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COMPARISON OF MEASURED AND CALCULATED URANIUM ISOTOPIC CONCENTRATIONS IN CASCADE STREAMS AT THE PADUCAH GASEOUS DIFFUSION PLANT

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ABSTRACT

A test has been performed at the Paducah Gaseous Diffusion Plant (PGDP) in connection with studies for the U.S. Arms Control and Disarmament Agency on the possibility of utilizing measurements of the concentrations of the minor uranium isotopes in ^{235}U enrichment cascade external streams as a safeguards technique (MIST). This is the fourth plant test that has been performed in connection with the MIST studies, the first three having been done at the Oak Ridge Gaseous Diffusion Plant (ORGDP). The main objectives of the test were to measure the isotopic composition and flow rates of the plant external streams over a period of time; to design an appropriate plant model in the manner an IAEA safeguards team might do it and calculate the isotopic compositions of the plant streams; and to compare the calculated isotopic values with the measured ones.

During the 39-day period of the test, the plant power level and the number of stages on stream were increased substantially so that two quite different operating regimes were experienced. In addition to the feeding of natural uranium, partially depleted uranium was also fed to the plant during the test. The PGDP consists of two cascades operating in an overlap arrangement. It being uncertain whether a plant operator would be required to inform a safeguards team of the existence of the two-cascade system, the Paducah plant was modeled both as a single-cascade and as a two-cascade complex.

The single-cascade model yielded ^{235}U to ^{234}U concentration ratios that differed from the average measured values for the low power period by -0.16 percent in the plant product stream and by +0.86 percent in the plant tails stream. The two-cascade plant model yielded corresponding values for the low power period that differed from the average measured values in the plant product and plant tails stream by <0.1 percent.

The calculated ^{235}U to ^{234}U concentration ratios in the product and tails streams did not match the average measured values in the high-power period as well as they did for the low-power period, when the same isotopic composition for natural U was assumed at both power levels--the actual composition of the natural U fed to the plant during the test not having been measured. Recalculation of the ^{235}U to ^{234}U concentrations with another assumed value for the ^{234}U concentration in natural U, that is still within the range of reported observed values for it, resulted in better agreement with the measured plant stream values: +0.7 percent for the product stream and +0.2 percent in the tails stream for the single-cascade model and +0.8 percent and -0.7 percent respectively for a two-cascade plant model. The record on sources of the natural U that was fed during the test supports the assumption that the average ^{234}U concentration in the natural U fed was probably different during the two operating periods.

Samples were taken along each of the cascades once during the low-power regime to obtain a typical isotopic concentration gradient for each cascade. An excellent match was obtained between the calculated concentration gradient values and the measured values.

FOREWORD

This document is the completion report on a plant test run at the Paducah Gaseous Diffusion Plant (PGDP) relating to the use of the measurements of the minor uranium isotope concentration in cascade external streams as an enrichment plant safeguards technique (MIST) conducted for the United States Arms Control and Disarmament Agency under its Reimbursable Agreement with the Department of Energy No. AC7NA309.

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COMPARISON OF MEASURED AND CALCULATED URANIUM ISOTOPIC CONCENTRATIONS IN CASCADE STREAMS AT THE PADUCAH GASEOUS DIFFUSION PLANT

INTRODUCTION

A test has been performed at the Paducah Gaseous Diffusion Plant (PGDP) in connection with a study conducted by the Operations Analysis and Planning Division of the Oak Ridge Gaseous Diffusion Plant (ORGDP) for the U.S. Arms Control and Disarmament Agency on the possibility of utilizing measurements of the concentrations of the minor uranium isotopes in enrichment cascade external streams as a safeguards technique (MIST). This is the fourth plant test that has been performed in connection with the MIST study, the first three having been done at the ORGDP. Each of the tests, with the exception of the third one, has had as its major objective the determination of how closely the predicted ^{234}U and ^{236}U concentrations match measured values. In the third test(1) this objective was secondary, the primary one having been to test an indirect method for measuring the uranium inventory in an enrichment cascade by the feeding of a transient spike of ^{236}U to the cascade. None of the tests to date have been directed specifically at demonstrating the effectiveness of MIST as an aid in the detection of a clandestine diversion of enriched uranium.

The fourth test, which is the subject of this report, was run at the PGDP rather than the ORGDP since the Paducah plant is comprised of two overlapped cascades rather than the single one at Oak Ridge, thereby presenting a more complex situation. The test was carried out for a period of 39 days during which the operating power level and the number of stages on stream were increased substantially. The main objectives of the Paducah plant test were to measure the isotopic composition and flow rates of the plant external streams for a period of time; to note the magnitudes of the daily fluctuations in them; to calculate the isotopic composition of the streams based on an average plant flow sheet in the manner an International Atomic Energy Agency's (IAEA) safeguards team might be expected to do it within the limitations of the Nuclear Non-Proliferation Treaty (NPT); and to see how closely the calculated isotopics match the measured values. This report describes the test and presents the data correlations and the results of the multicomponent productivity calculations that were made for comparison with the measured isotopic concentrations.

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SUMMARY AND CONCLUSIONS

A test has been conducted at the PGDP in connection with development studies on MIST for uranium enrichment plants. The main objectives of the test were to measure the isotopic composition and flow rates of the plant external streams over a period of time; to note the magnitudes of the daily fluctuations in them; to design an appropriate plant model and calculate the isotopic composition of the plant streams in the manner an IAEA safeguards team might be expected to do it; and to compare the calculated isotopic values with the measured ones.

During the 39-day period of the test, the plant power level and the number of stages on stream were increased substantially so that there were two quite different operating regimes with a transient period between them. Two feeds were utilized during the two operating periods in different average proportions: one was natural U and the other depleted uranium that had been withdrawn as tails from the ORGDP. Average values for the flow rates and the isotopic concentrations of the cascade external streams for the initial low-power period and the final high-power period were computed from the measured data, and the variations of the daily measured values about the corresponding period average were determined and plotted versus time.

The PGDP consists of two cascades operating conjointly in an overlap arrangement. Since it is uncertain whether the operator of a plant such as the Paducah one would be required under the NPT to inform the safeguards team of the existence of the two-cascade system, the Paducah plant was modeled both as a single cascade and as a two-cascade complex. The single-cascade model yielded ^{235}U-to-^{234}U concentration ratios that differed from the average measured values for the low power period by -0.16 percent in the plant product stream and by +0.86 percent in the plant tails stream. The two-cascade plant model yielded corresponding values for the low-power period that differed from the average measured values in the plant product and tails streams by <0.1 percent.

Both plant models, which were designed to match the average measured flow sheet for the low-power regime, were scaled up to match the corresponding flow sheet for the high-power regime to make the calculations for comparison of predicted ^{235}U-to-^{234}U concentration ratios with the period average measured values. The match between the two sets of values was significantly poorer than for the low-power regime. For the single-cascade model the calculated values differed from the average measured value by +2.5 percent for the plant product stream and by +1.6 percent for the plant tails stream. The corresponding differences for the two-cascade plant model were +3.2 percent and <0.1 percent. Since the plant power increase was accompanied by an increase in the number of stages on-stream and by some flow sheet changes, and since the initial choice to base the cascade model design on the flow sheet for the low-power regime is an arbitrary one, a second two-cascade plant model was designed to match the average measured high-power period flow sheet.

The correspondence between calculated and average measured ^{234}U concentrations was not better basically for the second model than it was for the first, though the solved flow sheet values necessarily matched the measured ones considerably better. The calculated ^{235}U to ^{234}U concentration ratios for the second two-cascade model differed from the average measured value for the product stream by +2.6 percent and from that in the tails stream by +0.8 percent.

The test plan did not call for the sampling of the natural U to be fed to the plant. An average composition was assumed for the natural feed for the test that was based on natural U sample data obtained some years earlier. Since the correspondence between the predicted and measured isotopic ratios did not turn out to be nearly as close for the high-power regime as it is for the low-power one, a plausible speculation is that the difference may be due to a variance in the composition of the natural U fed to the plant during the two periods. Calculations using the ^{235}U to ^{234}U concentration ratio for natural U that had been assumed for the basic MIST background studies were then made with the result that a considerably improved match between the calculated and measured ^{234}U concentrations in the plant withdrawal streams for all three plant models was obtained. For example, the difference between the two sets of values for the high power period was reduced to +0.7 percent for the product stream and +0.2 percent in the tails stream for the single cascade plant model and correspondingly to a +0.8 percent and -0.7 percent for the second two-cascade plant model. This is considered to be a strong indication that the average ^{234}U concentration in natural U fed during the high-power regime was larger by about 2 percent than it was during the low-power one. This also points out that one should determine the isotopic composition of all natural U fed to the cascade during such a test.

Samples were taken along each of the cascades once during the low-power regime to obtain a typical isotopic concentration gradient for each cascade. An excellent match between the calculated ^{235}U to ^{234}U concentration ratios and the measured values was obtained after small reasonable adjustments were made in the assumptions regarding the average ^{234}U concentrations present in the depleted and natural feed in the several days immediately prior to the gradient sampling.

PADUCAH PLANT DESCRIPTION

The Paducah plant consists of two cascades operated conjointly in an overlap arrangement. A schematic representation of this is shown in Figure 1. The upper cascade, the one from which the enriched plant product is withdrawn, consists of three equipment sizes. Most of the smallest size stages in this cascade form the purge system; the remainder of these functions as part of the isotopic enricher. The other cascade, the one designated as the lower one in the figure, is outfitted with two equipment sizes, the same two larger sizes that are employed in the upper cascade. To essentially maximize the separative efficiency of each of the two cascades, blocks of stages of the same size in each are operated at appropriately selected different power levels so that the cascades are in effect comprised of about ten square sections rather than the maximum of three that otherwise would be available.

The ^{235}U concentrations listed in the figure for the various feed and withdrawal streams of the two cascades represent a typical set of target values. The target values vary somewhat from time to time because of changes in demand or operating factors for the three-plant complex. Corresponding stream flow rates are not given in the figure since these are strongly dependent on the plant power level which is subject to occasional changes due primarily to external factors. The actual stream rates and concentrations that existed during the test are presented in the section of the report describing the measured plant data.

The plant description shows the existence of a feed stream of depleted uranium, denoted by F_D, to the lower cascade. This happened to be the situation that existed during the test. Sometimes only natural uranium is fed to both cascades. The use of a depleted feed may serve as a substitute for natural uranium feed in whole or in part. During the initial period of the test, natural U was fed only to the upper cascade and during the final period it was fed to both cascades.

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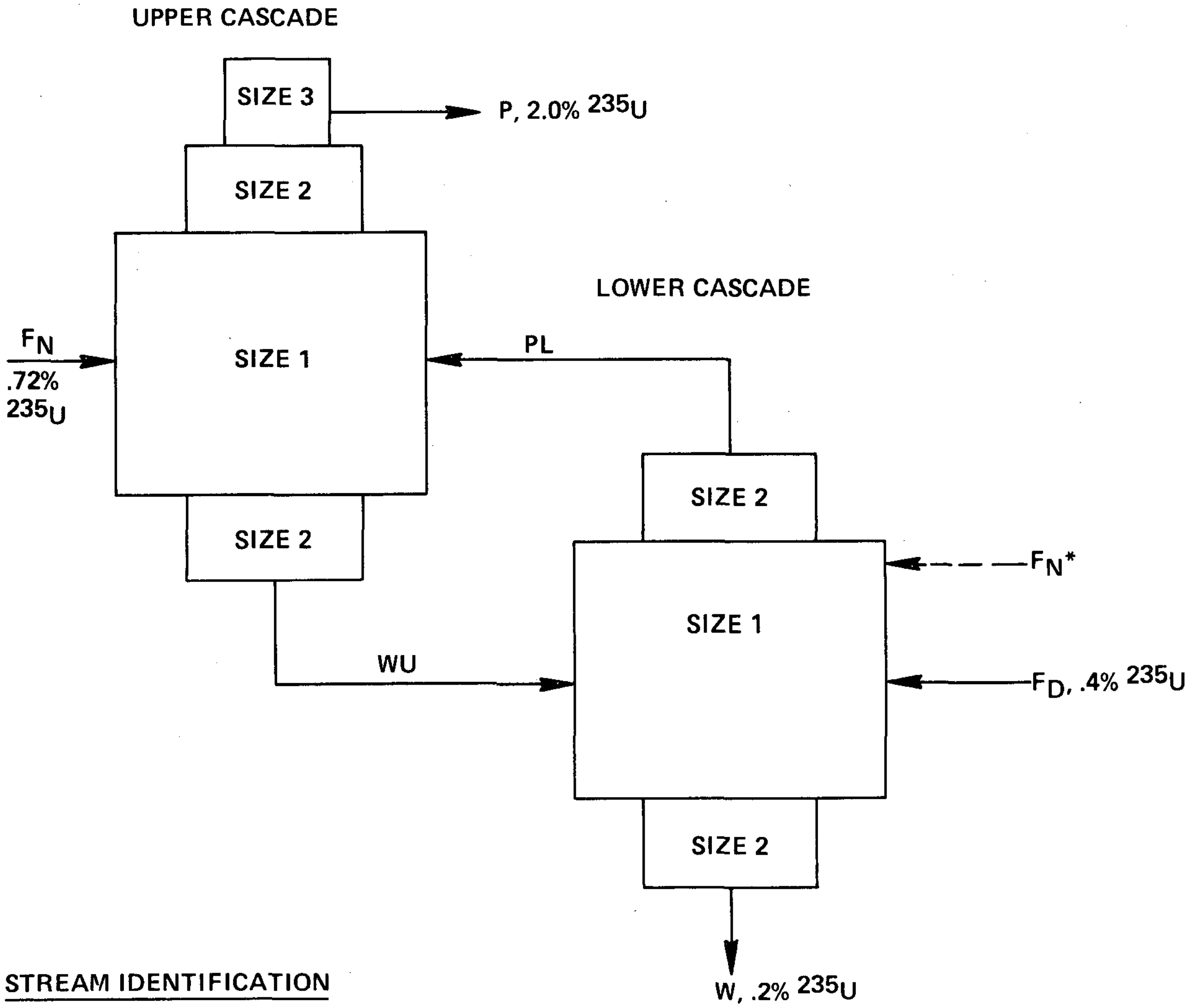

STREAM IDENTIFICATION

P IS THE PLANT PRODUCT
F_N IS NATURAL URANIUM FEED
F_D IS PARTIALLY DEPLETED URANIUM FEED
W IS THE PLANT TAILS
PL & WU ARE THE INTERCASCADE STREAMS
*NATURAL U (F_N) WAS FED TO BOTH CASCADES ONLY DURING THE FINAL PERIOD OF THE TEST.

Figure 1

SCHEMATIC OF THE PADUCAH PLANT AT THE TIME OF THE TEST

TEST DESCRIPTION

SAMPLING

Duplicate samples were taken daily for a period of 39 days, at approximately the same time each day, from the plant product stream (P), the plant tails stream (W) and the two intercascade streams (PL and WU). On-line sampling of the depleted uranium feed stream to the lower cascade was not feasible. Vapor-over-solid samples were taken from the 52 cylinders containing the depleted uranium fed to the plant during the test. The natural uranium fed to the plant during the test was not sampled since it was considered to be unnecessary at the time.

In addition, in-cascade samples were drawn on one day during the test at intervals along the length of each cascade. Fourteen samples were taken from the upper cascade and thirteen from the lower one. All of these samples, representative of the cascade concentration gradients, were taken at roughly the same time of day.

STREAM RATES AND PLANT POWER

The average flow rates of each of the cascade feed, product and tails streams were recorded for each working shift for each day of the test. The flow rates of the feed streams and the two intercascade streams are measured with flow meters and the plant product and tails streams by on-line cylinder weighings. The feed rate flow measurements were checked and corrected according to feed cylinder weighings before and after feeding.

The total plant power, for both cascades and plant auxiliaries, was also recorded for each shift for each day of the test.

OPERATING REGIMES DURING THE TEST

A sizeable plant power increase of just under 50 percent was targeted for the PGDP on the 26th day of the test. Consequently, three operating regimes prevailed during the test: a low power period for the first 26 days, a transition period of increasing plant power for 5 days, and finally a high power level period for 8 days. Additional stages were brought on-stream during the transition period so that the number of stages in operation in the final period was approximately 13 percent greater on the average than in the initial period. Further, the feed to the lower cascade for the high power period was augmented by the addition of a natural U feed stream, thereby materially changing the proportions of depleted and natural U fed to the plant.

ISOTOPIC ANALYSES OF THE SAMPLES

The ^{235}U concentration in each of the samples was measured in the PGDP mass spectrometry laboratory. A portion of each of the samples was then hydrolyzed at the PGDP laboratory and shipped to the Oak Ridge National Laboratory (ORNL) for measurement of the ^{235}U to ^{234}U and the ^{235}U to ^{236}U concentration ratios in high precision scans on a three-stage thermal emission mass spectrometer.

THE PADUCAH PLANT TEST DATA

PLANT POWER LEVELS

Two plant operating power levels prevailed during the test, with a transition period of several days duration between the initial low power level and the final high power one. Regular daily measurements were made only of the average daily plant total power load, which includes all the power for all auxiliary operations and utilities in addition to the cascade operating power. The total plant power in the low and high power periods was very steady, varying in a range of ±0.3 and 0.1 percent about the respective period average.

Individual cascade cell power load data, from which one can obtain the actual operating power for each of the two cascades, were reported just for three days: two during the low power period and one during the high power period. The power distributions in the two steady periods to the two cascades are given in Table 1, expressed as fractions of the initial power input to the cascade pair.

The values listed in Table 1 for the low power level operation are an average of the two sets of measurements made on the 3rd and 15th days of the test. Though the total cascade power on these two days differs by only 0.8 percent, the power load on the 15th day to the upper cascade was 5.6 percent less and to the lower cascade 3.6 greater than what each was on the 3rd day. If these two pairs of values can be considered to be representative, the power distribution between the cascades was significantly more variable than the total cascade power.

STAGES ON-STREAM

The number of stages in operation in each cascade was increased at an irregular rate throughout the test period, with most of the increase taking place concurrently with the operating power increase. The daily variation of the number of stages on-stream in each cascade and of the total of the two as a fraction of the total number of stages in operation on the first day of the test are presented in Figure 2. The average total number of stages in the plant on-stream during the high power regime was 12.6 percent greater than that during the low power regime; the increase for the upper cascade was 14.4 percent and for the lower one 10.7 percent.

Part of the plant power increase was then a result of additional stages being put into operation rather than just an increase in the average stage power levels. This can be seen in Table 2. The average power increase for the two cascades was 48.4 percent but the increase in the average power load per stage was only 31.9 percent.

Table 1

CASCADE POWER DISTRIBUTION

	Fraction of the Initial Power Input to the Cascade Pair		
	Low Power Level	High Power Level	Ratio, High/Low
Upper Cascade	0.464	0.719	1.550
Lower Cascade	0.536	0.765	1.427
Combined Cascades	1.000	1.484	1.484

Table 2

DISTRIBUTION OF THE POWER INCREASE

	Power Level Increase (%)	
	Average per Stage	Average per Cascade
Upper Cascade	35.4	55.0
Lower Cascade	28.9	42.9
Combined Cascades	31.9	48.4

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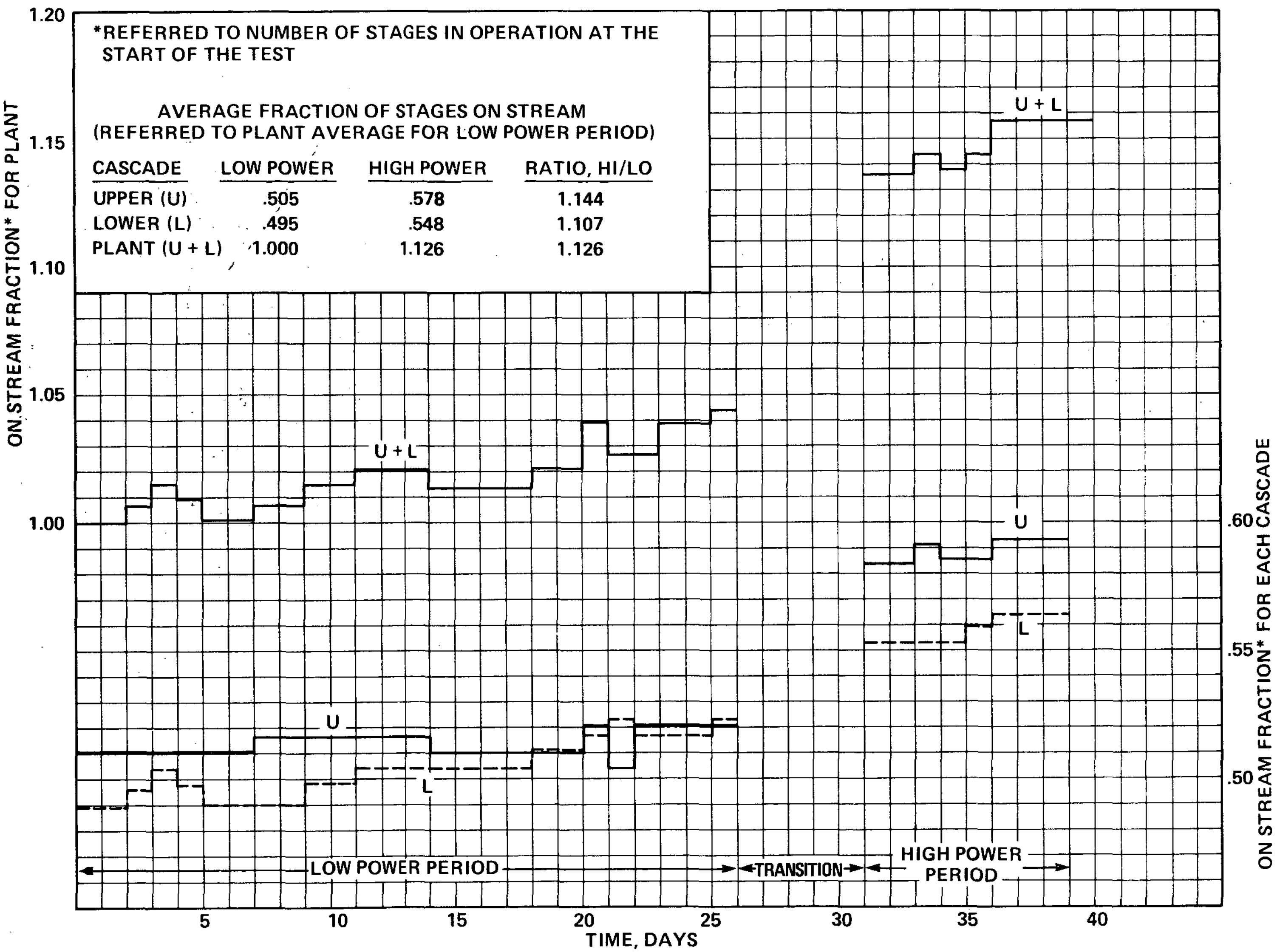

Figure 2

NUMBER OF STAGES IN OPERATION VERSUS TIME

PLANT STREAM RATES

Feed Streams

The plant was fed with both natural and depleted uranium during the test. The depleted uranium, with a ^{235}U concentration the order of 0.4 percent, had been collected as tails at an earlier time from the ORGDP. Average flow rates and the associated standard deviations were computed for the two feeds for each of the three operating regimes. Ratios of the average daily rate in the period to the period average were then computed and plotted as a function of time. Figure 3 presents the feed data in this form for both feed materials. The period average feed rates and the standard deviations of the data are also presented in tabular form in this figure.

During the low power period, natural uranium (F_N) was fed only to the upper cascade and the depleted feed (F_D) only to the lower cascade. During the high power period, natural U was fed to both cascades and the depleted feed still only to the lower cascade. Thus, in addition to the daily fluctuations in the ratio of the feed rates of the two uraniums, there was a substantial reduction in the quantity of depleted U relative to that of natural U fed to the plant during the high power regime; the average ratio being 0.687 for the low power and 0.355 for the high power level. The daily variations of the F_D/F_N values with respect to their period average values are shown in Figure 4. The daily variations in their relative rates, as one might expect, are somewhat larger than the fluctuations in the two streams individually.

Withdrawal Streams

The ratio of the daily plant product take-off rate to the corresponding period average for each operating regime, and similarly for the daily tails withdrawal rate, is plotted in Figure 5. The period averages and associated standard deviations are listed in the figure.

In the usual operation of a gaseous diffusion cascade the product take-off rate is varied to maintain the product concentration on target and the feed rate is varied to maintain the tails concentration as close as possible to its specified value. Examination of Figures 3 and 5 shows that in general the product rate was the steadiest of the four external streams. The daily rates of the two feed streams and that of the plant tails stream exhibited overall roughly the same degree of variability with respect to the period averages.

Plant Material Balance

The daily uranium material balance discrepancies as a percentage of the daily feed uranium are plotted in Figure 6. The overall material

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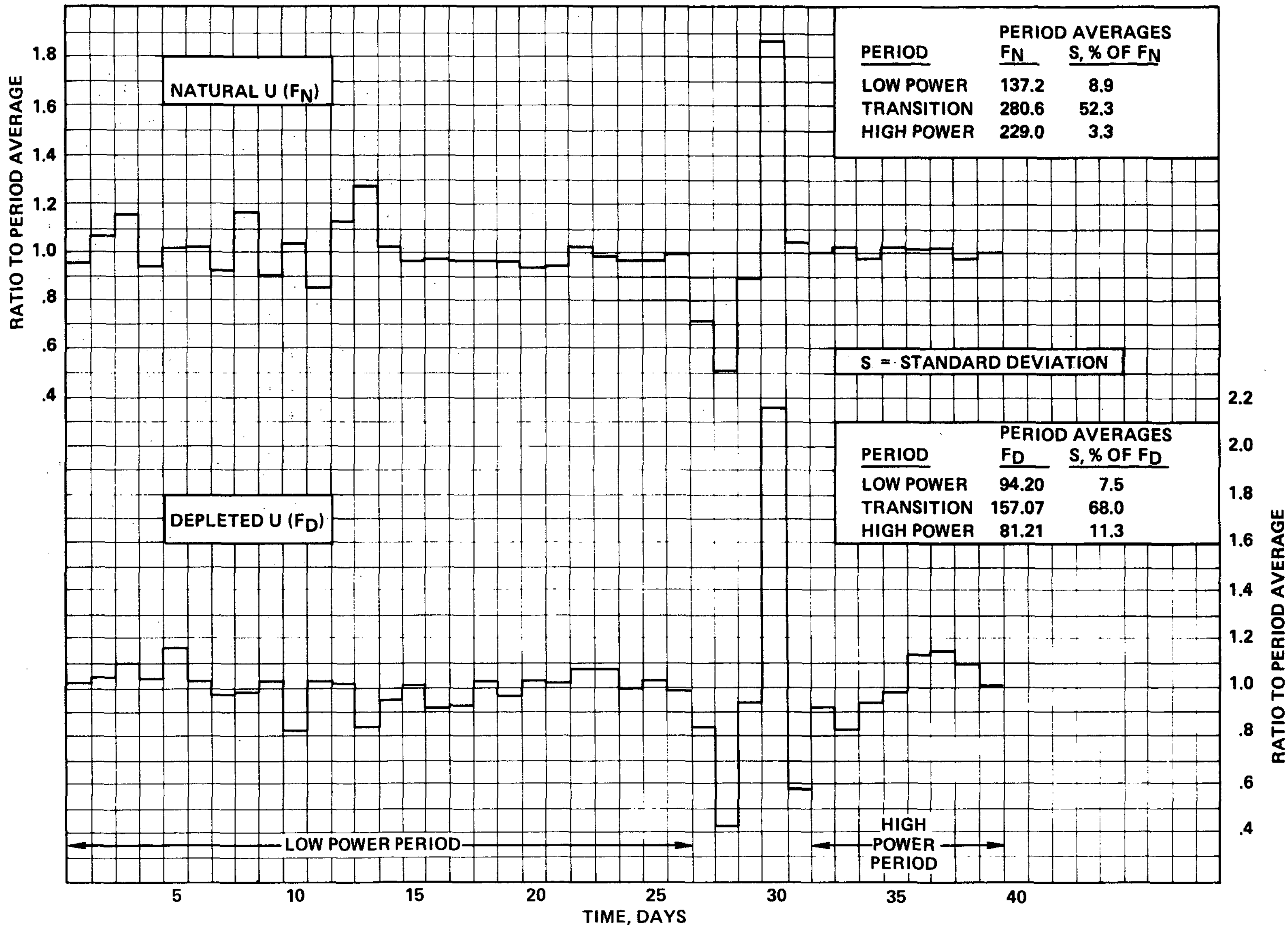

Figure 3

VARIATION IN THE AVERAGE DAILY PLANT FEED RATES WITH TIME

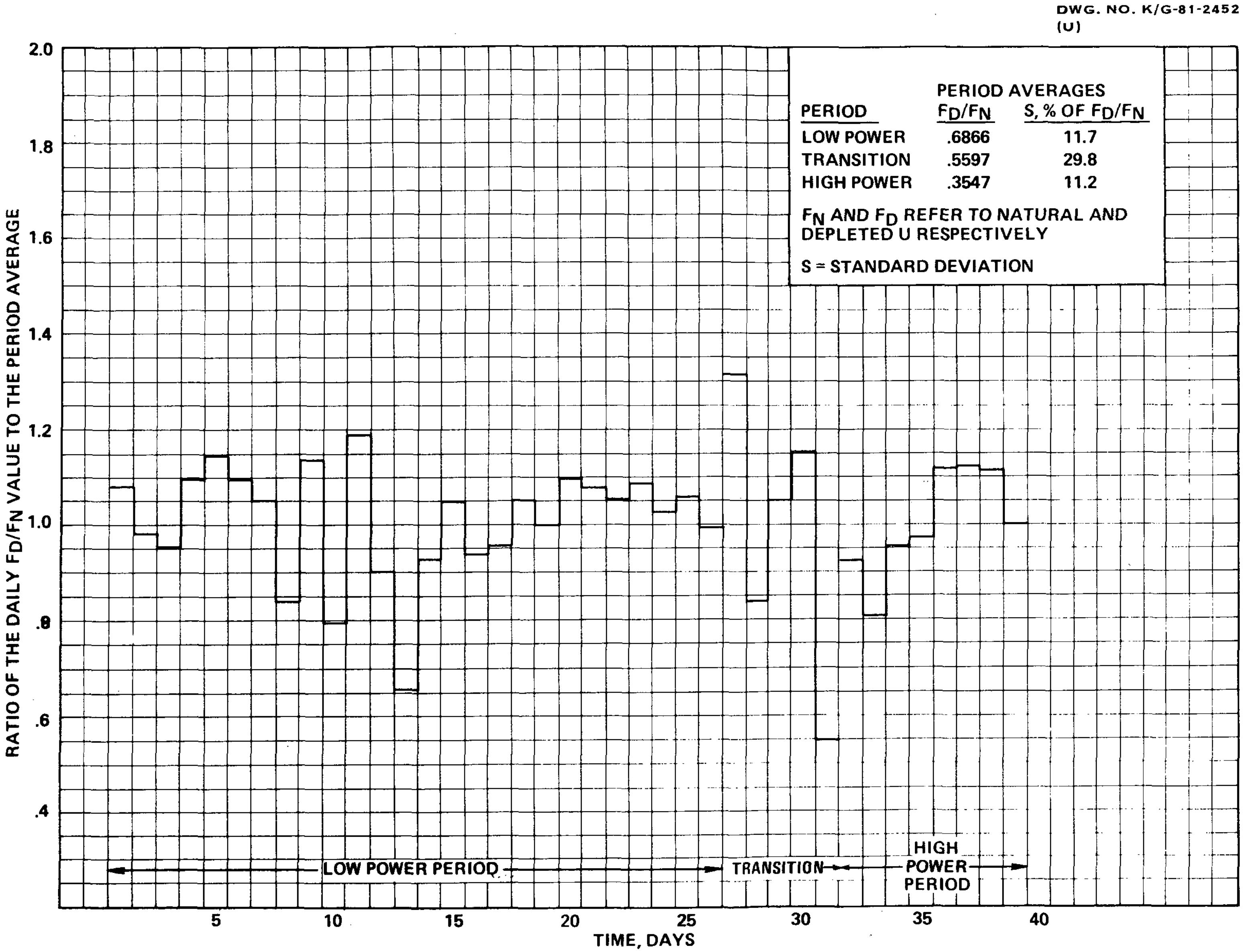

Figure 4

VARIATION IN THE RELATIVE QUANTITIES OF DEPLETED AND NATURAL U FED DAILY TO THE PLANT

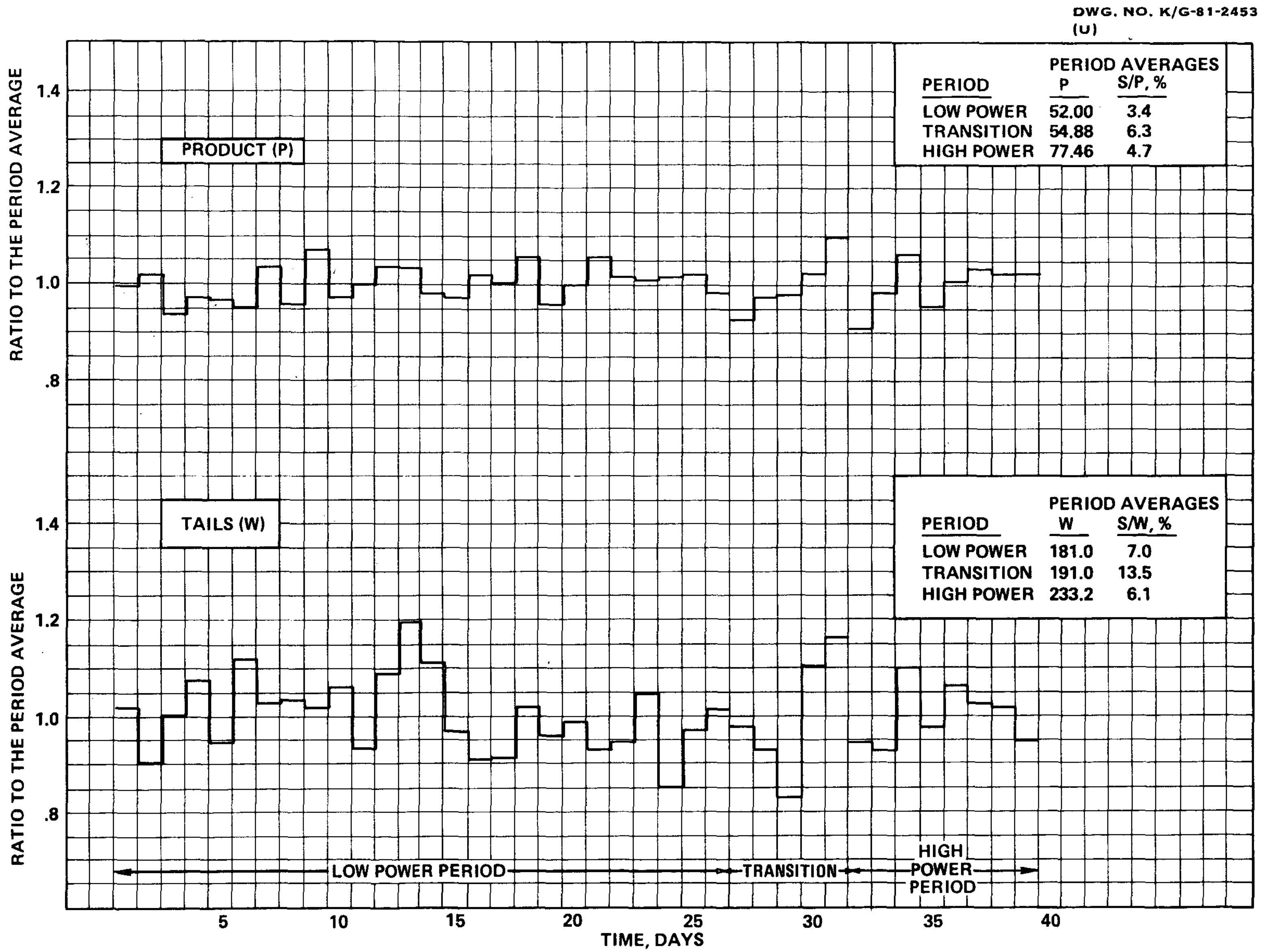

Figure 5

VARIATION IN THE AVERAGE DAILY PLANT WITHDRAWAL STREAM RATES

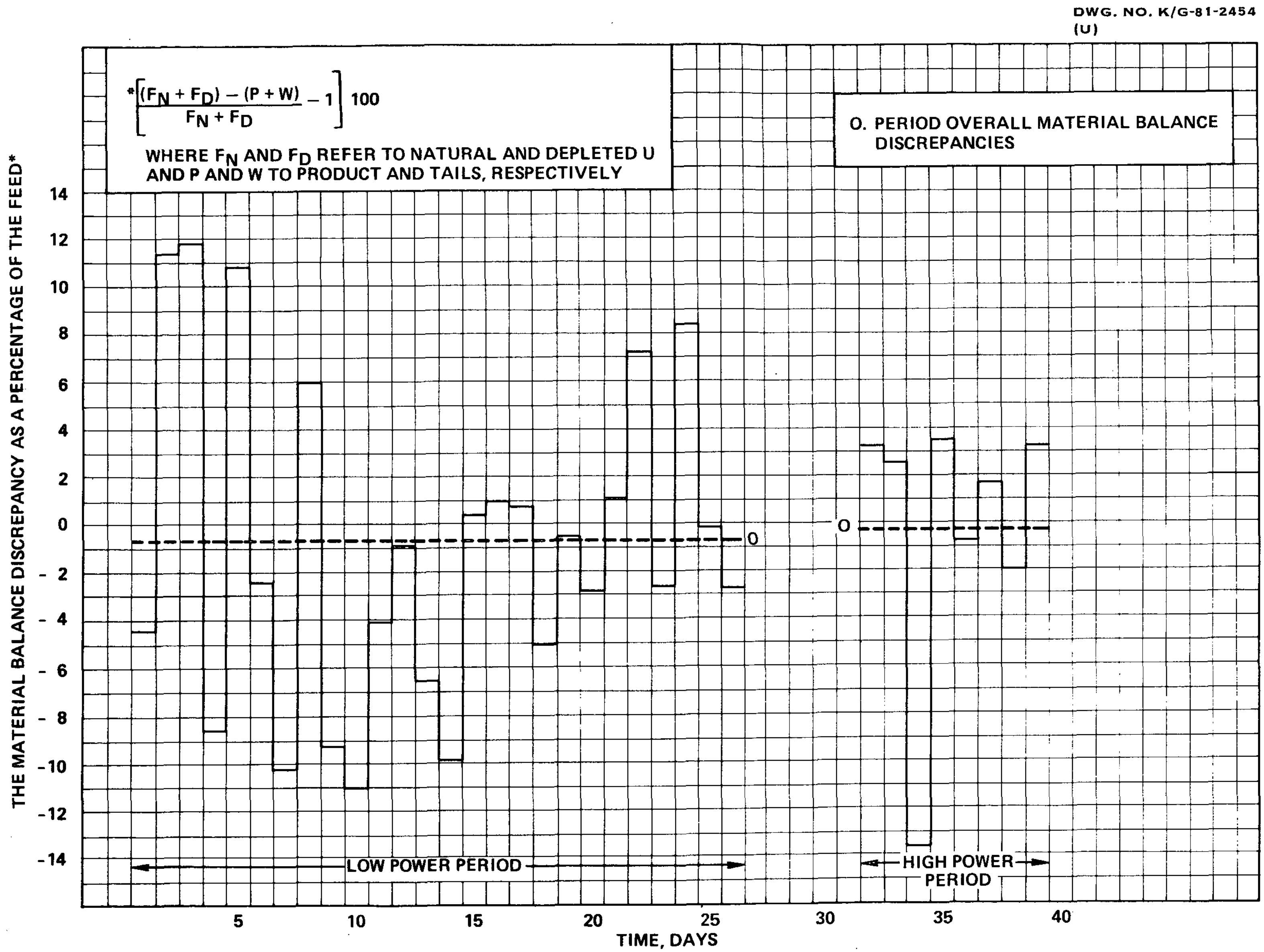

Figure 6

DAILY PLANT URANIUM MATERIAL BALANCE DISCREPANCIES balance discrepancy for each period computed from the average plant feed and withdrawal rates for each period is also shown. Though the daily discrepancies exhibit a range of +12 percent to -14 percent of the feed uranium, the overall balance was off only -0.7 percent in the low power period and -0.2 percent in the high power period. The daily component material balances were not computed but the overall ones were. Table 3 shows the overall material balance descrepancies for the U, ^{235}U and ^{234}U for the low- and high-power periods.

The Intercascade Stream Rates

The flow rate data for the two intercascade streams, the product take-off from the lower cascade (PL) and the waste withdrawal from the upper cascade (WU) were correlated in the same way as the plant external streams. The data for the PL and WU streams are plotted in Figure 7. The daily variations of these two streams seem to be roughly the same order of magnitude as that for the plant external streams. However, there is significantly less confidence in the validity of the reported rates for the intercascade streams than there is for the plant feed and withdrawal streams. Flow meters are employed to measure the PL and WU rates, with no substantiation from UF_6 cylinder weighings available as is the case with the external plant streams. A judgment made by PGDP personnel(2) of the order of magnitude of the error in the flow measurements for the two intercascade streams is that it may be as large as ±25 percent of the reported rate.

THE MEASURED ISOTOPIC CONCENTRATIONS

Samples were taken daily, at about the same time each day, from the plant withdrawal streams and the two intercascade streams. In regard to the plant feeds, samples were taken from each of the cylinders of ORGDP tails (F_D) that was fed to the cascade during the test, but none were taken of the natural U fed to the cascade. In addition to the sampling already mentioned, a set of about a dozen samples was taken on one day, all at roughly about the same time of day, from each of the two cascades from various points along its length.

The ^{235}U concentration and its ratio to that of ^{234}U and to that of ^{236}U were determined for each sample in the PGDP and ORNL mass spectrometry laboratories, respectively.

EXCLUSION OF THE ^{236}U DATA FROM THE CORRELATION

The ^{236}U concentrations in the plant turned out to be so dilute that the precision and accuracy of the ^{236}U analyses had to be considered insufficiently reliable for meaningful correlations. The only input source of ^{236}U to the plant during the test was the depleted uranium, F_D, fed to the lower cascade. Of the 52 cylinders of depleted U fed to the cascade, only 6 showed a ^{236}U concentration greater than 1 ppm; of the

Table 3

OVERALL MATERIAL BALANCE DISCREPANCIES

	The Discrepancy* as Percent of Plant Feed	
	Low Power	High Power
U	-0.7	0.2
^{235}U	-0.3	0.5
^{234}U	-0.2	-1.6

*The discrepancy is defined as total fed minus total withdrawn.

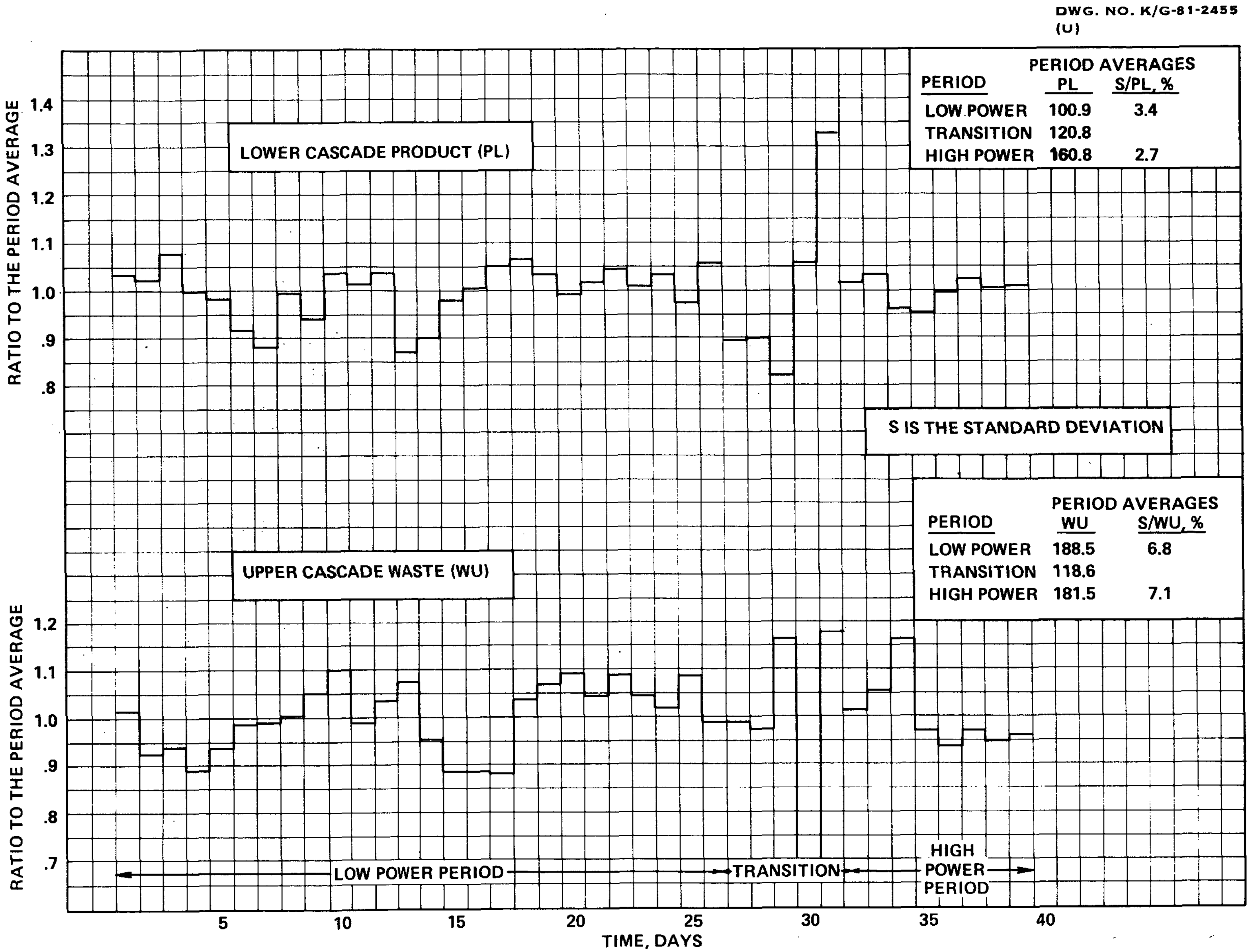

Figure 7

VARIATION IN THE AVERAGE DAILY INTERCASCADE STREAM RATES

6 only 4 had a concentration greater than 10 ppm and of the 4 only one greater than 100 ppm. Since the depleted uranium was fed only to the lower cascade the product stream from this cascade exhibited the largest ^{236}U concentration. There were just four samples of this stream that showed a ^{236}U concentration greater than 10 ppm: a range of 12 to 19 ppm on four consecutive days starting two days after one feed cylinder containing 159 ppm ^{236}U was fed to the lower cascade. The rest of the time the ^{236}U concentration in the PL stream was in the range of 0.3 to 9.0 ppm. All other cascade streams, with the exception of the depleted uranium feed, showed significantly lower ^{236}U concentrations. The precision of the ^{236}U measurements at a concentration of 10 ppm is estimated to be the order of ±4 percent, at 1 ppm ±15 percent and at 0.1 ppm the order of ±100 percent.[3] Furthermore, the accuracy of the measurements at these concentration levels is considered to be probably poorer than the precision.

Also, it was noted that the partially depleted U fed to the plant was quite variable in its ^{236}U assay from cylinder to cylinder so that the ^{236}U concentration in the plant was probably never near steady-state during the test. For this reason and the uncertainty attendant to the determinations of very dilute concentrations, the ^{236}U data were omitted from the isotopic data correlations.

THE DAILY VALUES OF THE ^{235}U AND ^{234}U CONCENTRATIONS IN THE PLANT STREAMS

The measured ^{235}U concentrations and their ratios to the ^{234}U concentrations for each set of daily plant stream samples have been plotted in the same reduced form that was used to present the stream rate data. Thus, the ratios of the measured daily isotopic values to the average value for the variable during the given operating period are presented in the plots. The period averages for the ^{235}U concentration and the ^{235}U-to-^{234}U concentration ratios and the standard deviations of each as a percentage of the average value are tabulated on each plot. Except for the sample data for the depleted uranium feed, all of the isotopic data must be considered to be point-in-time values rather than daily average values as was the case for the stream rate data. The data points in the plots have been connected with straight lines for the sake of continuity, with the recognition that samples at intermediate times if they had been taken could have yielded isotopic data that could very well fall above or below the connecting lines.

In the Depleted Uranium Feed

The variation in the isotopic data of the uranium in the ORGDP tails cylinders in the sequence that they were fed to the plant is plotted in Figure 8. There were rather large variations both in the ^{235}U assays and the ^{235}U-to-^{234}U concentration ratios in the depleted U feed from cylinder to cylinder during the low-power period. Furthermore, it appears that the data averages for the first half of the low power period are sharply different from the second half of the period.

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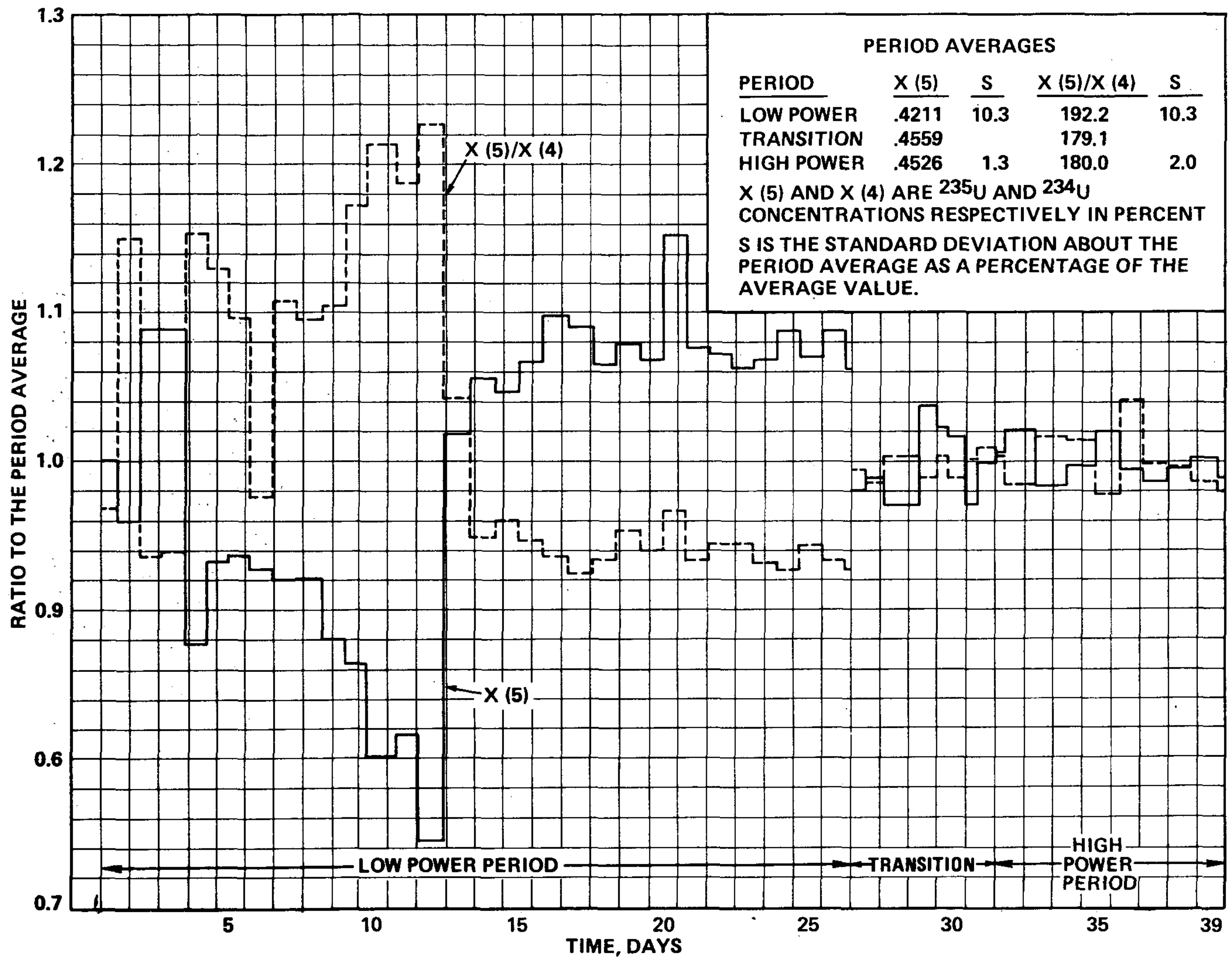

Figure 8

DAILY VARIATION IN THE COMPOSITION OF THE PARTIALLY DEPLETED URANIUM FEED

In Natural U Feed

No samples of normal feed were taken during the test. There is some very small variability in the concentration of ^{235}U and a slightly greater variability in that of ^{234}U in the natural U. Measurements made at PGDP on 17 ore concentrates from various parts of the world yielded a range for ^{235}U in natural U of 0.71094 to 0.71137 weight % (a range of 0.06 percent)(4) and for ^{234}U a range of 0.00500 to 0.00539 weight % (a range of 7.8 percent).(5) The average isotopic composition of natural U needed to make the productivity calculations was assumed to be that determined in a set of samples taken from cylinders of natural U at the time of an earlier plant test.

In the Plant Withdrawal Streams

Figures 9 and 10 are plots showing the time variation of the ^{235}U concentration and its ratio to that of ^{234}U in the plant product and waste streams. The ^{235}U concentration in the plant product stream was quite steady during the test, varying around the period average by less than 0.5 percent. The 5/4* in the product varied only by a few tenths of a percent more than did the ^{235}U concentration. The period average for the ^{235}U concentrations in the high-power period was greater than that of the low-power period by only 0.3 percent; however, the 5/4 was 5.2 percent smaller. This marked change in the 5/4 was mostly the result of the reduced relative quantity of depleted U fed to the plant; the average F_D/F_N being reduced from 0.687 to 0.355.

In comparison to the variations in the isotopics of the product stream, the fluctuations of the ^{235}U concentration and the 5/4 around the period average in the plant tails stream were quite large. The average 5/4 in the tails at the high-power level was 3.5 percent lower than it was at the low-power level, probably mostly for the same reason it was lower in the plant product.

In the Intercascade Streams

Figures 11 and 12 are plots showing the time variation of the ^{235}U concentration and the 5/4 values in the two intercascade streams: the product stream from the lower cascade (PL) and the tails stream from the upper cascade (WU), respectively. Inspection of the plots and the tabulations of the average values for the low- and high-power periods shows that there were significant changes made in the target ^{235}U concentrations, an increase by about 10 percent in the PL stream and a decrease by approximately 12 percent in the WU stream. The decrease of 16 percent in the 5/4 value in the PL stream is partly the result of the

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*The term "5/4" will be used as a shorthand expression for the ratio of the ^{235}U-to-^{234}U concentrations in most of the references to it in this report.

DWG. NO. K/G-81-2457
(U)

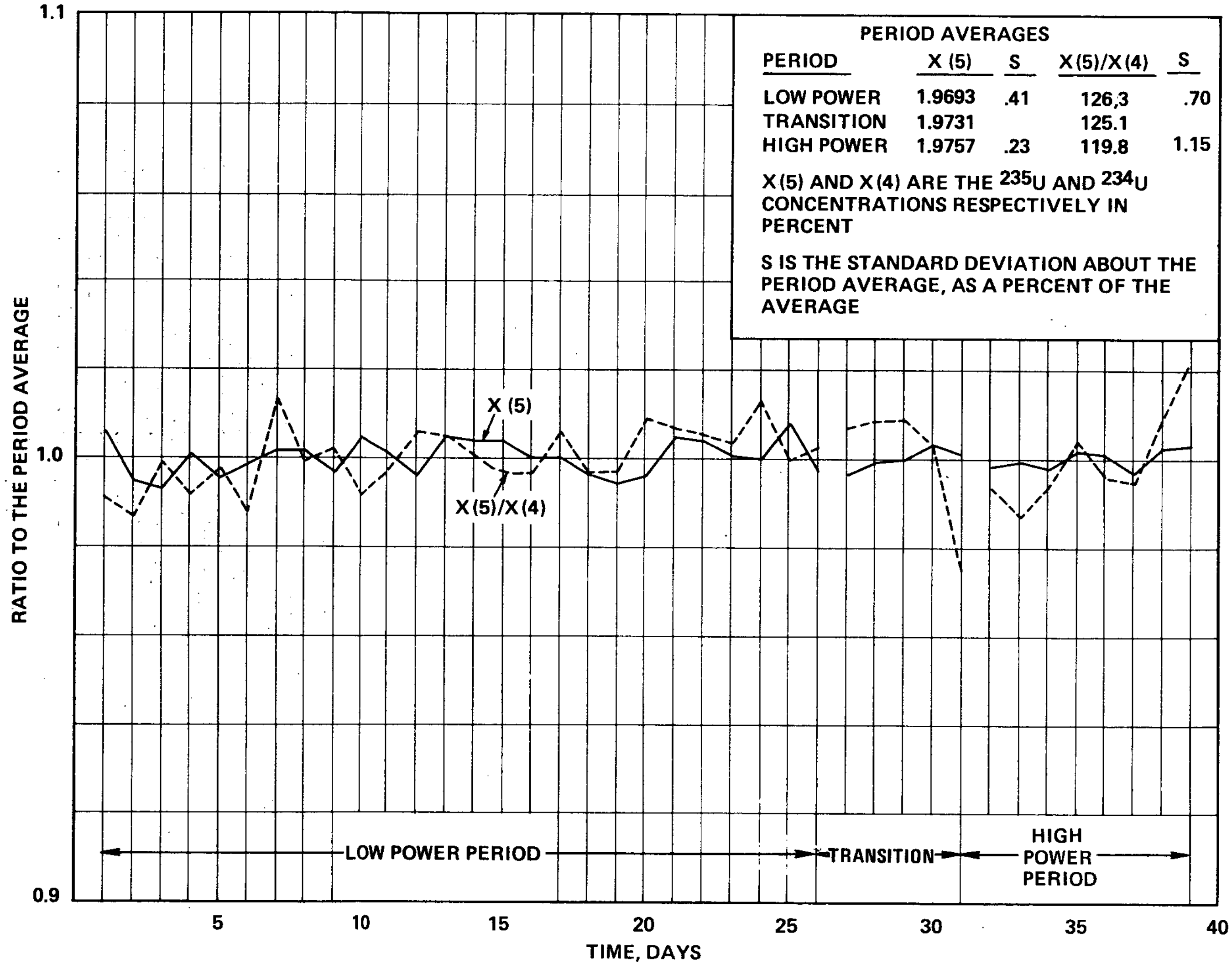

Figure 9

DAILY VARIATION IN THE PLANT PRODUCT COMPOSITION

DWG. NO. K/G-81-2458
(U)

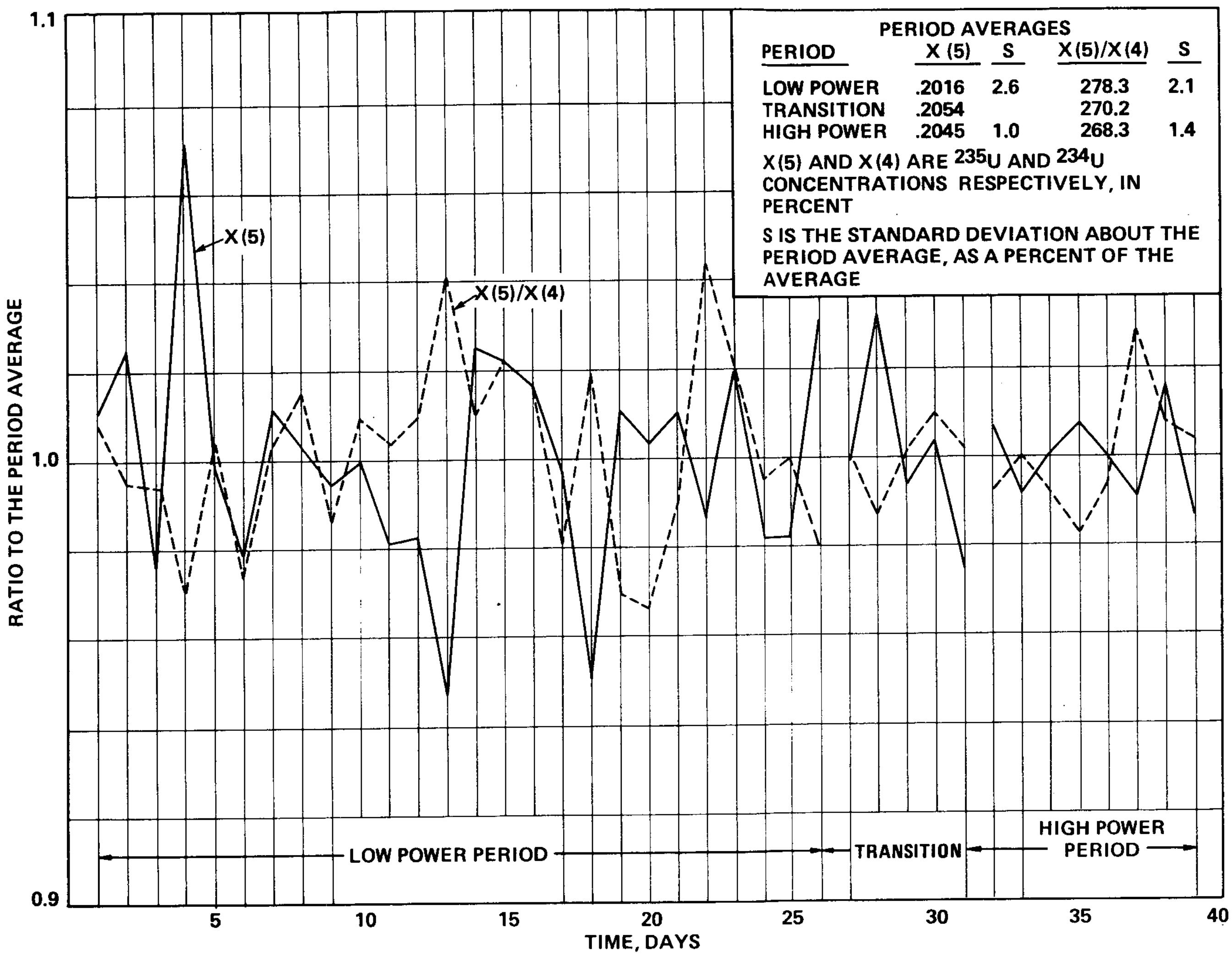

Figure 10

DAILY VARIATION IN THE PLANT TAILS COMPOSITION

DWG. NO. K/G-81-2459
(U)

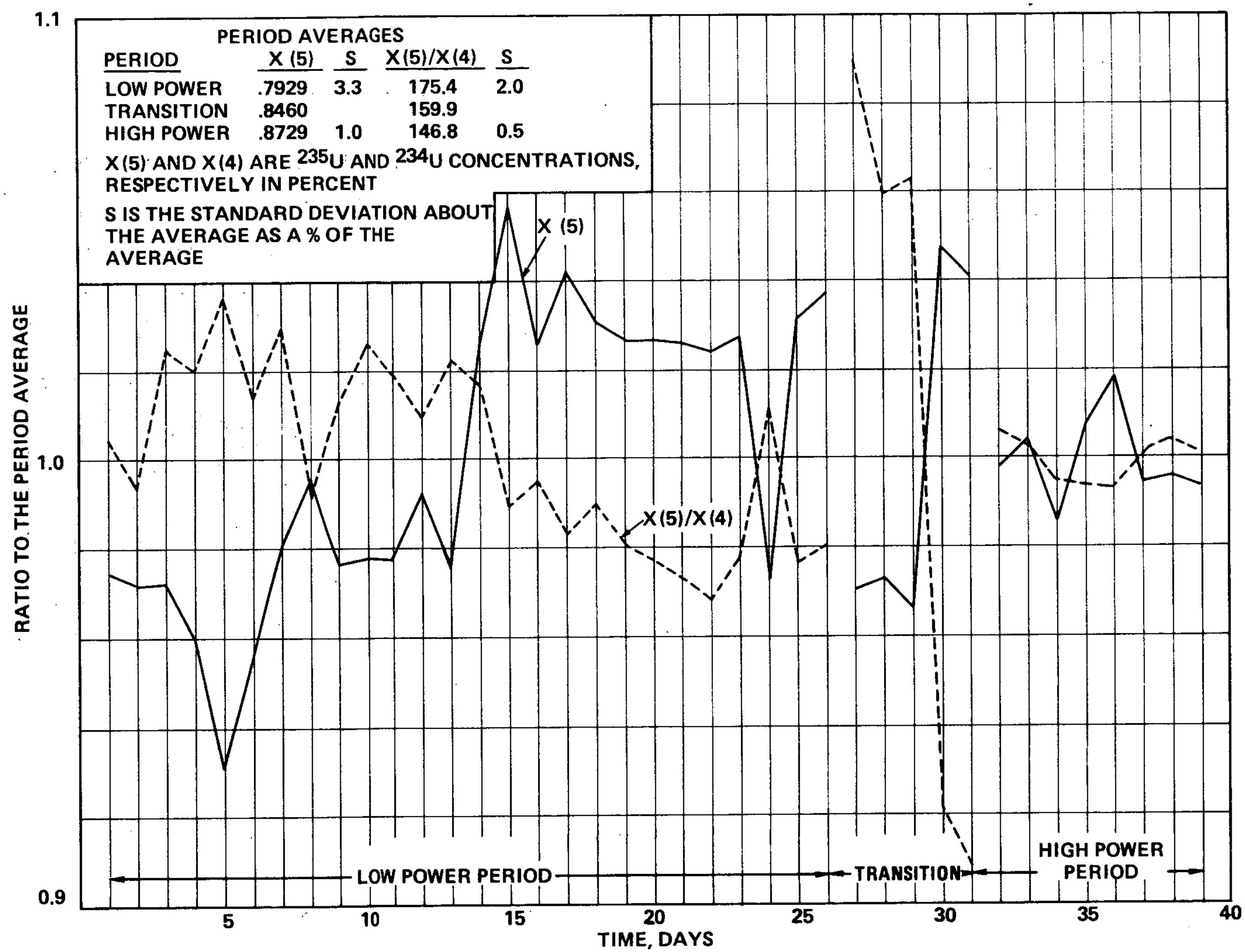

Figure 11

DAILY VARIATION IN THE COMPOSITION OF THE PL INTERCASCADE STREAM

DWG. NO. K/G-81-2460
(U)

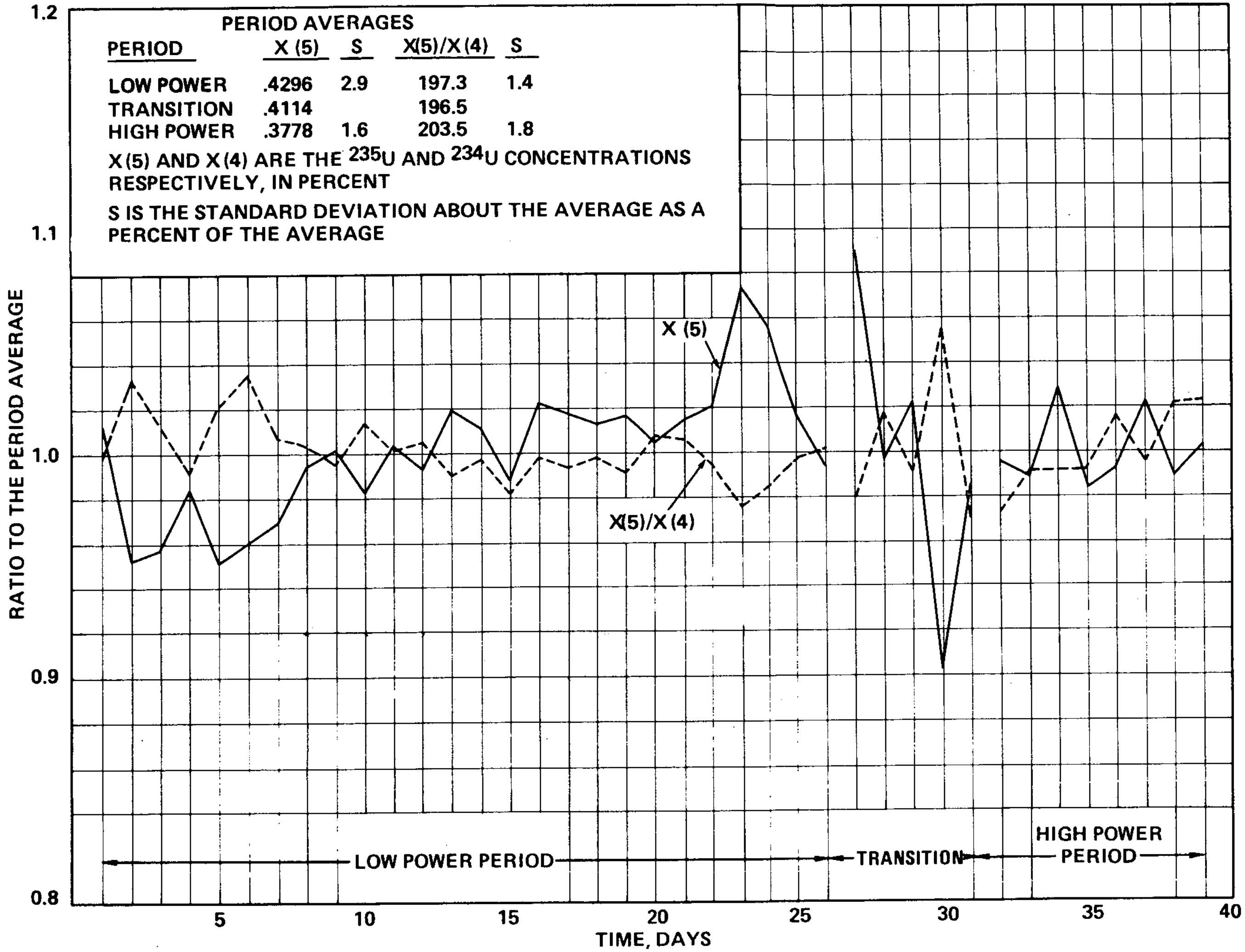

Figure 12

DAILY VARIATION IN THE WU INTERCASCADE STREAM increase in its ^{235}U concentration but mostly due to the addition of natural U as a feed stream to the cascade, thereby reducing the proportionate contribution of the depleted U isotopics to the composition of the cascade withdrawal streams. Within the low power regime there appears to be two different target levels for the ^{235}U concentration in the intercascade streams: for about half the period the ^{235}U concentrations are almost consistently lower than the average values and during the other half they are almost consistently greater than the average values. These correspond roughly to the differences observed between the first and second halves of the low power period for the depleted U feed (see Figure 8).

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COMPARISON OF CALCULATED ISOTOPIC CONCENTRATIONS WITH THE MEASURED VALUES

THE PLANT MODEL BASES

The calculation of the isotopic concentrations in the plant streams requires the assumption of a plant model. It is expected that the information furnished by the plant operator to an IAEA safeguards team would be limited essentially to the plant flow sheet and that the inspectors would not have access to actual plant design and performance information such as the number of cascade sections, the number of stages in each section, the stage separation factors and the interstage process gas flow rates. The plant model developed by a safeguards team would have to be based on an assumed stage separation factor and the declared plant flow sheet. It would therefore most likely be different in design, numbers of stages, and interstage flow rates from the real plant.

A basic question arises in setting up a model for the Paducah facility as a safeguards team might do it. That is, would the safeguards team, being limited to peripheral access, know or be informed that the plant consists of two overlapped cascades? Since the answer to this question is uncertain and the associated question of whether treatment of the plant as a single cascade or a pair of cascades would make a significant difference in the predicted isotopic concentrations in the plant withdrawal streams is also uncertain, it was decided to model the Paducah plant both ways; as a single cascade and as two overlapped cascades.

The Flow Sheet Assumption for the Plant Model Design

The designs of the plant models, for both the single cascade and the overlapped two-cascade representations were based on the average daily reported values of the ^{235}U concentrations and flow rates of the plant streams during the low power operating regime, the choice between the two power regimes being arbitrary. Since there is a small material balance discrepancy both in U and ^{235}U in this average measured flow sheet (see Table 3), the rates of the two plant feeds were adjusted to close the material balance for the base flow sheet keeping the plant tails concentration at its average measured value of 0.2016 atom percent. On the presumption that the probability of error in the measurement of the input rate for each of the two feeds was the same for both, the ratio of the two feed rates was kept at its average measured value for the period in adjusting them to close the material balance.

The ^{235}U Assay in Natural U

As has already been indicated no samples were taken of the natural U fed to the plant. The ^{235}U concentration was assumed to be 0.7200 atom percent in all calculations involving this parameter.

The Separation Factor Assumption

The stage separation factor, α, for $^{235}U/^{238}U$ separation by gaseous diffusion was assumed to be the point theoretical value, that is 1.00429.

SINGLE CASCADE REPRESENTATION OF THE PLANT

Cascade Model Description

A squared-off cascade consisting of four enricher sections and two stripping sections was designed for the separation job matching the adjusted average measured flow sheet for the Paducah plant during the low-power period. This is a minimum total flow cascade for the given number of cascade sections. The cascade separative efficiency is 96.4 percent. The cascade design and flow sheet is shown schematically in Figure 13. All of the isotopic concentrations are in atom percent. The cascade flow sheet stream rates are compared with the corresponding average measured ones in Table 4. Basically, it has been assumed that the ^{235}U concentrations are correct as measured and that the stream rates are less certain; and of these the feed and tails rates are the least certain. Since the two sets of values then differ only with respect to the stream rates, the ^{235}U concentrations are not given in the table.

The ^{234}U Assay of Natural U

No samples were taken and therefore no determinations were made of the isotopic composition of the natural U fed to the plant during the test. It was assumed that analyses made on samples of natural U[6] about the time of the first two MIST plant tests had established the natural U isotopics so there was no need to sample the normal feed during the Paducah plant test. The data obtained from the samples of natural U in those two plant tests are summarized in Table 5.

Both the ^{235}U and the ^{234}U measurements for Test I were made at the ORGDP mass spectrometry laboratory, whereas the ^{235}U measurements for Test II were also made at the ORGDP laboratory but the ^{234}U measurements were made at the ORNL mass spectrometry laboratory. Since the measurements of ^{234}U concentrations at ORNL are considered to be somewhat more accurate of the two, the data for Test II were assumed to be representative of the isotopics of natural U. The isotopic concentrations for natural U used in the calculations for this test are listed in Table 6. Since these are somewhat different, particualrly for ^{234}U, than the values used in the MIST background information studies[7] the latter are also listed for comparison.

Table 4

COMPARISON OF THE FLOW SHEET STREAM RATES

	Average Rates (lb-moles/day)	
	Cascade Model	Measured Value
Product (P)	52.00	52.00
Natural U Feed (F_N)	137.39	137.2
Depleted U Feed (F_D)	94.33	94.2
Tails (W)	179.72	181.0
F_D/F_N	0.6866	0.6866
Material Balance Discrepancy,		
U: $\Sigma F - (P+W)$, % of ΣF	---	-0.69
^{235}U: $F_N x_N + F_D x_D - (P x_p + W x_w)$, % of $(F_N x_N + F_D x_D)$	---	-0.32
where x is the ^{235}U concentration		

Table 5

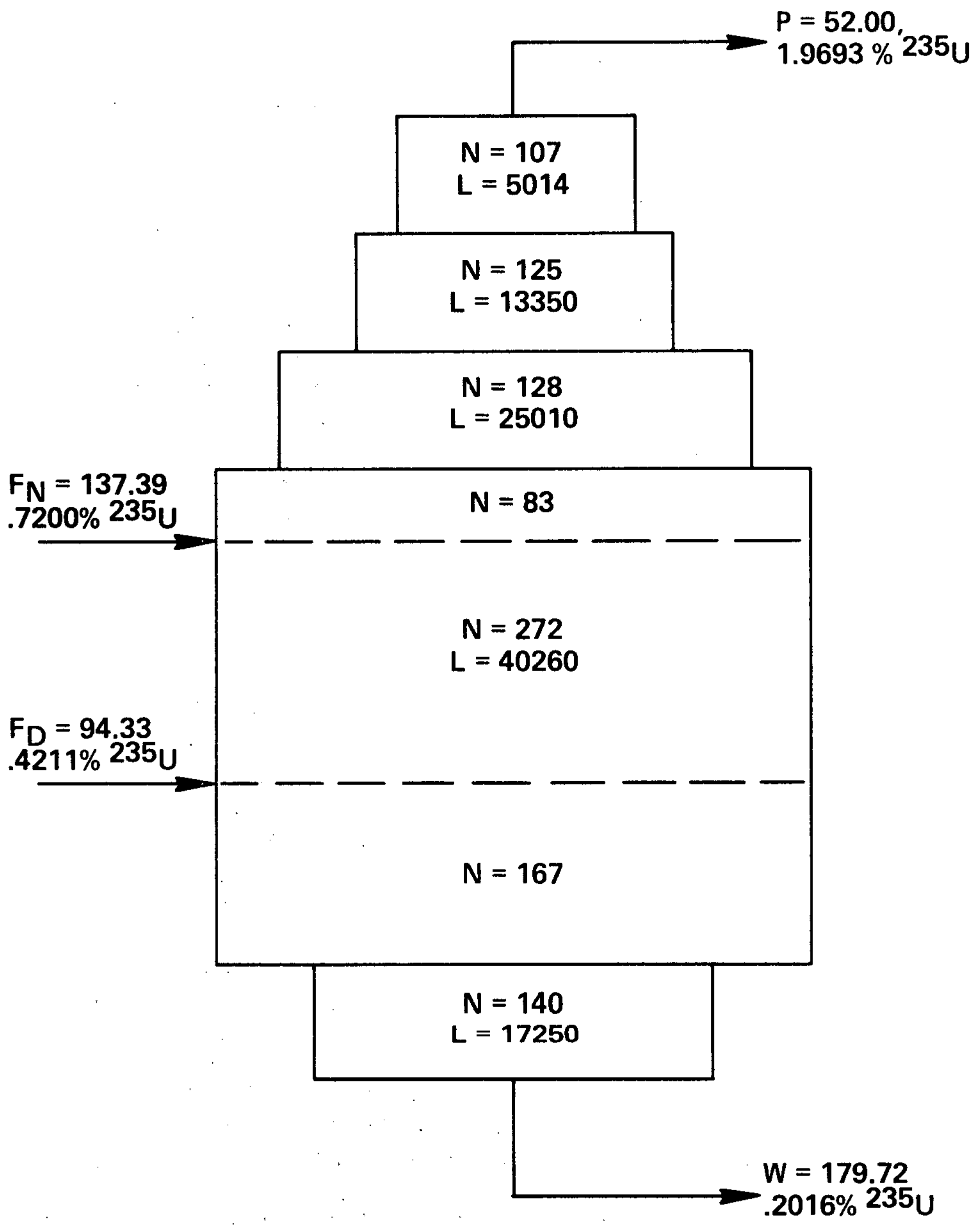
NATURAL U ISOTOPIC MEASUREMENTS

	Test I	Test II
Number of Cylinders Sampled	82	10
^{235}U Data		
Average Concentration, atom %	0.71986	0.71986
Standard Deviation, % of the Average	0.024	0.030
Concentration Range, atom %	0.7195-0.7203	0.7197-0.7201
^{235}U to ^{234}U Concentration Ratio		
Average Ratio	135.2	134.6
Standard Deviation, % of the Average	1.7	1.5
Range of the Measured Ratios	131.3-141.9	131.4-137.9

Table 6

NATURAL U ISOTOPICS ASSUMED FOR THE CALCULATIONS

	For this Test	For the Background Info Studies
^{235}U Concentration, atom %	0.72000	0.71974
^{234}U Concentration, atom %	0.00535	0.00546
^{235}U to ^{234}U Concentration Ratio	134.6	131.9



BASED ON ASSUMED THEORETICAL $(\alpha-1)$ OF .00429
N = NUMBER OF STAGES
L = THE STAGE UPFLOW RATE
STREAM RATES ARE IN LB-MOLS U/DAY

Figure 13
THE SINGLE CASCADE PLANT MODEL

Comparison of the Predicted and Measured Isotopics During the Low Power Period Using a Single-Cascade Plant Model

The ^{234}U concentrations in the product and tails streams of the plant model were then calculated for the conditions of the average daily flow sheet during the 26-day low power period. The stage separation factor for $^{234}U/^{238}U$ was assumed to be 1.00573. This is the theoretical point α for these two U isotopes for gaseous diffusion, consistent with the α value of 1.00429 that was assumed for the $^{234}U/^{238}U$ separation. The calculated ^{235}U to ^{234}U concentration ratios are compared with the average measured values in Table 7.

The calculated 5/4 ratios in the product streams match the corresponding average measured values very well. The standard deviations of the measurements are significantly larger than the difference between the predicted and average measured values. For the 5/4 data for the product stream the standard deviation is ±0.70 percent and for the tails stream it is ±2.1 percent of the respective average measured values, whereas the calculated 5/4 values differ from the corresponding average measured values by -0.16 percent and +0.86 percent.

Split of the Low Power Regime into Two Periods

If one inspects Figure 8, which is a plot of the daily variation of the isotopic concentrations of the depleted uranium (tails from ORGDP) fed to the Paducah plant during the test, it is apparent that there is a significant difference in the average isotopic concentrations of the depleted uranium fed during the initial 13 days of the low power period from those of the next 13 days. The corresponding plot for the PL stream (Figure 11) shows a similar but smaller difference and the plot for the WU stream (Figure 12) a still smaller but definite difference. However, neither the plant product nor tails stream shows a similar difference. The calculations for the low power period were redone, with the first 26 days split into two periods, each of 13 days duration, to see if the match between predicted and measured isotopics would be even closer than that already obtained. The changes resulting in the average plant flow sheets from the division of the low power operating period into two are given in Table 8.

The ^{234}U concentrations in the plant product and waste streams were then calculated for each of the two 13-day periods using the single cascade plant model that had been designed on the basis of the average flow sheet for the entire low power operating period (see Figure 13). These calculations were carried out with the ^{235}U concentrations in the feed and withdrawal streams and the ratio of the two feed rates (F_D/F_N) set at their average measured values. Thus only the calculated ^{234}U concentrations in the plant streams and the stream rates would differ from the average measured values. The predicted and measured values are compared in Table 9.

Table 7

COMPARISON OF CALCULATED AND MEASURED PLANT DATA

Single-Cascade Model
Low Power Period

Stream	Average Measured Values: ^{235}U Concentration (%)	Average Measured Values: 5/4	Calculated Values: ^{235}U Concentration (%)	Calculated Values: 5/4	Δ(5/4)[a] (%)
Product	1.9693	126.2	1.9693	126.0	-0.16
Natural U Feed	---	---	0.7200[b]	134.6[b]	---
Depleted U Feed	0.4211	192.3	AMV[c]	AMV	---
Tails	0.2016	278.3	0.2016	280.7	+0.86

[a]The calculated 5/4 minus the average measured value as a percentage of the latter.

[b]Assumed for computation. Value is based on measurements made for another test (see Tables 5 and 6).

[c]AMV denotes the average measured value during the subject test period.

Table 8

AVERAGED PLANT DATA FOR SPLIT LOW-POWER PERIOD
SINGLE-CASCADE MODEL

Stream	Average Measured Values Initial 13 Days	Next 13 Days	Combined 26 Days
Product			
Rate (lb-mol/day)	51.67	52.33	52.00
^{235}U Conc (atom %)	1.9682	1.9074	1.9693
5/4	125.9	126.6	126.3
Depleted Feed			
Rate (lb-mol/day)	94.86	93.54	94.20
^{235}U Conc (atom %)	0.3889	0.4540	0.4211
5/4	207.1	180.8	192.2
Tails			
Rate (lb-mol/day)	185.65	175.28	180.96
^{235}U Conc (atom %)	0.2011	0.2021	0.2016
5/4	278.3	278.3	278.3
F_D/F_N	0.6719	0.7021	0.6866
U Material Balance Discrepancy (% of Total Feed)	-1.0	-0.37	-0.69

Table 9

COMPARISON OF CALCULATED AND MEASURED PLANT DATA
SPLIT LOW POWER PERIOD
SINGLE CASCADE PLANT MODEL

	Averaged Measured Values			Calculated Values		
Stream	Rate (lb-mol/day)	^{235}U (%)	5/4	Rate (lb-mol/day)	5/4	Δ(5/4)[a] (%)
			First Half of Low Power Period			
Product	51.67	1.9682	125.9	51.97	126.3	+0.32
Natural U Feed	141.17	---	---	142.36	134.6[b]	---
Depleted U Feed	94.85	0.3889	207.1	95.65	AMV[c]	---
Tails	186.65	0.2011	278.3	186.04	284.8	+2.34
			Second Half of Low Power Period			
Product	52.33	1.9704	126.6	52.26	125.7	-0.71
Natural U Feed	133.23	---	---	133.01	134.6[b]	---
Depleted U Feed	93.54	0.4540	180.8	93.28	AMV[c]	---
Tails	175.28	0.2021	278.3	174.13	277.7	-0.22

[a]The calculated 5/4 minus the average measured value as a percentage of the latter.

[b]Assumed for computation. Value is based on measurements made for another test (see Tables 5 and 6)

[c]AMV denotes the average measured value for the subject period.

From a comparison of Table 9 with Table 7 it is evident that splitting the low power period into two does not result in an improvement in the match between the predicted and measured 5/4 values. In fact, in one instance (for the tails stream for the first half of the period), the agreement between the two values has been significantly diminished. Though the average ^{235}U concentrations in the depleted U fed to the plant were markedly different in the second half of the low power period from those in the first half, the effect of the differences evidently was barely reflected in the isotopic concentrations in the average product and tails streams for the two periods.

Comparison of the Predicted and Measured Isotopics During the High Power Period Using a Single-Cascade Plant Model

If the power operating level increase is implemented by increasing each of the interstage and feed stream flow rates by the ratio of the power level increase and the ^{235}U concentrations in the external streams remain the same, then the minor isotope concentrations in the plant product and tails streams would be unaffected. The 5/4 values previously computed for the low power level should then apply to the high power level.

However, in this case, the power level increase was accompanied by flow sheet and cascade changes. First, there was a 15 percent decrease in the depleted U feed rate and an increase of about 67 percent in the natural U feed rate to the plant so that their relative rates (F_D/F_N) went from 0.687 in the low power period to 0.355 in the high power period. Second, the average ^{235}U concentration in the depleted U was greater by about 7 percent and the 5/4 was lower by about 6 percent in the high power period. Third, there was about a 13 percent increase in the average number of stages on stream during the high power period over that in the low power one, so that though the overall cascade power increase was just over 48 percent, the average power increase per on-stream stage was only 32 percent. In consequence, one would not expect the 5/4 values in the plant product and tails streams in the high power period to be identical to those in the low power period. In addition to the differences between the two periods already mentioned, the average ^{235}U concentrations in the product and tails streams were slightly higher during the high power period than during the low power one. The latter difference was not of a magnitude to have more than a negligible effect on the 5/4 ratios.

The average measured flow sheets for the two periods (low and high power levels) are shown in Table 10.

The plant operator, it is assumed, would be obligated under the NPT to inform a safeguards inspection team of the plant power increase and the accompanying flow sheet change, but would not be obligated to inform the inspectors of the increase in the number of stages on stream, and would therefore not do so. To perform the productivity calculations

Table 10

AVERAGE MEASURED FLOW SHEETS FOR THE TWO OPERATING POWER LEVELS

Stream	Low Power: Rate (lb-mol/day)	Low Power: ^{235}U Concentration (%)	High Power: Rate (lb-mol/day)	High Power: ^{235}U Concentration (%)
Product	52.00	1.9693	77.46	1.9757
Natural U Feed	137.2	----	229.0	----
Depleted U Feed	94.2	0.4211	81.2	0.4526
Tails	181.0	0.2016	233.2	0.2045
F_D/F_N		0.6866		0.3546
Material Balance Discrepancy				
U: $\Sigma F-(P+W)$, % of ΣF		-0.69		-0.15
^{235}U: $\Sigma(Fx) - (Px_p + Wx_w)$, % of $\Sigma(Fx)$		-0.32		-0.45

for the high power regime, the safeguards team can appropriately adjust the plant model it has already designed, or alternatively it can design a second plant model, this time on the basis of the new flow sheet. The first option was chosen initially as the step a safeguards inspection team would probably take if it makes the assumption that the power to each stage was scaled up by the same ratio. In this instance, however, the inspectors would know that the feed mix to the plant (F_D/F_N) had been reduced at the same time, but probably would not know that the number of stages in operation had been increased.

Accordingly, all of the interstage flows in the plant model were increased by the ratio of the power levels and a productivity calculation was performed with the ^{235}U concentrations in the plant external streams and the ratio of the feed rate of the depleted U to that of the natural U fixed at their average measured values for the high power regime. The product rate obtained from this calculation was 82.20, which is significantly larger than the average measured value of 77.46 (see Table 10). The less than proportionate increase in the actual product rate is, of course, primarily due to the fact that the barrier efficiency and therefore the stage separation factor is an inverse function of the stage operating pressures. A second adjustment was then made to the interstage flow rates by the ratio of 77.46 to 82.20.* This resulted in a plant model that gave flow sheet values corresponding very closely to those for the high power regime (within 0.8 percent in the feed rates).

The isotopic concentrations obtained from the calculations with this plant model were then compared with the average measured values in the high-power period. The pertinent data are presented in Table 11. The F_D/F_N ratio and the ^{235}U concentrations of the feed and withdrawal streams were fixed at their average measured values in the calculations.

The calculated 5/4 values in the product and tails streams do not match the average measured values in the high power period as well as they did for the low power regime (see Table 7). What this can be attributed to is uncertain. One speculation is that the addition of stages to the plant and the change in the power distribution to the two cascades, neither of which is reflected in the plant model, made the difference. Another possibility is that the average ^{234}U concentration in the natural U feed was different during the high power regime from that in the low power one. For example, if one arbitrarily assumes the average ^{234}U concentration to have been that which had been used for the background MIST studies, namely 0.00546 percent (5/4 = 131.9) as

*The adjustment, more realistically, should be made to the stage separation factor for each component rather than the interstage flows; the adjustment factor on (α-1) then being $\sqrt{77.46/82.20}$. However, the results vis-a-vis the flow sheet and the 5/4 values would not be different.

Table 11

COMPARISON OF CALCULATED AND MEASURED PLANT DATA
SINGLE CASCADE MODEL
HIGH POWER REGIME

	Averaged Measured Values			Calculated Values		
Stream	Rate (lb-mol/day)	^{235}U (%)	5/4[a]	Rate (lb-mol/day)	5/4	Δ(5/4)[a] (%)
Product	77.46	1.9757	119.8	AMV[b]	122.8	+2.5
Natural U Feed	228.99	---	---	227.34	134.6[c]	---
Depleted U Feed	81.21	0.4526	180.0	80.62	AMV	---
Tails	233.22	0.2045	268.4	230.52	272.6	+1.3

[a]The calculated 5/4 value minus the average measured value as a percentage of the latter.

[b]AMV denotes the average measured value.

[c]This is the value assumed for the computations. It is based on measurements made in another test. See Table 7.

listed in Table 6, then the calculated 5/4 values in the product and tails streams differ from the average measured values by +0.67 and +0.15 percent, respectively, which is more in line with the agreement obtained from the corresponding values for the low power period as shown in Table 7.*

TWO-CASCADE REPRESENTATION OF THE PLANT

Flow Sheet Assumptions

The design for the two-cascade plant model was based, as was done for the single-cascade plant model, on the average plant flow sheet for the low power regime. Since the measurement uncertainty was considered to be the greatest for the two intercascade stream rates, the values used for the cascade flow sheets were not their average measured values but those necessary to close the U and ^{235}U material balances for the two cascades, on the assumption that the average measured ^{235}U concentrations in the cascades' external streams and the plant product stream rate are correct. Also the material-balance-adjusted plant feed rates previously obtained for the design of the single-cascade plant model were assumed rather than their average measured values.** The values used for the flow sheet for the design of the two cascade model are compared with the corresponding average measured values in Table 12.

Note that a considerably larger correction was required for the inter-cascade stream rates than was necessary for the plant feed streams for the single cascade model: +9.5 percent for the top withdrawal from the lower cascade (PL) and +3.9 percent for the tails from the upper cascade (WU).

Description of the Two-Cascade Model

Two squared-off cascades each consisting of five enricher sections and two stripping sections were designed, one to do the separation job for the upper cascade and the other to do the one for the lower cascade of the Paducah plant, given the assumed flow and concentration specifications listed in Table 12. Each is a minimum total flow cascade for the assumed number of cascade sections. The cascade efficiency for the upper cascade is 95.5 percent and for the lower it is 95.1 percent. A schematic diagram showing the cascade models in their overlap arrangement is presented in Figure 14.

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*Subsequent to the completion of the correlations, the record on the natural U sources during the test was examined, and it was found that the distribution of natural U feed from domestic and foreign suppliers was significantly different during the two periods.

**Actually, the adjusted plant feed rates are just 0.14 percent greater than the averaged measured values. The ratio of F_D to F_N remains at the period average measured value of 0.6866.

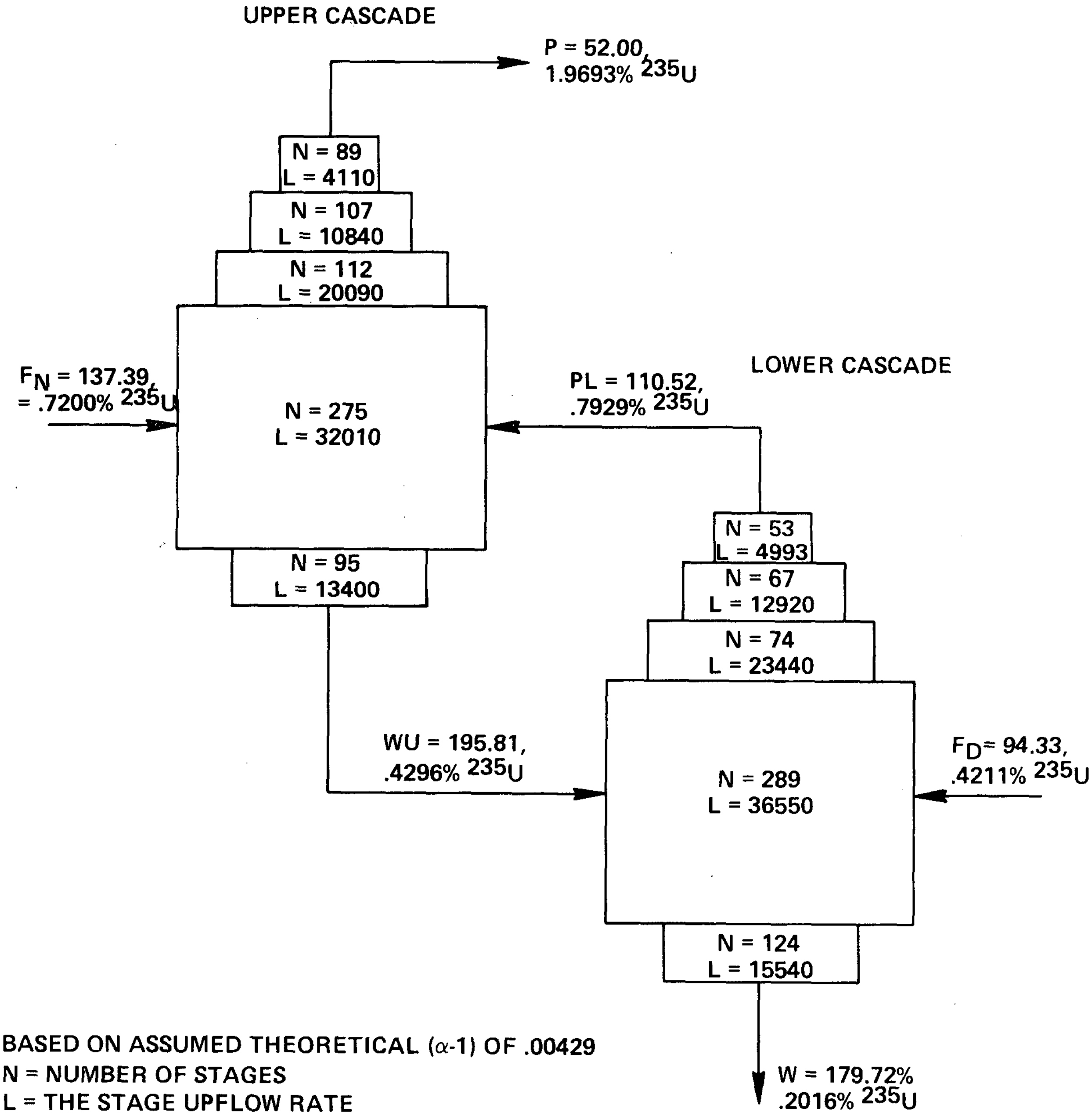
Table 12

FLOW SHEET ASSUMPTION FOR TWO-CASCADE PLANT MODEL DESIGN

Low Power Period

	Assumed for Cascade Models		Average Measured Values	
Stream	Rate (lb-mol/day)	^{235}U Concentration (atom %)	Rate (lb-mol/day)	^{235}U Concentration (atom %)
Plant Product	52.00	1.9693	52.0	1.9693
PL*	110.52	0.7929	100.9	0.7929
Natural U Feed	137.39	0.7200	137.2	---
WU*	195.81	0.4296	188.5	0.4296
Depleted U Feed	94.33	0.4211	94.2	0.4211
Plant Tails	179.72	0.2016	181.0	0.2016

*These are the intercascade streams. See Figure 1 for the arrangement.



BASED ON ASSUMED THEORETICAL (α-1) OF .00429

N = NUMBER OF STAGES

L = THE STAGE UPFLOW RATE

STREAM RATES ARE IN LB-MOLS U/DAY

Figure 14

THE TWO CASCADE PLANT MODEL

Comparison of the Measured and Predicted Isotopics During the Low Power Period Using a Two-Cascade Plant Model

The ^{234}U concentrations in the product and tails streams of each of the overlapped cascades in the plant model were then computed. The calculated results are compared with the average measured values in Table 13. The stream rates obtained from the productivity calculations are not given in the table; they differ slightly (<0.07 percent) from the cascade design values given in Table 12.

The match between the calculated 5/4 values and the measured ones is essentially exact for the plant product and tails streams. Though probably satisfactory, it is not nearly that close for the intercascade streams. It is not clear, at this point, what the maximum level of disparity between calculated and measured values should be for a safeguards team to find the agreement acceptable.

Comparison of the Measured and Predicted Isotopics During the High Power Period Using a Two-Cascade Plant Model

The philosophy adopted to make this comparison was to do it approximately in the way a safeguards inspection team might do it under the NPT. On this basis, it was assumed that the new power level and flow sheet information for each of the two cascades are furnished by the operator to the safeguards team, but that nothing is said about the increased number of stages on-stream.

On this basis, all of the stage upflow rates in each of the cascades of the two-cascade plant model, that was designed for the flow sheet for the low power regime, were scaled up by the power increase ratio reported for each cascade. As is given in Table 1, the ratios are 1.550 for the upper cascade and 1.428 for the lower one. Productivity calculations were then made for the two cascades operating in the overlap arrangement shown in Figure 14. All of the average measured ^{235}U stream concentrations and the ratio of the average measured depleted feed rate to that of the natural U feed rate were assumed to be correct for the calculations. The external stream rates and the ^{234}U concentrations in the withdrawal streams are then the solved variables. The product rate obtained was 80.65, whereas the average measured value is 77.46. As was discussed above (see page 56) for the treatment of the single cascade plant model the over-estimation of the product rate is mostly due to the fact that the stage separation factor is an inverse function of the stage power level. One can adjust for this either by multiplying the stage separation factor for each component by the square root of the ratio of the measured product rate to the calculated one or by multiplying the stage upflow rates by the unmodified ratio, that is by 77.46/80.65. The latter option was chosen and the three-component productivity calculation was repeated as a

Table 13

COMPARISON OF CALCULATED AND MEASURED PLANT DATA
Two-Cascade Model
Low Power Period

Stream	Average Measured Values ^{235}U Concentration (%)	Average Measured Values 5/4	Calculated Values ^{235}U Concentration (%)	Calculated Values 5/4	Δ(5/4)[a] (%)
Plant Product	1.9693	126.2	AMV[b]	126.2	0.0
PL[d]	0.7929	175.4	AMV	173.3	-1.2
Natural U Feed	--	--	0.7200[c]	134.6[c]	--
WU[d]	0.4296	197.3	AMV	196.1	-0.6
Depleted U Feed	0.4211	192.3	AMV	AMV	--
Plant Tails	0.2016	278.3	AMV	278.3	0.0

[a]The calculated 5/4 value minus the average measured value as a percentage of the latter.

[b]AMV denotes the average measured values fixed for the calculation.

[c]These are the values assumed for the computations. They are based on measurements made in another test. See Table 6.

[d]These are the intercascade streams. See Figure 14 for their connections.

check.* The calculated results are compared with the average measured values in Table 14.

The calculated 5/4 value for the plant product stream deviates more from the average measured value than for any of the other isotopic ratio comparisons made for this test, while the calculated value for the plant tails stream matches the measured value exactly. Also, for the two intercascade streams the match is significantly better for the top withdrawal stream from the lower cascade (PL) than it is for the other (WU). On the whole, the mismatches in the 5/4 ratios do not compare unfavorably with those made using the single cascade model for the calculations (see Table 11).

However, it is evident from inspection of Table 14 that the match between the calculated and average measured stream rates for the two-cascade stream complex is much poorer than for the isotopic ratios. For the natural U feed, the calculated value differs from the measured value by -23 percent in the upper cascade and by +14 percent in the lower cascade. On a total natural U feed basis the comparison is better: the calculated value is off by -3.3 percent with respect to the measured value and by -2.4 percent with respect to the value calculated using the single cascade plant model (see Table 10). Also, the calculated value for the depleted feed rate exceeds the average measured one by 13 percent and exceeds the value calculated using the single-cascade model by 14 percent. The calculated intercascade stream rates also differ from the corresponding average measured values significantly: for PL by +20 percent and for WU by +9 percent. Most or all of the stream rate discrepancies are probably attributable to the fact that the increase in plant power level was not accomplished by simply raising the level for each stage by a constant ratio.

The actual power level increase was a more complex thing. Some spare stages were brought on-stream, thereby increasing the number in operation by approximately 13 percent and the stage power distribution was presumably re-optimized so that the uniformly scaled two-cascade plant model was not a sufficiently good representation to match the flow sheet, which itself involved a marked change in the feed mix, the average F_D/F_N value in the high power regime being approximately 52 percent of what it was during the low power period. For this reason, it was of interest to design a two-cascade plant model for the high power regime that is based on the reported average flow sheets for

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*The productivity recalculation was not necessary. All of the stream rates could be determined directly by scaling with the ratio 77.46/80.65. The isotopic concentrations are unaffected by the scaling of all of the cascade stream rates or the separation factors, by a constant ratio.

Table 14

COMPARISON OF CALCULATED AND MEASURED PLANT DATA FOR THE HIGH POWER PERIOD

The Low Power Regime, Two-Cascade Model Scaled for the High Power Level

Stream	Average Measured Values			Calculated Values			
	Stream Rate	^{235}U Concentration (%)	5/4	Stream Rate	^{235}U Concentration (%)	5/4	Δ(5/4)[a] (%)
Plant Product	77.46	1.9757	119.8	AMV[b]	AMV	123.6	+3.2
PL[e]	160.84	0.8729	146.8	193.45	AMV	145.9	-0.7
FNU[d]	105.69	--	--	81.82	0.7200[c]	134.6[c]	--
WU[e]	181.48	0.3778	203.5	197.81	AMV	209.1	+2.7
FNL[d]	123.30	--	--	139.96	0.7200	134.6	--
FDL[d]	81.21	0.4526	180.0	92.17	AMV	AMV	--
Plant Tails	233.22	0.2045	268.4	236.49	AMV	268.4	0.0

[a]The calculated 5/4 value minus the average measured value as a percentage of the latter.

[b]AMV denotes the average measured value, fixed for the calculations.

[c]These were assumed for the computations. They represent the results of measurements made in another test. See Table 6.

[d]FNU and FNL are the natural U feeds to the upper and lower cascades, respectively. FDL is the depleted uranium feed.

[e]These are the intercascade streams. See Figure 13 for their connections.

the two cascades for the high power regime to see how the results differ from the ones obtained using the scaled two-cascade plant model that was designed initially for the low power plant flow sheet.

As the first step in doing this, the average measured stream rates for each cascade were adjusted to close both the U and ^{235}U material balance, keeping the product rate and the ratios of the three feed streams at their average measured values. This resulted in a larger correction to the rates of the intercascade streams than any of the others as can be seen in Table 15. The ^{235}U concentrations in the cascade external streams are not given in the table, since they were assumed to be correct for the material balance closure calculations: their average measured values for the high power period have been given in Table 14.

A Two-Cascade Plant Model Designed for the High Power Regime Average Flow Sheet

A two-cascade plant model was designed for the high power regime based on the material balance-adjusted stream rates shown in Table 15 and the average measured values for the ^{235}U concentrations in the cascade external streams as listed in Table 14. The number of enricher and stripper sections assumed is the same as that specified in the initial two-cascade model design for the low power regime. There are significant differences, as shown in Table 16, between the two-cascade model based on the adjusted flow sheet for the high power period and that obtained by scale-up to the high power level of the two-cascade plant model designed on the basis of the adjusted flow sheet for the low power period.

In reference to Table 16 note (1) that the Model B design provides for more stages than the Model A one does; (2) that for Model B the lower cascade is slightly smaller in size, in terms of total flow, than the upper cascade, whereas in Model A the lower cascade size is significantly larger than that of the upper cascade; (3) that the upflow rate from the feed stage in each cascade for Model B is considerably less than that for Model A; and (4) that the plant separative efficiency for Model B is 95 percent as compared to 88 percent for Model A. In consequence of these differences, one would expect that the 5/4 ratios in the external streams for the plant model represented by Model B might differ measureably from those in the plant Model A.

Comparison of the Measured and Predicted Isotopics During the High Power Period Using the Two-Cascade Model Designed for the Average Flow Sheet for the Period

The isotopic concentrations in the external streams of the two cascades for the second plant model (B) were then computed. The stream rates for the model correspond very closely (within 0.1 percent) to the adjusted values listed in Table 15, and thus differ from the average measured values by essentially the same extent. The 5/4 ratios for the

Table 15

MATERIAL BALANCE CORRECTIONS TO THE PLANT FLOW SHEET FOR THE HIGH POWER REGIME

Stream	Rate		
	Average Measured Value (AMV)	Adjusted Value	Difference (% of AMV)
Plant Product	77.46	77.46	--
PL[a]	160.84	177.47	+10.3
FNU[b]	105.69	104.93	- 0.7
WU[a]	181.48	204.94	+12.9
FNL[b]	123.30	122.41	- 0.7
FDL[b]	81.21	80.62	- 0.7
Plant Tails	233.22	230.49	- 1.2

[a]PL and WU are the intercascade streams.

[b]FNU and FNL are the natural U feeds. FDL is the depleted uranium feed.

Table 16

COMPARISON OF PLANT MODELS
TWO-CASCADE REPRESENTATION FOR THE HIGH POWER REGIME

	Upper Cascade	Lower Cascade	Plant
Scaled Low Power Model (Model A)			
Total Flow ($\Sigma L \times 10^{-7}$)	2.062	2.342	4.404
Separative Work Produced	88.12	90.86	178.92
Separative Efficiency, %	92.9	84.3	88.3
Number of Stages	676	607	1283
Upflow Rate from the Feed Stage ($L \times 10^{-3}$)	47.7	50.1	--
Design for High Power Period Flow Sheet (Model B)			
Total Flow ($\Sigma L \times 10^{-7}$)	2.054	1.992	4.046
Separative Work Produced	89.67	87.09	176.76
Separative Efficiency, %	94.9	95.0	95.0
Number of Stages	729	643	1382
Upflow Rate from the Feed Stage ($L \times 10^{-3}$)	40.8	41.8	--

two plant models for the high power regime are compared with the average measured values in Table 17. For the natural U feed in this calculation, the ^{235}U concentration was assumed to be 0.72 percent and the ^{234}U 0.00535 percent, thus corresponding to a 5/4 ratio of 134.6. This is the composition that has been used in all of the productivity calculations in this study, except where otherwise stated.

Though Model B matches the high power regime average measured flow sheet almost exactly and Model A deviates from it significantly, the 5/4 ratios obtained with Model B do not match the average measured ratios much better than do those for Model A. For comparison, the 5/4 values obtained with the single-cascade model for the plant (see Table 11) deviate from the average measured values by +2.5 percent in the plant product and +1.6 percent in the plant tails. One explanation that has been put forth (see page 56) for the poorer match of the calculated to the measured 5/4 values for the high power regime is that the average ^{234}U concentration in the natural U feed was different during the high power period from that in the low power period. If the average ^{234}U concentration in the natural U fed in this period is arbitrarily assumed to have been the value used for the background MIST studies (0.00546 percent or 5/4 equal to 131.9) a somewhat better match between the measured and predicted values is obtained as shown in Table 18.

Table 17

COMPARISON OF CALCULATED AND MEASURED ISOTOPIC DATA FOR THE TWO TWO-CASCADE MODELS FOR THE HIGH POWER REGIME

Stream	Average Measured Value 5/4	Calculated Values: Model A 5/4	Model A Δ(5/4)[a] (%)	Model B 5/4	Model B Δ(5/4)[a] (%)
Plant Product	119.8	123.6	+3.2	122.9	+2.6
PL[c]	146.8	145.9	-0.7	146.6	-0.1
WU[c]	203.5	209.1	+2.7	207.2	+1.8
Depleted Feed	180.0	AMV[b]	----	AMV	----
Plant Tails	268.4	268.4	0.0	270.5	+0.8

Model A: The two-cascade plant model originally designed on the basis of the average measured flow sheet for the low power period scaled up to the high power level.

Model B: The two-cascade plant model designed directly on the basis of the average measured flow sheet for the high-power regime. (See Table 16).

[a]The calculated 5/4 value minus the average measured value as a percentage of the latter.

[b]AMV denotes the average measured value adopted for the calculation.

[c]These are the intercascade streams. See Figure 14 for their locations.

Table 18

EFFECT OF THE 5/4 ASSUMPTION IN NATURAL U ON THE MATCH BETWEEN THE PREDICTED AND MEASURED 5/4 VALUES

High Power Regime
Two-Cascade Plant Model B

Stream	Average Measured Value	Calculated Values			
		5/4	Δ(5/4)[a] (%)	5/4	Δ(5/4)[a] (%)
Plant Product	119.8	122.9	+2.6	120.8	+0.8
PL[c]	146.8	146.6	-0.1	144.1	-1.8
Natural Feed	---	134.6	---	131.9	---
WU[c]	203.5	207.2	+1.8	203.4	0.0
Depleted Feed	180.0	AMV[b]	----	AMV[b]	----
Plant Tails	268.4	270.5	+0.8	266.5	-0.7

[a]The calculated 5/4 minus the average measured value as a percentage of the latter.

[b]AMV denotes the average measured value adopted for the calculation.

[c]These are the intercascade streams (see Figure 14).

PLANT CONCENTRATION GRADIENTS

The major objective of the first two plant tests and a secondary one of the third test at the ORGDP was to determine how well the computational model could match the measured minor isotope cascade gradients. The results have been very successful with respect to the 5/4 gradients but rather unsatisfactory with respect to the 5/6 gradients. The problem with respect to the 5/6 correlations has been attributed to the fact that in each case the ^{236}U concentration varied considerably in successive cylinders of non-normal U fed during the tests so that the measured ^{236}U concentrations represent transient values rather than steady-state ones. A code designed to compute steady-state conditions would not be expected then to give results that match the transient conditions.

THE MEASURED ISOTOPIC DATA

To obtain typical isotopic concentration gradients for the Paducah plant cascades, samples were drawn at roughly regular intervals along the cascades from each of the two cascades approximately simultaneously on a day midway during the low power period. The 5/4 values found in the gradient samples are plotted versus the logarithm of the ^{235}U concentrations in Figure 15. Curves have been drawn through the data to get some feeling for the degree of scatter of the data. It is apparent that the scatter is very small, apparently <±1 percent. The one datum point that seems to be off the most is the bottom sample from the lower cascade: ^{235}U concentration at 0.21 percent and 5/4 equal to 276.

BASES CHOSEN FOR THE ISOTOPIC CALCULATIONS

The two-cascade plant model that had been designed to fit the average measured flow sheet for the low power regime was used as the model for the calculation of the plant isotopic gradient for comparison with the measured ones. The calculation requires input values for the ^{234}U and ^{235}U concentrations of the depleted U feed. A four-day average of the reported values prior to and including the sampling date was chosen for this. It was noted that the ^{235}U concentrations and the 5/4 values in the cylinders of the depleted U fed to the plant during the period up to the sampling date had varied considerably, by up to 25 percent of the period average value, with the largest variation occurring three days prior to the sampling date. Since the gradient will reflect some mix of the most recent feed concentrations the four-day average was selected, though it may very well be that a five-, six- or seven-day average would have been better. Three component productivity calculations were carried out for the two cascade complex with the ^{235}U concentrations in the cascades' external streams fixed at their measured values. The cascade stream rates obtained from the calculation are compared in Table 19 with the flow sheets for the four-day average used to set the depleted feed concentrations for the calculations, and also with the 26-day low power period average.

Table 19

FLOW SHEET COMPARISON FOR GRADIENT SAMPLES

	Calculated[a] for Plant Model		Measured 4-day Average: Days 10-13		Measured Low-Power Period Average: Days 1-26	
	Stream Rates (lb-mol/day)	^{235}U Concentration (atom %)	Stream Rates (lb-mol/day)	^{235}U Concentration (atom %)	Stream Rates (lb-mol/day)	^{235}U Concentration (atom %)
Plant Product	54.99	1.9586	52.56	1.9717	52.00	1.9693
PL	86.42	0.8689	96.48	0.7873	110.52	0.7929
Natural U Feed	157.78	0.7200	146.33	---	137.39	---
WU	189.21	0.4280	190.94	0.4320	195.81	0.4296
Depleted U Feed	89.90	0.3854	89.29	0.3854	94.33	0.4211
Plant Tails	192.70	0.2104	195.43	0.1982	179.72	0.2016

[a]All of the ^{235}U concentrations representing the corresponding measured gradient values, are fixed input values for the calculation. The stream rates are solved values.

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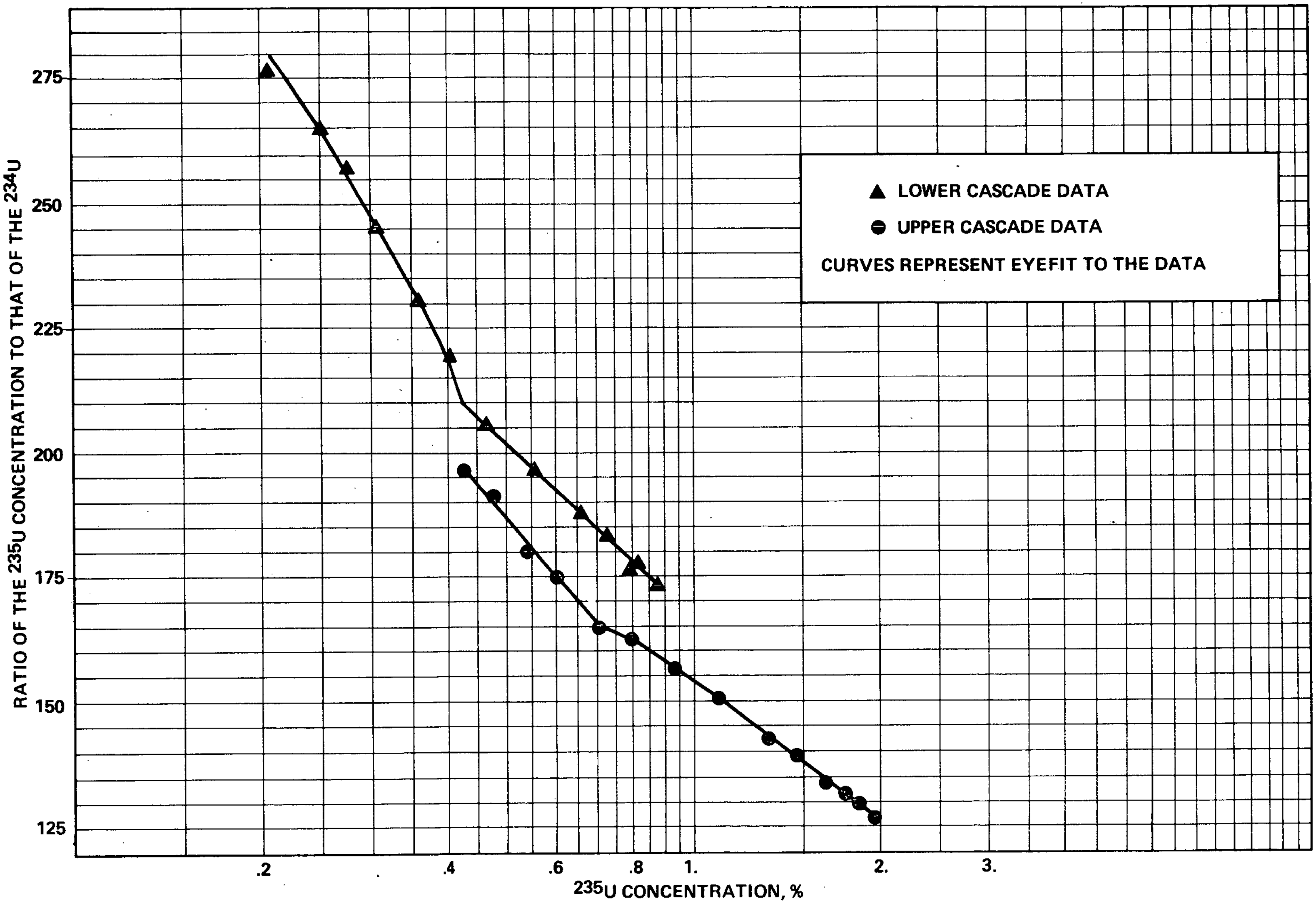

Figure 15

THE MEASURED CASCADE GRADIENTS ON DAY 13

COMPARISON OF THE MEASURED AND PREDICTED ISOTOPIC GRADIENTS

Curves representing the calculated concentration gradients for the two cascades are plotted in Figure 16 along with the sample data. The computed values represented by the pair of curves marked "A" appear to have a consistent bias with respect to the measured values, falling below them by the order of 2 to 4 percent. Since there is some uncertainty as to the appropriate average isotopic composition of the depleted U feed that should have been used in the calculation, it was considered of interest to determine ^{234}U concentration in this feed that would lead to a match between the computed and measured data, at least in the lower cascade. A reduction in the ^{234}U concentration in F_D from 0.00188 to 0.00170 percent (a reduction of 9.6 percent) led to an excellent match of the measured and calculated 5/4 values in the lower cascade but cut the bias in the upper cascade by only about one-half. Because of the isotopic interaction between the two cascades via the intercascade streams it was concluded that one should determine the simultaneous change in the ^{234}U concentrations in both feeds (natural and depleted U) that would be needed to match the calculated and measured gradients. A reduction in the ^{234}U concentration in F_D from 0.00188 percent to 0.00183 percent (2.6 percent) and a reduction in the ^{234}U in F_N from 0.00535 to 0.00525 percent (1.9 percent) resulted in an excellent match as is shown by the curves labeled B in Figure 16. A value of 0.00525 percent for the ^{234}U concentration (5/4 = 137.1) in natural U is within the range of reported measurements (see Table 5). It may have been that the natural U fed for a period just prior to the gradient sampling had average ^{234}U concentrations in this range. This indicates, of course, that the cylinders containing natural U fed to the cascade should have been sampled for this test and should be sampled in any future tests.

One might expect that the isotopic concentrations of those gradient samples that represent the product and tails of each of the two Paducah cascades would be bracketed by those of the last daily stream samples taken before the gradient sampling and the first ones taken after. With one exception, this is not so for the ^{235}U concentrations. Only the ^{235}U concentration in the tails stream from the upper cascade (WU) is bracketed by the before and after samples as can be seen in Table 20. This of course, is a single example of the fluctuations in plant stream concentrations that occur continually with the plant nominally at steady-state.

Table 20

BRACKETING OF THE ^{235}U CONCENTRATION IN THE CASCADE EXTERNAL STREAM GRADIENT SAMPLES

Stream	Regular Daily Sample on 13th Day	^{235}U Concentration Gradient Sample on 13th Day	Regular Daily Sample on 14th Day
Plant Product	1.9763	1.9586	1.9764
PL	0.8134	0.8689	0.8380
WU	0.4339	0.4280	0.4240
Plant Tails	0.2065	0.2104	0.2059

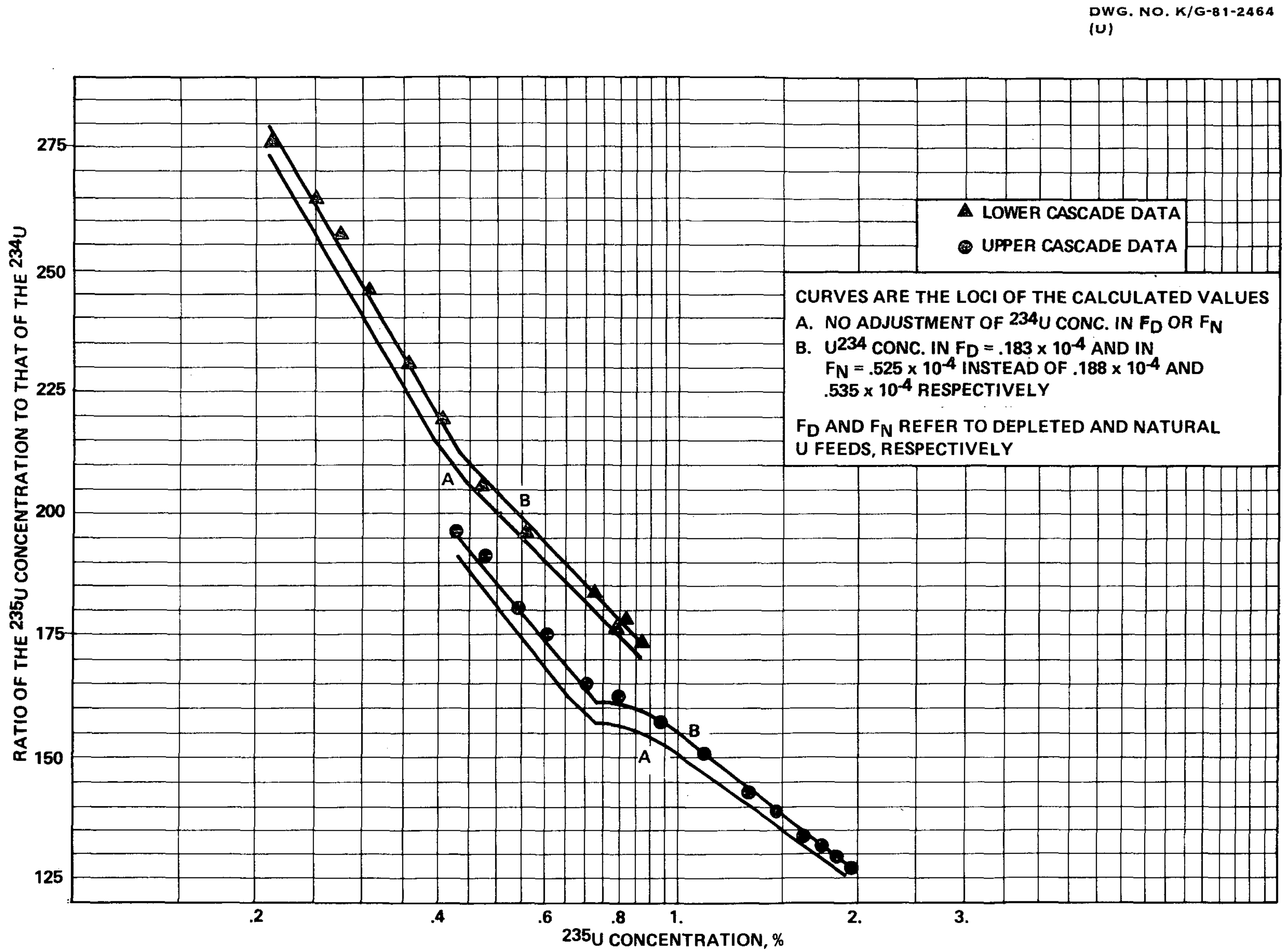

Figure 16

COMPARISON OF THE CALCULATED PLANT GRADIENTS WITH THE MEASURED ONES

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