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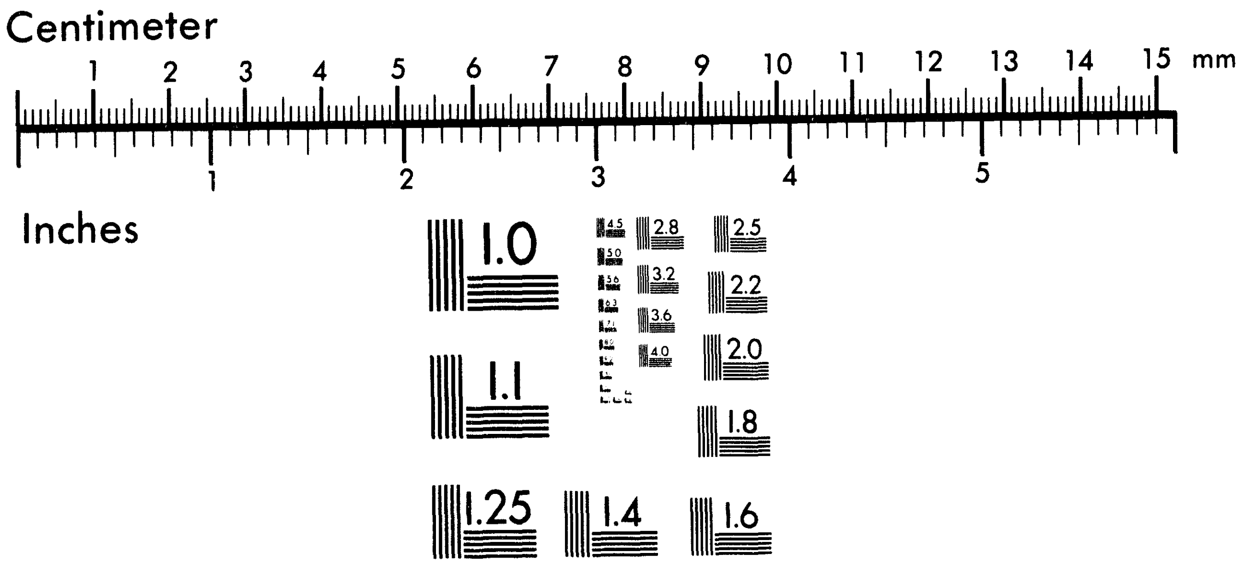


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OPERATIONAL PHYSICS REPORT

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March 6, 1963



DR BALL 3X DROP
OPERATIONAL PHYSICS REPORT

March 6, 1963



# DR BALL 3X DROP
# OPERATIONAL PHYSICS REPORT

## 1. INTRODUCTION

An accidental ball 3X trip occurred at DR Reactor[1] on July 11, 1961. Startup was attempted on July 21, 1961, subsequent to the ball recovery operations, at which time a large reactivity loss was apparent. The loss was assigned to inaccessible poison balls remaining within the graphite structure.

Enriched uranium (0.947% $U^{235}$) columns were charged during successive outages to immediately recover the minimum excess reactivity required for operational transients and effective control. The large increase in enrichment inventory in the reactor complicated evaluation of total control and speed-of-control requirements necessary to comply with the control criteria.

An additional effect of the remaining ball poison was observed as a skewed front-to-rear flux distribution with downstream peaking, indicating a much larger concentration of the balls in the upstream regions of the reactor.

Summaries of various physics analyses performed as a result of the ball drop and some of the analytical techniques used in evaluating and resolving the flux distribution and reactivity and control problems are outlined in the report. The ball boron burnout rate and total estimated costs incurred due to the decreased conversion ratio, reduced operating level, and increased rupture potential are also provided.

## 2. SUMMARY

The extreme reactivity loss experienced from the ball poison could have been drastic except for the availability of enrichment and supplemental control techniques. Resultant losses incurred by increased fuel costs and production losses have been estimated at an average of 3.9% of the net return during the 15 months following the ball drop. Residual poison remaining due to the steel will result in a permanent loss of approximately 0.4% of the net return.

### 2.1 Poison Reactivity Evaluation

Analyses of the lost reactivity due to the ball poison within the reactor have been performed and the results are shown as a function of production in Figure 1. The rate of the boron burnout with production is evident from the plotted data. The initial reactivity loss was evaluated at 17.2 mk, and the residual poison expected to remain after total boron burnout (due to the steel alone) has been estimated at 1.9 mk.

Initially, 190 additional columns of enriched metal and 12 ball valve channels converted back to natural uranium columns (equivalent to approximately 30 enriched columns) were required to compensate the poison effect of the remaining balls. The enrichment loadings before and after the drop are shown in Figures 2 and 3 at equivalent exposures.

/1/ HW-70454, Investigation of Ball 3X Trip Incident at 105-DR, WD Richmond, 7-20-61

2.2 Flux Redistribution

On the basis of analytical studies special charges were designed containing 26 natural uranium elements and five enriched (0.947% $U^{235}$) elements located upstream in the depressed flux regions. Sixty-nine tubes were loaded during January, 1962, with this upstream enriched fuel configuration. Figures 4-9 show the front-to-rear distributions observed in various regions before and after the special charges were loaded into the reactor.

By redistributing the flux, the rupture potentials were improved, leakage losses reduced, and boron burnout accelerated. The calculated average rupture potential was initially reduced 40-50% using the special charges and the burnout rate of boron was increased approximately 30% in the upstream regions.

2.3 Conversion Ratio

The over-all reactor conversion ratio decrease was measured by the large enrichment inventory required to compensate for the ball poison (on the basis of the lower yield per MWD in enrichment columns). It has been estimated that the initial reduction in plutonium production rate (assuming a constant power level) was 35-40 grams of plutonium per day or approximately 2.6% of the production.

2.4 Operating Losses

It was evident from tube power factor distributions that a large portion of of the balls were located in the fringe areas. However, since enrichment could be charged only in the central two zones to remain within total control requirements, the over-all flattening efficiency was reduced. The average ECT (effective central tubes - equal to reactor power/average-top-ten-tube powers) changed from approximately 1530 before the drop to approximately 1490 after the drop. Correspondingly, the average production factor in the central zone increased by 2.1%, thus, lowering reactor production by 2.1% during operation when the reactor power level was limited by specific tube heat generation rates.

2.5 Reactor Control

Due to the possibility that the residual balls were congregated only around the safety system channels, it was necessary to assume shadowing of both the vertical safety rod system and the ball 3X system to the extent of the residual poison until the required experimental evaluations could be made. This possibility required that all compensating enrichment be counted as contribution to total control requirements. Thus, after the ball drop, insertion of supplemental control was required for enrichment compensation before minimum outages were attainable. This poison extended minimum outages 4-6 hours.

Re-evaluations of the vertical safety rod strengths were made during January, 1962, by rod drop experiments at DR and D reactors. These experiments showed some shadowing of the DR rods, but strengths equivalent to those at D reactor.

By reducing system strengths to those at D reactor, direct enrichment compensation by the ball poison was allowed and minimum outages were again attainable without supplemental control requirements.

Speed-of-control requirements were evaluated on the assumption of maximum shadowing of the vertical rod system and more restrictive power levels were specified at low graphite temperatures. This restriction caused only minor production losses because graphite temperature increased rapidly following startup.

## 2.6 Costs

### 2.6.1 Fuel

Fuel costs were evaluated on a per megawatt day basis for the maximum ball poison effect of 17.2 mk. These calculated costs were integrated over the boron burnout period (0-650 x $10^3$ MWD) as shown in Figure 1. Fuel costs were reduced slightly by the addition of the special charged columns in January, 1962. The calculated costs are summarized below in the table.

Table 1

| | |
|---|---|
| Ball drop cost per MWD ( $\rho$ poison = 17.2 mk) | $ 1.215 |
| Ball drop cost per MWD ( $\rho$ poison = 17.2 mk)-split charges | $ 1.168 |
| Integrated costs to January 1962 | $206,000 |
| Integrated costs from January 1962 to residual effect | $283,000 |
| Total fuel cost to residual poison status | $489,000 |
| Residual poison cost per MWD ( $\rho$ poison = 1.9 mk) | $ 0.129 |
| Estimated residual cost/year | $ 65,000 |

The equivalent tons of enriched metal used during the burnout and residual periods are given below.

Table 2

| | |
|---|---|
| Tons of enrichment/MWD ( $\rho$ poison = 17.2 mk) | $0.140 \times 10^{-3}$ |
| Tons of enrichment used during burnout period | $\sim 58.6$ |
| Tons of enrichment/MWD for residual poison | $0.813 \times 10^{-5}$ |
| Tons of enrichment/year for residual poison compensation | $\sim 4.0$ |

### 2.6.2 Rupture Rate Costs

The rupture rate costs were based upon theoretical rupture rates determined from experimental flux distributions and material loadings in the reactor. A loss of 10 hours production per rupture was assumed with a net return of $29/MWD. The additional rupture costs attributed to the skewed distributions were evaluated at $93,000 during the boron burnout period.

2.6.3 Leakage Losses

The skewed flux distributions caused an additional loss from increased neutron leakage rates. This loss was evaluated by determining the enrichment required to comepnsate the loss. The cost was calculated at $13,000 during the burnout period.

2.6.4 Operational Costs

Losses were also incurred by the decrease in reactor flattening efficiency caused by the irregularly distributed balls. This loss caused an estimated decrease in reactor power of 2.1 per cent during operation on tube outlet limitations. This loss integrated over the burnout period was evaluated at $145,000.

2.6.5 Total Costs

The total losses incurred by the ball drop for the listed items are estimated at $740,000 for operation during boron burnout conditions.

Use of the split charges (26 natural and 5 enriched elements per column) from January, 1962, reduced fuel costs an estimated $11,000, reduced rupture costs an estimated $74,000, and reduced leakage losses an estimated $5,000 for a total savings of $90,000.

## 3. DISCUSSION

### 3.1 Reactivity Loss

3.1.1 Purpose

Continual evaluation of the reactivity effect of the poison balls was necessary for efficient short term operation and compliance with total control criterion requirements.

Block loading enrichment predictions were complicated by the poison burnout. By underestimating the burnout, more enriched metal than necessary might be charged in the reactor, thus contributing to inefficient operation. Startup predictions required consideration of the burnout since previous startups at equivalent exposures were not representative with the burnout effect.

After the VSR drop tests,/2/ direct compensation of some enriched columns by the ball poison was allowed in total control calculations. Therefore, to ensure that the reactor always complied to total control requirements, it was necessary that the reactivity of the allowed number of compensated E-columns never exceed the equivalent ball poison remaining within the reactor. The numbers allowed throughout the burnout period are given in reference /2/.

/2/ HW-75407, Final Report PT IP-447-C - Rod Drop Transient Comparison D and DR Reactors Redefinition of DR Vertical Safety System Strength, AD Vaughn, 10-10-62

### 3.1.2 Analysis

Buckling techniques/3/ were used in the analyses of the ball poison reactivity effect since it was found that the flux squared weighting methods did not apply sufficiently well for the large numbers of enriched columns involved in the calculations. Each burnout data point was determined by analysis of cold startup data to eliminate calculation of the hot transient effects of metal and graphite temperature. The reactor was set up into four cylindrical regions in the calculations: (1) central zone, (2) E-ring, (3) fringe zone, and (4) augmentation zone.

Since critical data from the startup was used in each case, the geometric bucklings in each region equaled the material bucklings. Therefore:

$$B^2_{R_i} + B^2_{L_i} = B^2_{M_i} \qquad (1)$$

Where:

$B^2_{R_i}$ = radial geometric buckling of ith region

$B^2_{L_i}$ = longitudinal geometric buckling of ith region

$B^2_{M_i}$ = material buckling of ith region

The material bucklings in each region, except for the ball poison effect, were calculated knowing previous operating levels, loadings, exposures, discharge, and outage duration. The material buckling of each region was calculated by:

$$B^2_{M_i} = B^2_{m_i} - B^2_{Xe_i} - B^2_{Sm_i} - B^2_{Np_i} + B^2_{LTG_i} - B^2_{Rod_i} - B^2_{P_i} - B^2_{BP_i} \qquad (2)$$

Where: $B^2_{m_i}$ = weighted material bucklings of green clean metal in the ith region

$B^2_{Xe_i}$ = buckling equivalent of the xenon reactivity in the ith region

$B^2_{Sm_i}$ = buckling equivalent of the samarium reactivity in the ith region

$B^2_{Np_i}$ = buckling equivalent of the neptunium holdup in the ith region

$B^2_{LTG_i}$ = buckling equivalent of the long term gains of the metal-uranium burnout plus plutonium buildiup

/3/ HW-70780, An Operational Reactivity Accounting System Based on One-Group Diffusion Theory, GF Bailey, 4-1-62

$B^2_{Rod_i}$ = buckling equivalent to the control rods in the ith region at critical

$B^2_{P_i}$ = buckling equivalent of the supplemental control at critical

$B^2_{BP_i}$ = unknown buckling equivalent of ball poison

In the analysis, $B^2_{Rod_i}$ and $B^2_{P_i}$ were applied to regions 1 and 2 and $B^2_{BP_i}$ applied over regions 1, 2, and 3. Thus, the calculated value $B^2_{BP_i}$ was in each case the pile buckling effect.

The unknown ball poison effect was then calculated using a general purpose one-group, one-dimension, diffusion theory code, ZILCH./4/ This code evaluated $B^2_{BP_i}$ for the critical case and this buckling was then converted to equivalent pile reactivity.

The analytical techniques described above were checked by determining a hypothetical $B^2_{BP_i}$ for case before the ball drop. The calculated reactivity was within 0.4 mk of the expected results which was within the expected accuracy of the calculations.

### 3.1.3 Burnout Results

The pile reactivity effect of the ball poison is shown in Figure 1 as a function of the reactor production following the ball drop. As shown, the boron burnout appeared to be fairly slow initially. This was probably due to self-shielding within the balls and, the depressed flux in the excessive ball regions caused by the tremendous absorption increase in these areas.

The data shown in Figure 1 are extrapolated to show that almost all boron burnout should occur by 650,000 MWD after the drop. This value has been used in the cost computations described later.

### 3.1.4 Residual Poison

The steel in the balls will result in permanent poison in the reactor. Once all the boron has burned out, the steel will remain as a poison for the life of the reactor. Earlier studies/5/ have indicated that the poison effect of the steel will be approximately ten percent of the initial poison value with the boron. This would result in a residual poison effect of 1.7 mk.

Another approximation of the residual effect using self-shielding factors/6/ and assuming no shadowing between balls yielded a predicted

/4/ ZILCH, A One-Dimension, One-Group, Buckling Calculation Code, to be issued by G. F. Bailey

/5/ Personal Communication, W. S. Nechodom

/6/ Neutron Self-Shielding, Nucleonics, Vol. 18, No. 11, P. F. Zeifel, page 174-175, November, 1960

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poison value of 1.9 mk. Self-shielding between groups of balls would increase the predicted permanent poison value.

## 3.2 Flux Redistribution

### 3.2.1 Purpose

The flux distribution, which was skewed downstream near the enrichment ring by the ball poison, affected pile rupture rates and the front-to-rear leakage rates considerably.

Analysis of spline traverse data following the drop showed specific slug power increases of 15-20 per cent for the downstream elements near the flux peaks. Using the rupture model, this increase in specific powers resulted in an increase in rupture potential of 200-400 per cent. The high rate of actual ruptures which occurred during the block cycle following the ball drop made it desirable to redistribute the flux by some means to reduce the rupture potentials to less than 150 per cent of those in an equivalent cosine flux distribution.

The increase of leakage rate resulted in increased reactor cost since the neutrons are lost for productive purposes. Although leakage rates were not the primary reason for redistributing the flux, a net gain in productivity resulted.

Redistribution of the flux accelerated boron burnout in the depressed regions of large ball concentrations and thus shortened the recovery period of the reactor.

### 3.2.2 Enrichment Requirements

Special charges containing five enriched elements located upstream with natural elements in the remainder of the charge were designed to redistribute the flux. The special charges were concentrated in the skewed regions of the reactor depending on the severity of the skewing. It was necessary in the analysis to determine the optimum number and location of enriched elements per special charge and the concentration of the charges required in each region of the reactor.

#### 3.2.2.1 Traverse Program

An extensive traverse program was initiated after the ball drop to define the front-to-rear distributions in each region of the reactor using spline traverses. Each traverse was interpreted by the NOLA-2 code. /7/

A value of the buckling at the center of each element is included in the output of the NOLA-2 code. From these slug bucklings, it was possible to closely match the distributions using the ZILCH code.

/7/ HW-69486, Rev. 1, NOLA-2 Code, G.F. Bailey, October 31, 1961

[redacted]

Relative rupture potentials, maximum peaking factors, and weighted bucklings are also given in the output of the NOLA-2 code. These parameters were used in evaluating the effectiveness of the redistribution program.

3.2.2.2 Buckling Analysis

Once the traverses were closely matched using the ZILCH code, changing the enriched slug positions, length and concentrations were easily evaluated using the IBM 7090 computer. For instance, if slugs 7, 8 and 9 in the tube charge were to be changed to enriched metal with a concentration of ten per cent (one tube out of ten loaded as a special charge), then the bucklings of these slugs were changed by +21μb (difference between wet material bucklings of enriched I&E slugs and natural I&E slugs equals 210 μb in the old piles). Figures 10, 11, and 12 show respectively the effects of the various special (or split) charge tube concentrations upon a typical flux distribution using respectively 3, 4, and 5 enriched elements per charge. The slugs were located in the charge as shown in Figure 13.

The ZILCH code also determined the relative rupture potentials of each slug. It was, therefore, possible to compare directly from ZILCH the rupture potentials for various numbers of enriched slugs and concentrations of special charges. This comparison is shown in Figure 14 for two typical traverses. As shown in Figure 14, a smaller concentration of special charges each containing five slugs of enriched metal is required for the same effect upon the rupture potential than the charges containing three or four enriched elements. However, the total number of enriched elements required for a given change in rupture potential was found to be about the same for each charge design.

Another result obtained from the ZILCH analysis was the pile buckling effect as a function of the special charge concentration for different front-to-rear distributions. By similar analyses for full columns of enriched metal, it was possible to determine the equivalence between number of enriched slugs added in the special charge tubes to those that could be discharged from full columns of enrichment for a constant pile reactivity. These results are shown in Figure 17 and resulted from the buckling data shown in Figures 15 and 16 for the five-piece special charge.

Figure 17 shows that less enriched metal could have been used for the same result with the three-piece enriched charge rather than the five-piece charge for redistributing the flux. However, many more tubes would have been involved with the three-piece charge, so the five-piece charge was used.

To determine the concentrations of special charges required in each region of the reactor, it was found from the studies that the concentration required was somewhat proportional to the number of full columns of enrichment originally charged in each region to overcome the ball poison reactivity loss. For the initial loading of the special charges, one was charged in each region for approximately every two full columns of enrichment required to compensate the ball poison effect on reactivity in that region.

The power generation in a special charge tube compared to that of a natural charge was determined. By changing the last downstream slug to an expendable, it was found that the power was approximately 1.3 per cent greater than that of the regular natural charge. However, it was also estimated that a flow increase of about the same magnitude would occur and thus result in no change in the outlet temperature of the tube.

The effect of the special charged columns upon total control was considered. Since the purpose of the special charges was to redistribute a skewed distribution caused by the balls to a more reactive cosine distribution upon which total control requirements were already based, their effect should be negligible. However, it was also possible to overcompensate using special charges so that their equivalent full column enrichment was used and counted as spike enrichment in total control calculations. The initial 69 special charged columns were calculated to have equivalent reactivity of six full columns of enrichment, and therefore, the number of spike columns of enrichment was increased by six in total calculations for the special charged columns.

### 3.2.3 Flux Redistribution Results

In January, 1962, 69 special charges each containing five enriched elements were charged into the reactor. The results upon the flux distributions are shown in Figures 4-9. A few additional charges were required in the top-far corner of the pile.

Table 3 shows relative factors to cosine distributions resulting from spline traverses obtained before and after the special charges were loaded in each of six general regions:

Table 3

| Region | Upstream Flux | | Peak Flux | | Relative Rupture Potential (22nd Piece From Front) | |
|---|---|---|---|---|---|---|
| | Before | After | Before | After | Before | After |
| Top-near | .56 | 1.00 | 1.14 | 1.07 | .74 (?) | 1.54 |
| Center-near | .71 | .91 | 1.13 | 1.11 | 2.11 | .40 |
| Bottom-near | .66 | .86 | 1.16 | .99 | 3.13 | 1.13 |
| Bottom | .89 | 1.00 | 1.05 | 1.05 | 2.37 | .96 |
| Top-far | .72 | .73 | 1.11 | 1.12 | 5.29 | 2.22 |
| Center-far | .72 | .90 | 1.07 | 1.02 | 3.42 | 1.68 |

By averaging many traverses, it was found that the longitudinal buckling was reduced from 19.4 to 16.99 μb, a reduction in leakage equivalent to about 13 spike enriched columns of metal. The average, longitudinally weighted, relative, rupture potential was reduced from 2.402 to 1.340, and the average, relative rupture potential of the 22nd slug was reduced from 2.96 to 1.32. It has been estimated that the reduction of the rupture potential prevented about 1.7 ruptures per cycle. The costs associated with these savings are described in section 3.6.

A further savings, described in section 3.6 resulted from the improved conversion ratios with the more uniform flux distributions. Although the additional enriched slugs reduced the conversions of the specific tubes containing special charged columns, the improved flux distributions provided a net increase in the over-all reactor.

## 3.3 Conversion Ratios

### 3.3.1 Analysis

The conversion ratio at DR reactor after the ball drop was reduced by: (1) substitution of 0.947 per cent $U^{235}$ enriched metal for natural metal in approximately 210 tubes and, (2) its skewed flux distributions. In each case, conversion ratios were calculated using Plutonium Conversion Tables./8/

The conversion tables give tube production as a function of tube exposure for cosine distributions. Using the actual flux traverses, the exposure of each element was calculated and its production estimated using the tube-conversion ratios at that exposure. By integrating these slug productions over the entire tube for both cosine and skewed distributions, an estimate of the effect of skewed distributions upon production for identical tube goal exposures was found. The percentage losses in the skewed distributions of tubes 1787 and 3964, were found to be respectively 0.58 per cent and 1.60 per cent from that for a cosine distribution. A correlation between per cent conversion ratio loss and per cent special charge tube concentration was assumed using the data shown in Figure 14 for the

/8/ HW-50300-B - IPD Plutonium Conversion Tables, D. W. Hoba, June 30, 1961 five-piece charges. The average concentration of special charge tubes in the central two zones was 69/1236 = 5.58 per cent. Using the correlation, it was estimated that the average conversion ratio loss in the central two zones was 0.52 per cent. It was assumed that 75 per cent of the loss was regained by using the split charge loading.

The conversion ratios of the special charge tubes were evaluated by integrating slug productions for a cosine distribution. The conversion ratio of a special charged tube was calculated as 0.58 per cent less than that of a natural tube for the same tube goal exposure.

An additional effect of the large increase in the enrichment inventory was to lower the daily exposure of the surrounding natural metal columns for a constant reactor power level. This results from enrichment tubes producing approximately 1.057 times the power of a natural tube in the same flux region. The split charged tubes also produce more power than an equivalent natural tube by a factor of 1.013. These values were used in determining the number of production days required for the average tube to reach its goal exposure.

An assumption was made in the analysis that the production in the fringe zone remained constant. Although this assumption was not true, its effect upon the calculated productions should only be slight. The place where the total production between the central zones and the fringe played an important part was in the changes in ECT and maximum power level during operation limited by outlet tube temperatures.

### 3.3.2 Results

The results of the calculated conversion ratios of the central two zones are given in Table 4. The second and third columns correspond to a reactivity effect of the ball poison of 17.2 mk. In determining integrated losses after the ball drop, the losses were assumed proportional to the reactivity effect as shown in Figure 1.

## 3.4 Production Efficiency

### 3.4.1 Effective Central Tubes (ECT)

The ECT at DR reactor dropped from approximately 1530 to 1490 after the ball drop. As indicated by the enrichment loadings, much of the ball poison was located in the E-ring and fringe zones of the reactor. Loading of the enriched metal in the central two zones to compensate the ball poison in the fringe caused a general shift in tube powers from the fringe to the central zones.

[redacted]

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Table 4

| | | Before Ball Drop | After Ball Drop | After Adding Split Charges |
|---|---|---|---|---|
| Assumed reactor power level, MW | | 1750 | 1750 | 1750 |
| Number of tubes charged (Zones 1&2) | nat. | 1084 | 874 | 811 |
| | enr. | 130 | 340 | 334 |
| | s.c. | | | 69 |
| Goal exposure, MWD/Ton | nat. | 625 | 625 | 625 |
| | enr. | 925 | 925 | 925 |
| | s.c. | | | 625 |
| Relative tube powers | nat. | 1.000 | 1.000 | 1.000 |
| | enr. | 1.057 | 1.057 | 1.057 |
| | s.c. | | | 1.013 |
| Avg. tube factors | nat. | 1.1800 | 1.1685 | 1.1679 |
| (Assuming F = const. for Zones 1&2) | enr. | 1.2473 | 1.2351 | 1.2345 |
| | s.c. | | | 1.1831 |
| Days/cycle at full power to goal | nat. | 68.942 | 69.621 | 69.656 |
| (Zones 1&2) | enr. | 74.636 | 75.373 | 75.410 |
| | s.c. | | | 65.746 |
| Tube production/cycle, gm-Pu | nat. | 62.13 | 61.81 | 62.03 |
| (Zones 1&2) | enr. | 59.01 | 59.01 | 59.01 |
| | s.c. | | | 58.32 |
| Tube production/day, gm-Pu | nat. | 0.9012 | 0.8878 | 0.8905 |
| | enr. | 0.7906 | 0.7829 | 0.7825 |
| | s.c. | | | 0.8871 |
| Daily production (Zones 1&2), gm-Pu | nat. | 976.9 | 775.9 | 722.2 |
| | enr. | 102.8 | 226.2 | 261.4 |
| | s.c. | | | 61.2 |
| Total | | 1079.7 | 1042.1 | 1044.8 |

nat. - natural metal column
enr. - enriched metal column
s.c. - special charged column

Comparison of the average tube power factors in the central zones from factor maps for several months before and after the drop showed that the average factor increased from 1.181 to 1.206. This indicated that the average central zone tube powers increased 2.12 per cent and during periods of tube power limits to reactor power, the total power would be reduced by 2.12 per cent.

For approximately eight months after the ball drop, the power level at DR reactor was limited by graphite temperature limits or tube outlet temperature limits imposed to reduce tube corrosion. It has been estimated that the total production lost during the operationally limited periods due to the lower ECT was approximately 5000 MWD. With a net return of approximately $29/MWD, this amounted to a loss of $145,000.

[redacted]

3.4.2 Nonequilibrium Losses

Nonequilibrium losses were slightly lower after the ball drop indicating little or no loss due to the ball drop. Increased proficiency of the operating personnel with the use of splines during turnaround probably overweighted any losses that might have been noticeable.

## 3.5 Control Effects

### 3.5.1 Total Control

Total control requirements, after insertion of 190 enriched columns to compensate the ball poison, became quite limiting. Supplemental poison was required for enrichment compensation in the near and far side E-rings before minimum outages could be attained. Minimum outages were lengthened 4-6 hours by the insertion of 5-6 mk of supplemental poison required for total control.

Initially, no compensation was allowed for the 17.2 mk of ball poison in the reactor since the degree of shadowing of the vertical rods by the balls was not known and the worst case was assumed for reactor safety. The vertical rod strengths were measured by rod-drop experiments in January, 1962 in both D and DR reactors. The tests and final results are given by A. D. Vaughn./2/

Under unshadowed conditions, the vertical safety rod strengths and ball system at DR would be greater than at D due to the larger diameter rods and channels in DR. Some shadowing was apparent from the tests; however, DR rods were found to be at least equivalent to those in D reactor. It was then concluded that the control strengths at DR be reduced to those at D reactor and that the enriched columns required for ball poison compensation not be included in the total control calculations. This again allowed minimum outages without supplemental poison requirements.

Since enriched columns were then assumed compensated directly by the ball poison, it was necessary to keep close evaluation of the poison effect to prevent any overcompensation. The number of allowable compensated columns as a function of time is given in reference 2. In October, 1962, total control techniques were returned to their original status and all compensation for ball poison was removed due to the decreased value of the poison reactivity effect.

### 3.5.2 Speed of Control

Speed-of-control requirements were readjusted after the ball drop/9/ due to the assumed shadowing and flux distortions in the reactor.

/2/ HW-75407, Final Report PT IP-447-C Rod Drop Transient Comparison D and DR Reactors Redefinition of DR Vertical Safety System Strength, AD Vaughn, 10-10-62

/9/ HW-70630, Speed of Control Limits - 105-DR, WS Nechodom, 8-1-61

Lower limits on maximum power level as a function of average graphite temperature were established. These lower limits, however, had little effect upon nonequilibrium losses. Under cold startup conditions, the graphite temperature did not limit power ascension once temperature maps were taken. On secondary cold startups, however, it was necessary under certain conditions to wait several minutes at lower power levels before raising to turnaround power levels, to allow the graphite to heat to the specified minimum temperatures. These specific conditions were quite infrequent.

## 3.6 Ball Drop Cost Analysis

### 3.6.1 Fuel Costs

In the analysis of the fuel costs attributed to the ball drop, the cost per MWD has been calculated at a time when the ball poison reactivity was 17.2 mk. These costs have then been integrated over the entire boron burnout period (assumed to be 650,000 MWD). Figure 1 was used for the poison effect as a function of production after the drop.

Costs have been calculated for two cases. The first are the predicted costs had the special charges not been used for redistributing the flux. For this case the average poison effect during the 650,000 MWD production was 10.9 mk. In second case, costs are given with the special charges added after the initial 187,000 MWD production. For this case, the average poison effect during the initial 187,000 MWD production was 15.6 mk and 9.0 mk for the remaining 463,000 MWD production. Table 5 summarizes the analysis and costs.

The residual poison effect of the balls has been calculated to be 1.9 mk due to the steel alone.

Table 5

| Fuel Costs | Before Ball Drop | After Ball Drop | After Drop, With Special Charges |
|---|---|---|---|
| Avg. power level, MW | 1,750 | 1,750 | 1,750 |
| Daily production (Zones 1&2) gm-Pu | 1,079.7 | 1,042.1 | 1,044.8 |
| Productivity/day ($50/gm-Pu) | $53,985 | $52,105 | $52,240 |
| Uranium cost/day (Zones 1&2) nat | 9,622 | 7,643 | 7,114 |
| ($9.85/gm-Pu-nat enr | 1,357 | 3,514 | 3,450 |
| 13.20/gm-Pu-enr) s.c. | | | 630 |
| Total | $10,979 | $11,157 | $11,194 |
| Processing costs/day (Zone 1&2) nat | 3,837 | 3,064 | 2,841 |
| ($2071/Ton - nat enr | 529 | 1,371 | 1,346 |
| $3373/Ton - enr) s.c. | | | 263 |
| Total | $ 4,366 | $ 4,435 | $ 4,450 |
| Net return/day (Zone 1&2) | $38,640 | $36,513 | $36,596 |
| Net return/MWD (1304 MW-Zones 1&2) | 29.61 | 27.98 | 28.05 |
| Initial ball drop cost/MWD ($\rho$ = -17.2 mk) | | 1.215 | 1.168 |
| Total cost to residual poison status | | 500,000 | 489,000 |
| Residual cost ($\rho$ = -1.9 mk) | | | $ 0.13/MWD |

approximately $15,000/cycle
or $65,000/year

### 3.6.2 Rupture Costs

The rupture rates calculated for rupture costs are based upon a rupture rate of 2.79/6 months [10] had skewing not occurred.

Table 6

| Rupture Costs | Before Ball Drop | After Ball Drop | After Drop, With Split Charges |
|---|---|---|---|
| Avg. rupture potential | 1.000 | 2.402 | 1.340 |
| Calculated rupture rate/day | 0.0240 | 0.0576 | 0.0322 |
| Lost days/day (10 hr/rupture) | 0.0100 | 0.0240 | 0.0134 |
| Rupture cost/MWD ($29/MWD net return) | 0.290 | 0.696 | 0.389 |
| Net rupture cost /MWD due to balls ($\rho$ = -17.2 mk) | | 0.406 | 0.099 |
| Cost to residual poison status | | $167,000 | $93,000 |

/10/ Personal Communications, W. I. Neef

[redacted]

### 3.6.3 Leakage Costs

The leakage costs attributed to the ball drop were calculated from the longitudinal buckling values before and after insertion of the special charged columns. The reactivity equivalence of the leakage was calculated for each case in terms of enriched columns required. The calculations show a savings of approximately 13 columns of enriched metal by changing the front to rear flux distribution. However, previous calculations, section 3.2.2.2, showed a savings of only 6 columns. The difference can qualitatively be accounted to increased boron burnout rate, thus restoring the reactor to its original state within a shorter period of time.

Table 7

| Leakage Costs | Before Ball Drop | After Ball Drop | After Drop, With Split Charges |
|---|---|---|---|
| Longitudinal bucklings, μb | 15.17 | 19.04 | 16.99 |
| Reactivity equivalent, mk | - 9.10 | -11.40 | -10.19 |
| Reactivity loss, mk | | 2.30 | 1.09 |
| Equivalent No. of E-columns | | 25.6 | 12.1 |
| Tube production relative to nat, gm/day | | -0.1049 | -0.1080 |
| Production, gm/day | | -2.685 | -1.307 |
| Productivity loss/day | | $ 134.25 | $ 65.35 |
| Uranium costs/day | | -40.69 | $ -18.85 |
| Processing costs/day | | -13.46 | $ -6.36 |
| Net leakage cost/day | | $ 80.10 | $ 40.14 |
| Net cost/MWD ( $\rho$ = -17.2 mk) | | $ 0.0458 | $ 0.0229 |
| Leakage cost to residual poison status | | $ 18,900 | $ 13,300 |
| Total Costs - Fuel, ruptures, leakage | | $686,000 | $595,000 |

With the estimated production losses due to tube outlet limits, the total costs for the ball drop described here are $595,000 + 145,000 or approximately $740,000. These costs do not include the economic effects of reduced TOE or additional manpower and equipment costs, etc., the consideration of which is beyond the scope of this document.

JW Hagan:gs

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Process Physics - Process Eval. & Control
Research and Engineering Section
N REACTOR DEPARTMENT
(Previously with
Operational Physics Sub-Section
Research and Engineering Section
IRRADIATION PROCESSING DEPARTMENT)

[redacted]



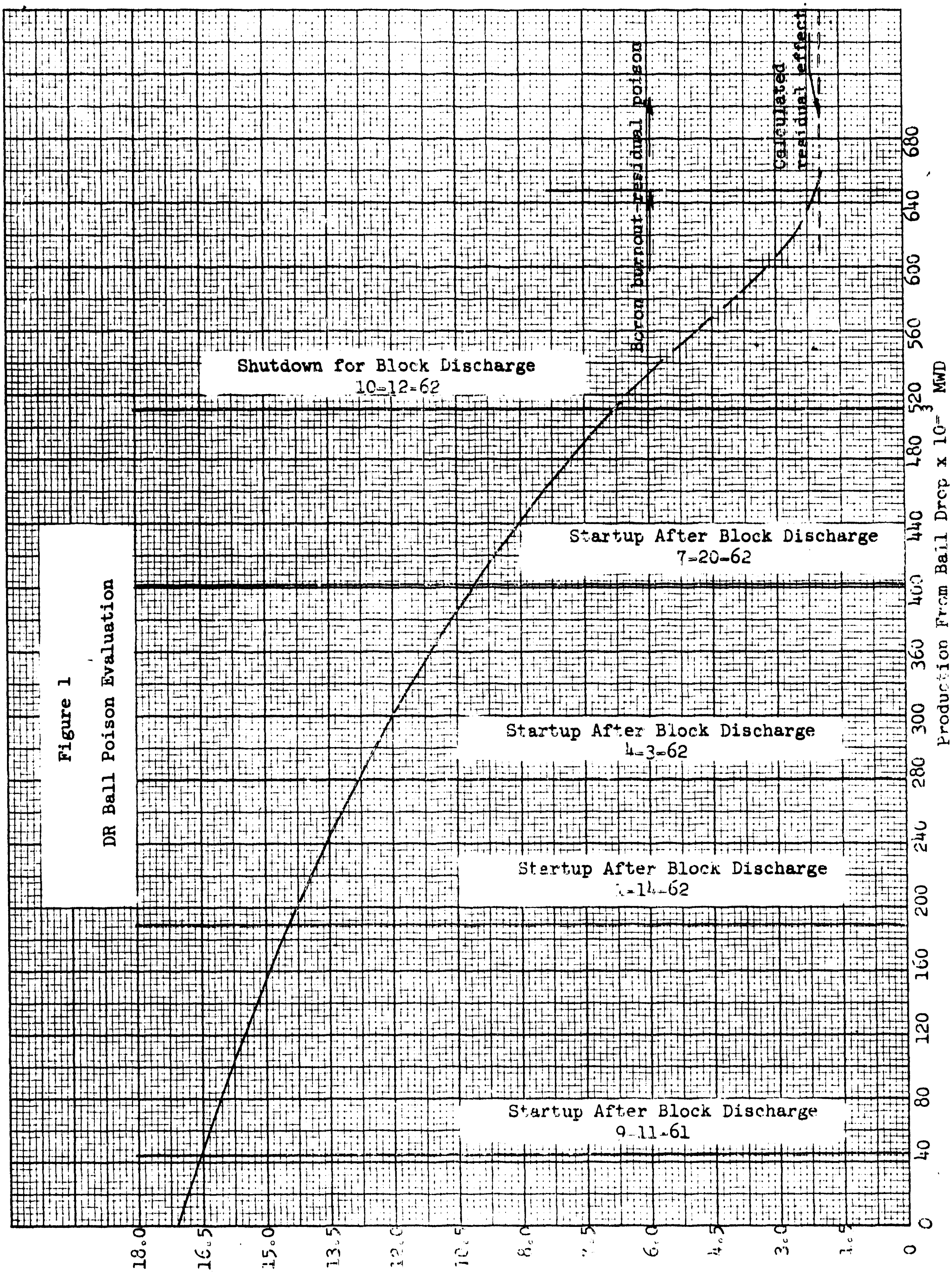


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Figure 2

DR Enriched Column Inventory
Typical Before Ball Drop 4-1-61

[X] = Enriched Column

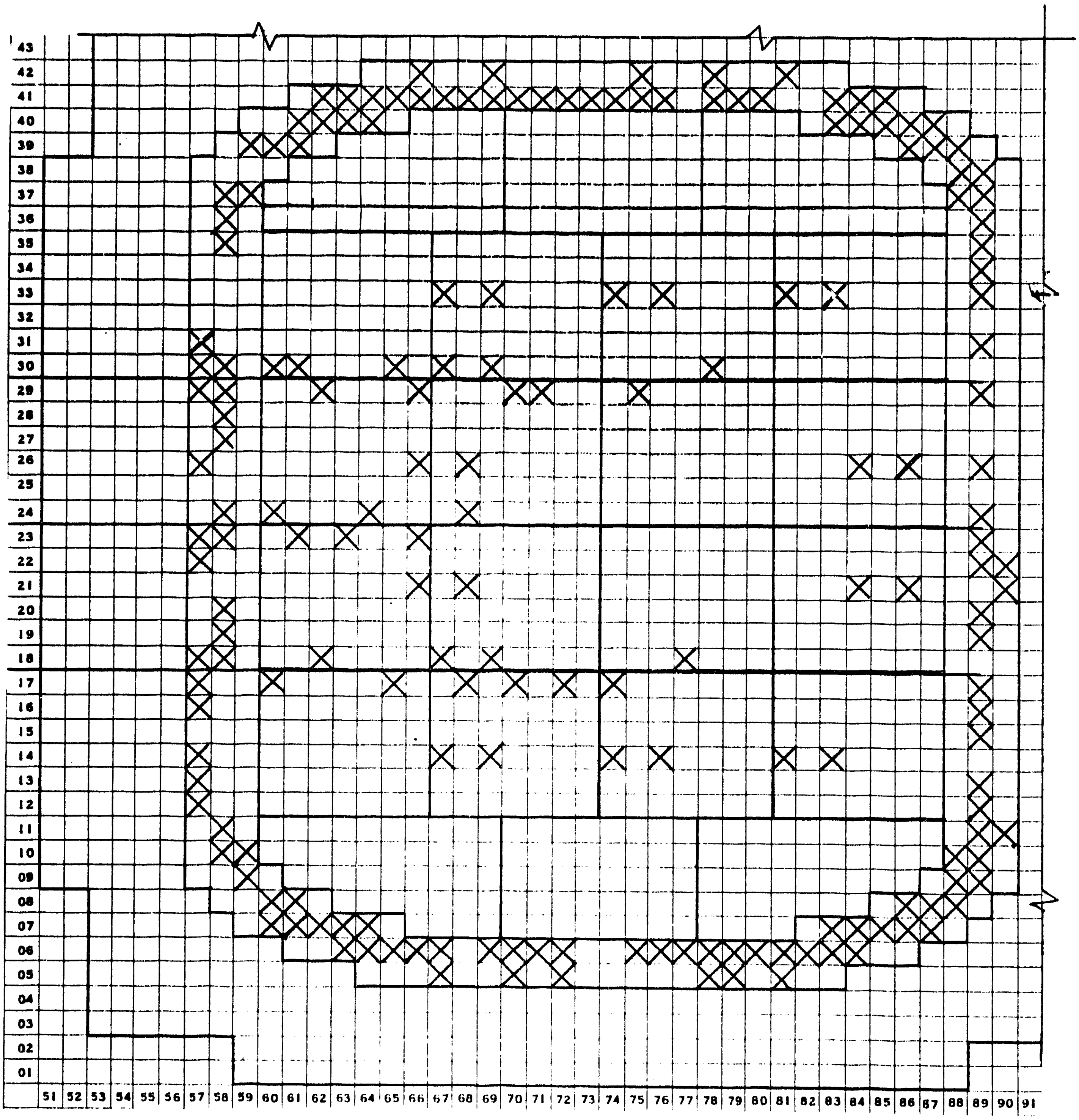

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Figure 3

DR Enriched Column Inventory
Typical After Ball Drop 9-4-61

[X] - Enriched Column

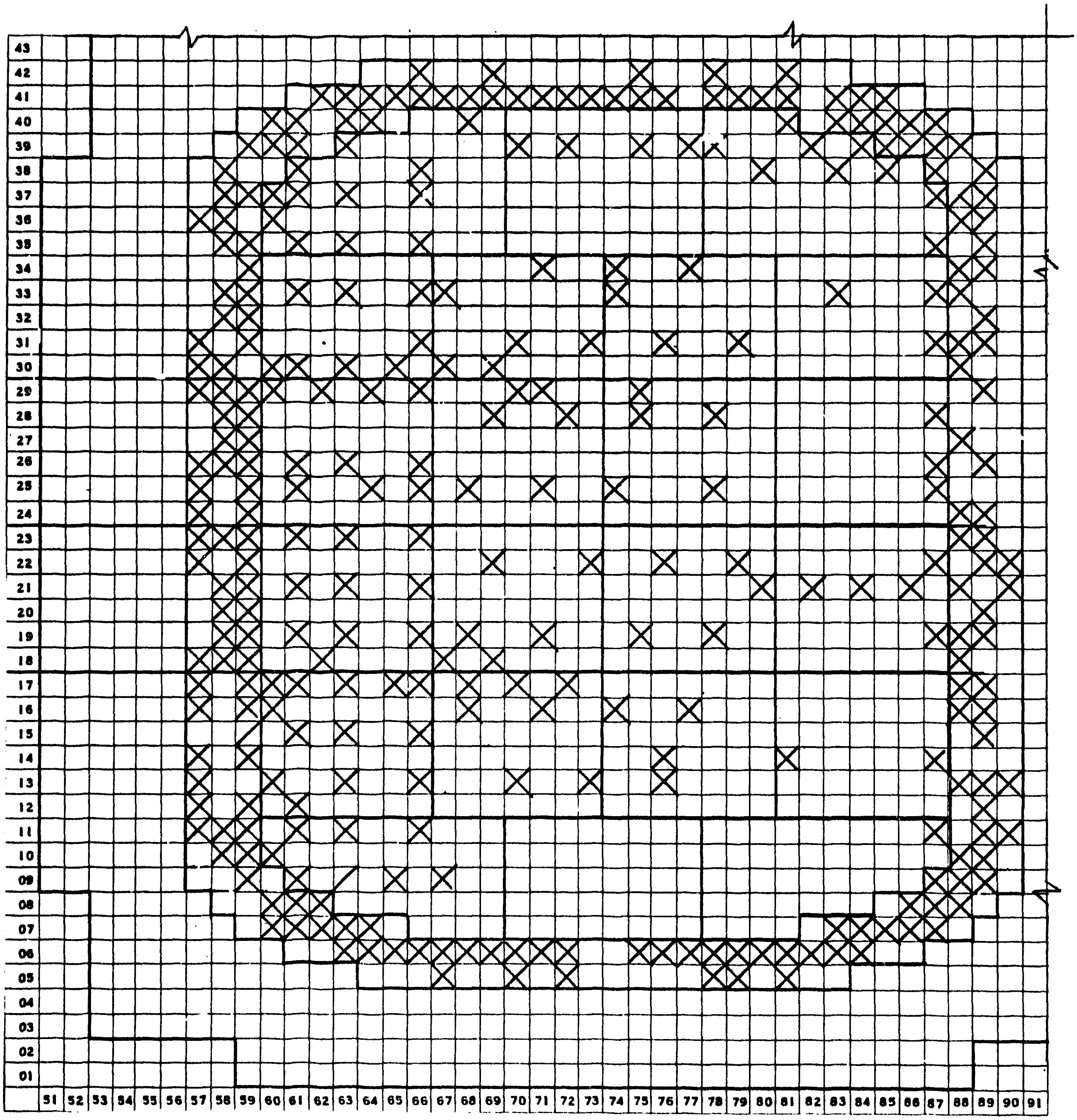


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Figure 4

DR Flux Distributions - Top Near
Before and After Redistribution Measures

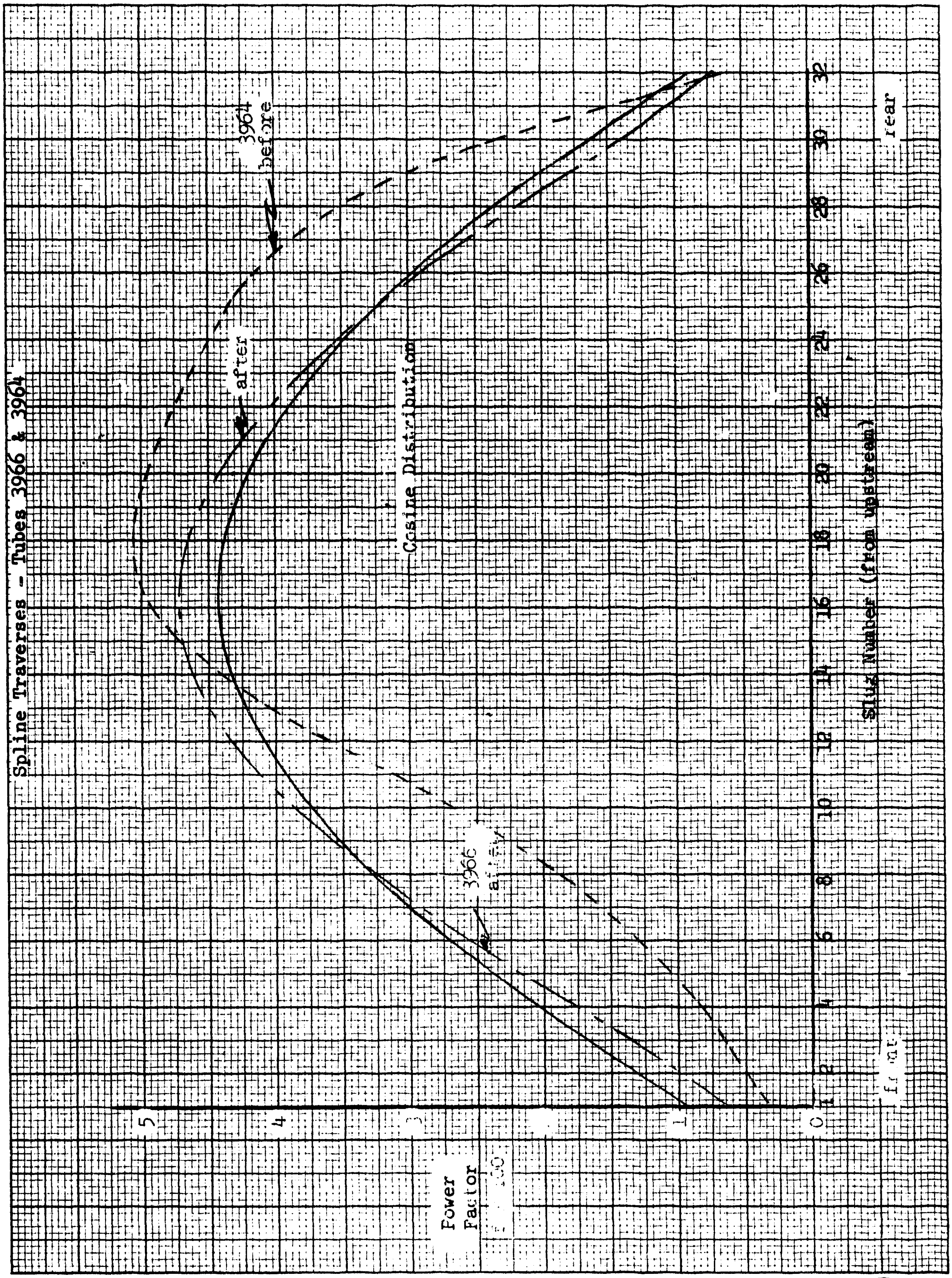


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Figure 5
DR Flux Distributions - Center Near
Before and After Redistribution Measures
Spline traverses - Tube 25[illegible]

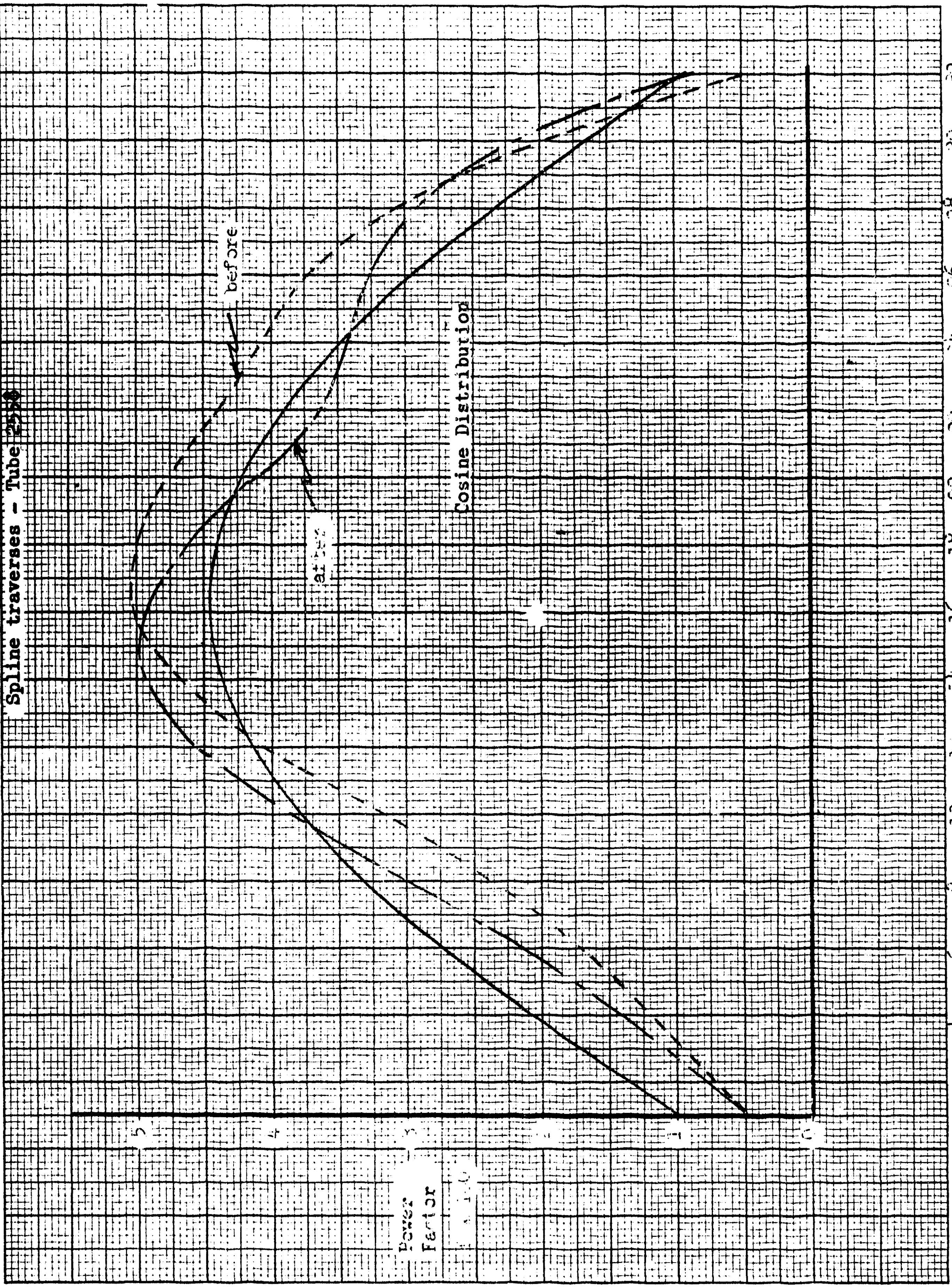

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Figure 6

DR Flux Distributions - Bottom Near
Before and After Redistribution Measures

Spline Traverses - Tube 1858

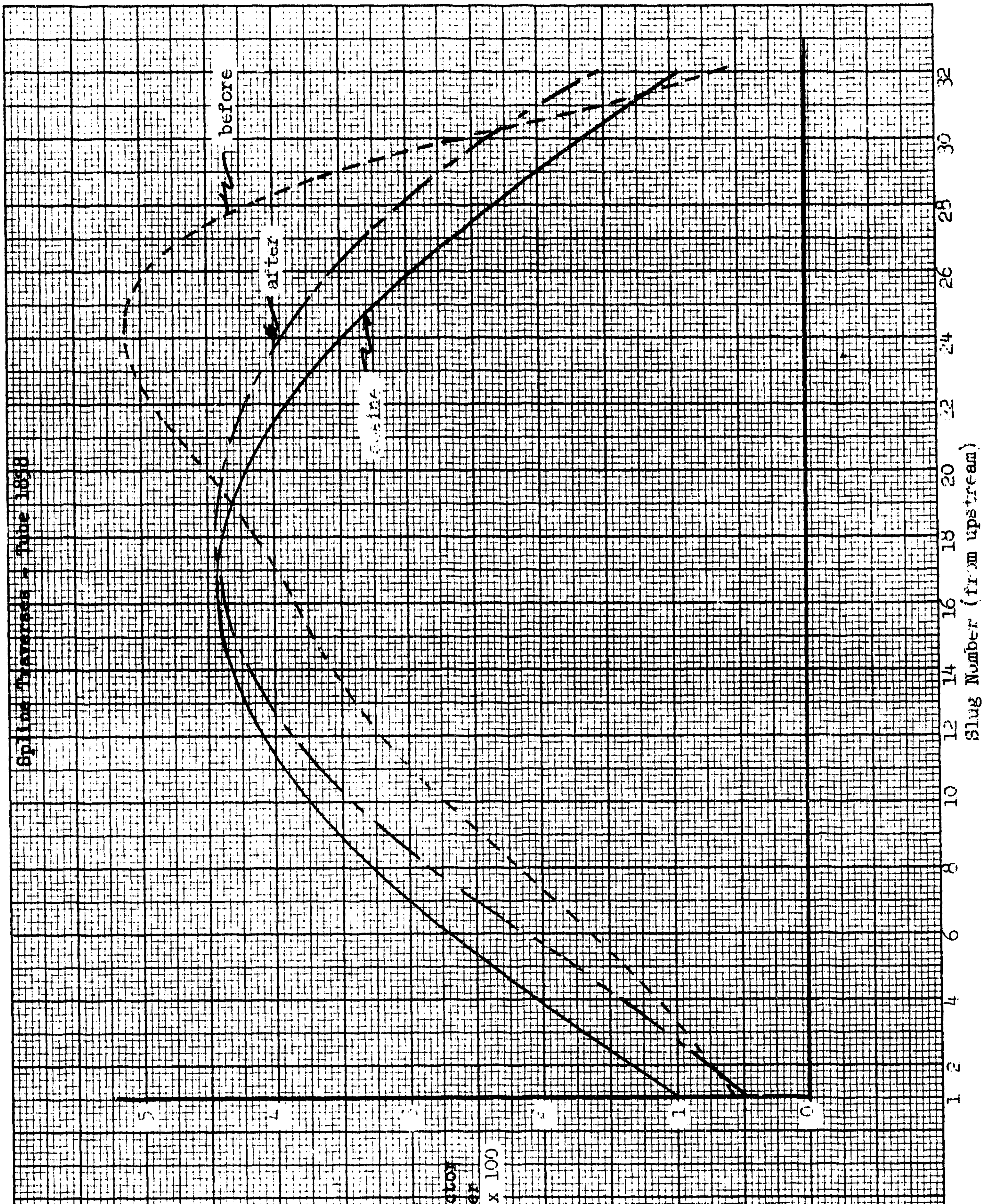


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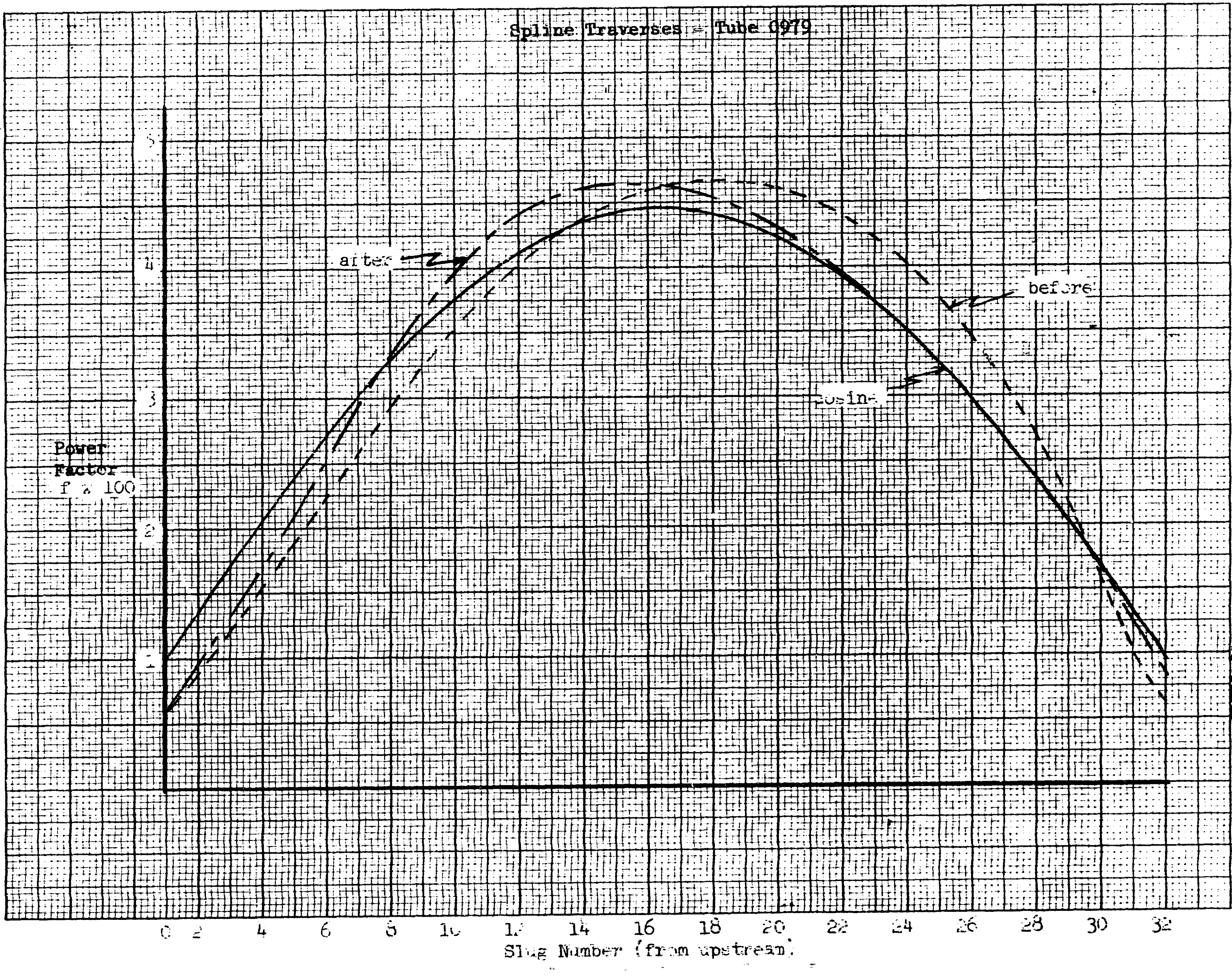
Figure 7

DR Flux Distributions - Bottom Center
Before and After Redistribution Measures



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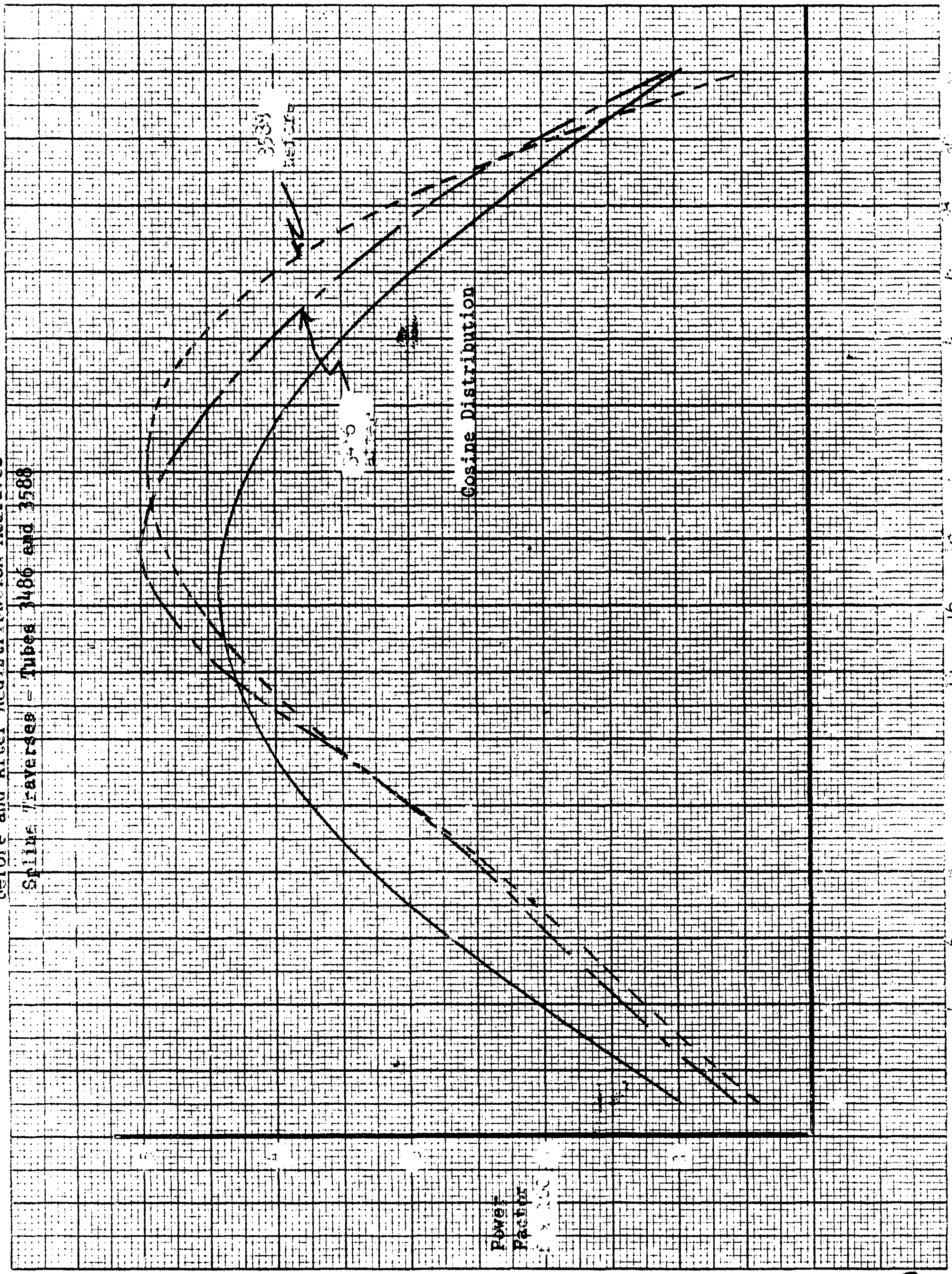


Figure 8

DR Flux Distributions - Top Far
Before and After Redistribution Measures
Spline Traverses - Tubes 3486 and 3588

[redacted]

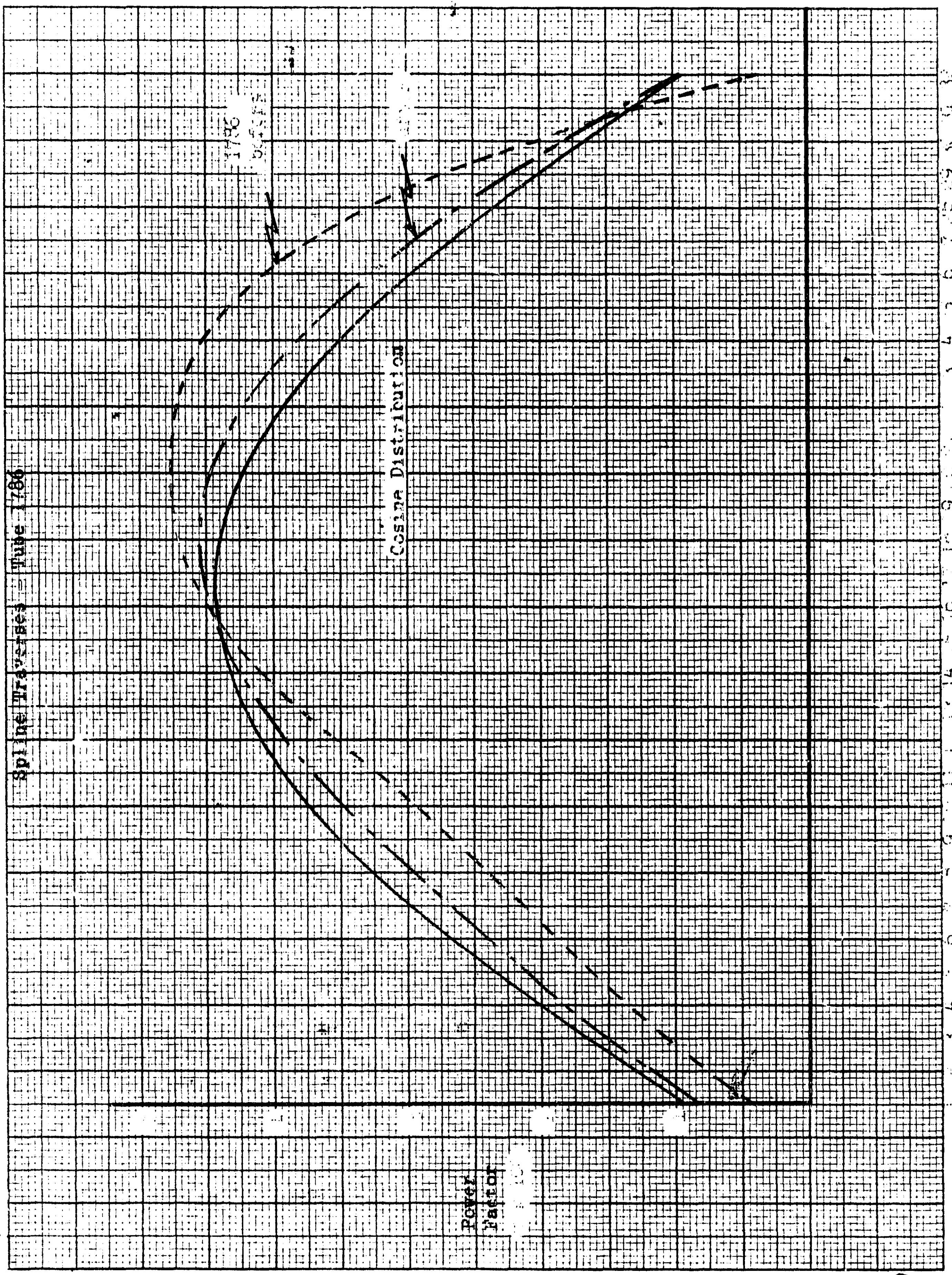


Figure 9

DR Flux Distributions - Center Far
Before and After Redistribution Measures
Spline Traverses - Tube 1786

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Figure 10

Flux Distributions for Various Special Charge Concentrations
Special Charge = 3 Enriched Elements
= 29 Natural Elements

(ZILCH Analysis Tube 3964)

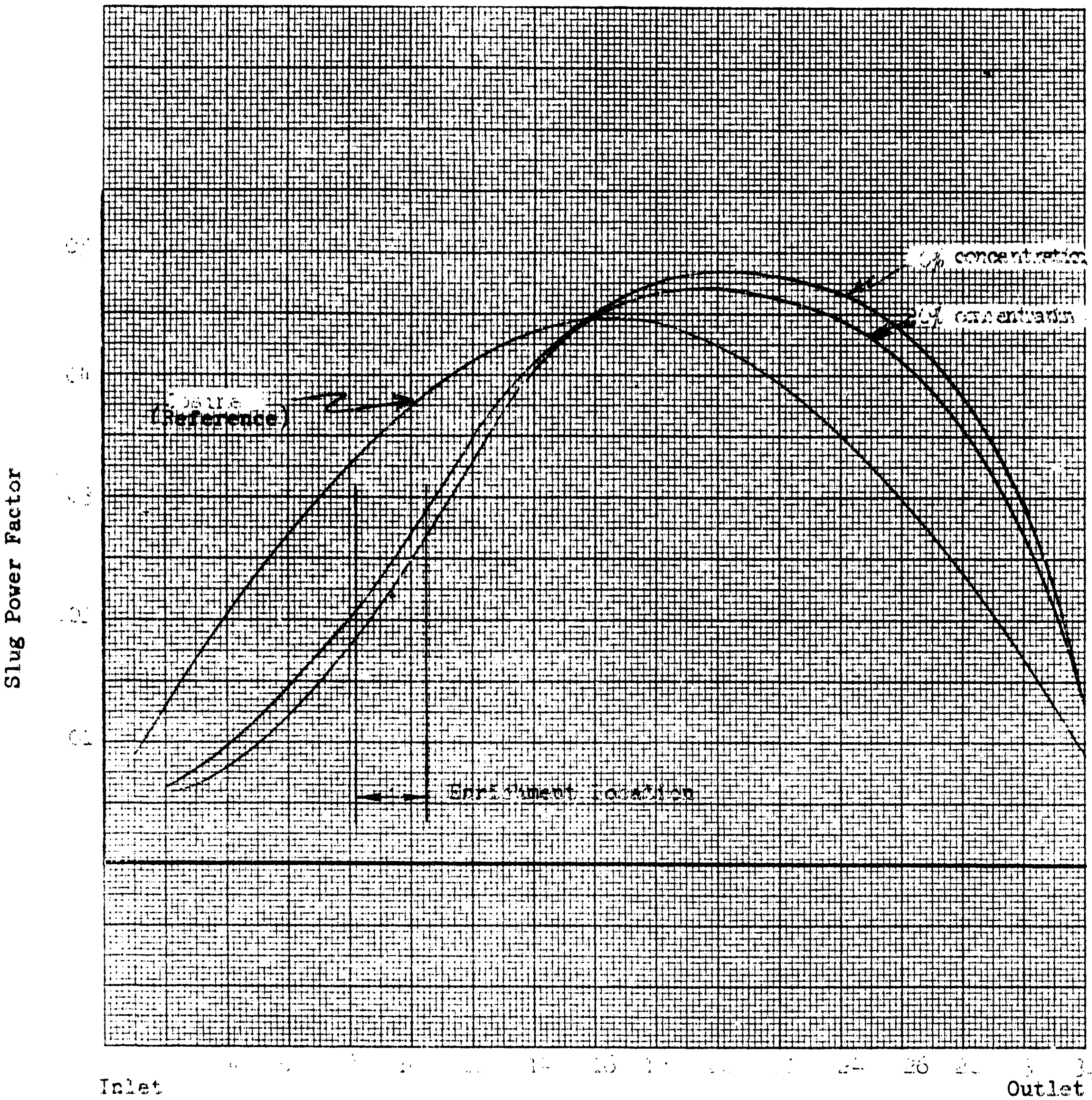


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Figure 11

**Flux Distributions for Various Special Charge Concentrations**
**Special Charge - 4 Enriched Elements**
**29 Natural Elements**

(Zilch Analysis Tube 3964)

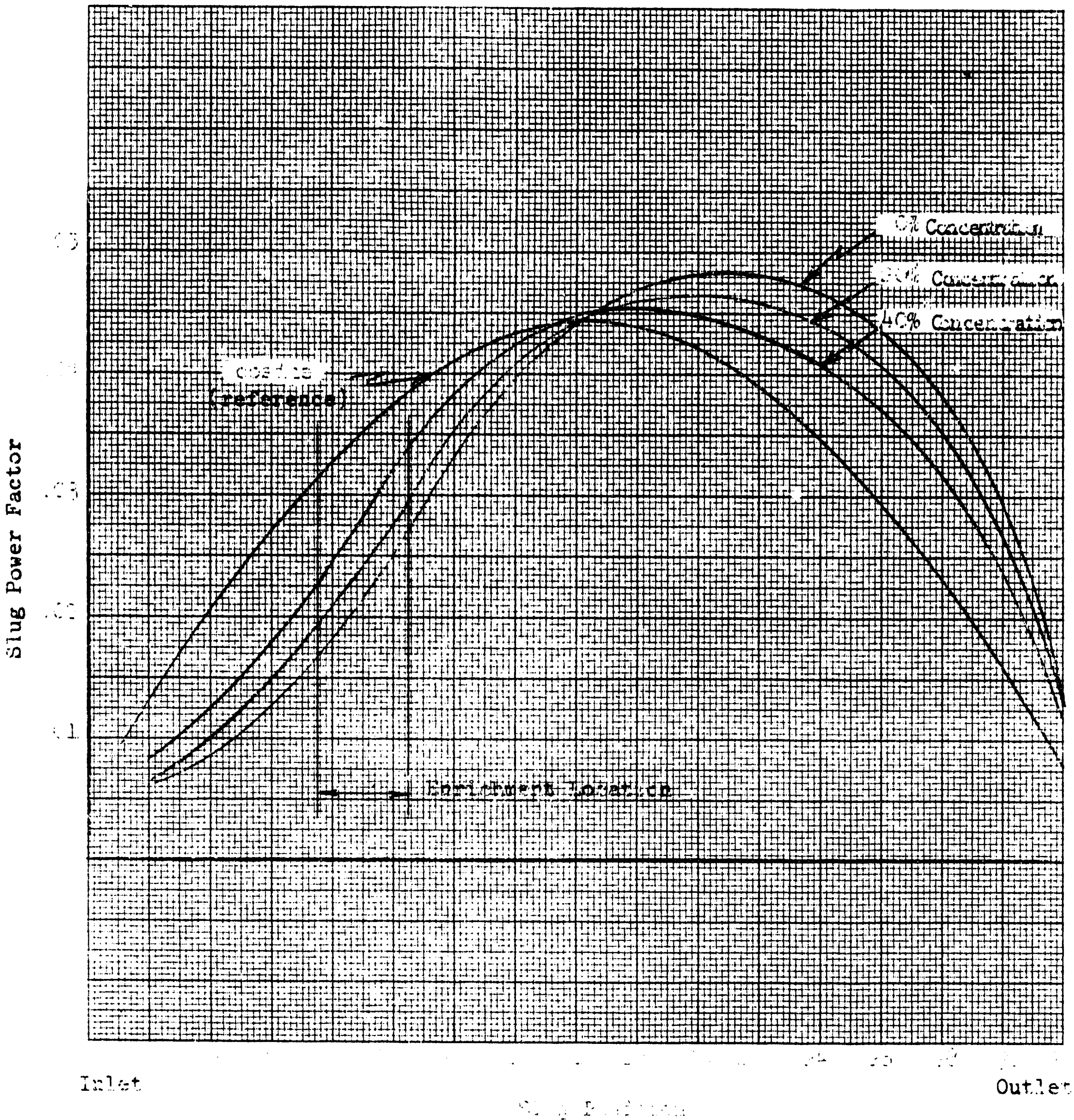


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Figure 12

Flux Distributions for Various Special Charge Concentrations
Special Charge - 5 Enriched Elements
28 Natural Elements

(Zilch Analysis Tube 3964)

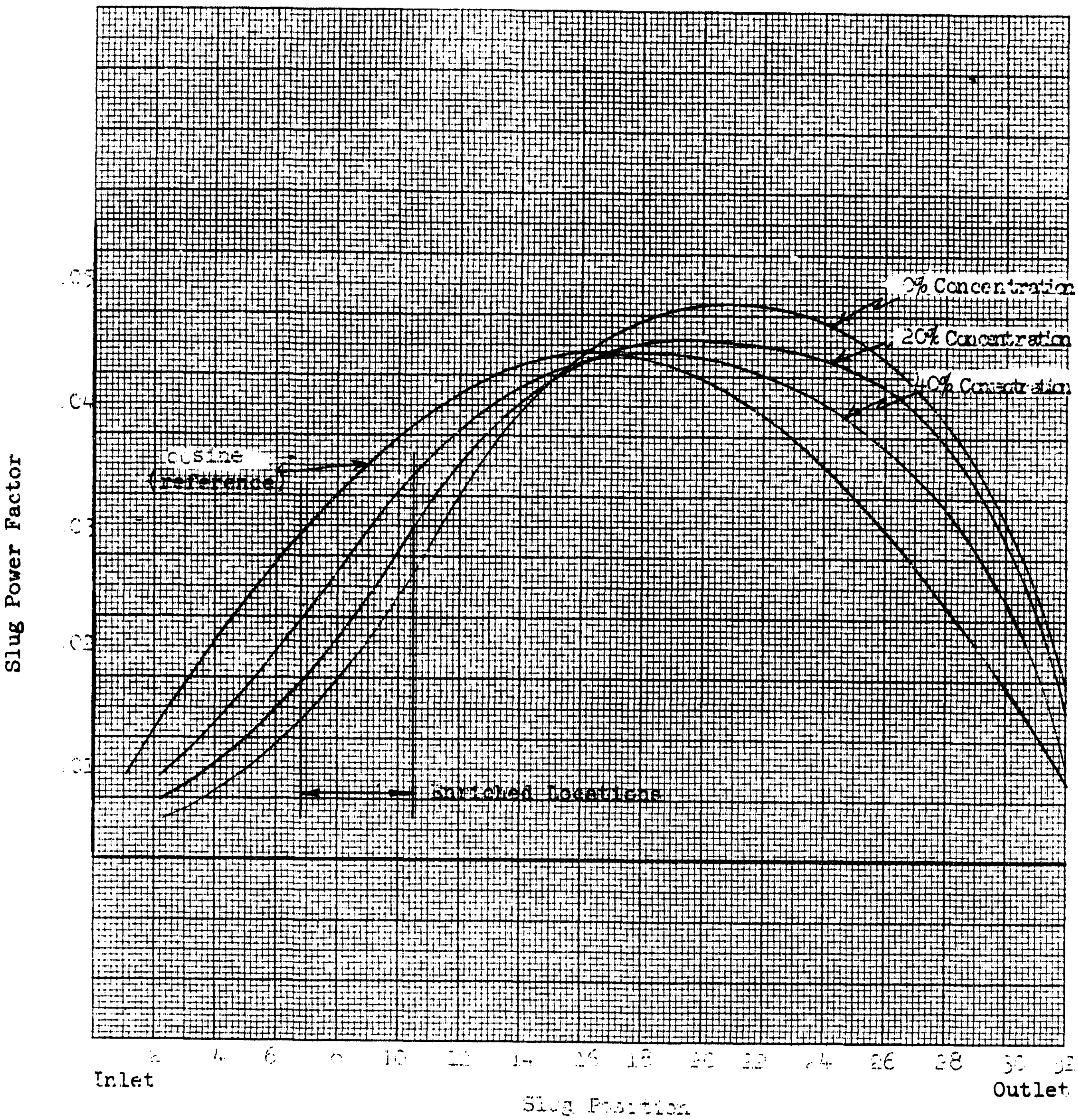

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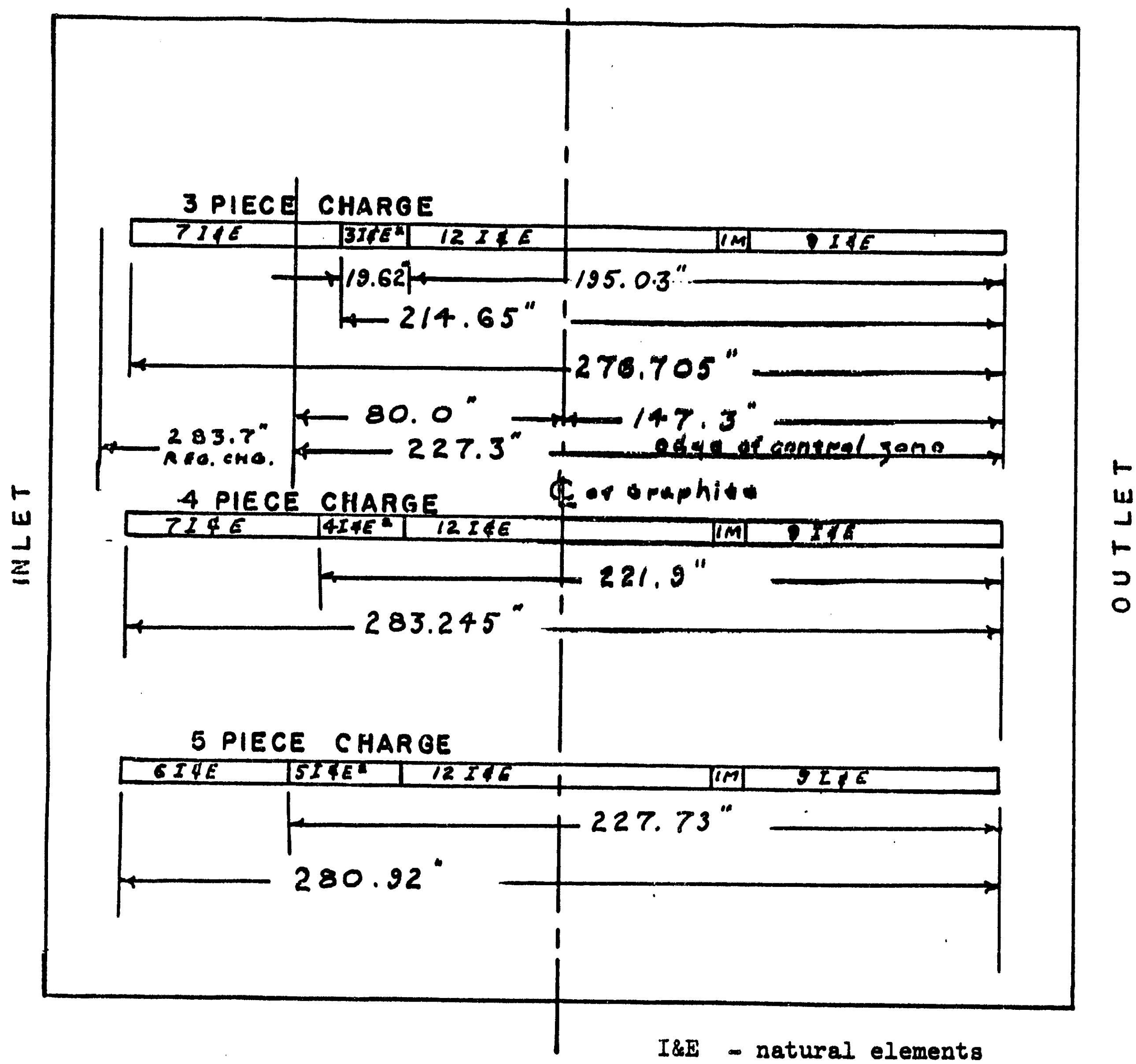
FIG 13

PROPOSED SPLIT CHARGE PLACEMENT




I&E - natural elements

I&E² - enriched elements

M - natural mixer elements

[redacted]

[redacted]

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Figure 14

Relative Rupture Potential vs. Special Charge Concentration
(3-, 4-, and 5-Enriched Elements/Special Charge)
For Typical Flux Distributions - Tubes 3964 and 1787

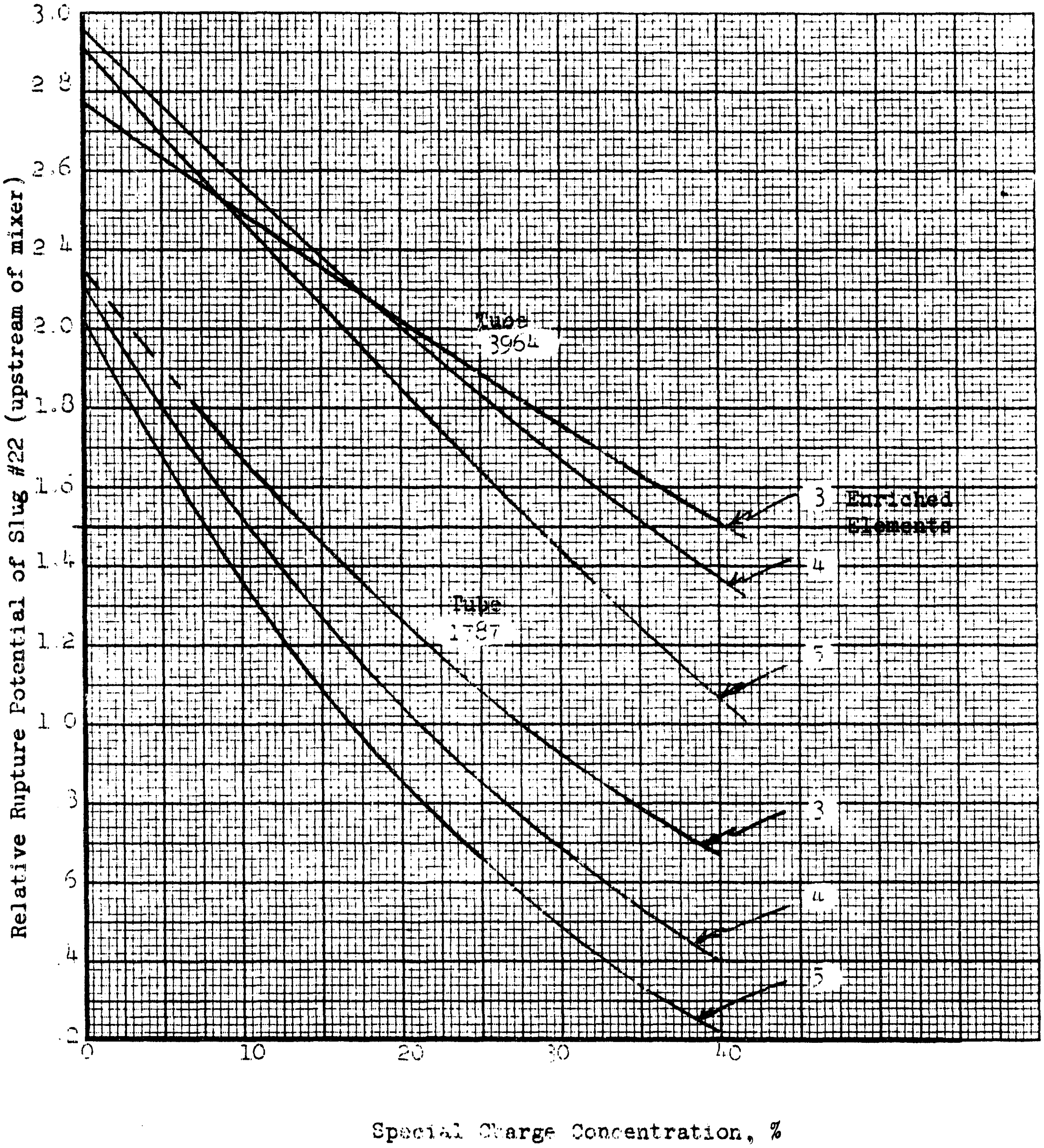


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Figure 15

Pile Buckling vs Special Charge Concentration
Special Charge 5 enriched elements
28 natural elements
Typical Skewed Distributions - Tubes 3964 & 1787



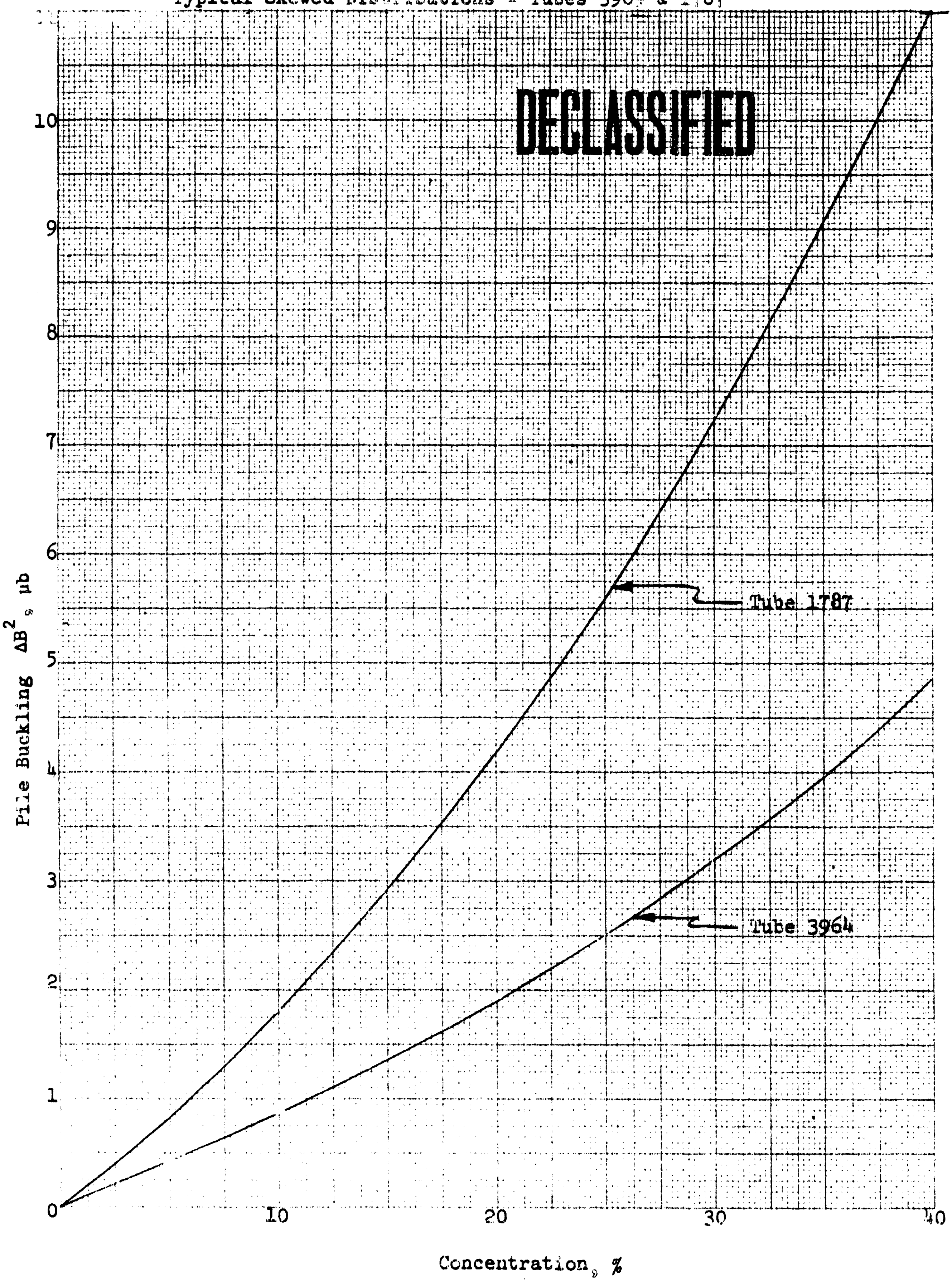

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Figure 16

Pile Buckling vs. Enriched Column Concentrations
for Various Flux Distributions

Distributions: Cosine
Tube 1787
Tube 3964

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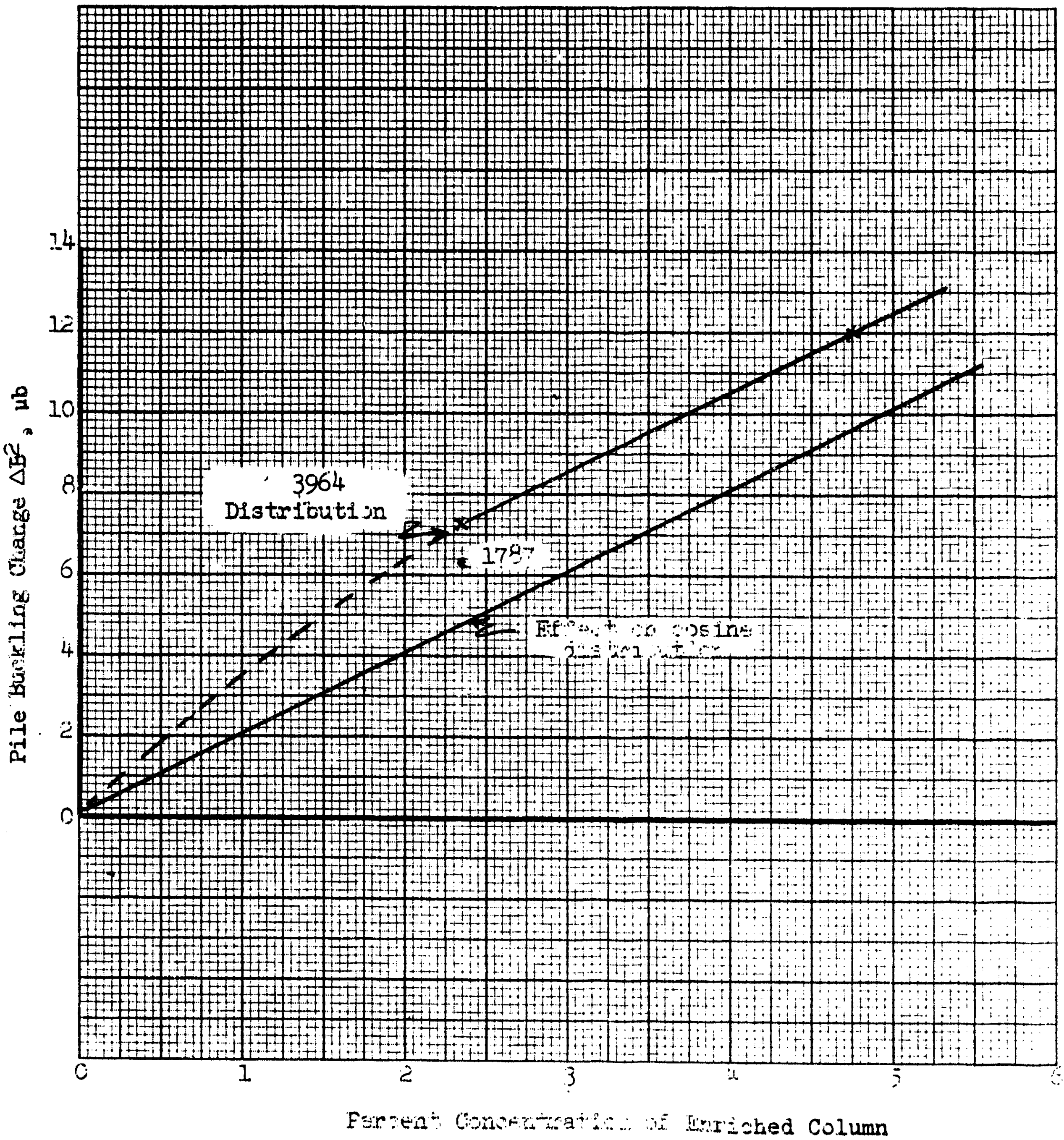


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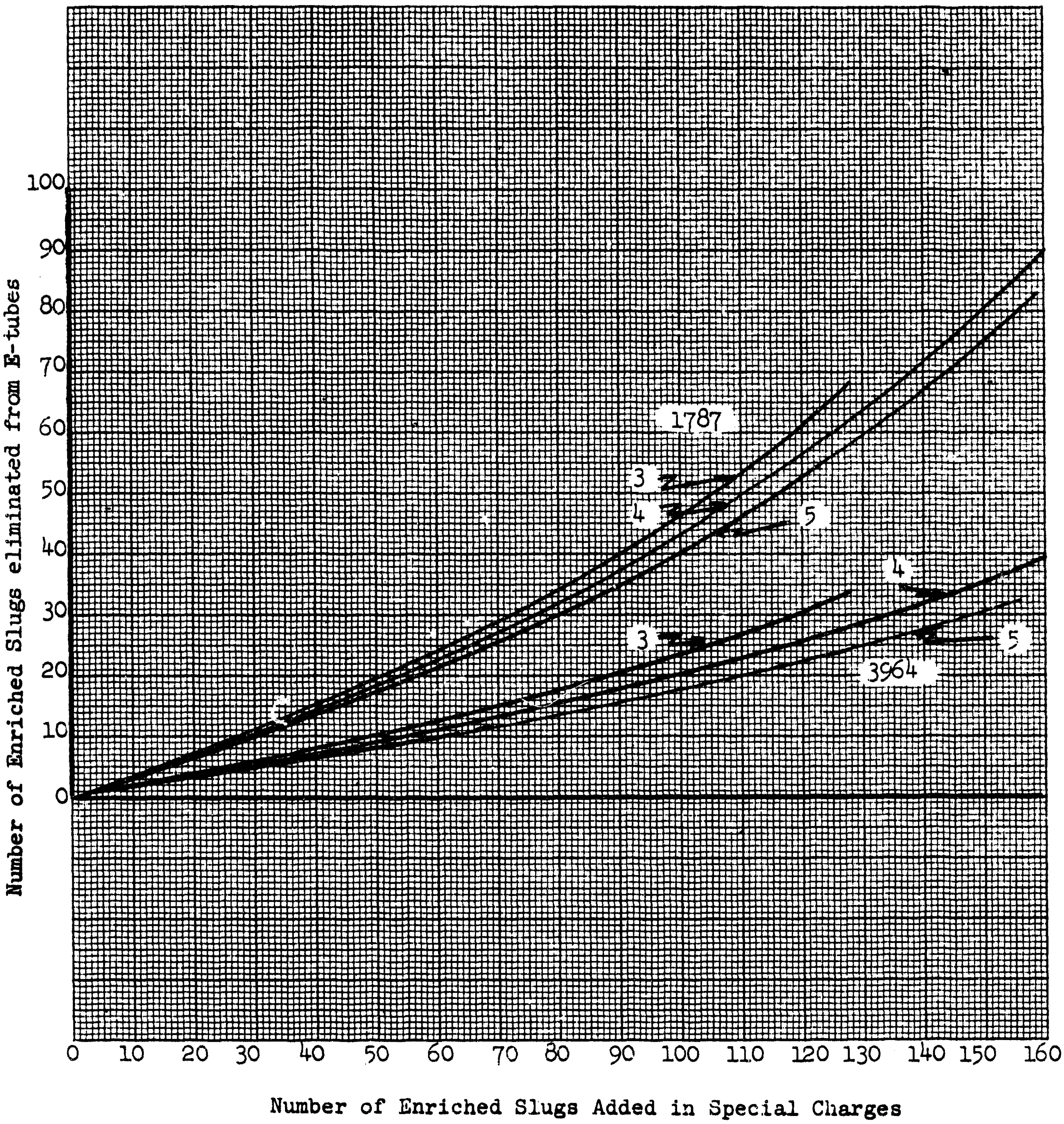
Figure

Split Charge Efficiency
(3-, 4- and 5-Piece Enrichment)

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