DOE/ER/75271--T2

Report on Conversion of the Worcester Polytechnic Institute Nuclear Reactor Facility to Low-Enriched Uranium

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I. INTRODUCTION

On 20 December 1988, WPI received 28 LEU 18 plate aluminide elements for use in the reactor core, replacing HEU fuel unloaded on 16 December 1988. Initial loading began on 27 December 1988, with initial criticality being achieved on 29 December 1988.

Testing on the LEU core was performed and the results compared with calculations performed for WPI by Argonne National Laboratory (ANL). It should be noted that the ANL calculations were in all cases based on the reference 24 element core shown in Figure 1. HEU measurements were made using the reference core. It was not possible, however, to perform LEU measurements with the reference 24 element core since criticality occurred at a fuel loading of slightly greater than 21 elements.

II. CRITICAL MASS

The critical loading for the HEU core was 3.242 kg U-235. Although no calculations were performed by ANL for HEU critical mass, excess reactivities were very close (see below) to measured values.

The loading at criticality for the LEU core was 3.560 kg U-235 (21 elements + 4 plates as shown in figure 2) compared with the ANL calculated 4.000 kg (24 elements). The reason for this discrepancy is currently under investigation by ANL. The difference between measured and calculated values in and of themselves do not have a significant impact on normal operations or accident conditions.

III. EXCESS REACTIVITY

Excess reactivity measurements through the 29 years of operation for the HEU fuel has shown a variation between 0.23% and 0.26% $^{\Delta k}/k$. ANL calculations show good agreement with a value of 0.29%.

For the 21-1/3 element LEU arrangement, the measured value is 0.16% $^{\Delta k}/k$. Subsequent ANL calculations show this arrangement to be subcritical by about 2.5% $^{\Delta k}/k$. Although the calculations are far from the measured values, measurements show the excess reactivity to be well below the 0.5% technical specification limit.

IV. POWER CALIBRATION

After LEU fuel loading was complete, a complete survey of radial and axial neutron flux distribution at about 200W was made using gold foils. Calculations based on this distribution showed that the neutron detectors for power level indication which was set for the HEU core would read about 26% too high. The initial calibration showed the instrumentation to be reading between 24% and 33% too high. Cadmium covered gold foils were also used to determine if any spectral differences existed between LEU and HEU cores, which would affect detector output for a given flux. These results showed virtually no difference between cores. The original radial position of all detectors remain unchanged in the LEU core.

V. THERMAL NEUTRON FLUX DISTRIBUTION

Average thermal neutron flux distributions were determined using gold foils placed in each element and irradiated during operations of about 200W. The HEU core flux distribution is shown in Figure 3. The measured values show good agreement with ANL calculations. LEU core measurements and calculations are shown in Figure 4. Since the actual measured values are distributed over less fuel than the ANL calculated values, the percent power is naturally higher. Similar trends, however, can be seen between the two values as well as with the HEU core. The higher LEU measured value at position E-7 is due to thermal flux peaking in the partially loaded removable plate element.

VI. CONTROL AND REGULATING BLADE WORTHS

The reactivity worths for the regulating blade and four configurations of control blades are shown below. The LEU measured values are for the 21-1/3 element core, while all other values are for the 24 element reference core.

		Worths of Blades, $\Delta k/k$ HEU	LEU
Regulating Blade	Measured	0.4%	0.52%
	Calculated	0.7%	0.7%
Blades 1,2 in; 3, R out	Measured	3.8%	6.6%
	Calculated	6.5%	6.5%
Blades 2,3 in; 1, R out	Measured	8.3%	12.2%
	Calculated	7.8%	7.7%
Blades 1,3 in; 2, R out	Measured	7.2%	9.9%
	Calculated	8.2%	8.1%
Blade 2, in; 1,3, R out	Measured	2.5%	3.9%
	Calculated	3.6%	3.5%

Although there are some discrepancies between calculated and measured values, the relative worths of different configurations are consistent, showing adequate shutdown worths for any blade configuration.

Measured differential control blade worths are shown in figures 5 & 6. Although no calculations were made because of the differing worth values for many different configurations, the measured values show the same trends as calculations for the total rod worths for both the LEU and HEU cores. The differences in LEU worth of blades 1 and 2 as compared with total worths values are due to the fact that differential worth measurements were made at different blade configurations than total measurements. Measured differential regulating blade worths are shown in figure 7. Again, the same trends as total worths can be seen.

VII. SHUTDOWN MARGIN

The shutdown margin for each of the blades out was measured for both the LEU and HEU cores, and are shown below. Again, the LEU measured values are for the 21 1/3 element core, while all others are for the 24 element reference core.

	Reactivity Worth % $\Delta k/k$			
Blade out	HEU Measured	HEU Calculated	LEU Measured	LEU Calculated
1	8.3	7.8	12.2	7.7
2	7.2	8.2	9.9	8.1
3	3.8	6.5	6.6	6.5

These values show reasonably good agreement with ANL calculations and all show the highest worth blade to be No. 3. All values are well above the 1% technical specifications limit.

VIII. PARTIAL ELEMENT WORTHS

The partial element, loaded in position E-7, was loaded with 4 plates when criticality occurred. Subsequent loadings of one plate each showed a reactivity worth of 0.08% $\Delta k/k$ per plate. ANL calculations made for position F-3 showed a worth of between .06% and .085% per plate.

IX. VOID AND TEMPERATURE COEFFICIENTS

Accurate measurements of void and temperature coefficients are difficult. Attempts have been made over the years to introduce voids into the core for reactivity measurements and all have shown negative values in the core region. However, the method of introducing voids into the core frequently causes significant reactivity effects in addition to the voiding. It is even more difficult to extraplate from an individual measurement to an average coefficient for the entire core. Because of these uncertainties, no attempt to verify actual values of coefficient has been made. Small voids can, however, be introduced into the core to verify a negative reactivity value.

Similarly, attempts have been made to measure the temperature coefficient by heating or cooling the entire pool of water and comparing with the original critical blade positions. These attempts typically take several days to accomplish and do not accurately reflect conditions under which reactivity effects would be seen with changing temperature during operation. A recent measurement for the HEU core gave a value of $-5.2 \times 10^{-5}\ \Delta k/k°F$, compared with the ANL calculated $-1.7 \times 10^{-4}\ \Delta k/k°F$.

Because of these reasons, as well as the fact that fuel heating has a significant Doppler effect in the LEU core, it was decided to measure reactivity changes with increasing power to determine the overall temperature coefficient of the LEU core. At 10 kw, the average temperature rise across the core was 5.5°C. The reactivity change, based on the change in the regulating blade position was about $-0.05\%\Delta k/k$, giving an overall temperature coefficient of $-9 \times 10^{-5}\ \Delta k/k°C$ compared with ANL calculations of $-1.7 \times 10^{-4}\ \Delta k/k°C$. These are both more negative than the $-2 \times 10^{-5}\ \Delta k/k°C$ technical specification limit. The measured value has some uncertainties involved, such as the variation of temperature from measured points. Any difference in average temperature can change the coefficient significantly.

X. INITIAL LEU LOADING

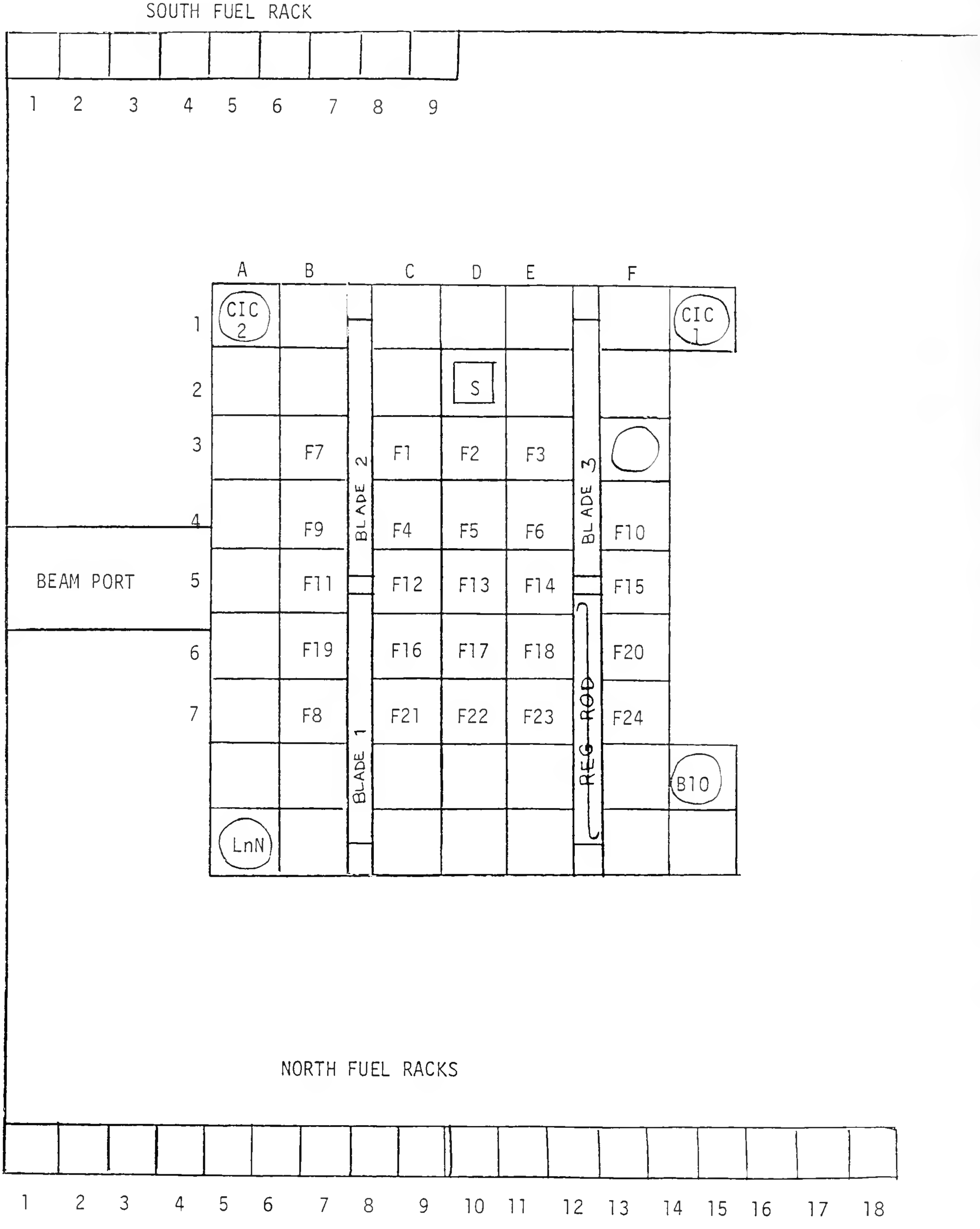
The LEU fuel loading began on 27 December, 1988 in 2 steps of six elements each and a 1/m plot made to predict the critical configurations. Thereafter, fuel was loaded in steps corresponding to one/half of the updated estimated critical configuration from the 1/m plots. The plots, made for all rods out and ratio of rods in to rods out are shown in figures 8 and 9. Figures 10 and 11 show the 1/m plots on a per plate basis during loading steps 6 through 8. The loading steps are presented below with loading steps 7 and 8 showing total fuel plate loading rather than element loading.

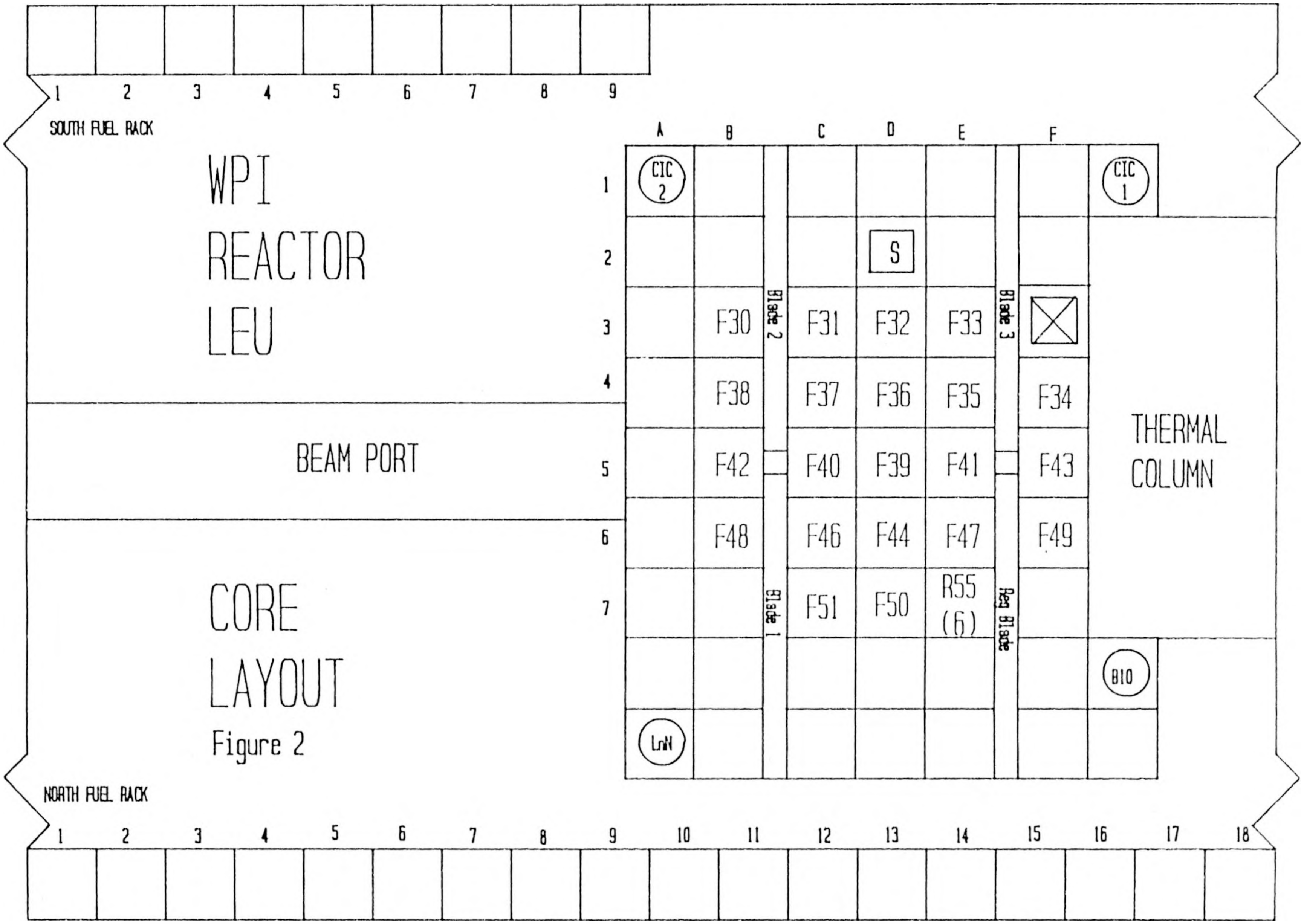
		1/m critical predictions		
Loading Step	Number of Elements	Rods out	Rods in/ Rods out	Additional Loading
1	6	-	-	-
2	12	16	27	4
3	16	18	23.5	2
4	18	21	22-1/2	2
5	20	20.8	22-1/3	1
6	21	21-1/3	21-1/3	2 plates
7	21 + 2 plates(380p)	382-1/2	382-1/2	1 plate
8	381 plates	382-1/2	381-1/2	1 plate
9	382 plates		critical	

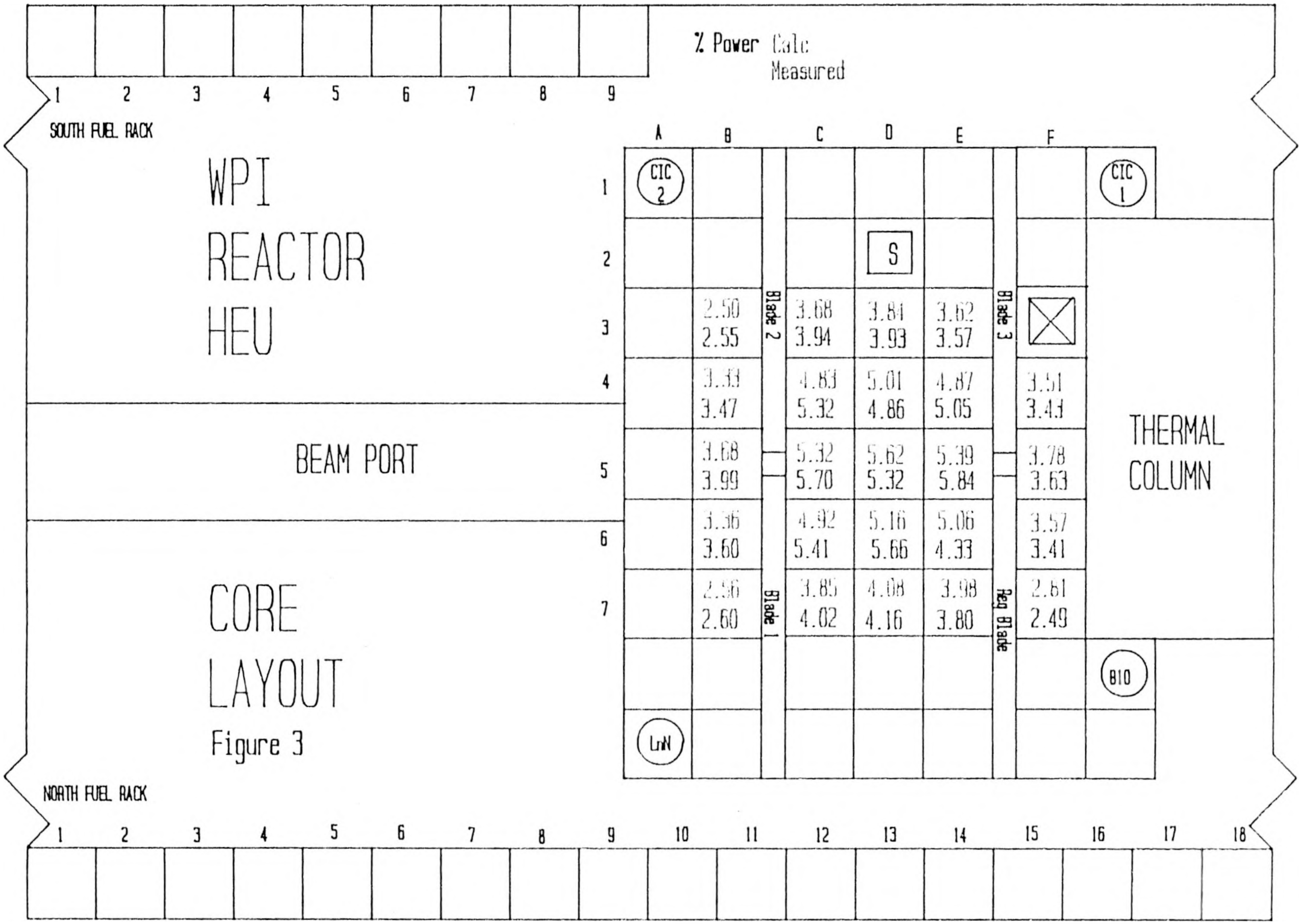
The excess reactivity at 382 plates was measured to be $6 \times 10^{-4}\% \ ^{\Delta k}/k$. Two plates were later added to increase the excess reactivity to 0.16%.

Figure 1

WPI OPEN POOL REACTOR
HEU REFERENCE CORE

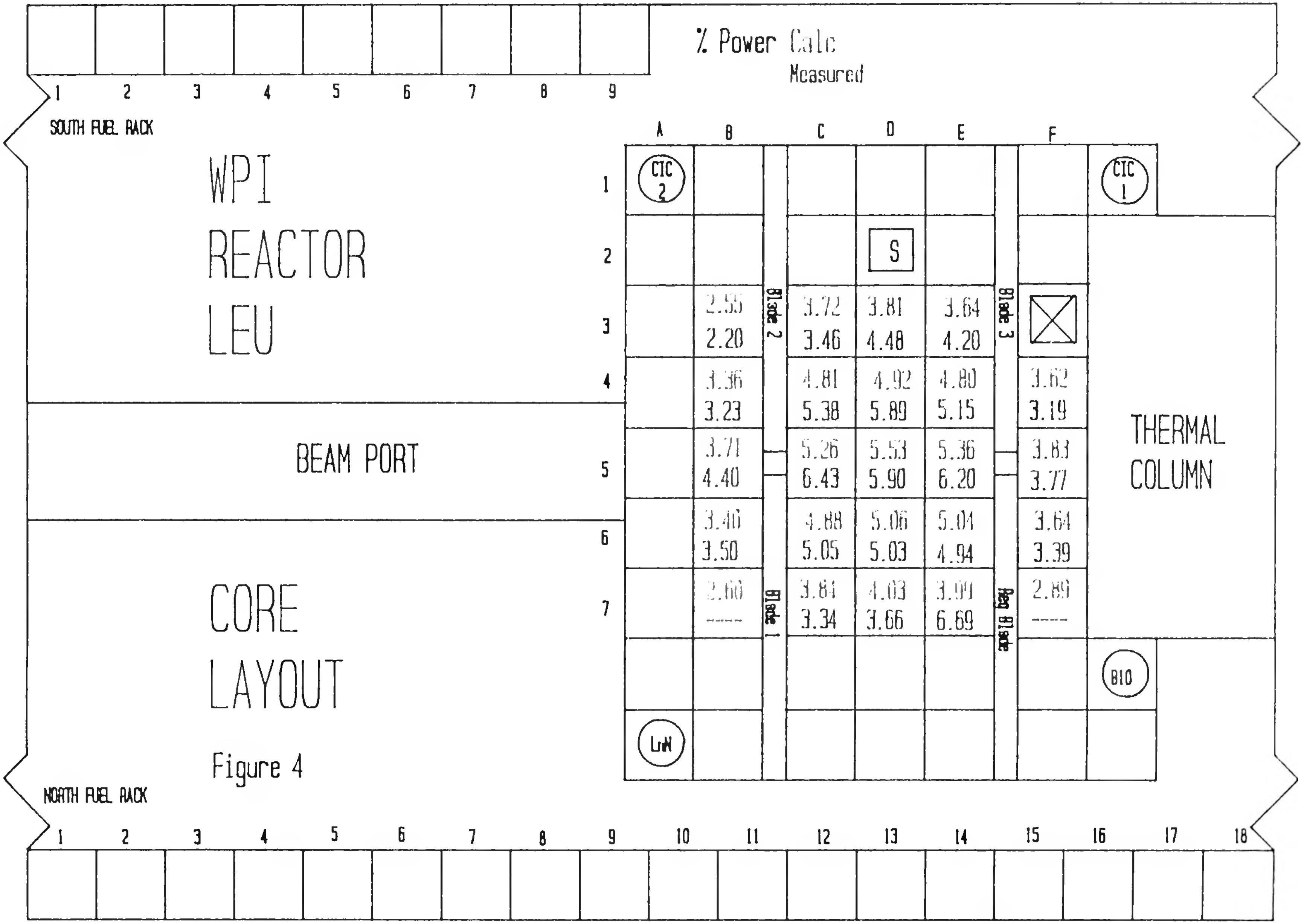



1
2
3
4
5
6
7
8
9
SOUTH FUEL RACK
WPI
REACTOR
LEU
BEAM PORT
CORE
LAYOUT
Figure 2
NORTH FUEL RACK
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
A
B
C
D
E
F
1
2
3
4
5
6
7
CIC 2
CIC 1
S
Blade 2
Blade 3
Blade 1
Reg Blade
F30
F31
F32
F33
F38
F37
F36
F35
F34
F42
F40
F39
F41
F43
F48
F46
F44
F47
F49
F51
F50
R55 (6)
BIO
LnN
THERMAL COLUMN



WPI REACTOR HEU CORE LAYOUT

Figure 3


% Power Calc
Measured
SOUTH FUEL RACK
1 2 3 4 5 6 7 8 9
WPI
REACTOR
LEU
BEAM PORT
CORE
LAYOUT
NORTH FUEL RACK
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
A B C D E F
1 2 3 4 5 6 7
CIC 2
CIC 1
S
Blade 2
Blade 3
Blade 1
Reg Blade
THERMAL COLUMN
BIO
LnN
2.55
2.20
3.72
3.46
3.81
4.48
3.64
4.20
3.36
3.23
4.81
5.38
4.92
5.89
4.80
5.15
3.62
3.19
3.71
4.40
5.26
6.43
5.53
5.90
5.36
6.20
3.83
3.77
3.46
3.50
4.88
5.05
5.06
5.03
5.04
4.94
3.64
3.39
2.60

3.84
3.34
4.03
3.66
3.99
6.69
2.89

Figure 4

Figure 5 HEU Control Blade Worths

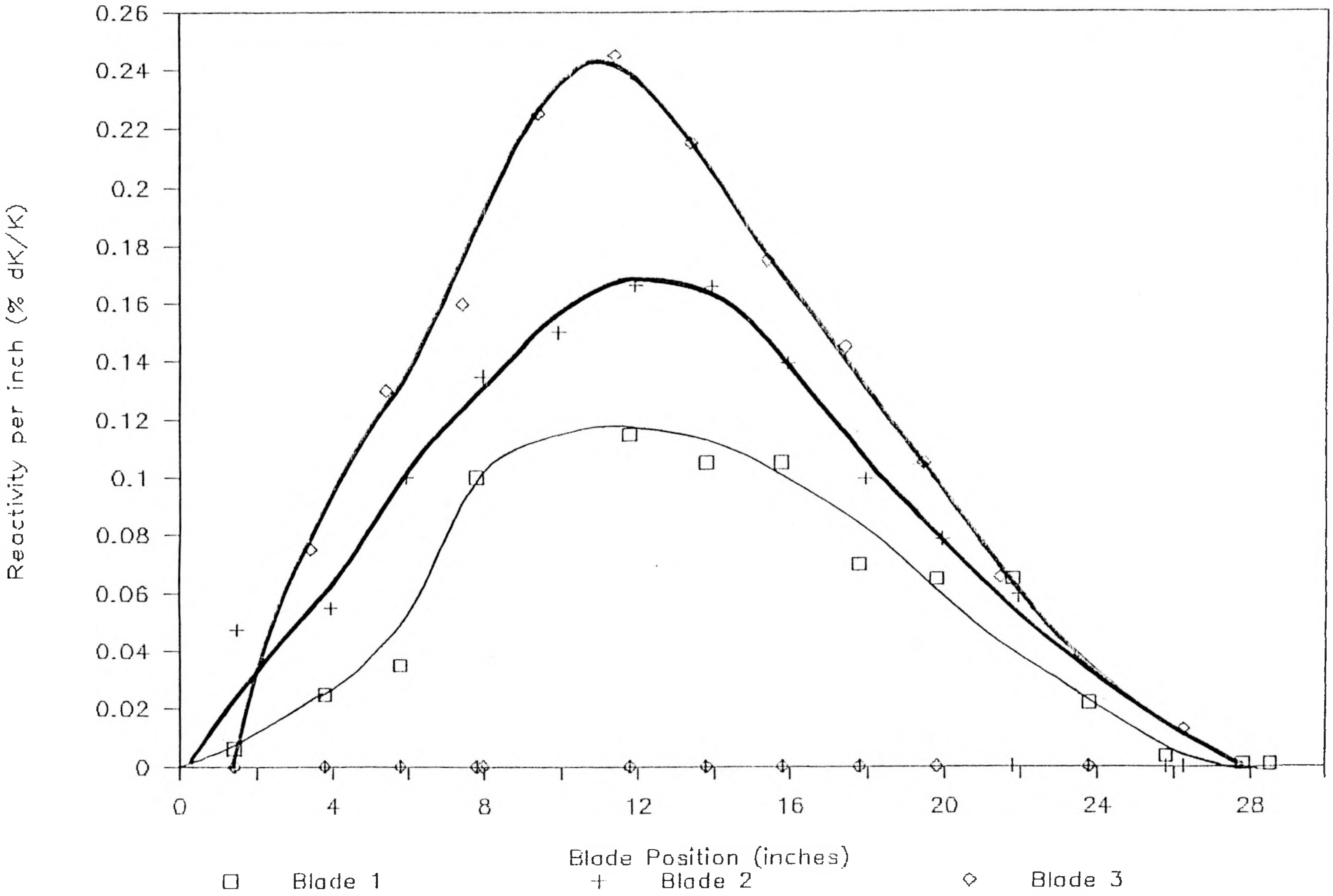


Figure 6 LEU Control Blade Worths

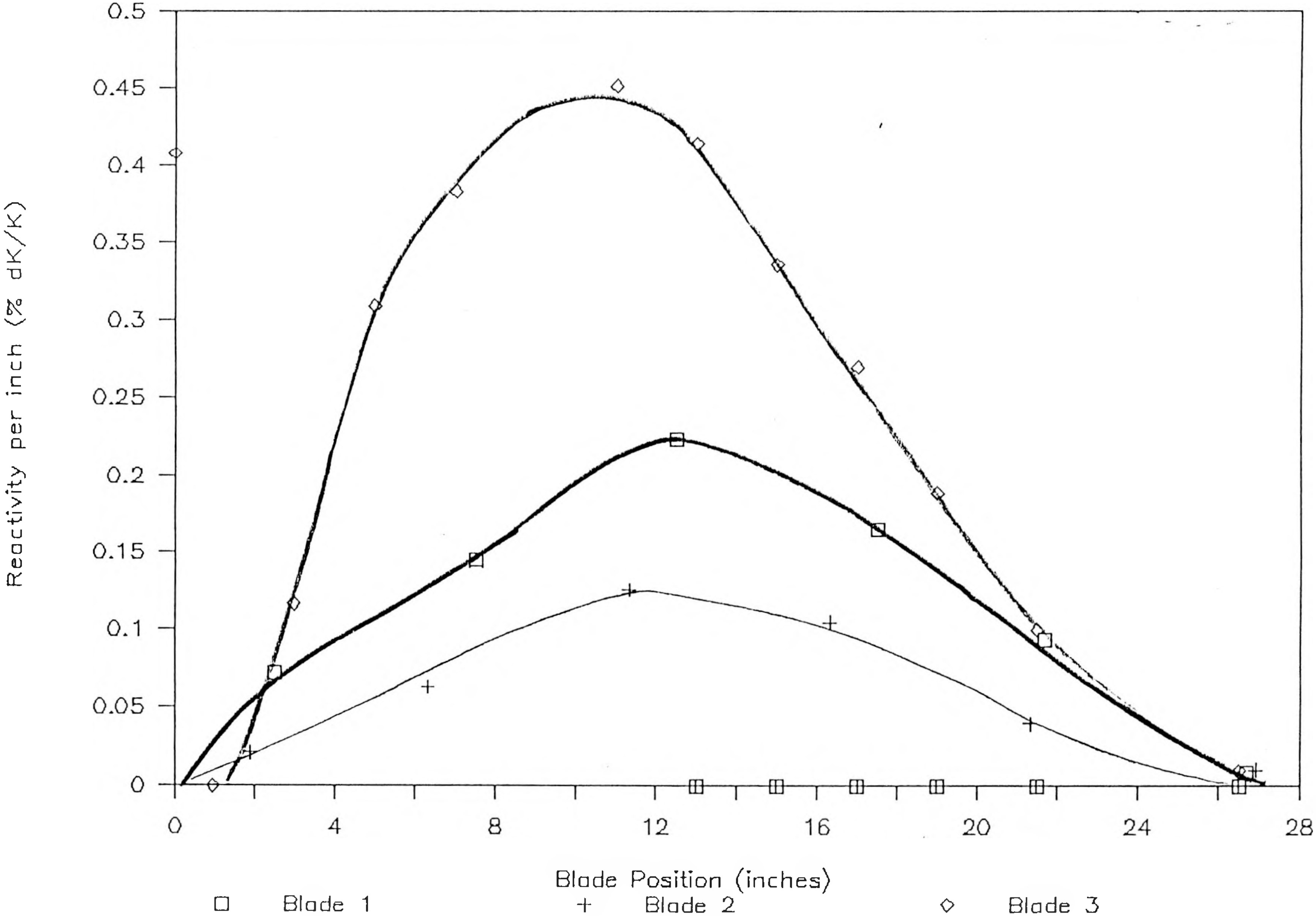
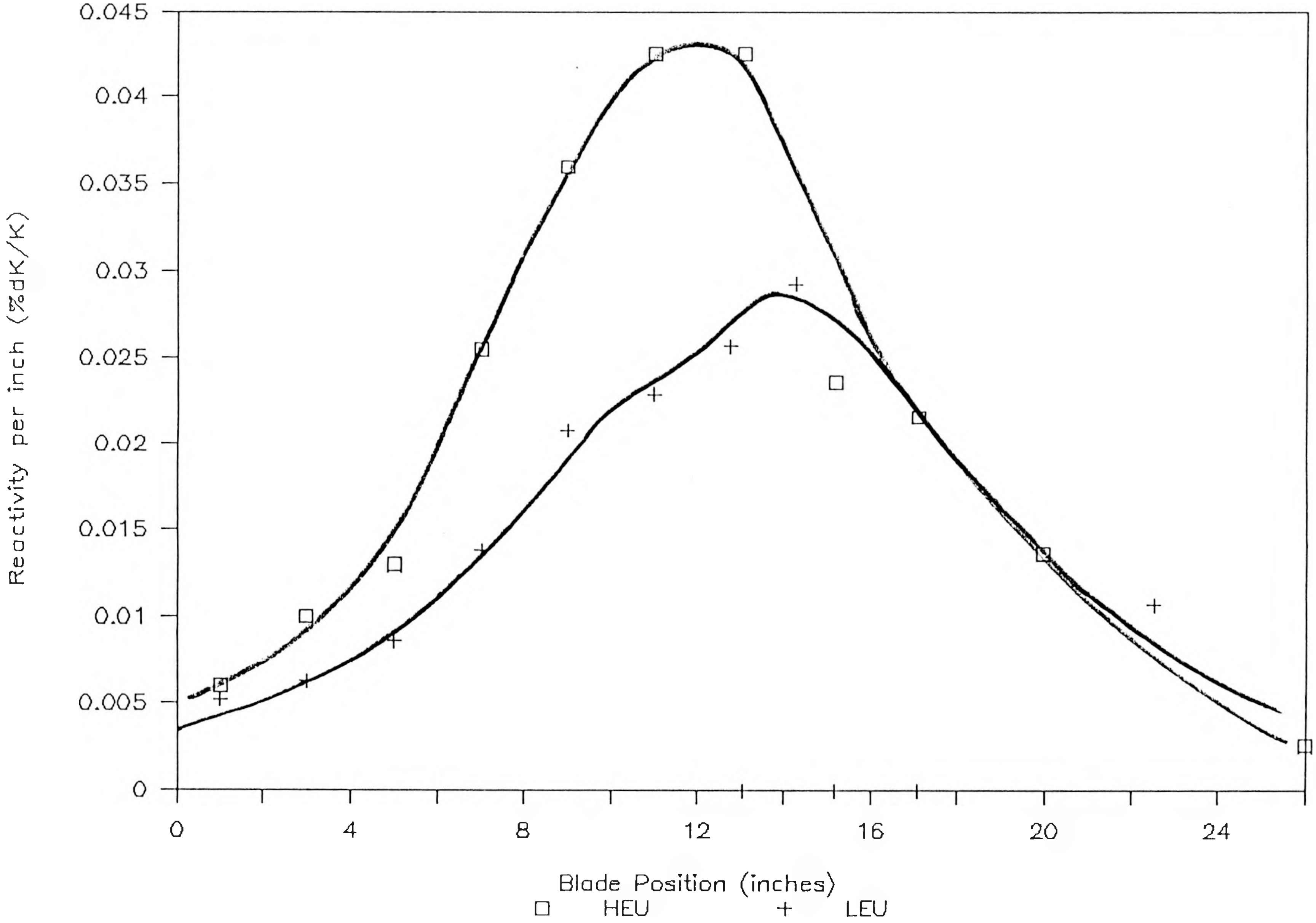


Figure 7 Regulating Blade Worths



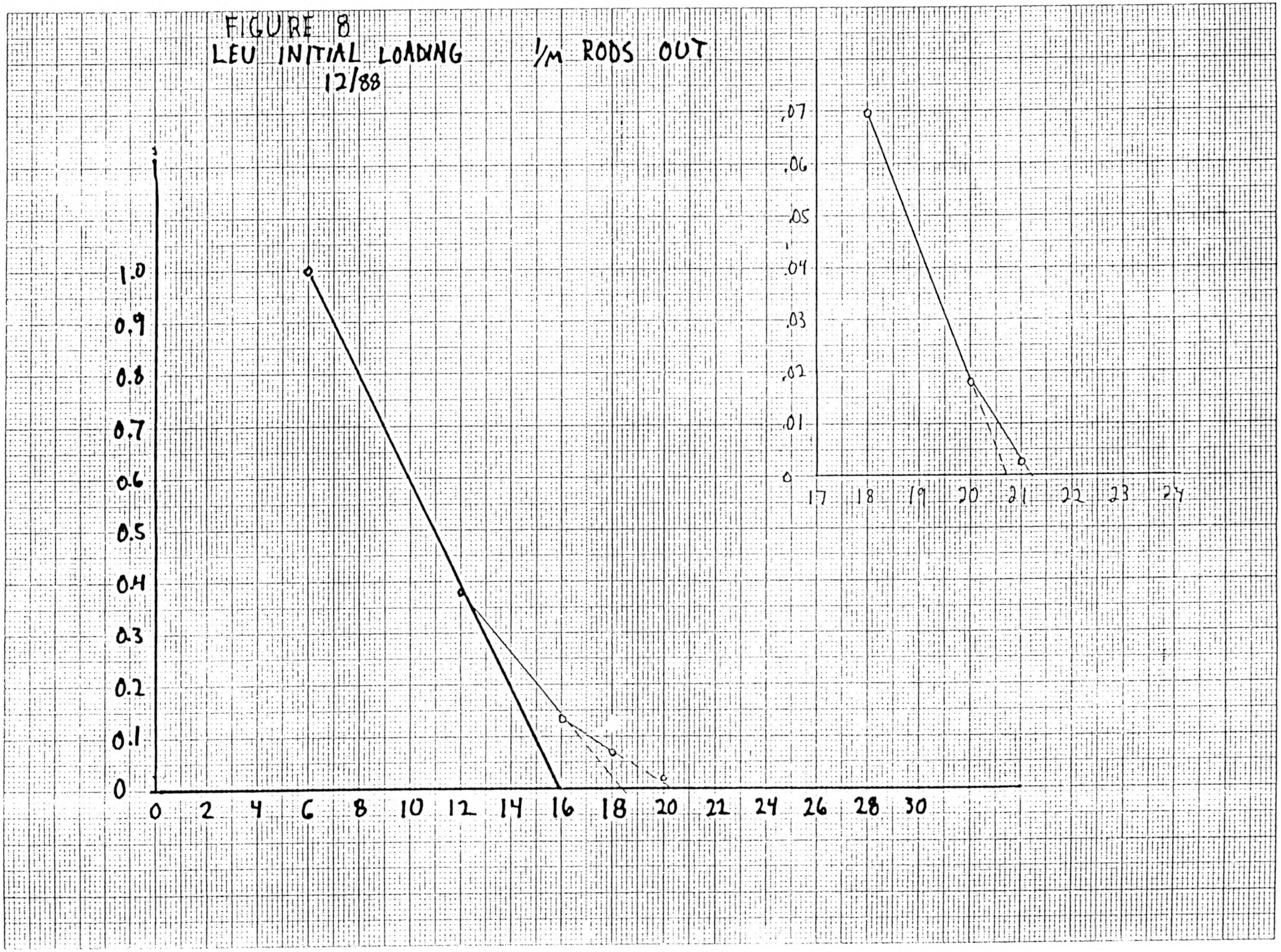


FIGURE 8
LEU INITIAL LOADING 1/M RODS OUT
12/88
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
.07
.06
.05
.04
.03
.02
.01
0
17 18 19 20 21 22 23 24

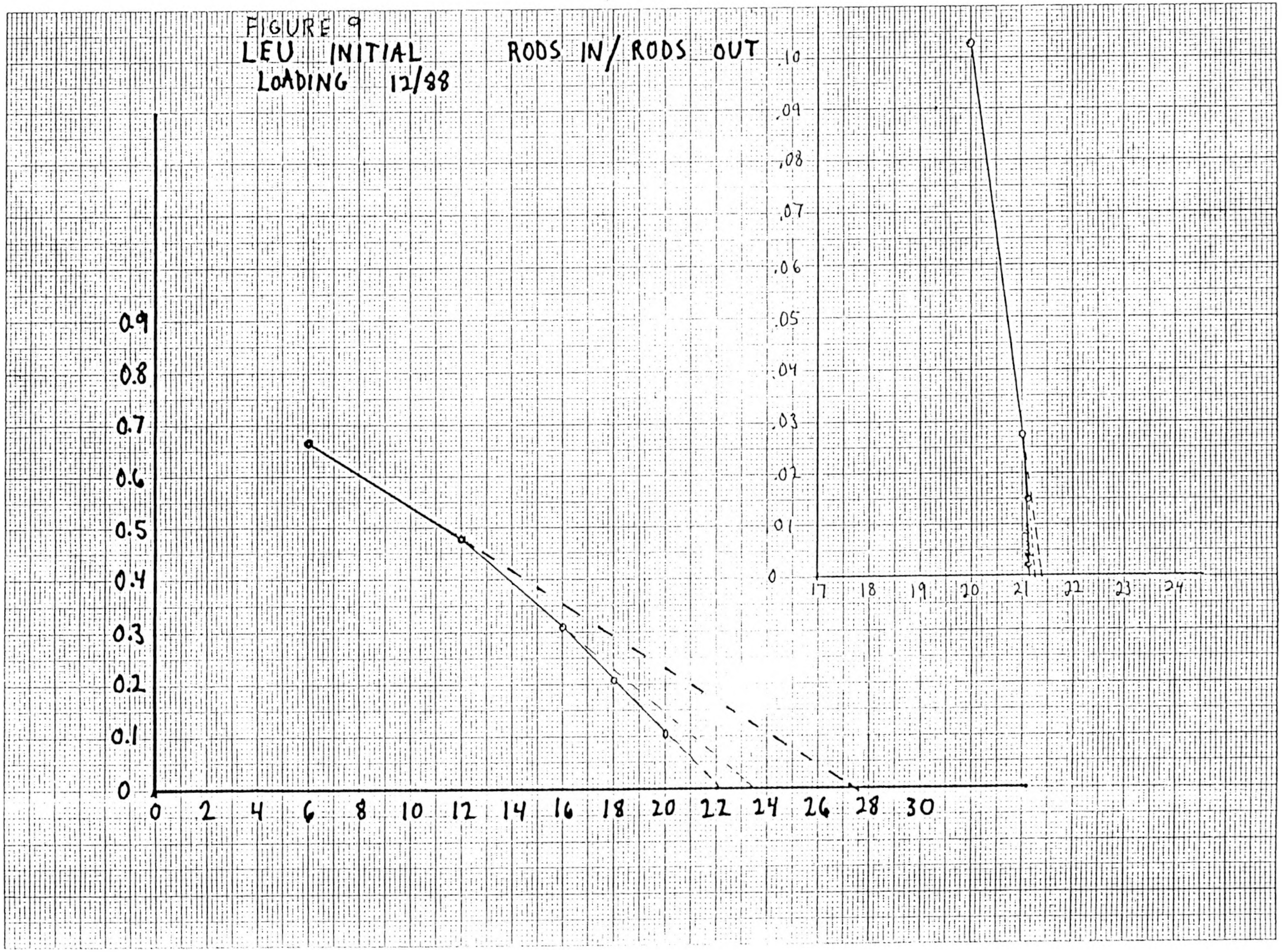


FIGURE 9
LEU INITIAL LOADING 12/88
RODS IN/RODS OUT
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
17 18 19 20 21 22 23 24

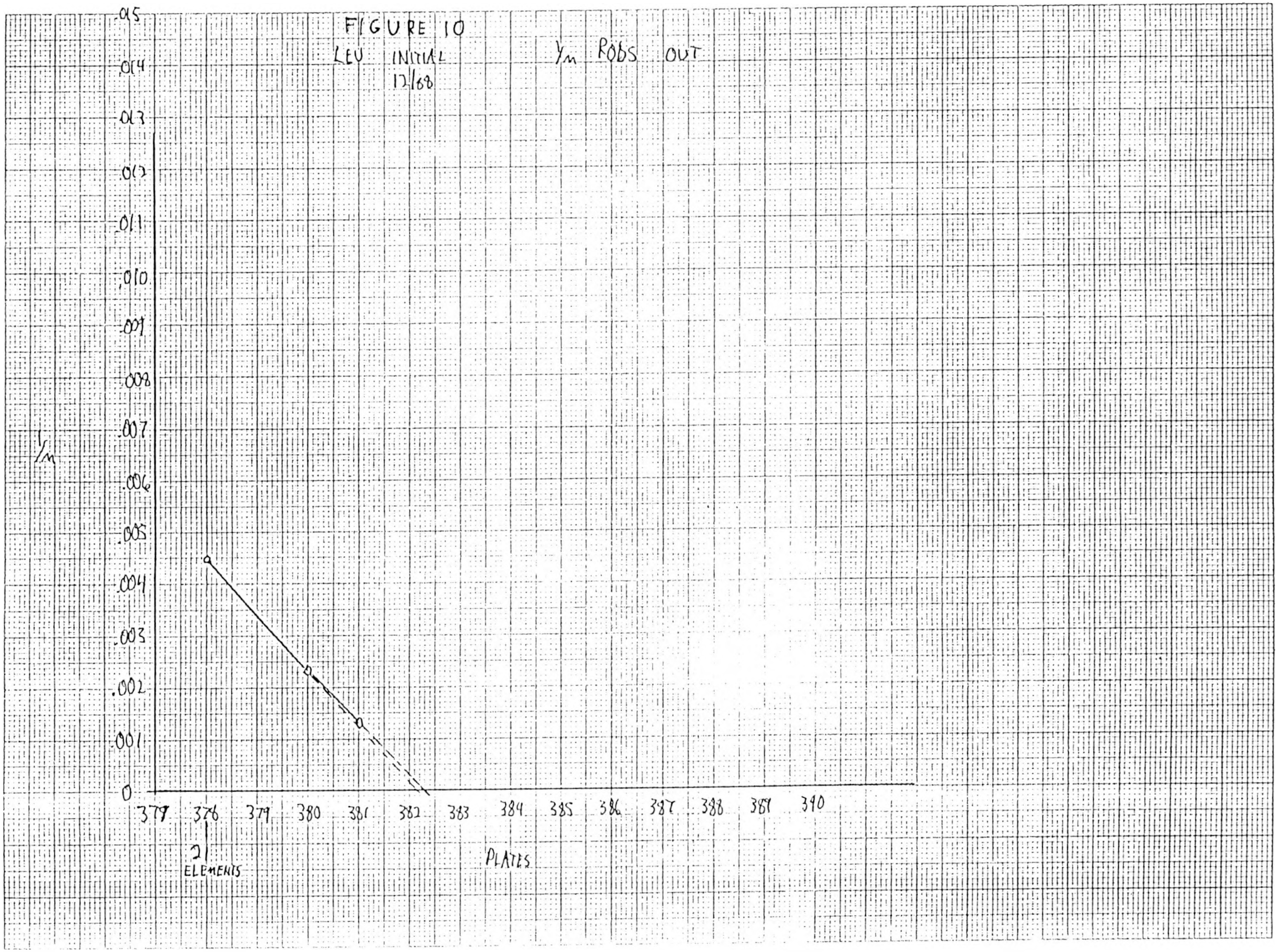


FIGURE 10
LEU INITIAL 12/68
1/m RODS OUT
1/m
.015
.014
.013
.012
.011
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
0
377
378
379
380
381
382
383
384
385
386
387
388
389
390
21 ELEMENTS
PLATES

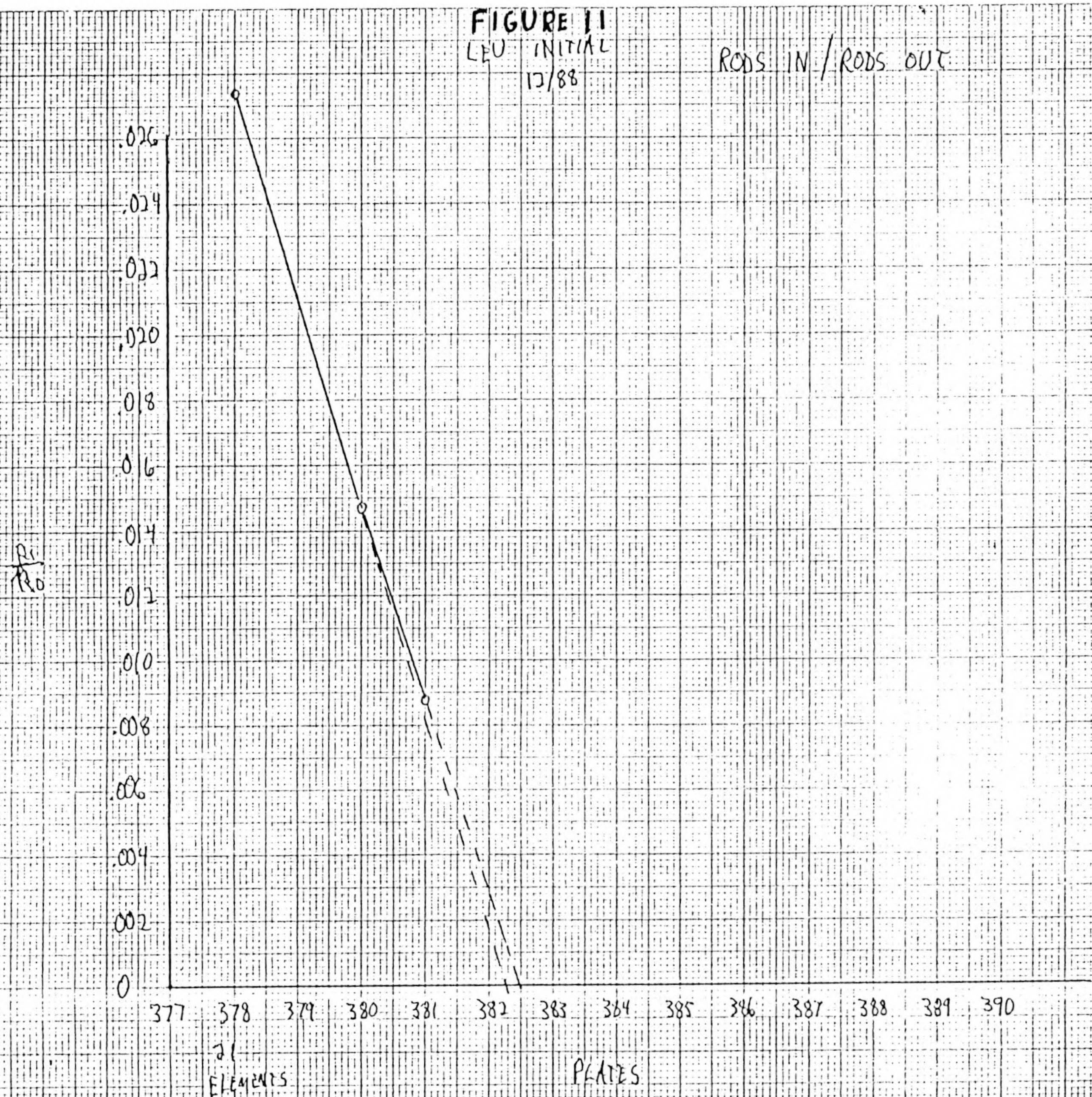


FIGURE 11
LEU INITIAL
12/88
RODS IN / RODS OUT
.026
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
0
377 378 379 380 381 382 383 384 385 386 387 388 389 390
21 ELEMENTS
PLATES