry integral worth curves. Using the dry calibration integral worth curve for determining the incremental sodium worth during draining

TABLE IX
ROD WORTHS AT THE 83 ELEMENT LOADING

Gang	Control Rod	Worth Above Bank * (cents)	Worth Below Bank * (cents)	Total Worth (cents)
5	CR - 1	36	189	225
4	CR - 6	26	127	153
	CR - 9	26	127	153
	CR-12	23	122	145
3	CR - 2	28	131	159
	CR - 3	26	122	148
	CR - 4	26	121	147
2	CR - 5	7	41	48
	CR - 7	7	42	49
	CR - 8	8	44	52
	CR-10	7	40	47
	CR-11	7	38	45
	CR-13	7	38	45
1	CR-14	2	16.5	18.5
	CR-15	5	28	33
	CR-16	2	18	20
	CR-17	4	30	34
	CR-18	2	16	18
	CR-19	4	26	30
Total (cents)		253	1316.5	1569.5
(%)		1.75	9.12	10.87

* Bank position was 68.6 inches

TABLE X
RELATIVE ROD WORTHS AT WET CRITICAL,
68 ELEMENT, AND 83 ELEMENT LOADINGS

Gang	83 Element Worth	83 Element Relative Worth	68 Element Relative Worth	Predicted Wet Critical Relative Worth
5	225	1.0	1.0	1.0
4	451	2.0	1.64	1.7
3	454	2.0	1.62	1.7
2	286	1.3	0.93	0.6
1	153.5	0.7	0.3	0.2

TABLE XI
SODIUM WORTH DATA 83 ELEMENT LOADING

Sodium Level	Elev.	Gang 5 Position (inches)	Bank Position (inches)	Incremental Worth (cents)	Total Worth (cents)
6' above Mod Cans	1425' - 0"	65	65	0	0
3' above Mod Cans	1422' - 0"	64.9	65	0	0
Top of Mod Cans	1419' - 0"	64.7	65	1	1
Top of Active Core	1417' - 0"	64.1	65	2	3
Core $\mathbb{C}$ plus 5' 4"	1415' - 7"	63.9	65	4	7
Core $\mathbb{C}$ plus 4' 0"	1414' - 3"	63.4	65	5	12
Core $\mathbb{C}$ plus 2' 8"	1412' - 11"	61.0	65	11	23
Core $\mathbb{C}$ plus 1' 3"	1411' - 6"	55.4	65	29	52
Active Core $\mathbb{C}$	1410' - 3"	42.7	65	82	134
Core $\mathbb{C}$ minus 1' 5"	1408' - 10"	5.2	65	179	313
Core $\mathbb{C}$ minus 2' 4"	1407' - 11"	10.2	56.75	149	462
Core $\mathbb{C}$ minus 3' 2"	1407' - 1"	8.7	51.0	132	594
Core $\mathbb{C}$ minus 3' 11"	1406' - 4"	2.5	46.15	114	708
Core $\mathbb{C}$ minus 4' 9"	1405' - 6"	1.0	41.7	96.5	804.5
Core $\mathbb{C}$ minus 5' 6"	1404' - 9"	8.2	37.55	75	879.5
Bottom of Active Core	1403' - 6"	14.45	33.95	53	932.5
Bottom of Mod Cans	1401' - 0"	13.85	33.95	1	933.5

shows the sodium worth to be 8.45 percent. These values are, of course, much higher than expected and established that further analyses were required. Figure 710-11 depicts the sodium worth curve utilizing the calibration of gang 5 prior to draining.

Intercomparison of all the rods in the dry core with the calibrated gang 5 (dry) gave the results shown in Table XII.

It was concluded from the data obtained that the axial flux distortions due to the all rods banked configuration resulted in higher apparent sodium and rod worth values than really existed. The movement of the bank during the calibrations accentuated the flux peaking and drove the measured values still higher.

Figure 710-11. Sodium Worth vs Elevation of Sodium

TABLE XII
ROD WORTHS AT THE 83 ELEMENT LOADING, REACTOR DRAINED

Gang	Control Rod	Worth Above Bank	Worth Below Bank	Total Worth
5	CR- 1	135	158	293
	CR- 6	104	100.5	204.5
4	CR- 9	104	104.5	208.5
	CR-12	*102		202
	CR- 2	111	106	217
3	CR- 3	106.5	103	209.5
	CR- 4	105	100	205
	CR- 5	35	36	71
	CR- 7	34	37	71
2	CR- 8	36	37.5	73.5
	CR-10	35	36	71
	CR-11	* 35	40	75
	CR-13	* 35	38.5	73.5
	CR-14	* 12	19	31
	CR-15	* 22	28	50
1	CR-16	12	19	31
	CR-17	22	28	50
	CR-18	* 12	19	31
	CR-19	* 22	26	48
Totals		1079.5	1136.0	2215.5

* Not measured; values derived by extrapolating similar rod values according to previous relative worths.

The only information derived from the draining experiment was that the shutdown margin in the dry core was represented by all rods being at 38.7 inches at criticality. In the event of a scram in the dry core, all nineteen control rods would each fall 38.7 inches to shutdown the reactor.

In an attempt to interpret the data obtained from the wet and dry banked rods configuration, the following was done:

- 1) Differential worth data were developed from the gang 5 dry and wet calibration data.
- 2) The original gang 5 worth curve, as determined by the fuel loading instruments, was considered as most representative of the true flux shape in the reactor with all rods in or out (all other rods were out when the curve was being developed). A flux shape curve was developed

by plotting the square root of the gang 5 differential rod worths vs rod position (considering flux to be proportional to the square root of differential rod worth). This curve was considered as the flux shape in the reactor with all rods in.

- 3) Gang 5 dry and wet curves were similarly developed and superimposed over the "true" flux shape curve. Figure 710-12 displays the resulting curves. The dry and wet curves were normalized to the area under the true flux shape curve before they were plotted. The normalization assumes the areas (rod worth) under the "true" curve to be constant.
- 4) Ratios were then utilized to correct the measured values for shutdown margin. The rod worth under the 38.7 inch bank was measured to be 7.9 percent in the dry core. Thus, 7.9 percent was the measured shutdown margin. Figure 710-12 curves show that if this shutdown margin had been measured with all rods in (flux returned to true shape), the value determined would have been four percent.
- 5) Similarly, the rod worth under the 68.6 inch bank in the wet core represented sodium worth plus shutdown margin. This value was measured to be 9.12 percent. The value under the "rods in" curve shows that the 9.12 percent value would really be 8.8 percent with the reactor shutdown and drained. The difference in the two bank positions represents sodium worth in the dry core. This value can be seen to be 4.8 percent. At this time, the numbers thus established were considered crude but at least indicative of reactor condition.

It was concluded that adequate shutdown margin was available to load the reactor to two percent greater excess. These loadings would still allow the "no-less-than two percent" shutdown margin value to be maintained as required by the loading procedure.

I. 92 ELEMENT LOADING

Criticality was achieved with gangs 1, 2, and 3 full out, gang 5 full in, and gang 4 at 34.75 inch with the reactor loaded to 92 fuel elements. The excess reactivity added to the reactor by increasing the core loading from 83 to 92 elements was determined by calibrating gang 4 from 34.75 inch to 57.3 inch. Gang 4 position at 83 fuel elements was 57.3 inch, all other gangs positioned as described above. Gang 2 was used to compensate during the calibration.

Figure 710-12. Analysis of Rod Worths at the 83 Element Loading - Reactor Drained

The nine elements added to the 83 element reactor resulted in an excess reactivity increase of 141.769 cents. The plotting of this point on the linear excess loading curve (Figure 710-4) shows the curve to continue on the same slope, establishing the next loading as nine fuel elements. The k_{eff}^{-1} vs buckling factor graph (Figure 710-3) displays the continued divergence of total measured excess loaded from the theoretical value.

Figure 710-9 was continued with the data obtained at the 92 element loading. It was apparent that the next loading would complete this curve; gang 4, as well as gang 5, would, hence, be in during measurements made with subsequent fuel loadings.

J. 101 ELEMENT LOADING

Critical rod positions at the 101 fuel element loading were: gangs 1 and 2 full out, gangs 4 and 5 full in, and gang 3 at 111.3 inches. To determine the excess reactivity added by this seventh fuel loading increment, it was necessary to calibrate gang 4 from full in to 34.75 inches (the critical position with 92 elements), and gang 3 from 111.3 inches to full out. These calibrations were accomplished, compensating with gang 2, and an excess of 134.03 cents was obtained.

The linear plot of excess loading vs the number of fuel elements, Figure 710-4, shows this 101 fuel element point to make the curve "break" only slightly. The one percent extrapolation again showed that only nine fuel elements could be loaded in the next increment. The buckling plot continued to diverge, indicating that summation of incrementally determined excess reactivities was improper. This plot also supported the assumption that the linear plot was showing an incorrect result of loading the increment. Considering that the divergence was in the conservative direction (indicating more excess reactivity than really existed) the continuation of the loading, based on the plots as drawn, was safe.

The approximate integral worth curve for gang 4 (Figure 710-9) was completed at the 101 element loading. This plot was a reasonable approximation of gang 4 worth and was utilized in predicting control rod positions

for criticality and period measurements. An ultimate evaluation of the loading increment curves became available at the operational loading (140 fuel elements), following a complete calibration of gang 3. The results of that calibration and the comparison to the loading increment curve is discussed in detail under Section M., 140 Element Loading.

K. 110 ELEMENT LOADING

1. Excess Reactivity Measurements

Gang 3 was positioned at 76.9 inch to achieve criticality at the 110 element loading. Gangs 1 and 2 were full out and gangs 4 and 5 full in. The change of 34.4 inch in gang 3 position was calibrated to determine the amount of excess reactivity contributed by the nine elements contained in the eighth loading increment. Gang 2 was used to compensate during the calibration. The excess added was 96.488 cents.

Addition of the 110 element loading point to the excess loading curves (Figure 710-3 and -4) showed a "break" and approach to the shape of the calculated curve on the linear plot, as was expected. The buckling graph, on the other hand, showed the continued divergence.

The gang 3 approximate integral worth curve, initiated at the 101 element loading (Figure 710-13) was continued to 76.9 inch using the data obtained from the period measurements.

A sodium draining test was set up at the 110 element loading, to verify the required 2 percent shutdown margin. A measured (but uncorrected) 2.6 percent excess had been added since the measurement of 4 percent (minimum) shutdown margin at the 83 element loading.

2. Sodium Draining Test

Prior to performing the sodium draining test at the 110 element loading, the fuel loading criteria were re-evaluated. It was determined that the major requirement was to ensure a two percent shutdown margin. This decision was based on the fact that inconsistent data were being obtained (subsequently determined to be due to the extremely "mobile" quality of reactor

Figure 710-13. Approximate Gang 3 Integral Worth Curve Based on Worth of Successive Loading Increments.

flux) with respect to rod worths, sodium worth, and excess reactivity. Therefore, a direct measurement of shutdown margin was advisable. This was accomplished by calibrating the rods out of the reactor with the reactor drained.

In addition to performing the direct measurement of shutdown margin in the dry reactor, the technique of determining rod worths and sodium worth as used at the 83 element loading, was utilized in the 110 element reactor in an attempt to discover any possible correlations. Gang 5 was not re-calibrated in the wet core as it was at the 83 element loading, because it was felt the worth would not be changed appreciably.

Gang 2 was fully withdrawn (to serve as safety rods) and all remaining rods were banked at 48.7 inches, just prior to the start of sodium draining. The removal of poison by the draining of sodium was compensated for by the insertion of gang 5. The incremental sodium worths were then determined from the gang 5 calibration curve. When gang 5 reached full in, it was withdrawn to the bank position and the bank inserted to maintain criticality. The cycle was then repeated.

When the sodium had been drained to approximately three feet below the core centerline, gang 5 was full in and the bank was positioned at 15.0 inches. It was apparent that the fully withdrawn gang 2 worth was more than two percent. All six rods of gang 2 were then positioned at 100.0 inches, which returned all other rods banked to 29.8 inches to maintain criticality. Draining was then continued until the reactor was dry. Rod positions at that time were; all rods at 15.1 inches, except gang 2 which was at 100.0 inches. Table XIII lists the results of the draining.

The large number of critical positions in Table XIII is due to gang 5 worth below the bank being very small. Each time gang 5 was inserted, it had to be withdrawn and criticality regained with the bank. As a result, in many instances, gang 5 had to be fully inserted to compensate for draining as little as an inch of sodium. Subsequent draining procedures were modified to eliminate the requirement for determining so many critical positions.

Total measured worth of the sodium is higher than the real value, because the 83 element gang 5 calibration curve was used to measure the increment worths. The assumption that gang 5 worth would not be changed

TABLE XIII
SODIUM WORTH DATA 110 ELEMENT LOADING

Sodium Level	Elev. (ft. - in.)	Gang 5 Position (inches)	Bank Position (inches)	Incremental Worth (cents)	Total Worth (cents)
6' above mod. cans	1425' - 0"	48.55	48.7	0	0
3' above mod. cans	1422' - 0"	48.55	48.7	0	0
Top of mod. cans	1419' - 0"	48.4	48.7	1	1
Top of active core	1417' - 0"	48.2	48.7	1	2
Core $\mathbb{C}$ plus 5' - 4"	1415' - 7"	47.75	48.7	1.5	3.5
Core $\mathbb{C}$ plus 4' - 0"	1414' - 3"	46.5	48.7	4	7.5
Core $\mathbb{C}$ plus 2' - 8"	1412' - 11"	42.4	48.7	16.5	24
Core $\mathbb{C}$ plus 1' - 3"	1411' - 6"	31.25	48.7	44	68
Active core	1410' - 3"	16.5	46.3	97	165
Core $\mathbb{C}$ minus 1' - 1"	1409' - 2"	22.4 *	39.5	163	328
Core $\mathbb{C}$ minus 1' - 10"	1408' - 5"	50.8 **	20.0	88.5	416.5
Core $\mathbb{C}$ minus 2' - 10"	1407' - 5"	0	25.3	39	455.5
Core $\mathbb{C}$ minus 3' - 0"	1407' - 3"	8.0	23.4	30	485.5
Core $\mathbb{C}$ minus 3' - 1"	1407' - 2"	14.5	22.1	17	502.5
Core $\mathbb{C}$ minus 3' - 2"	1407' - 1"	4.0	21.5	28.5	531
Core $\mathbb{C}$ minus 3' - 3"	1407' - 0"	8.0	20.25	22	553
Core $\mathbb{C}$ minus 3' - 4"	1406' - 11"	3.0	19.3	23.5	576.5
Core $\mathbb{C}$ minus 3' - 5"	1406' - 10"	6.0	18.0	19	595.5
Core $\mathbb{C}$ minus 3' - 6"	1406' - 9"	3.0	17.0	19	614.5
Core $\mathbb{C}$ minus 3' - 7"	1406' - 8"	3.0	16.0	17	631.5
Core $\mathbb{C}$ minus 3' - 10"	1406' - 5"	3.0	15.0	15	646.5
Core $\mathbb{C}$ minus 4' - 1"***	1406' - 2"	14.2***	29.8	38.5	685
Core $\mathbb{C}$ minus 4' - 4"	1405' - 11"	5.0	28.3	46	731
Core $\mathbb{C}$ minus 4' - 7"	1405' - 8"	2.0	26.6	42.5	773.5
Core $\mathbb{C}$ minus 4' - 10"	1405' - 5"	4.5	24.85	36	809.5
Core $\mathbb{C}$ minus 5' - 1"	1405' - 8"	2.0	23.4	33	842.5
Core $\mathbb{C}$ minus 5' - 4"	1404' - 11"	2.9	21.9	30	872.5
Core $\mathbb{C}$ minus 5' - 7"	1404' - 8"	5.1	20.4	25.5	897
Core $\mathbb{C}$ minus 5' - 10"	1404' - 5"	5.0	19.3	23	920
Core $\mathbb{C}$ minus 6' - 6"	1403' - 9"	5.0	18.2	21	941

* Gang 5 at 71.3 prior to insertion

** Gang 5 at 111.0 prior to insertion

*** Gang 2 inserted to 100" from 156" at this point

significantly by the addition of 27 elements was in error. Gang 5 had decreased in worth appreciably, as was to be determined in the dry core. Figure 710-14 shows the sodium worth as derived from the 83 element wet calibration of gang 5.

Criticality was achieved in the dry core, with all rods banked at 32.0 inches. This value was plotted in Figure 710-6, and shows that shutdown margin was represented by all 19 rods at the 32.0 inches level. Figure 710-6 also shows that only 6 inches insertion of the all rods banked configuration was required to compensate for the measured 2.6 percent excess added since the 83 element loading.

Gang 5 was calibrated in the dry core, from full in to full out, compensating with all other rods banked. The bank was moved from 35.1 inches (with gang 5 at 0 inches) to 28.0 inches (with gang 5 at 156.0 inches). The total worth of gang 5 was thus determined to be 247.9 cents. Figure 710-15 shows the developed integral worth curve. The worth of gang 5 in the dry 83 element core was 293.2 cents. Ratios of these values, utilized to obtain a 110 element core worth for the wet gang 5 (multiply the ratio by the 83 element gang 5 wet worth), yield an approximate worth of 190 cents. Utilizing this curve in determining the worth of the sodium increments, as opposed to the 83 element wet curve (which was used), the seemingly high value of 6.5 percent for sodium worth would be decreased to a value of 5.5 percent.

Intercomparison of control rods with gang 5 calibrated in the dry core was performed with all remaining rods banked at 32.0 inches. Table XIV lists the results.

TABLE XIV
ROD WORTHS AT THE 110 ELEMENT LOADING - REACTOR DRAINED

Gang	Control Rod	Worth Below Bank	Worth Above Bank	Total Worth
5	CR- 1	100.4	147.5	247.9
4	CR- 6	79.7	140.4	220.1
3	CR- 3	77.8	135.4	213.2
2	CR- 5	37.6	59.4	97.0
1	CR-14	25.6	44.4	70.0
1	CR-15	24.1	38.4	62.5

Figure 710-14. Sodium Worth vs Elevation of Sodium

Figure 710-15. Gang 5 Worth Curve, 110 Element Loading ,
Dry Core.

Prior to the measurements in Table XIV, it had been demonstrated that individual rods within a gang were of similar worth, except gang 1, which demonstrated two rod worths at this time. The rod worths in Table XV were developed for the five gangs, by multiplying each of the measured values by the number of rods in the associated gang.

TABLE XV
GANG WORTHS AT THE 110 ELEMENT LOADING -
REACTOR DRAINED

Gang	Worth Below Bank	Worth Above Bank	Total Worth
5	100.4	147.5	247.9
4	239.1	421.2	660.3
3	233.4	406.2	639.6
2	225.6	356.4	582.0
1	<u>149.1</u>	<u>248.4</u>	<u>397.5</u>
Total (cents)	947.6	1579.7	2527.3
(%)	6.6	10.9	17.5

The above measured rod worths were considerably higher than anticipated. Non-validity of measurements made with the all rods banked configuration, which results in flux distortions and subsequent tilting was thus verified. These results also showed direct measurement of shutdown margin, in a configuration other than all rods banked, as a very desirable part of the test.

The reactor was made critical with gang 1 full out, gangs 2, 3, 4, and 5 full in, except for one rod of gang 2 (CR-8), which was at 123.1 inches. Thus, shutdown margin was represented by the withdrawal of six complete rods and 123.1 inches of a seventh rod. One rod of gang 1 (CR-15) was run full in and one rod of gang 3 (CR-4) was withdrawn to 90.0 inches to compensate. CR-15 was then calibrated to full out, by the differential period technique, compensating with CR-4. CR-15 was determined to be worth 92 cents. Figure 710-16 shows the integral worth curve for CR-15. Each of the remaining gang 1 rods was then intercompared with CR-15 to obtain their worths. Following is a list of the results of the intercomparison:

Figure 710-16. CR-15 Worth Curve, 110 Element Loading, Dry Core.

<u>Control Rod No.</u>	<u>Worth (cents)</u>
14	25.5
15	92
16	139.5
17	66.5
18	37
19	20

The test was terminated before the worth of CR-8 could be determined by intercomparison with CR-15. Test termination was caused by operational limitations imposed on reactor vessel temperatures while in the drained condition. The worth of CR-8 was estimated by averaging the worths of the adjacent gang 1 rods and ratioing it up by the relationship of gang 2 to gang 1, as determined by the all rods banked intercomparison. It was felt that, although the actual values as determined by the all rods banked configuration were non-valid, the relative worths could be considered as reliable. CR-8 worth at 123.1 inches was thus estimated to be 150 cents.

Total shutdown margin (gang 1 plus CR-8 at 123.1 inches) was equal to 3.67 percent at the 110 element loading, according to these calculations. An excess reactivity of 1.67 percent could be added to the reactor and the required two percent shutdown margin would still be maintained. This was the criterion on which the next fifteen fuel elements were loaded.

Although not completely recognized at the time, a significant flux tilt was imposed on the reactor when the shutdown margin configuration of gang 1 full out and CR-8 at 123.1 inches was arranged. The wide variation in gang 1 individual rod worths was the first positive indication that flux tilting or control rod shadowing was having an effect. This effect was investigated in detail at the 125 and 140 fuel element loadings. It was concluded at the 110 element loading that the shadowing effect of the rods would result in a conservative determination of shutdown margin, when determined by the intercomparison method. This conclusion was verified by measurements made at the 140 fuel element (operational) loading.

L. 125 ELEMENT LOADING

1. Excess Reactivity Measurements

Gang 3 critical rod position with 125 fuel elements loaded into the reactor was 32.0 inches. Gangs 1 and 2 were full out and gangs 4 and 5 were full in. Gang 3 was calibrated from 32.0 inches to 76.9 inches (gang 3 critical position at 110 elements), to determine the excess reactivity added to the reactor by the ninth loading increment (15 elements). The calibration showed that 191.299 cents (1.33 percent) had been added. Gang 2 was used to compensate during the calibration.

The 191.299 cents measured by the differential period technique was considerably higher than anticipated. Figure 710-4 shows that not only did the linear excess loading curve not continue to bend as was expected, but the slope actually increased with the fifteen elements loaded. These results indicated that only 0.34 percent of the additional total allowable excess loading, as determined at 110 fuel elements (shutdown margin of 3.67 percent minus 2 percent), was now available for loading (1.67 percent minus the 1.33 percent measured at this loading). Thus, another sodium draining test was required, to measure the shutdown margin directly and determine if fixed control rods would have to be installed in the reactor prior to further fuel loading. The rods would be required to maintain the 2 percent shutdown margin (minimum) if 1.33 percent had been loaded and at least 12 more elements were to be installed in the reactor to reach the operational loading.

2. Sodium Draining Test

The sodium was drained at the 125 fuel element core loading, to obtain a direct measurement of shutdown margin. No calibration of control rods was performed prior to draining, as determination of sodium worth was not a prime reason for performing the draining at this point. However, critical rod positions were observed and recorded during the draining. This information was combined with a gang 5 calibration in the dry core to give an indication of maximum sodium worth. Critical rod positions during the

draining operations are shown in Table XVI. With the reactor drained, all rods were in, except gang 1 at 121.6 inches. Shutdown margin was thus represented by six gang 1 rods at 121.6 inches.

TABLE XVI
CONTROL ROD POSITIONS DURING 125 ELEMENT DRAINING TEST

Sodium Level+ (ft. - in.)	Elev.	Rod Positions				
		Gang 5 (inches)	Gang 4 *	Gang 3 *	Gang 2 (inches)	Gang 1 (inches)
25' - 0"	1415' - 6"	120	in	in	117.8	out *
26' - 9"	1413' - 9"	78	in	in	117.8	out *
27' - 6"	1413' - 0"	in *	in	in	117.8	out *
27' - 6"	1413' - 0"	150	in	in	96.8	out *
28' - 4"	1412' - 2"	78	in	in	96.8	out *
28' - 11"	1411' - 7"	19.5	in	in	96.8	out *
28' - 11"	1411' - 7"	150	in	in	79.65	out *
29' - 11"	1410' - 7"	78	in	in	79.65	out *
30' - 2"	1410' - 4"	in *	in	in	79.65	out *
30' - 2"	1410' - 4"	150	in	in	59.1	out *
31' - 1"	1409' - 5"	78	in	in	59.1	out *
31' - 7"	1408' - 11"	25	in	in	59.1	out *
31' - 7"	1408' - 11"	150	in	in	in	147.9
33' - 1"	1407' - 5"	781	in	in	in	147.9
34' - 6"	1406' - 0"	18.1	in	in	in	147.9
34' - 6"	1406' - 0"	150	in	in	in	97.0
36' - 6"	1404' - 0"	78	in	in	in	97.0
38' - 9"	1401' - 9"	75.6	in	in	in	97.0
38' - 9"	1401' - 9"	in *	in	in	in	121.6

* Fully inserted

+ Measured from top of reactor loading face shield.

Gang 5 was calibrated from full in to 80 inches withdrawn, compensating with gang 1 rods CR-15, -17, and -19 as a bank. The worth of gang 5 to this point was 95.767 cents. Figure 710-17 shows the partial integral worth curve developed for gang 5. Sodium worth was determined by extrapolating the dry gang 5 curve from 80 inches to full out (Figure 710-17), allowing the sodium worth curve as a function of sodium level to be plotted (Figure 710-18).

Each of the gang 1 rods was intercompared from 121.6 inches to full in, with the partially calibrated gang 5. The results were as follows:

<u>Control Rod No.</u>	<u>Worth (cents)</u>
14	55
15	58
16	63
17	62.5
18	67
19	<u>48</u>
Total	353.5 (2.45%)

This measurement of shutdown margin indicated that 1.22 percent excess had been loaded by increasing the reactor loading from 110 to 125 elements (shutdown margin 3.67 percent - 2.45 percent = 1.22 percent). Shutdown margin of 1.33 percent had been measured by the calibration method.

The variation in gang 1 rod worths again showed that control rod shadowing was affecting measurements. CR-15 worth had been determined to be 58 cents by intercomparison with gang 5. To verify that shadowing was occurring, CR-14 (gang 1 rod adjacent to CR-15) was inserted, and gangs 3 and 4 withdrawn to 20.4 inches to compensate. CR-15 was again compared to gang 5 and the worth determined to be 31 cents, or about one-half of the original value. CR-16 was also inserted (other gang 1 rod adjacent to CR-15), and gangs 3 and 4 withdrawn to 29.95 inches to compensate. A re-comparison of CR-15 with gang 5 showed its worth had decreased to only 13 cents, less than one-fourth of the original value.

Figure 710- 17. Gang 5 Integral Worth Curve to 80" at 125 Elements
Reactor Drained

Figure 710-18. Sodium Worth at 125 Element Loading

CR-14, -15, and -16 are separated by gang 2 control rods. The above test demonstrated that even adjacent gang 1 rods have significant shadowing effects on each other. The intercomparisons at 110 fuel elements, which utilized CR-8 (a gang 2 rod) at 123.1 inches therefore, undoubtedly contained large discrepancies due to shadowing effects.

The above results lessened the validity of the 3.67 percent shutdown margin measured at the 110 element loading, and removed some credibility from the measured 2.45 percent shutdown margin at this loading, even though the comparisons were made in a much more symmetrical pattern. The difference in CR-18 (67 cents) and CR-19 (48 cents) worths indicated that some effect was present in the reactor, causing the discrepancies.

Considering the above results, a decision was reached to install three fixed poison columns in the reactor. Criticality was achieved in the dry reactor with all rods at 29.0 inches, just prior to reactor shutdown for insertion of the fixed poison columns.

3. Fixed Control Rods Data

Three fixed control rods (control rods without drive mechanisms) were installed in core positions C-5, C-8, and C-11. The installations were made with the reactor drained at the 125 fuel element loading. The premeasured fuel element in C-5 was moved to core position C-13 and the regular fuel element in C-13 was placed in empty channel C-131. The instrumented (long probe) fuel element in C-8 was moved to C-10 and the regular fuel element in core position C-10 was placed in the previously empty C-178. The regular element in C-11 was placed in channel C-154.

Criticality was achieved in the dry, 125 element core (with fixed rods installed), with gang 3 at 64.0 inches, gang 1 out, and all other rods full in. The installation of the fixed rods thus resulted in the addition of that amount of negative reactivity corresponding to the amount of positive reactivity which would be added by withdrawing gang 1 from 126.1 inches to full out, plus pulling gang 3 from full in to 64.0 inches. (Recall that critical rod positions in the dry, 125 element core, without fixed rods, were all rods in except gang 1 at 126.1 inches.)

Gang 5 was calibrated from full in to full out, compensating with gang 1. Gangs 2 and 4 remained fully inserted and gang 3 at 66.4 inches (source separated position) during the calibration. Gang 5 worth was determined to be only 43.51 cents in the dry core. Figure 710-17 shows the integral worth of gang 5 under these conditions, as well as showing gang 5 worth prior to fixed rods.

The installation of the three fixed rods resulted in a decreased in worth of gang 5 from 80 inches to full in (only 80 inches had been calibrated prior to fixed rods) of 62.867 cents (95.767 cents - 32.9 cents). It was thus verified that the three fixed rods had depressed the flux significantly in the center of the reactor and undoubtedly peaked it near the outer ring of control rods.

Each of the gang 1 and gang 3 rods which were out at criticality were inter-compared with the calibrated gang 5. The results of the inter-comparisons are as listed in Table XVII.

TABLE XVII
ROD WORTHS AT THE 125 ELEMENT LOADING -
REACTOR DRAINED AND FIXED RODS INSTALLED

Gang	Control Rod No.	Worth (cents)
1	14	59.7
1	15	61.75
1	16	60.0
1	17	67.5
1	18	63.25
1	19	58.0
3	2	44.0 *
3	3	44.5 *
3	4	42.5 *
Total Worth		501.20

* From 66.4 inches to full in

The total worth of gang 1 was 370.2 cents, of gang 3 from 66.9 inches to full in, 131.0 cents. The measured shutdown margin was the sum of these values, namely, 501.2 cents, or 3.47 percent. When compared to the 2.45 percent shutdown margin measured before fixed rod installation, the insertion of the three fixed rods in the reactor had a combined effect of 1.02 percent negative reactivity worth.

Three critical positions (40 inches, 80 inches, 120 inches) were obtained on CR-15, -17, and -19, during the intercomparison with gang 5. The finding of the three critical positions allowed integral worth curves to be drawn for the three rods. Figure 710-19 displays the three integral worth curves. These three rods were then intercompared as a bank against gang 5 in an attempt to determine the significance of shadowing effects in symmetrical rod configurations. Control rods CR-15, -17, and -19 were pulled as a bank from 76.7 inches to 97.7 inches. Gang 5 had to be inserted from 103 inches to full in, to compensate. The worth of gang 5 from 103 inches to full in was 39.5 cents, corresponding to the worth of the three-rod bank from 76.2 inches to 97.7 inches. Summing the values from the three integral worth curves on Figure 710-18, from 76.2 inches to 97.7 inches, shows that a 42 cent change resulted from the maneuver. Thus, a discrepancy of 5 percent in the measured reactivity worth was noted in the symmetrical reactor, and attributed to the shadowing that occurs when intercomparing individual rods.

The rods banked critical position was 41.75 inches. This was 11.75 inches higher than prior to fixed rod installation, demonstrating that shutdown margin had been appreciably increased. This critical bank position would not be so high, however, if all rods were, in fact, banked. Since three of the rods extend through the bank to full in, with a 22 control rod reactor, improper comparison of the 41.75 inches bank position with the 38.7 inches bank position associated with the 83 element drained reactor should be avoided. Excess reactivity in the amount of 4.1 percent (as measured) had been added since that loading, drawing the all banked position down from 38.7 inches to 29.0 inches. The addition of 1.02 percent more shutdown margin did not move this same bank back up to 41.75 inches. It moved 19 rods of lesser worth to 41.75 inches, while holding three new rods in. The reactor was re-filled with

Figure 710-19. Integral Worth Curves for CR-15, -17, and -19 at 125 Element Loading, Reactor Drained and Fixed Rods Installed

sodium, following the above measurements, in preparation for loading 15 more fuel elements. Critical rod positions in the 125 element, fixed-rod, sodium filled reactor were; gangs 1 and 2 full out, gangs 4 and 5 full in, and gang 3 at 95.5 inches. Installation of the fixed rods, therefore, contributed negative reactivity corresponding to gang 3 from the prefixed rods critical position of 33.7 inches (source out) to the new position of 95.5 inches. Figure 710-13, which is a calibration of loading increments by gang 3, as well as an approximation of gang worth, shows this rod movement to be equivalent to 153 cents (1.06 percent). This value agrees reasonably well with the 1.02 percent measured in the dry reactor and shows that the 1.02 percent is conservative, probably due to shadowing during the intercomparisons. The new gang 3 critical position must be associated with the fixed-rods-installed calibration curve for gang 3 on Figure 710-13, not the prefixed rods curve. Using this curve gives a value of approximately 0.94 percent for the fixed rods. However, the original critical position would have been lower on this lesser worth rod. Therefore, the best value available for the fixed rods worth, from these data, is 1.00 percent $\pm$ .06 percent, which does not refute the measured 1.02 percent.

The all rods banked position in the sodium filled, fixed-rod reactor was 77.8 inches, an increase of 27.2 inches over the prefixed-rod position. Note that three rods are still in, and that the 77.8 inches banked rods worth had diminished due to the insertion of the fixed rods.

M 140 ELEMENT LOADING

1. Excess Reactivity Measurements

The tenth excess loading increment contained 15 fuel elements, bringing the reactor to the final operational fuel loading of 140 elements. Criticality was achieved in the 140 element reactor with gang 2 at 122.6 inches, gang 1 full out, and gangs 3, 4, and 5 full in. The change in critical rod positions resulting from this loading increment was the value of gang 3 being fully inserted from 91.2 inches, plus gang 2 being run in to 122.6 inches from full out. These two sections of rods were calibrated by the differential period technique and determined to be worth 212.703 cents excess reactivity, bringing

the total reactor loading to 9.73 percent (1403.4 cents). With 1.02 percent being unavailable due to the fixed rods, the net excess loaded was 8.71 percent.

The loading of these fifteen fuel elements allowed the completion of Figure 710-13, Loading Increment Calibrations by gang 3. An excellent comparison of the fixed-rod effect on gang 3 worth is shown on Figure 710-13, also. Prior to installation of the fixed-rods, the worth of gang 3 was approaching 3.7 percent. After the fixed rods were installed, the worth decreased to approximately 1.5 percent, substantiating the conclusion that installation of the rods considerably depressed the core center flux. Subsequent measurements verified that the worths of gangs 1 and 2, further from the reactor center, were increased appreciably.

2. Sodium Draining Test

Gang 5 was calibrated prior to initiation of the sodium draining operation to allow compensation for sodium removal, by use of gang 5 and thus to determine the incremental worths of the sodium. The calibration showed gang 5 to be worth only 18.77 cents, making it impractical to compensate for sodium draining with gang 5. Therefore, gang 3 was calibrated for this purpose. Gang 1 was used as the compensating bank during the calibration, gang 2 was full out, and gangs 4 and 5 were full in. Figure 710-20 shows the integral worth curve developed for gang 3 with its associated total worth of 215.324 cents.

The reactor was then drained, compensating with gang 3. When gang 3 reached full in, it was withdrawn and gang 2 inserted to compensate. When gang 2 reached full in, gang 1 was used to maintain criticality when gang 3 was withdrawn. Gangs 4 and 5 were full in during the entire draining operation. Table XVIII shows the sodium draining results.

Criticality was achieved in the 140 element, dry reactor with all rods in, except gang 1, at 109.8 inches. Shutdown margin was thus represented by six gang 1 rods at 109.8 inches.

Gang 3 was calibrated in the dry core, for comparison with the previous wet calibration. The dry total worth was determined to be 244.09 cents as compared to the wet value of 215.2 cents. Thus, gang 3 showed an apparent increase of 28.9 cents due to draining the sodium. The dry

Figure 710-20. Gang 3 Worth Curve, 140 Fuel Elements

TABLE XVIII
SODIUM WORTH DATA 140 ELEMENT LOADING

Sodium Level * (ft. - in.)	Elev. (ft. - in.)	Gang 3 Pos (inches)	Gang 2 Pos (inches)	Gang 1 Pos (inches)	Increment Worth (%)	Total Worth (%)
19' - 0"	1421' - 6"	156 "	73.3"	100 "	0	0
25' - 11"	1414' - 7"	120 "	73.3"	100 "	10	10
27' - 5"	1413' - 1"	100 "	73.3"	100 "	19	29
29' - 4"	1411' - 2"	70 "	73.3"	100 "	56	85
30' - 3"	1410' - 3"	50 "	73.3"	100 "	59	144
31' - 1"	1409' - 5"	10 "	73.3"	100 "	71	215
31' - 1"	1409' - 5"	125 "	41.4"	100 "	--	---
31' - 6"	1409' - 0"	100 "	41.4"	100 "	23	238
32' - 3"	1408' - 3"	70 "	41.4"	100 "	56	294
32' - 11"	1407' - 7"	50 "	41.4"	100 "	59	353
33' - 9"	1406' - 9"	10 "	41.4"	100 "	71	424
33' - 9"	1406' - 9"	125 "	in	80.6"	--	---
34' - 2"	1406' - 4"	100 "	in	80.6"	23	447
35' - 3"	1405' - 3"	74.5 "	in	80.6"	45	492
36' - 0"	1404' - 6"	65 6 "	in	80.6"	23	515
36' - 6"	1404' - 0"	62.85"	in	80.6"	9	524
37' - 0"	1403' - 6"	62.85"	in	80.6"	0	524

* Measured from top of loading face shield.

calibration was made with all rods in except the compensating gang 1 rods. Wet calibration was performed similarly, except that gang 2 was full out. The dry calibration was therefore more shadowed than the wet calibration, nevertheless, resulting in an increase of 28.9 cents. Figure 710-20 shows the comparison of the two calibration curves.

Using the dry gang 3 curve for determining the incremental sodium worths gives a total sodium worth of 4.13 percent, as opposed to the 3.64 percent listed in Table XVIII. Analysis of reactor condition during the sodium draining operation shows that neither curve is appropriate for measuring the sodium worth directly. The wet curve is proper at the start of

the draining, but the dry curve should be used at the end of the draining. It was concluded that the best approximation was to use the dry curve when the sodium increment being measured was compensated for by gang 3 out of the sodium, and the wet curve when gang 3 was below sodium level while compensating. This approach gives a sodium worth of 4.0 percent.

A second measurement of sodium worth was made by critical rod positions. Prior to draining sodium, gang 1 was at 109.5 inches, gang 2 was out, and all other rods in. In the drained reactor, gang 1 was at 109.8 inches and all other rods were in, including gang 2. For all practical purposes, reactivity effect of draining the reactor of sodium was equal to the effect of withdrawing gang 2 to the full out position. Therefore, sodium worth is equal to gang 2 worth. A calibration of gang 2 in the dry core was started, but had to be terminated at 42.6 inches, due to operational limitations imposed on reactor vessel temperatures with the reactor in the drained condition. A calibration of gang 2 in the wet core was made following the refill of the reactor. The worth of gang 2, hence, the value for sodium worth, was determined to be 4.2 percent. An estimate of gang 2 worth in the dry core was made by scaling up the measured wet value of 4.2 percent by the ratio of gang 3 dry-to-wet worths, both of which were calibrated. This resulted in an estimate of 4.7 percent as gang 2 worth (and sodium worth) in the dry core.

In the drained reactor, the six gang 1 rods at a critical position of 109.8 inches were individually intercompared from that position to full in, with the dry-core calibrated gang 3. Results were as follows:

<u>Control Rod No.</u>	<u>Worth (cents)</u>
14	56.5
15	61.5
16	60.0
17	64.0
18	58.0
19	<u>59.0</u>
Total	359.0 (2.49%)

Reactor drained shutdown margin was thus measured as 2.49 percent.

Additional effort was expended to determine the complete effects of control rod shadowing in the dry core, because of the desirability of accuracy in shutdown margin measurement. As in the 125 element dry core, gang 1 control rods CR-14 and -16 were inserted, while compensating with gang 4. CR-15 (which had been determined to be worth 61.5 cents by the above inter-comparison with gang 3) was again compared with gang 3. CR-15 worth was determined to be 18.0 cents when shadowed by CR-14 and -16. These results agree with the 125 element worth determination. The test was extended at this operational loading to check the worth of CR-18. CR-18 was worth 77.0 cents with CR-14 and -16 inserted and CR-15 worth 18 cents. These measurements demonstrated that depressing the flux in one region of the reactor, by the insertion of control rods, results in increased rod worth in other parts of the reactor, indicating flux peaking in that region. Thus, a flux tilt is created when the reactor control rods are not operated symmetrically.

In the next measurement, the gang 1 rods representing shutdown margin were split into two symmetrical banks. The one bank was then calibrated by the differential period technique, while compensating with the other bank. It was felt this arrangement of symmetrical banks would eliminate the "mobile" flux problem described in the previous paragraph. Control rods CR-15, -17, and -19 were inserted full in and CR-14, -16, and -18 and gang 3 were withdrawn to compensate. CR-14, -16, and -18 were pulled to full out and gang 3 was positioned at 109.5 inches, to maintain criticality.

CR-15, -17, and -19 were calibrated from full in to full out, compensating with CR-14, -16, and -18, and then with gang 3. CR-15, -17, and -19 worth was determined to be approximately 330 cents. The compensating bank, CR-14, -16, and -18, was measured to be worth approximately 280 cents. The difference in the two bank values can be attributed to CR-15, -17, and -19 being uncovered by gang 3 during the calibration (gang 3 at 109.5 inches), thus giving a higher value than is real. CR-14, -16, and -18 were covered by all immediately adjacent rods during the calibration, and hence, represent the true worth of one-half of the gang 1 rods in the all rods in configuration. Figure 710-21 depicts the two measured curves, plus a curve equal to twice the worth curve for CR-14, -16, and -18. This curve is considered the dry core gang 1 worth curve.

Figure 710-21. "Split" Gang 1, Integral Rod Worths
at 140 Element Loading, Reactor Drained

Figure 710-21. "Split" Gang 1, Integral Rod Worths at 140 Element Loading, Reactor Drained

Utilizing the Figure 710-21 curve as the gang 1 curve gives a value of 3.2 percent to that amount of rod under 109.8 inches, which represents shutdown margin. The partial gang 2 calibration curve developed in the dry core used gang 1 to compensate. Gang 1, as the compensating bank, moved from the critical position of 109.8 inches, down to 61.8 inches as gang 2 was withdrawn. Plotting the worth of gang 1, as determined by the compensating operation, on Figure 710-21, shows that the points do fall on the curve. The lower section of the gang 1 compensating curve would probably be of slightly higher value if the calibration had continued (due to the gangs passing into an unshadowed region). This would push the total worth curve up and place the measured points even more closely on the gang 1 curve, thus substantiating the curve as being actual.

Gang 1 worth as determined by the wet gang 2 calibration (gang 1 again compensating) was 2.9 percent (404 cents). The integral worth curves for both gangs 1 and 2 are shown on Figure 710-22. Scaling the gang 1 curve up by the same proportion determined from the difference in the gang 3 dry and wet curves, brings the total worth to 3.3 percent (468 cents). This curve agrees reasonably well with the gang 1 curve shown on Figure 710-21 and substantiates that a shutdown margin of approximately 3.0 percent did exist in the 140 fuel element loading.

3. Effect of Dummy Fuel Elements

Thirty dummy fuel elements (reflector fillers) were added to the reactor following the loading of the last fuel increment. These dummy elements completed the reactor operational loading, except for the three ICNI chambers incore positions C-191, -215, and -239. The chambers will be removed and three dummy elements inserted following the completion of reactor zero power testing. The thirty dummy elements presently installed are in the following core positions:

Figure 710-22. Gangs 1 and 2 Integral Worth Curves
at the 140 Element Loading, Dry Core

C-132	C-139	C-211	C-222	C-162	C-173	C-179
C-133	C-202	C-213	C-224	C-233	C-175	C-181
C-135	C-191	C-152	C-226	C-235	C-296	C-122
C-198	C-142	C-153	C-159	C-237	C-248	C-185
C-200	C-209	C-155	C-161	C-172	C-250	C-181
						C-189

Critical rod position prior to insertion of the dummy elements was all rods banked at 65.95 inches. With the dummies in place, criticality was achieved with all rods banked at 63.85 inches. Gangs 1 and 2 were calibrated individually and gangs 3, 4, and 5 as one bank from 63.85 inches to 65.95 inches, to determine the worth of the dummy elements. The results are as follows:

<u>Gang</u>	<u>Worth</u>	
3, 4, and 5	9.88 cents	
2	9.98 cents	
1	<u>7.54 cents</u>	
Total	27.40 cents	(0.19%)

The effect of the 36 dummies was, therefore, the addition of 27.4 cents excess reactivity. This brings the total reactor excess fuel loading to 1432.166 cents (9.9 percent) positive with 1.02 percent negative contained in the fixed rods for a net excess of 1284.88 cents (8.9 percent).

N. REMOVAL OF FIXED RODS

A detailed analysis of the data obtained at the 140 element loading was made to determine if the fixed control rods could be removed. The results of the study indicated that such action would not reduce the shutdown margin below the 2 percent desired. The fixed rods were subsequently removed from the reactor.

The three fixed rods were installed at the 125 element loading to ensure that a 2 percent shutdown margin would be maintained in the event of loss of sodium. Control rod gang 5 was calibrated by the differential period technique prior to fixed rod insertion, compensating with gang 1. After draining sodium, but before inserting the three fixed rods, the gang 1 rods out of the reactor

were intercompared with gang 5 and a dry shutdown margin of 2.45 percent was determined. The calibration and intercomparisons were repeated after the fixed rod insertion, giving a shutdown margin measurement of 3.47 percent. Therefore, the fixed rods were considered to be worth 1.02 percent (negative).

Flux tilting during the intercomparison of the gang 1 rods with gang 5 was indicated by measurements made at the 125 element loading. Specific tests were performed at the 140 element loading to verify that the tilting did exist. It was determined that measuring rod worths by the intercomparison method resulted in flux tilting in the reactor (away from the inserted rods), and a subsequent low measured value of rod worth. The 1.02 percent worth of the fixed rods is believed to be reliable, however, because it is the difference of two measurements that were made in the same manner.

Shutdown margin was measured at the 140 element loading by three methods:

- 1) Intercomparison of rods
- 2) Calibration of "split" gang 1 rods, and
- 3) Calibration of gang 1 as a bank

Methods 2 and 3 were utilized for the measurement, in addition to 1, because Method 1 had been determined unreliable due to flux tilting (discussed previously). Method 1 gave a value of 2.49 percent for shutdown margin. The "split" gang 1 calibration (Method 2) was performed with gang 3 withdrawn 110 inches, thus decreasing radial flux peaking. This "split" gang configuration was also chosen in order to minimize flux tilt. Method 2 gave a value of 3.20 percent for shutdown margin. Method 3 was accomplished in the wet core with all center rods out, except the three fixed rods. This rod configuration also minimized flux tilting. Method 3 led to a value of 3.15 percent for the shutdown margin in the dry core, which was obtained by multiplying the wet value by a factor of 1:1. This factor had been determined by repeating specific measurements in both the dry and wet core. Moreover, the calculated value for increased rod worth in the dry core over that in the wet core (due to absence of sodium) was also 10 percent of the wet core value, or a factor of 1:1.

The "split" gang calibration was considered the most meaningful, and it was concluded that a conservative value for shutdown margin with the three fixed rods in place was 3.1 percent. The calibration of gang 1 as a bank, compensating with gang 2, substantiates this conclusion.

The HNPF Final Summary Safeguards Report (NAA-SR-5700) required that 1 percent shutdown margin be available in the drained reactor. Data obtained during the post-critical isothermal temperature coefficient test were used to determine the reactivity increase due to temperature increase from 350 F, to the operating temperature of 945 F. A resultant 0.36 percent reading was obtained. This value was determined by taking the measured change in reactivity created by increasing core temperature from 350 F to 540 F and extrapolating to the operating temperature of 945 F. The isothermal temperature coefficient was also measured during the dry zero power experiments, but only up to a maximum temperature of 350 F. Extrapolation of this information gives a reactivity increase of 0.57 percent as a result of increasing temperature from 350 F to 945 F. This value is considered less reliable than the wet core coefficient determination, due to the magnitude of the extrapolation required of the dry core data. Both values are high, of course, as the 945 F temperature is not the reactor isothermal temperature, but the maximum sodium temperature during normal operation.

Control rod calibrations at 350 F and 540 F indicate that change in rod worth with temperature is not significant and will not effect the shutdown margin as measured.

A conservative estimate of the shutdown margin for a loading of 140 fuel elements with the three fixed rods removed was obtained as follows:

Measured shutdown margin with 3 fixed rods present . . .	3.1%
Worth of 3 fixed rods	1.0%
Temperature coefficient	0.5%
Estimated shutdown margin at 945 F with 3 fixed rods removed	1.6%

The required shutdown margin of 1.0 percent is thus assured with a safety margin of 0.6 percent. This was ample to allow the safe removal of the three fixed control rods.

Test procedure AI-PC-710, Wet Excess Fuel Loading, was amended to include a determination of the reactivity change in the reactor due to removal of the fixed rods. The technique utilized to determine this change was to calibrate the change in critical control rod positions due to removal of the rods. The differential period method was employed in the calibration.

Critical rod positions before and after fixed rod removal were as follows:

	<u>Before</u>		<u>After</u>
Gang 5	in	Gang 5	in
Gang 4	in	Gang 4	in
Gang 3	in	Gang 3	in
Gang 2	out	Gang 2	out
Gang 1	109.5 inches	Gang 1	74.05 inches

The worth of the fixed rods was therefore equal to the worth of gang 1 from 109.5 inches to 74.05 inches.

Gang 1 was calibrated from 74.05 inches to full out, compensating with gang 2. The worth of gang 1 attributable to the fixed rods (74.05 inches to 109.5 inches) was 128 cents, or 0.89 percent in the wet core. Scaling this value up by the proportion determined previously, gives a value of 144.6 cents in the dry core, or 1.0 percent.

The fixed rod worth of 1.0 percent in the dry core for the 140 element reactor is in fine agreement with measurements made previously. The value of the fixed rods at the 125 element loading was 1.02 percent in the dry core.

In summary, the measured shutdown margin of 3.1 percent at the 140 element loading was decreased to 2.1 percent by the removal of the fixed rods.

O. 140 ELEMENT LOADING - FIXED RODS REMOVED

With the removal of the fixed control rods, the fuel loading operation may be considered as a continuation of the conditions described in Section L., 125 Element Loading, Part 1, Excess Reactivity Measurements, where fixed rods had not yet been installed. Gang 3 critical position with 125 fuel elements loaded was 32.0 inches, with gangs 1 and 2 full out and gangs 4 and 5

full in. The loading of the reactor to 140 fuel elements and the addition of the dummy fuel elements resulted in a critical position of 80.25 inches on gang 2, with gang 1 full out and gangs 3, 4, and 5 full in. Thus, the fuel and dummy elements were worth the bottom 32.0 inches of gang 3 and gang 2 from 80.25 inches to full out.

The change in critical rod positions was calibrated by the differential period technique, compensating with gang 1. The worth of the loading increment was determined to be 205.7 cents, or 1.43 percent. This value agrees with that determined with the fixed rods installed (1.47 percent). The slight decrease can be attributed to a lesser flux depression in the reactor center with the fixed rods removed.

It was previously determined that the dummy elements were worth 0.19 percent (for 36 dummy elements). Since three more dummy elements were loaded to fill the channels vacated by the fuel elements which replaced the fixed rods, a total value of $0.19 \text{ percent} \times \frac{39}{36}$ or about 0.21 percent is attributed to the dummy elements. This value must now be subtracted from the measured 1.43 percent to get the worth of the 15 fuel elements (1.22 percent), but must be retained when considering total excess reactivity in the reactor.

Calibration of the change in critical rod position due to the last loading increment was done in a peaked flux region (gangs 3, 4, and 5 inserted - except lower 32.0 inches of gang 3 during that measurement). A re-determination of excess loaded in the last increment was made after purposely peaking the flux away from the calibration area. Gang 1 was fully inserted, gang 5 fully withdrawn, gangs 3 and 4 positioned at 46.8 inches and gang 2 controlling criticality at 67.1 inches for the measurement. A similar configuration had been achieved at the 125 element loading (prior to fixed rods), except gang 2 at 117.8 inches. The actual comparison is as follows:

<u>Gang</u>	<u>125 FE</u>	<u>140 FE</u>
1	in	in
2	117.8 inches	67.1 inches
3	46.8 inches	46.8 inches
4	46.8 inches	46.8 inches
5	out	out

The 140 element configuration was modified as described, driving gang 1 to full in, and withdrawing gangs 3 and 4 to 46.8 inches, to compensate. The 140 element calibration was performed at 530 F rather than 350 F, and required a correction of 18 cents (addition) to the measured reactivity change.

A worth of 113.8 cents was determined for the last loading increment in the depressed flux region. Adding the temperature correction brings the total to 131.8 cents or 0.91 percent. Again, one must deduct the value of the dummy elements to obtain a value for the excess reactivity added by the fuel. It is proper to deduct the 0.21 percent value for dummy elements, as it was determined from a banked configuration. Thus, the excess loaded was determined to be only 0.7 percent for the last 15 elements. Averaging the depressed and the peaked flux region calibrations gives a value of 0.96 percent excess reactivity for the last 15 fuel elements.

P. CONCLUSIONS

Large flux perturbations are created in the HNPF core by utilizing particular control rod configurations. Banking the rods results in axial flux peaking under the bank and axial flux depression above the bank. Inserting the center seven rods (10 including the three fixed rods) peaks the radial flux at the outer control rod rings and depresses it in the reactor center. Positioning the rods of the outer control rod rings in an asymmetrical pattern results in radial flux tilting; i. e., a depression at the rods inserted portion of the pattern across the reactor.

The choice of rod configurations for reactivity measurements are, therefore, very crucial. Those measurements requiring considerable rod manipulation develop questionable results. The following paragraphs discuss the determination of shutdown margin, sodium worth, excess reactivity and control rod worth, in light of the above statements.

1. Shutdown Margin

The reactor shutdown margin was measured at the operational loading by three methods;

- a) intercomparison of rods,
- b) calibration of "split" gang 1 rods, and
- c) calibration of gang 1 as a bank in the wet core and extrapolating to the dry condition,

Method a) gave a value of 2.49 percent, and methods b) and c) a value of 3.15 percent and 3.20 percent, respectively. Inter-comparison of rods representing shutdown margin was performed in a somewhat radially peaked region (gang 2 was inserted, as well as the center rods and also created a flux tilt during the measurement). The "split" gang calibration was performed with gang 3 withdrawn 110 inches, thus decreasing the radial peaking, and did not create a flux tilt, as far as can be determined. The wet gang 1 calibration (as a single bank) was accomplished with all center rods out, except the three fixed rods. This configuration also minimized flux tilting.

The "split" gang calibration is considered the most meaningful, leading to the conclusion that a 3.1 percent shutdown margin existed in the reactor with the fixed rods installed. Measurement of the effect of removing the fixed rods showed the rods to be worth 1.0 percent in the dry core. Therefore, shutdown margin in the operational reactor is 2.1 percent.

2. Sodium Worth

The insertion of gang 2 rods from full out to full in is required to compensate for draining the reactor of sodium, as determined by critical rod configurations at the 140 element loading. Gang 2 is worth 4 percent in the wet core and 4.4 percent in the dry core.

Gang 3 was used to compensate for the draining of sodium at the 140 element loading and shows the sodium to be worth 4.13 percent. The gang 3 calibration was performed in the least perturbed state that could be arranged; gangs 2, 4, and 5 inserted, and gang 1 being inserted as gang 3 was withdrawn.

Sodium is worth at least 4.13 percent at the operational reactor fuel loading (in the drained condition). Sodium worth may be slightly greater, but the exact value is not worth pursuing as it has no direct application to reactor operation, since shutdown margin is measured directly and has the greatest importance.

3. Excess Reactivity

Excess reactivities, loaded and measured in specific increments, are not additive. The measured increments cannot be summed, because they were determined in an increasingly perturbed radial flux pattern and the core size was changed with each added increment. Also, the method necessarily involves some axial peaking (although slight). Correction of the measured values is required, and must be theoretical. One method of analysis established that initial measurements were not involved in the error that accumulated due to the summing of the increments. Therefore, these values are extrapolated to give a reactor excess fuel loading of 7.5 percent. Figure 710-3, plot of $k_{\text{eff}} - 1$ vs a number proportional to radial buckling, displays the extrapolation.

4. Control Rod Worths

The calibration of all rods involves numerous rod patterns and manipulations. These configuration changes invalidate the measurements made, due to the axial and radial flux peaking and flux tilting described earlier.

The best approximation of rod worth, therefore, is the summation of other derived values; namely, excess reactivity (7.5 percent), shutdown margin (2.3 percent), and a sodium worth (4.1 percent) or 13.9 percent. The shutdown margin and sodium worth values are for the dry core. A better approximation of wet core rod worth is 13.3 percent.

IV. COMPLIANCE WITH TEST COMPLETION CRITERIA

Following are the test completion criteria associated with post critical test completion report AI-PC-710, Wet Excess Fuel Loading Test, as listed in NAA-SR-5700, Supplement 4, Page XI (c) - 40, with remarks regarding the test to explain compliance with the criteria.

a) Criterion: An operational fuel loading is in the core.

Remarks: The core loading has been completed. The reactor contains:

1)	Fuel elements	140
2)	Dummy elements.	39
3)	Reflector filler elements	75
4)	Control Rods	19
5)	Source	1
6)	Sodium level elements.	2
7)	Sodium temperature elements.	3
8)	Incore nuclear instrumentation thimbles . .	3

The three incore nuclear instrumentation thimbles will be replaced with dummy elements at the completion of zero power testing.

- b) Criterion: The shutdown margin in the core is equal to or greater than the worth of sodium plus 1 percent.
Remarks: The shutdown margin in the 350 F, wet core is 2.1 percent greater than the worth of the sodium. At operating temperatures the shutdown margin will be at least 1.6 percent greater than sodium worth.
- c) Criterion: The excess reactivity in the core is known.
Remarks: One method of analysis of test data indicated the core excess reactivity is 7.5 percent. The fuel loading increment excess measurements made by the test have been determined to be non-additive, and the total of 9.47 percent derived in this manner is not correct. The calculated excess reactivity for a 140 element loading is 6.4 percent. There is no method available for accurately measuring the excess reactivity in the core.
- d) Criterion: The reactor cannot be made critical by fully withdrawing any one control rod with the remaining control rods fully inserted.
Remarks: This criterion was verified as having been met throughout the loading operation and at the complete core loading (140 elements), by withdrawing the two rods of greatest worth, CR-1 and CR-6, and establishing that the reactor was not made critical.

V. EVALUATION

A. INTRODUCTION

The operational (or wet excess) loading of the HNPF was accomplished by loading fuel elements into the wet core in increments of approximately 1 percent $\frac{\Delta k}{k}$. At least 137 fuel elements were to be loaded, in order to provide sufficient heat transfer surface for achievement of design thermal power (256 Mwt). A maximum of 153 fuel elements was available. It was expected that the core excess reactivity at the operational loading would be in the range of 6 to 7 percent $\frac{\Delta k}{k}$, based on multigroup core calculations.

During the loading, it was desired to maintain a shutdown margin of 2 percent $\frac{\Delta k}{k}$ plus sodium worth, as a margin of safety, and to allow for the positive isothermal temperature coefficient. Of the 2 percent figure, 1 percent was allowed for safety, and 1 percent for the increase in reactivity expected to result from heating the core from 350 F to 850 F for power operation.

It was also desired to obtain a preliminary estimate of total control rod worth, sodium worth, and the reactivity change caused by replacing the source element with a fuel element.

B. DETERMINATION OF EXCESS REACTIVITY

After the first four fuel increments were loaded, it was noted that the measured excess reactivity obtained by summing the incremental reactivities was becoming larger than the calculated excess. At the operational loading of 140 fuel elements, the value of the measured k_{eff} was 1.109 as compared with an "analytical" value of 1.069. (Figure 710-23).

Two effects are postulated as to the cause of the discrepancy. They are; the change in reactor size with fuel loading, and distortion of flux due to control rod insertion.

As core size increases, the flux in the center of the core tends to get flatter. Thus, the reactivity value of a fuel element loaded toward the center of the core decreases as more fuel is loaded. The total excess

Figure 710-23. K_{eff} vs Number of Fuel Elements at 140 Fuel Element Loading.

reactivity was determined by summing the reactivities of the individual loading increments. The final value obtained by this procedure is therefore high.

A more important problem is the one caused by the insertion of control rods. As fuel was loaded, the excess reactivity was compensated for by insertion of the most centrally located control rods. As more and more fuel was loaded, more control rods were inserted into the core in an increasing radius from the core center. This depresses the flux in the central regions of the core, while peaking the flux in the uncontrolled outer portions of the core. Fuel elements were loaded in this high flux region, and thus given greater importance than they would have had assuming no flux perturbation. These two effects added together caused most of the discrepancy between the analytical and experimental values.

Three methods have been used to obtain a true estimate of the excess reactivity actually loaded. They are: (a) perturbation correction of measured excess; (b) two-region calculation of excess based on measured banked rod positions; and (c) extrapolation of excess loaded in the first two increments.

1. Perturbation Correction

From perturbation theory, the excess reactivity measured at each fuel loading is:

$$\rho_1 = \frac{\int_{V_0}^{V_1} \phi_0^* P'_1 \tilde{\phi}_1 dV}{\int_{V_0}^{V_n} \phi_{n-1}^* R'_1 \phi_1 dV} \quad \dots (1)$$

$$\rho_n = \frac{\int_{V_{n-1}}^{V_n} \phi_{n-1}^* P'_n \tilde{\phi}_n dV}{\int_0^V \phi_{n-1}^* R'_n \tilde{\phi}_n dV} \quad \dots (2)$$

where:

ρ_n is reactivity loaded during loading increment n

V_n is core volume after n loadings

V_{n-1} is core volume after n-1 loadings

ϕ^* is the adjoint flux matrix

$\tilde{\phi}$ is the perturbed flux matrix

R_n^1 and P_n^1 are cross section matrixes as shown below

$$P_n = \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix}$$

$$P_{11} = -\delta \sum a_1 + \delta \nu \sum f_1 + \delta \sum n_1 \quad \dots (3)$$

$$P_{12} = \delta \nu \sum f_z$$

$$P_{21} = \delta \sum n_1$$

$$P_{22} = -\delta \sum a_2$$

$$R_n = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix}$$

$$R_{11} = \nu \sum f_1 + \delta (\nu \sum f_1) \quad \dots (4)$$

$$R_{12} = \nu \sum f_2 + \delta (\nu \sum f_2)$$

$$R_{21} = 0$$

$$R_{22} = 0$$

What we would like to be able to measure is shown in equation 5.

$$\rho_a = \frac{\int_{V_0}^{V_1} \phi_1^* P_1 \tilde{\phi} dv + \dots + \int_{V_{n-1}}^{V_n} \phi_1^* P_n \tilde{\phi} dv + \dots + \int_{V_{L-1}}^{V_L} \phi_1^* P_L \tilde{\phi} dv}{\int_0^{V_L} \phi_1 R_2 \tilde{\phi}_2 dv}$$

where L is the final loading.

By substitution of equation 2 into equation 5, we obtain the correction factor, $K_n L$ for the individually measured reactivities.

$$\begin{aligned}
 \rho_a = & \rho_1 \frac{\int_0^{v_1} \phi_1^* R'_1 \tilde{\phi}_1 dv}{\int_0^{v_1} \phi_1^* R_1 \tilde{\phi}_1 dv} \cdot \frac{\int_{v_0}^{v_1} \phi_1^* P_1 \tilde{\phi}_1 dv}{\int_{v_0}^{v_1} \phi_1^* P'_1 \tilde{\phi}_1 dv} + \\
 & \dots + \underbrace{\rho_n \frac{\int_0^{v_n} \phi_{n-1} R'_n \tilde{\phi}_n dv}{\int_0^{v_n} \phi_{n-1} R_n \tilde{\phi}_n dv} \cdot \frac{\int_{v_{n-1}}^{v_n} \phi_{n-1} P_n \tilde{\phi}_n dv}{\int_{v_{n-1}}^{v_n} \phi_{n-1} P'_n \tilde{\phi}_n dv}}_{K_n L} + \dots \quad (6) \\
 & \dots + \rho_l \frac{\int_0^{v_l} \phi_{l-1}^* R'_l \tilde{\phi}_l dv}{\int_0^{v_l} \phi_{l-1}^* R_l \tilde{\phi}_l dv} \cdot \frac{\int_{v_{l-1}}^{v_l} \phi_{l-1}^* P_l \tilde{\phi}_l dv}{\int_{v_{l-1}}^{v_l} \phi_{l-1}^* P'_l \tilde{\phi}_l dv}
 \end{aligned}$$

Using the measured control rod positions to volume weight the core cross sections, the FOG * program was run. The adjoint and perturbed fluxes were thus obtained and used in equation 6 to determine the correction factors for the incremental loadings. The resulting corrected excess loading curve is shown in Figure 710-23 where it is compared with the measured (uncorrected) curve and the calculated curve.

---

* The FOG One-Dimensional Neutron Diffusion Equation Codes, by H. P. Flatt, January 1961. NAA-SR-6104

2. Two-Region Calculation of Excess Reactivity

Excess reactivity was also calculated using the axial banked control rod positions, recorded at each loading increment. A poison search was made using the FOG program to find the absorption cross section which would provide a shutdown k_{eff} of 0.94. This value was used throughout the whole study. Radial flux calculations were run for each fuel loading, both with and without the poison. Using the leakages calculated by the program, radial bucklings were determined for both groups. The cross sections in the core were flux, adjoint flux, and volume weighted to provide core cross sections. Axial FOG runs were then made using these bucklings and cross sections. The buckling from the radial calculation without poison was used for the lower reflector and lower uncontrolled core, and the buckling from the radial calculation with poison was used for the upper controlled core and upper reflector. This technique approximates the correct leakage. For loading X, the critical rod position for loading X and X-1 was run. The difference between the two reactivities is the excess loaded at that loading. Summing over all loadings provides the total excess reactivity.

The resulting excess loading curve is also shown in Figure 710-23. It follows the analytical curve quite closely.

3. Extrapolation of Initial Loading Increments

To obtain a "lower limit" estimate of excess reactivity loaded, the migration area M^2 of the lattice was experimentally determined as follows.

Following the method used by Dr. F. L. Fillmore in the HNPF dry critical calculations, k_{eff} was plotted as a function of geometrical buckling, as defined below:

$$B^2 = \left(\frac{\pi}{H}\right)^2 + \left(\frac{2.405}{R + \delta}\right)^2 *$$

---

* Glasstone and Edlund; The Elements of Nuclear Reactor Theory, 1952, page 214.

where:

H = Height of reactor with axial reflector savings

δ = Radial reflector saving

R = Effective core radius $\sqrt{\frac{NA}{\pi}}$

where:

N = number of fuel elements loaded and

A = cross sectional area associated with each fuel element

For $N < 95$, $A = 870 \text{ cm}^2$

For $N > 95$, $R = \sqrt{\frac{95 \cdot 870}{\pi} + \frac{(N-95) A'}{\pi}}$ where $A = 724 \text{ cm}^2$

This change in the expression for R at $N = 95$ is due to the fact that there is one control rod for every 5 elements up to element 95, but no additional control rods for fuel elements in excess of 95.

The above expression strictly applies only to a bare homogeneous thermal reactor, but was found to yield a migration area for the dry critical loading within 8 percent of that calculated.

It can be shown that:

$$1 - k_{\text{eff}} \cong M^2 B^2 - (k_{\infty} - 1)$$

Therefore, a plot of $1 - k_{\text{eff}}$ vs B^2 should yield a curve which is approximately a straight line, with a slope equal to M^2 , and a y-intercept equal to $k_{\infty} - 1$. Figure 710-1 is the plot of $k_{\text{eff}} - 1$ vs $B^2 \times 10^6$; the deviation from a straight line is caused largely by the flux perturbations already discussed.

Plotted on the same graph is the multigroup calculation of k_{eff} vs B^2 . It can be seen that this curve agrees fairly well with the first four experimental points. At a fuel loading of 140 elements, k_{eff} was calculated to be 1.069, giving an excess reactivity of 6.5 percent.

The dashed curve is a straight line extrapolation of the first two experimental points. This curve extrapolates to a k_{eff} of 1.063 at the 140 element loading, or an excess reactivity of 5.9 percent.

The calculated value of M^2 for the "wet" lattice is 422 cm^2 at 350 F. The slope of the dashed curve is 435 cm^2 , within 4 percent of the calculated value. This agreement lends weight to the argument that the first few experimental measurements of excess reactivity are essentially correct, and that the extrapolation to the 140 element loading gives a valid estimate of the excess reactivity.

C. SUMMARY

The following table summarizes the various estimates of excess reactivity at the 140 element loading.

TABLE XIX
ESTIMATE OF EXCESS REACTIVITY - 140 ELEMENT LOADING

Method	k_{eff}	$\rho \left(\% \frac{\Delta k}{k} \right)$
Measured (by summing incremental excesses)	1.109	9.8
Perturbation correction	1.074	6.9
Axial two-region calculation	1.072	6.0
Extrapolation of first two loading increments	1.063	5.9
Calculated prior to loading	1.069	6.5

Examination of the numbers in the above table shows that the best estimate of excess reactivity actually loaded is between 5.9 and 6.9% $\frac{\Delta k}{k}$. The calculated value of 6.5% $\frac{\Delta k}{k}$ lies almost in the middle of the range.

As will be discussed in the report on control rod calibration, (AI-PC-750), the excess determined by control rod calibration curves is 983.1 cents, or about 6.8% $\frac{\Delta k}{k}$. Since this value also lies in the estimated range, it is suggested that the excess determined by control rod calibration be accepted as the "standard".