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AGNS-35900-3.1-111

STUDIES AND RESEARCH CONCERNING BNFP

PILOT-SCALE PULSED COLUMNS COLUMN PROFILE AND HOLDUP STUDIES

Dr. Anthony F. Cermak

November 1980

MASTER

Work Performed Under Contract DE-AC09-78ET-35900

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The contributions of the AGNS Operating, Analytical, and Maintenance Departments in performing the laboratory and analytical work as well as maintenance work are gratefully acknowledged.

ABSTRACT

Experimental studies were conducted on pilot-scaled pulsed columns for the purpose of obtaining data for verification of contactor computer programs. This work is in support of Safeguards programs related to determination of near real-time inventories in pulsed columns.

Holdup tests were performed resulting in the derivation of an empirical equation for estimation of the dispersed phase holdup in a column. Uranium solvent extraction mass-transfer tests were conducted in which all four process cycles were simulated under coprocessing flowsheet conditions. Extensive data were obtained during these tests on uranium profiles and inventories within the columns. Transient profile data were also determined between selected runs under the tested operating conditions. No concentration peaks could be observed during the transient period. Based on the extensive inventory data taken, empirical equations were developed for relating uranium inventory in a column to the test parameters. These equations were found useful for predicting and estimating the column inventory under the known run conditions.

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1.0 INTRODUCTION

Considerable interest has come about in recent years in developing advanced nuclear materials accounting systems for plutonium and enriched uranium in spent fuel reprocessing facilities subject to international inspection and inventory verification. The proposed goals of the International Atomic Energy Agency (IAEA) are the detection of a diversion of:

(1) 75 kilograms of U-235 contained in low-enriched uranium over a period of one year

(2) 8 kilograms of separated plutonium as the oxide or nitrate in 1 to 3 weeks (abrupt diversion)

(3) 8 kilograms of plutonium over an entire year (protracted diversion)

(4) 8 kilograms of plutonium contained in irradiated fuel in 1 to 3 months.

In support of this need, the Los Alamos Scientific Laboratory (LASL), Allied-General Nuclear Services (AGNS) and other laboratories are developing advanced techniques for nuclear materials measurement.(1) In support of this program, under the sponsorship of LASL, researchers at the Ames Laboratory, Iowa State University, under the direction of Dr. L. E. Burkhart, are developing theoretical models for pulsed column behavior which will predict solute profiles.(2) This technique, when properly applied with signals coming from on-line process instruments interfaced to a computer can produce column inventories in near real-time. To date, the SEPHIS program(3) has been used for the purpose of predicting solute profiles and end stream concentrations from contactors. However, this program was originally designed for mixer-settler contactors and is not directly applicable to differential contactors, such as pulse columns, since it does not incorporate such factors as back-mixing.

Work was initiated in 1979 at AGNS, under contract to the Department of Energy (DE-AC09-78ET-35900 Sub-Task 4.1), to carry out experimental studies on proposed coprocessing flowsheets in which a portion of the uranium is allowed to remain with the plutonium throughout the second and third plutonium purification cycles.(4) This work was conducted in pilot scale pulse columns using uranium only. These columns were equipped with samplers along the height of the column, such that samples could be obtained and solute profiles determined. An example of such a profile is shown in Table 1-1 in which the AGNS determined experimental profile is compared to that obtained by the SEPHIS and Burkhart models. As can be seen, excellent agreement was obtained with that predicted by the Burkhart model.

The work initiated in 1979 was further expanded in 1980 to include solute profile and dispersed phase hold-up studies on all Purex purification cycles under coprocessing conditions for purposes of verification of contactor computer programs. Also, some transient profile data were obtained between selected runs as well as column uranium inventory at the termination of a run. Comparisons are made with that predicted by the SEPHIS model. The data were made available to LASL and Dr. L. E. Burkhart for comparison to the Burkhart model in advance of the publication of this report.

TABLE 1-1(*)

EXPERIMENTAL URANIUM CONCENTRATIONS VERSUS SEPHIS AND THE BURKHART MODEL (2-IN.-I.D. EXTRACTION/SCRUB PULSED COLUMN)

Distance (ft) from Column Bottom	Uranium Concentration (grams/liter)					
	SEPHIS		Experiment		Burkhart Model	
	Aq	Org	Aq	Org	Aq	Org
24 (scrub)	0	52.5	0	54.0	0	54.0
21	17.2	65.0	15.0	62.7	15.0	62.7
18	25.0	71.0	19.7	67.5	19.8	67.5
15 (feed)	25.0	71.0	20.0	68.5	21.4	69.0
12.8	10.0	32.5	9.0	38.0	9.1	39.2
12.2	1.5	6.2	1.5	20.1	1.5	17.6
11.2	0.4	1.0	0.4	8.0	0.4	7.0
9	0	0	0	1.0	0	1.0
7	0	0	0	0	0	0

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*Table 1-1 reproduced from Reference 2 with the permission of LASL.

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2.0 SUMMARY

Ninety hydraulic tests were performed on pulsed columns in the pilot-plant to determine the effect of basic hydrodynamic variables on the dispersed phase holdup in the column. Evaluation of experimental holdup data resulted in an empirical equation showing the dependence of the holdup on the pulse velocity in the direction of the dispersed phase flow. The equation applies to tested columns and the experimental range shown in Table 4-2 and 4-3. Dispersed phase holdup values were determined through both the volumetric measurement in the column, and weight recorder readings. Tests have shown that the method developed at AGNS(5) for holdup determination in a pulsed column through weight recorder readings is reliable.

Fifteen mass-transfer tests using uranium were performed on the pilot-plant equipment to simulate runs in the first uranium-plutonium cycle, second uranium cycle, and second and third plutonium cycles under coprocessing conditions. Run conditions are shown in Tables 4-4 through 4-8.

The pilot plant experiments were designed to obtain detailed concentration profiles, operational holdup data, and uranium inventory in each tested column. The first three tests (HS-1, HS-2, and HS-3), simulating the HS and 1C columns, were performed with 15 v/o TBP. The other three tests on these columns (HS-4, HS-5, and HS-6), as well as tests simulating the 2D-2E, 2A-2B, and 3A-3B columns, were performed with 30 v/o TBP as the organic phase. During tests HS-1 through HS-6, the HSF feed flow rate was varied as shown in Tables 4-4 and 4-5 to determine its effect on column concentration profiles. Tests simulating runs in the second uranium cycle (2D-2E columns), and second (2A-2B columns) and third (3A-3B columns) plutonium cycles were performed changing the organic phase flow rate as shown in Tables 4-5 through 4-8, respectively. During tests, the 2-inch diameter 1A dual process column was used for extraction and scrubbing, and the 3-inch diameter 1BX column for stripping, with the exception of the last three runs (3A-1, 3A-2, and 3A-3) where the 2-inch diameter 1BS column was used.

In all runs, samples were taken along the tested columns under steady state conditions and analyzed for solutes content (uranium and nitric acid). Analytical data were evaluated and the actual concentration of uranium and nitric acid was determined for each sampling point. From these data, the concentration profiles of solutes along each tested column were determined.

Mass-transfer tests have shown that both the HS and 2D columns will be flooded if the HSX/HSF and 2DX/2DF ratio value, respectively, goes below 2.8, considering the organic phase and aqueous scrubbing stream flow rates of the coprocessing flowsheet.(8)

Four transient tests between subsequent runs shown in Tables 4-24 through 4-27 resulted in smooth uranium concentration curves

(Figures 4-39 through 4-42) at sampling points around the feed solution inlet to the dual process column, indicating no concentration peaks in that part of the column during transient period.

Experimental concentration profiles of three runs (HS-1, HS-6, and 2D-1) along the dual process column were compared with profiles obtained by the SEPHIS code under the same conditions. Due to considerable backmixing of the continuous phase, the computed SEPHIS uranium profiles were not in agreement with the experimentally determined concentration profiles.

Uranium inventory in tested columns was determined both through volume and concentration measurement at the end of the run, and through calculations from experimental concentration profile and holdup data. Both results are in good agreement as shown in Table 4-28. Inventory data in the table were evaluated. The evaluation resulted in empirical equations usable for estimation of the uranium content (inventory) in pulsed columns operating under similar conditions as tested. See Section 4.4 for details.

3.0 EXPERIMENTAL

3.1 Equipment Description

The experimental equipment shown in Figure 3-1 consisted of three glass pulse columns and ancillary equipment such as stainless steel tanks and pumps. The 2-inch (50-millimeter) diameter 1A column, used for extraction and scrubbing, had an overall height of 26.5 feet (8.15 meters) with a working extraction section of 13 feet (3.96 meters) (lower section) and scrubbing section of 9.3 feet (2.8 meters). The 3-inch (75-millimeter) diameter 1BX column, used for stripping (simulating the 1C and 2E columns), was 22 feet (6.71 meters) high, with a working section of 17 feet (5.20 meters). The 2-inch (50-millimeter) diameter 1BS column for stripping (simulating the 2B and 3B columns) had an overall height of 23 feet (7.02 meters) and working section height of 18 feet (5.49 meters).

All three columns were provided with stainless steel nozzle plates with 23% free surface area, 1/8-inch (3.2-millimeter) orifice diameter, and 1/16-inch (1.6-millimeter) plate thickness. The plates were assembled on a central 1/4-inch (6 millimeter) diameter stainless steel tie rod on a 2-inch (50-millimeter) plate spacing. Each column was provided with a 6-inch (150 millimeter) diameter top and bottom disengaging section made of glass. The bottom disengaging section was connected to a bellows-type pulser. The top disengaging section was vented. The interface was automatically controlled in the 1A column in the bottom disengaging section and in the 1BX and 1BS stripping columns in the top disengaging section. This was accomplished by means of sensors consisting of two titanium conductivity probes used to regulate an air-operated, stainless steel control valve at the aqueous phase outlet line.

All three columns were provided with several samplers at different locations along the column's working section. Sampler locations at each column are shown in Figure 3-2. Aqueous and organic samplers were each made of stainless steel tubing with an inside diameter of about 1/8 inch (3 millimeters). The organic sampler was provided (within the column) with a tubular end piece made of Teflon.

The feed preparation tank consisted of a 500-gallon stainless steel vessel equipped with a mechanical agitator, cooling-heating jacket, sight glass, temperature and pressure instrumentation. Connections were provided for liquid and air inlet and outlet and for sampling. All feed and receiving tanks were provided with sight glasses, liquid and air inlets and outlets, piping, and connections for vacuum and samplers. The tank volumes are shown in Figure 3-1. Feed flow rate was controlled by calibrated displacement pumps.

3.2 Procedure

Experimental work performed on pilot-plant pulse columns included hydrodynamic and mass-transfer tests. Hydrodynamic tests were made to determine the flooding curve and dispersed phase holdup. Mass-transfer tests were performed to determine the uranium concentration profile along the column. Accountability of uranium and other solutes in a pulse column requires the knowledge of both the holdup of liquid phases and concentration profile of the given solute in the column.

3.2.1 Flooding Tests

The maximum operational capacity is generally determined by the column flooding test. Flooding tests using 15 v/o TBP - 0.1 $\underline{M}$ HNO_3 were made in the 1A and 1BX columns only. All three columns were tested for flooding with the system 30 v/o TBP - 0.1 $\underline{M}$ HNO_3. (NOTE: For all runs the diluent was n-dodecane.)

In addition, each column was flooded temporarily during mass-transfer tests to verify and determine the actual flooding point for a given set of process conditions. Flooding data are discussed in Section 4.1. Flooding curves are presented in Figures 4-1 to 4-6.

3.2.2 Holdup Determination

A method has been developed at AGNS(5, 6) for determination of the dispersed phase holdup in a pulse column based on weight recorder readings. The weight recorder is calibrated to measure the average liquid density in the column. A mathematical relationship exists among the dispersed phase holdup, densities, and column geometry. The dispersed phase holdup can be reliably determined from known density values and column dimensions and is generally given by the ratio of the dispersed phase volume in the column-active section to the total liquid volume of that section. Knowing the dispersed phase holdup, it is possible to determine the holdup of the continuous phase in the column.

In a glass pulse column, the dispersed phase holdup can also be visually determined through liquid volume measurements in the column. The interface location is marked with the pulse column operating under steady-state conditions. The feed streams and the aqueous outlet stream are then shut off simultaneously and the phases allowed to separate. The dispersed phase volume is then measured between the new interface location and the original one. The dispersed phase holdup is determined by dividing the measured volume of the dispersed phase by the total liquid volume of the column active section.

Each of the above techniques was used during holdup tests at the BNFP. Tests were performed first with the liquid system 15 v/o TBP - 0.1 $\underline{M}$ HNO_3 and then with 30 v/o TBP - 0.1 $\underline{M}$ HNO_3, so the effect of TBP volume concentration on the dispersed phase holdup could be evaluated. Holdup values were measured in the same manner during actual mass-transfer tests which were made to determine uranium concentration profiles. Holdup measurement data are summarized in Tables 4-2 and 4-3 and in Figures 4-7 and 4-8.

3.2.3 Mass-Transfer Tests with Uranium

Cold uranium runs (utilizing natural uranium only) were used to simulate all four process cycles, i.e., the first uranium-plutonium extraction cycle, second uranium cycle, and second and third plutonium cycles. The objectives were: (a) to optimize operating process conditions, (b) to determine the uranium concentration profile in each column, and (c) to verify dispersed phase holdup calculations by volumetric measurements at the end of each run.

Optimization of process conditions for each run is discussed in Section 4.0. Concentration profiles were determined, based on chemical analyses of replicate samples of each liquid phase drawn at each sampler along the column during steady-state operation of the column.

The methods for chemical analyses are described in Appendix A. The model for the calculation of solute concentration profiles, based on chemical analyses, is given in Reference 4.

Data for the four runs, simulating the four process cycles at BNFP, are presented in Tables 4-4 through 4-8. These data are discussed in Section 4.0. A description of the method used for dispersed phase holdup measurements is presented in Section 3.2.2. All tests were conducted at room temperature (approximately 24°C).

3.2.4 Solutes Inventory (Accountability)

Inventories for accountability of uranium, plutonium, or other solutes in a pulse column may be made either experimentally or analytically (see Figure 3-3). Experimental determinations are done either: (a) through volume-concentration measurement or (b) by concentration profiles used in conjunction with holdup data for both liquid phases within the contactor. The first method (volume-concentration) is convenient but gives no indication of the effect of mass-transfer and hydrodynamic variables on the solute content within the column during process performance.

This measurement is accomplished by draining the column after reaching the operational steady state, decanting, and determining the solute concentration in each liquid phase. The quantity of any given solute within a column is:

$$M_{(solute)} = V_A \cdot \bar{C}_{(A)} + V_O \cdot \bar{C}_{(O)} \qquad \ldots\ \underline{1}$$

where:

$M_{(solute)}$ = Solute content in the column (grams)

V_A = Total volume of the aqueous phase within the column (liters),

V_O = Total volume of the organic phase within the column (liters),

$\bar{C}_{(A)}$ = The average solute concentration in the aqueous phase (grams/liter),

$\bar{C}_{(O)}$ = The average solute concentration in the organic phase (grams/liter).

The second method (Concentration Profile-Holdup) is more complex and time consuming than the previous one, but it provides for determination of the effect of mass-transfer and hydrodynamic variables on the solute inventory during operation. The holdup measurement is described in Section 3.2.2, and the measurement of concentration profiles is described in Section 3.2.3. The solute inventory in an operating pulse column may be calculated as follows:

(1) Single Process Column (Stripping)

With reference to Figure 3-4, the solute's content within the column can be determined from the equation:

$$\begin{aligned} M_{(solute)} &= V_1 \cdot C_{(O)_1} \\ &+ V_2 \cdot \left[\bar{C}_{(A)_2} + X_d \cdot \left(\frac{D_c}{D_s}\right)^2 \left(\bar{C}_{(O)_2} - \bar{C}_{(A)_2}\right)\right] \\ &+ V_3 \cdot \left[\bar{C}_{(A)} + X_d \cdot \left(\bar{C}_{(O)} - \bar{C}_{(A)}\right)\right] \\ &= V_4 \cdot C_{(A)_4} \qquad \ldots\ \underline{2} \end{aligned}$$

where:

$M_{(solute)}$ = total solute content within the column (grams),

V_1 to V_4 = Column sectional volumes (liters); see Figure 3-4,

$C_{(A)}$ = Solute concentration in the aqueous phase (grams/liter),

$C_{(0)}$ = Solute concentration in the organic phase (grams/liter),

$\overline{C}_{(A)}$, $\overline{C}_{(0)}$ = Solute average concentrations within the column working section (grams/liter),

X_d = Dispersed phase (organic phase) holdup (number),

D_c = Diameter of the column working section (cm),

D_s = Diameter of the column disengaging section (cm).

(2) Dual Process Column: (Extraction and Scrubbing)

Solute's content within the dual process column shown in Figure 3-5 can be determined by use of the equation:

$$\begin{aligned} M(\text{solute}) = {} & V_1 \cdot C_{(A)_1} \\ & + V_2 \left[\overline{C}_{(0)_2} + X_{d_E} \cdot \left(\frac{D_c}{D_s}\right)^2 \cdot \left(\overline{C}_{(A)_2} - \overline{C}_{(0)_2}\right)\right] \\ & + V_3 \left[\overline{C}_{(0)_E} + X_{d_E} \cdot \left(\overline{C}_{(A)_E} - \overline{C}_{(0)_E}\right)\right] \\ & + V_4 \left[\overline{C}_{(0)_S} + X_{d_S} \cdot \left(\overline{C}_{(A)_S} - \overline{C}_{(0)_S}\right)\right] \\ & + V_5 \cdot C_{(0)_5} \qquad \ldots. \ \underline{3} \end{aligned}$$

In this equation:

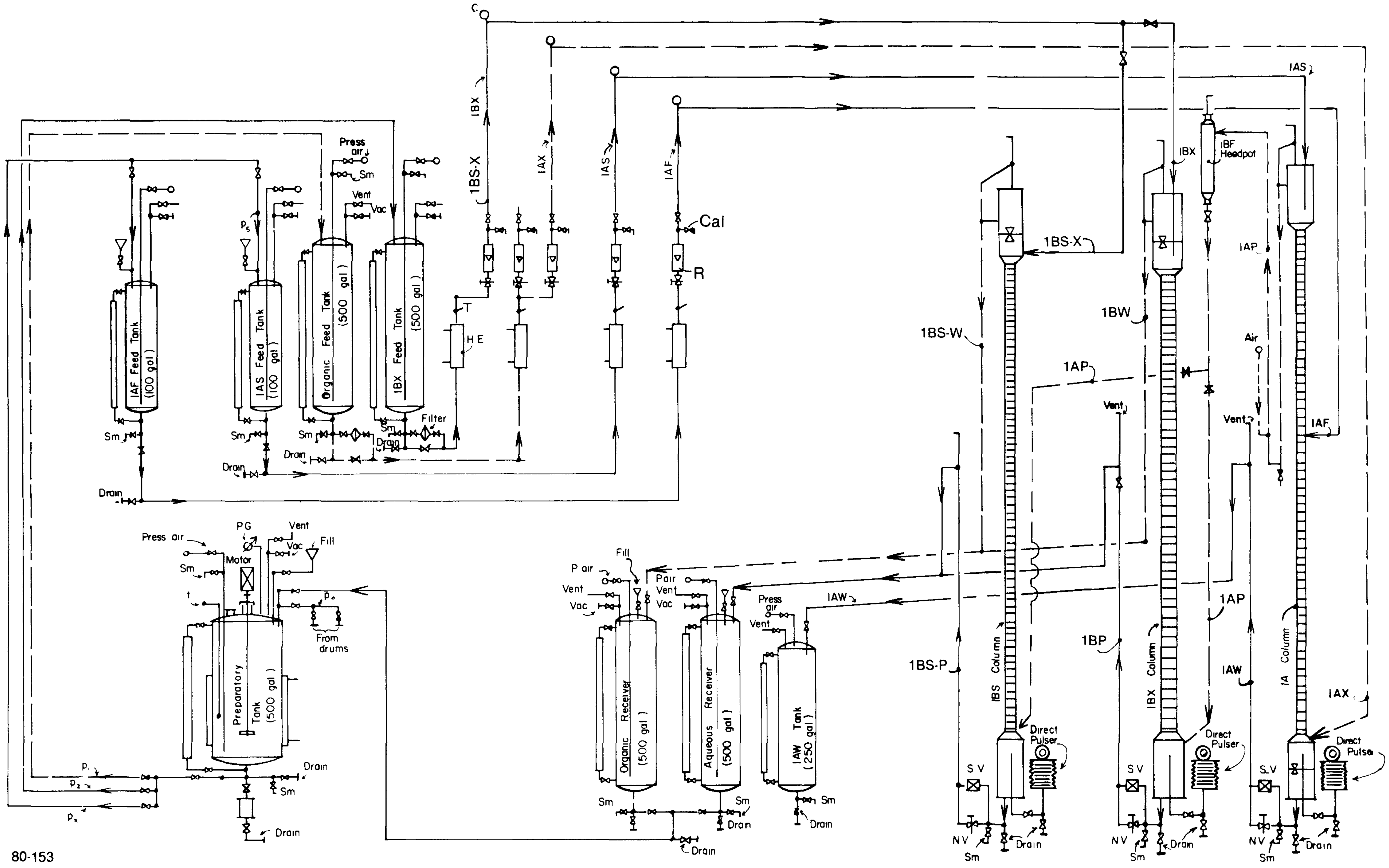
V_1 to V_5 = Column sectional volumes, (liters); see Figure 3-5

Index S = Scrubbing section

Index E = Extraction section

Each of the three equations above was used for determining the uranium inventory in each column during tests. Test data are summarized in Table 4-28 and discussed in Section 4.4.

A promising computer program,(1, 2, 7) based on the pulsed column model considering the continuous phase axial mixing (back-mixing) within the contactor, is being developed by L. E. Burkhart. After completion, this program should provide near real-time determination of uranium and plutonium concentration profiles and their inventory in the column. Experimental concentration profiles, as well as holdup data from our pilot-plant runs, are being used by L. E. Burkhart for verification of the computer code.

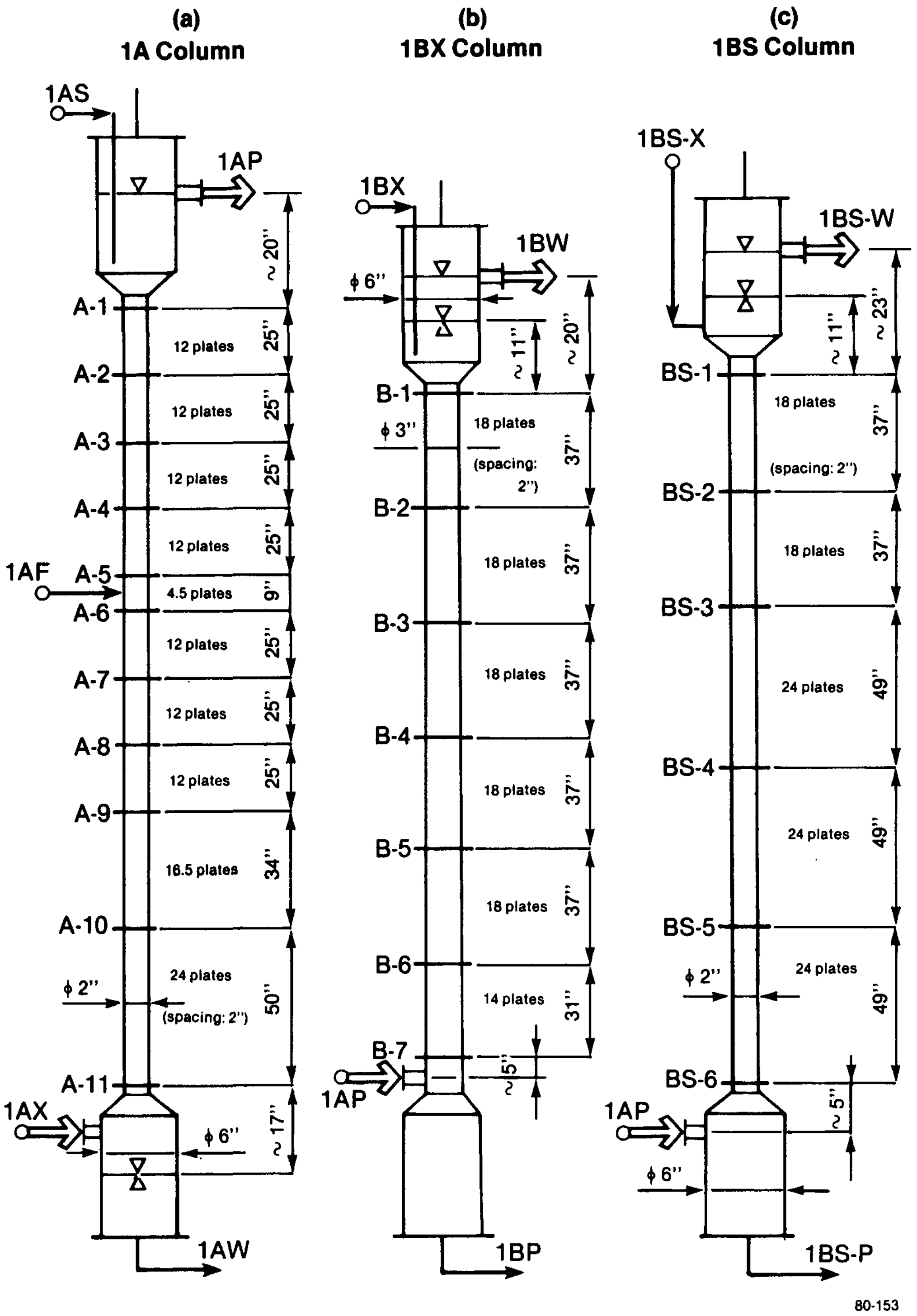


LEGEND

SM	- Sampling
P.G.	- Pressure Gage
P. Air	- Pressurized Air
H.E.	- Heat Exchanger
R	- Rotameter
Cal	- Calibration
S.V.	- Solenoid Valve
N.V.	- Needle Valve
T	- Temperature
C	- Surge Pot
⧖	- Interface Control

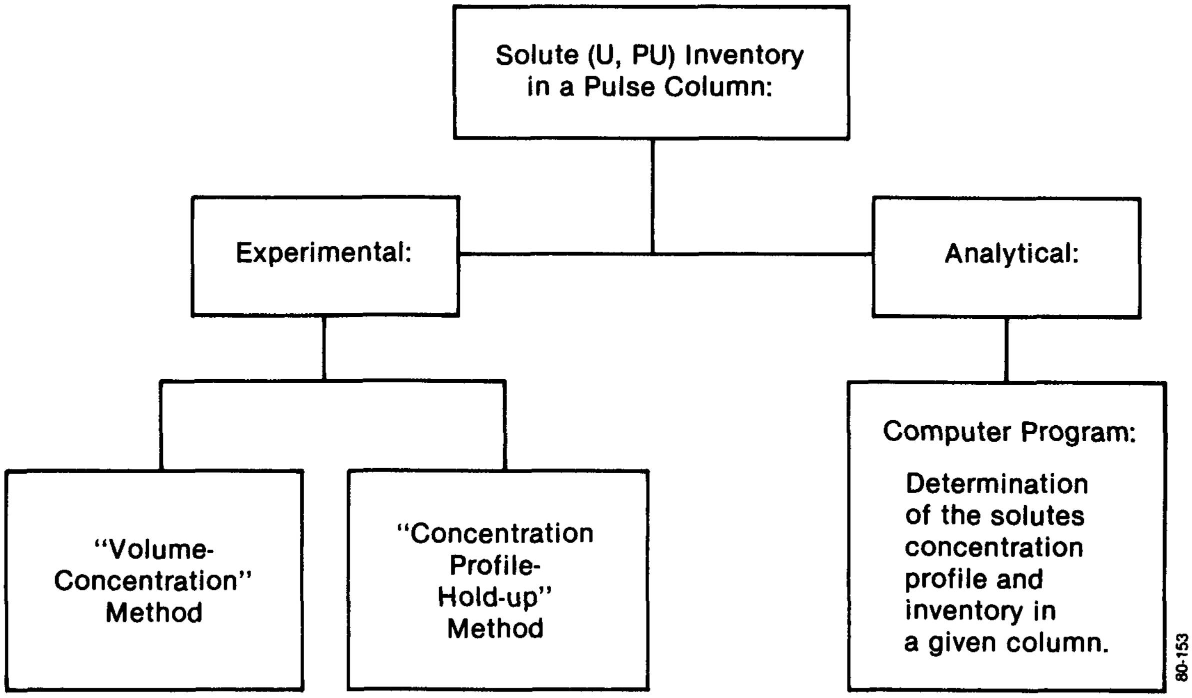
FLOW DIAGRAM

FIGURE 3-1



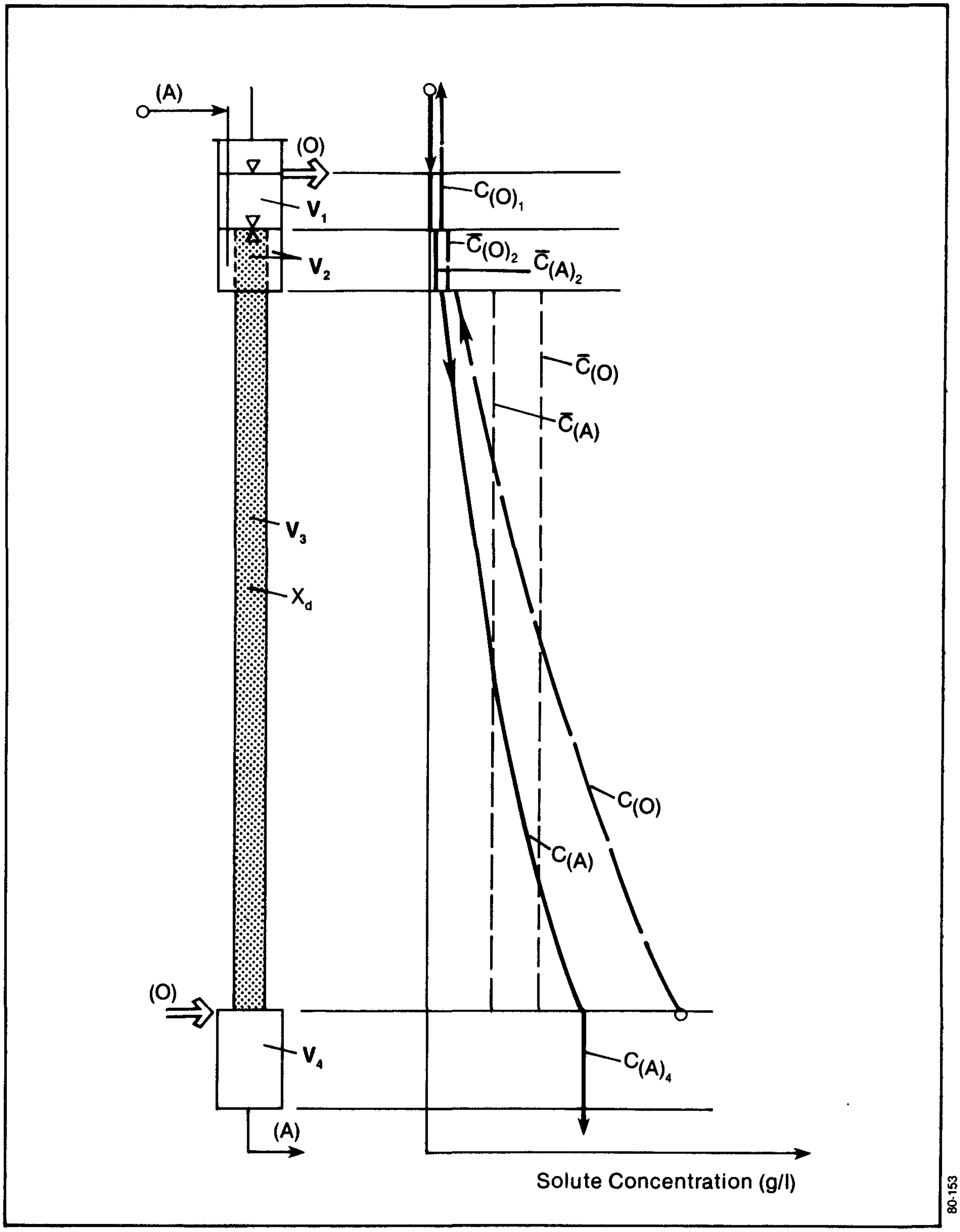
SAMPLERS LOCATION AT THE 1A, 1BX, AND 1BS COLUMNS

FIGURE 3-2



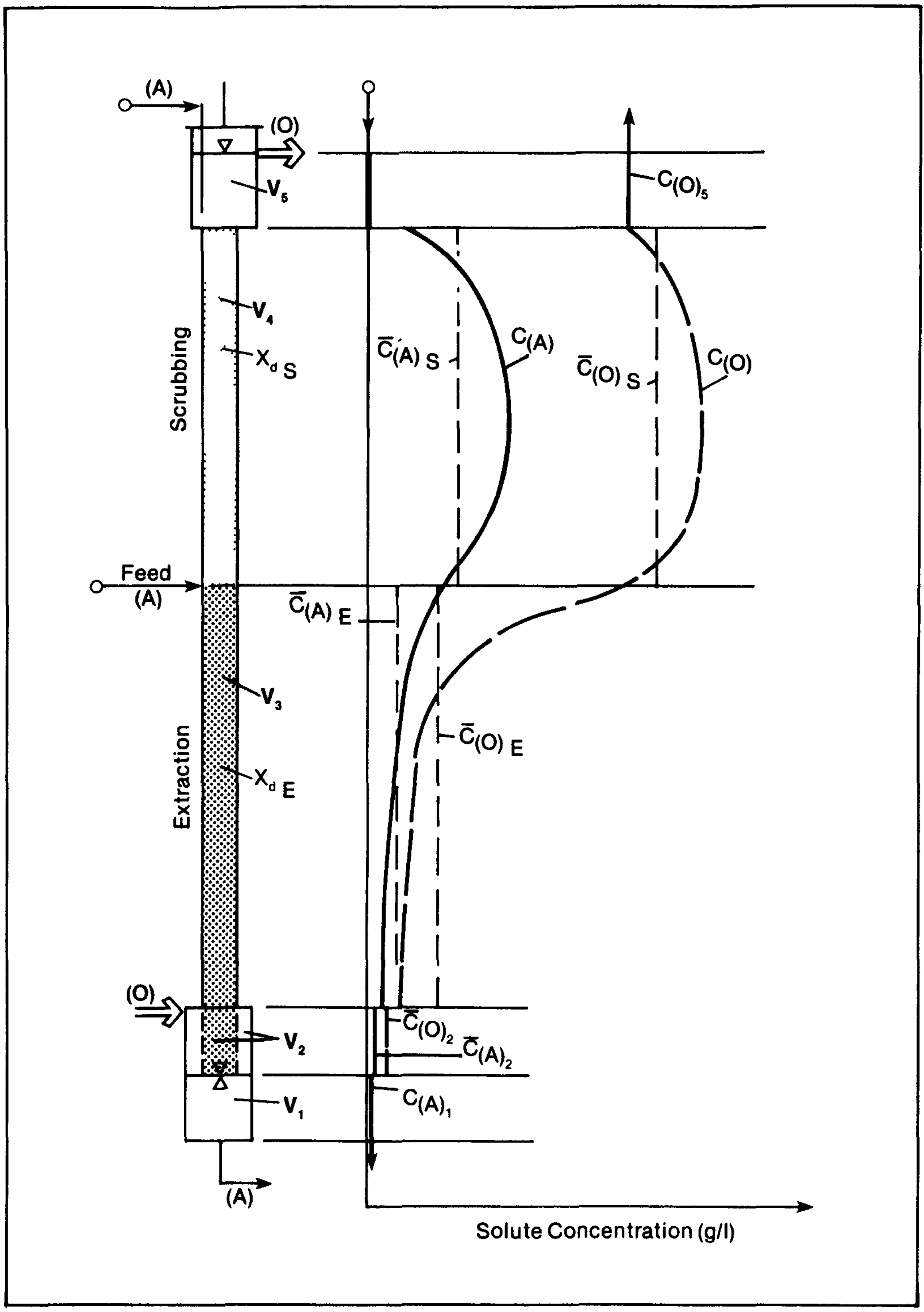
SOLUTES INVENTORY DETERMINATION IN A PULSED COLUMN

FIGURE 3-3



SOLUTE CONCENTRATION ALONG THE SINGLE PROCESS (STRIPPING) COLUMN

FIGURE 3-4



SOLUTE CONCENTRATION ALONG THE
DUAL PROCESS (EXTRACTION-SCRUBBING) COLUMN

FIGURE 3-5

4.0 RESULTS AND DISCUSSION

4.1 Column Capacity

The highest operational capacity of a pulse column is generally estimated from the corresponding flooding curve. Flooding tests performed on the 1A, 1BX, and 1BS columns resulted in curves shown in Figures 4-1 through 4-6.

Flooding curves for the 1A and 1BX column with 15 v/o TBP as the organic phase are shown in Figure 4-1. The estimated maximum operational total liquid velocity (U_{tot}) of the 1BX stripping column is 1.2 centimeters/second while that of the 1A extraction column is 100% higher or 2.4 centimeters/second.

Pulse columns are generally designed to operate at approximately 25-to 30% below the estimated highest total linear liquid velocity (U_{tot}). In our case, the operational liquid velocities (which have to be considered for the columns design) are as follows:

The 1A column: $U_{A_{(op)}} = 0.7 \times 2.4 = \underline{1.8}$ centimeters/second

The 1BX column: $U_{B_{(op)}} = 0.7 \times 1.2 = \underline{0.9}$ centimeters/second

By knowing the total required liquid flow rate of a column (from flowsheet) and the corresponding operational liquid velocity, the column cross-sectional area and diameter can be calculated. The recommended operational velocity can be used also for estimation of the existing column operational capacity (total liquid flow rate or throughput). For example, the 1A column of a diameter of D = 30 centimeters, operating with the organic phase continuous (15 v/o TBP), will have a capacity of:

$$V_{tot} = 0.785\ D_c^2 \times U_{A_{(op)}} = 0.785 \times (30)^2 \times 1.8$$

$$\approx 1270 \text{ milliliters/second} \approx 4570 \text{ liters/hour}$$

Flooding curves in Figures 4-2 to 4-4 were evaluated in this manner. Resultant data, which include both the maximum and recommended operational liquid velocities, are summarized in Table 4-1. This table shows that the above velocities are of about 40 to 50% higher when extraction is performed with 15 v/o TBP than with 30 v/o TBP. On the other hand, the operational velocities for stripping with 15 v/o TBP would be approximately 10 to 15% lower than with 30 v/o TBP. This may also be surmised from diagrams in Figures 4-5 and 4-6 where flooding curves for both 15 v/o and 30 v/o TBP are compared.

Mass-transfer tests with 15 v/o TBP (Runs HS-1 to HS-3) fixed a limit for the aqueous solution (HSF) feed rate to the dual process column (extraction-scrubbing) at constant solvent (HSX) and scrubbing stream (HSS) flow rates. See run conditions and data in Table 4-4. The column was found to flood from the HSF feed point onwards when the HSF feed rate was increased above 185 milliliters/minute. This is probably due to the local increase in the dispersed phase holdup caused by local density changes. Further investigation would be required to confirm this, however.

Flow rate ratios resulting from data in Table 4-4 (Run HS-1), considered optimal for runs with 15 v/o TBP, are as follows:

Scrubbing section: $\text{HSX/HSS} \approx 13.0$

Extraction section: $\text{HSX/HSF} \approx 6.3$

and $\text{HSX/HSF} + \text{HSS} \approx 4.3$

During these experiments, when HSX/HSF and HSX/HSF + HSS ratios dropped below 5.6 and 4.0, respectively, the column flooded. See Figures 4-43 and 4-44 for details.

Data for runs with 30 v/o TBP as the organic phase are shown in Table 4-5. The HS dual process column flooded when the HSF feed rate was increased above 370 to 375 milliliters/minute. Flow rate ratios for Run HS-5 in Table 4-5, considered optimal with 30 v/o TBP, are as follows:

Scrubbing section: $\text{HSX/HSS} \approx 7$

Extraction section: $\text{HSX/HSF} \approx 3.2$

and $\text{HSX/HSF} + \text{HSS} \approx 2.2$

When HSX/HSF and HSX/HSF + HSS ratios dropped below 2.8 and 2, respectively, the column became flooded (see Figures 4-45 and 4-46). Again, further studies would be required to establish the cause of this phenomenon.

A similar observation was made at the 2D column operating with 2DS and 2DF flows as indicated in Table 4-6. When 2DX organic flow was reduced to about 850 to 860 milliliter/minute (2DX/2DF ratio reduced to about 2.75), the column was flooded starting from the 2DF feed inlet.

4.2 Dispersed Phase Holdup

Experimental run conditions, test data from holdup tests, and mass-transfer tests are described in Section 3.2.2 and summarized in Tables 4-2 and 4-3. The 91 dispersed phase holdup (X_d) values in the tables were determined by volumetric measurements. Forty-four of these X_d values were checked by calculations based on weight recorder charts. Data in the tables show that the volumetric and weight recorder X_d values correlate well within the tested range. The X_d was found to increase with an increase in the ratio of the dispersed to continuous phase flow rate. At a constant ratio, it was also found to increase with an increase in the total flow rate. These data are shown in Tables 4-2 and 4-3.

Experimental holdup data in both tables were mathematically analyzed and correlated. The diagram in Figure 4-7 shows a high dependence of the X_d value on the expression $2fA_o + \Delta U_{d-c}$, which can be taken as twice the pulse velocity in the direction of the dispersed phase flow. Theoretically, the pulse amplitude at upstroke equals the pulse amplitude at downstroke, only at a flow ratio of O/A = 1. At a ratio of O/A $\neq$ 1, the upstroke amplitude will be different from that of the downstroke. Consequently, the upstroke pulse velocity will be different than the downstroke velocity in the column.

Liquid velocity difference ΔU_{d-c} in the above expression takes into account the effect of the flow rate, as well as of the flow rate ratio on the X_d.

The velocity difference

$$\Delta U_{d-c} = U_d - U_c$$

can be rewritten in the form

$$\Delta U_{d-c} = U_d \left(1 - \frac{1}{P_{d/c}}\right) \qquad \ldots\ \underline{4}$$

where:

U_d = dispersed phase linear velocity (centimeters/second)

U_c = continuous phase linear velocity (centimeters/second)

and $P_{d/c} = Ud/Uc$ ($\equiv Ld/Lc$); dispersed to continuous phase flow ratio.

Equation (4) indicates that an increase in either velocity U_d, or ratio $P_{d/c}$, or both will increase the velocity difference ΔU_{d-c}, and consequently, will increase the dispersed phase holdup (X_d) value.

Based on all experimental data in Tables 4-2 and 4-3, an empirical equation was derived in the form

$$X_d \approx 0.185\ (2fA_o + \Delta U_{d-c})^{2.8} \qquad \ldots\ \underline{5}$$

which describes the effect of the pulse velocity in the direction of the dispersed phase flow on the X_d within the experimental range.

where:

X_d = dispersed phase holdup (%),

f = pulse frequency (1/second),

A_o = pulse amplitude (centimeter), and

ΔU_{d-c} = $U_d - U_c$, i.e., the difference between the dispersed and continuous phase linear velocities (centimeter/second).

Figure 4-8 shows graphically the relationship between the dispersed phase holdup (X_d) and function $(2fA_o + \Delta U_{d-c})^{2.8}$. Statistical analysis indicates the following uncertainties about the fixed line in this figure (Appendix B):

±9% at the low end of the data,
±5.5% at the middle, and
±13.3% at the high end.

This equation applies to the experimental run conditions and ranges shown in Tables 4-2 and 4-3.

4.3 Concentration Profile

Uranium and nitric acid concentrations along the pulse column were determined through sampling as described in Section 3.2.3. This method was also used for the test runs shown in Tables 4-4 through 4-8. Actual concentration profile data for each run are summarized in Tables 4-9 through 4-23 and Figures 4-9 through 4-38.

Uranium concentration profiles for the HS-1, HS-2, and HS-3 runs are shown in Figures 4-9 through 4-14. During these runs, only the HSF aqueous solution feed rate was changed as indicated in Table 4-4. Other feed rates were held constant.

Under operating conditions shown in Table 4-4, the HS column was always flooded when the HSX to HSF ratio was below 5.6 to 5.7. The flooding began locally at the HSF feed inlet. Uranium concentration in both the organic (15 v/o TBP) and aqueous phase around the HSF feed point increased with any decrease in the HSX/HSF ratio, up to the above flooding ratio value. This observation is shown graphically in Figure 4-43. The extrapolated "organic" curve in the figure indicates that the organic phase was about saturated with uranium at flooding (about 55 to 60 grams uranium/liter).

Uranium concentration profiles for the HS-4, HS-5, and HS-6 runs are shown in Figures 4-15 through 4-20, and Tables 4-12 through 4-14. During these runs, the HSF aqueous solution flow rate was changed while the other two feed rates (HSX and HSS) were held constant, as noted in Table 4-5.

Uranium concentration in the organic, as well as in the aqueous phase around the HSF feed inlet, increased with a decrease in the HSX/HSF ratio up to an extrapolated value of about 2.7 to 2.8. At that ratio, saturation of the organic phase with uranium was found to occur at the HSF feed point causing column flooding, again starting around the feed inlet, as was observed during the above runs with 15 v/o TBP. See Figure 4-45 for details. The flooding was also demonstrated during two (of three) additional tests performed for the determination of transient conditions in the HS column.

Uranium concentration profiles for the 2D-2E, 2A-2B, and 3A-3B experimental runs are shown in Tables 4-15 through 4-23, and Figures 4-21 through 4-38.

Changes in transient uranium concentration were determined between the following two subsequent runs: HS-4 and HS-5, 2D-1 and 2D-2, 2A-1 and 2A-2, and 3A-1 and 3A-2. During transient tests, when the operational steady-state of the initial run (e.g., HS-4) was reached, flow conditions of the subsequent run (e.g., HS-5) were adjusted. Then samples of both the continuous and dispersed phase were drawn along the dual process column at samplers A-4 through A-7 in 5, 20, and 35 minutes after the above flow adjustment. When the column operated under steady-state conditions for the subsequent run (in 100 to 120 minutes) the last set of samples was taken. Resultant data are shown in Tables 4-24 through 4-27 and Figures 4-39 through 4-42. Figure 4-39 includes transient concentration curve of the HSF feed inlet computed by SEPHIS program (assuming theoretically a settling volume of 5% in each "stage" of the column).

Concentration profiles obtained experimentally of runs HS-1, HS-6, and 2D-1 were compared with those computed by the SEPHIS(3) code. For the SEPHIS calculations, the number of stages for the program was obtained from the column operating diagram (Figures 4-47, 4-49, and 4-51). The same feed concentration and flow conditions were considered as in the experimental runs. Comparison of the experimental concentration profile for runs HS-1, HS-6, and 2D-1 with that obtained from SEPHIS program is shown in Figures 4-48, 4-50, and 4-52, respectively.

4.4 Uranium Inventory in Pulsed Columns

The uranium inventory i.e., its holdup within the pulse column operating under steady-state conditions, was calculated as described in Section 3.2.4. The "Concentration Profile-Holdup" method for inventory determination was applied for each test. In several cases, the inventory determination was verified by use of the "Volume-Concentration Measurement" method. Data obtained by the two methods are summarized in Table 4-28 and in Figure 4-53.

Test results indicate that for any column, the uranium inventory is a direct function of the rate of uranium entry into the column and an inverse function of the flow rate of the stripping stream. The rate of entry for uranium is in turn a function of both the flow rate and concentration of the feed solution. Test data confirm that the uranium holdup (inventory) in the column increases with an increase in both the feed solution to stripping solvent flow ratio and uranium concentration in the feed solution. This can be explained by the following analytical evaluation of the solute's inventory in pulse columns:

(1) Dual Process Column for Extraction and Scrubbing (Figure 3-5)

Considered parameters and variables:

M = solute's inventory (grams),
V = volume (liters),
v = flow rate (liters/minute),
$\bar{C}$ = average solute concentration (grams/liter),
C = solute concentration (grams/liter),
X_d = dispersed phase holdup,
K = coefficients,
O = organic phase,
A = aqueous phase,
E = extraction,
S = scrubbing,
St = stripping
f = feed

Solute inventory in the column scrubbing section is

$$M_S = V_S \cdot (1 - X_d) \cdot \bar{C}_{(O)_S} + V_S \cdot X_{d_S} \cdot \bar{C}(A)_S$$

$$= V_S \cdot \left[\bar{C}_{(O)_S} + X_{d_S} \cdot \left(\bar{C}_{(A)_S} - \bar{C}_{(O)_S}\right)\right] \qquad \ldots.\ \underline{6}$$

Assuming that the average concentrations can be expressed as

$$\bar{C}_{(O)_S} = K_{1S} \cdot \frac{v_f \cdot C_f}{v_{(O)}} = K_{1S} \cdot \frac{v_f \cdot C_f}{v_{St}}$$

and $$\bar{C}_{(A)_S} = K_{2S} \cdot \frac{v_f \cdot C_f}{v_S}$$

where K_{1S} and K_{2S} are coefficients <1.0, the above equation will have the form

$$M_S = \left[K_{1S} + X_{d_S}\left(K_{2S} \cdot \frac{v_{St}}{v_S} - K_{1S}\right)\right] \cdot V_S \cdot \frac{v_f \cdot C_f}{v_{St}} \qquad \ldots.\ \underline{7}$$

The value of the expression

$$X_{d_S} \cdot \left(K_{2S} \cdot \frac{v_{(St)}}{v_S} - K_{1S}\right)$$

is very small in comparison to K_{1S} due to the dispersed phase hold up (X_{d_S}) which varies within a range of about 5 to 15% in the column scrubbing section. Under given flow and operating conditions the expression in brackets can be considered constant; therefore, the above equation can be rewritten in the form:

$$M_S = K_S \cdot V_S \cdot \frac{v_f \cdot C_f}{v_{St}} \qquad \ldots .\ \underline{8}$$

Analogously, the equation which applies to the column extraction section will be:

$$M_E = \left[K_{1E} + X_{d_E} \cdot \left(K_{2E} \frac{v_{(St)}}{v_f \cdot v_S} + K_{1E}\right)\right] \cdot V_{col} \cdot \frac{v_f \cdot C_f}{v_{St}}$$

$$= K_E \cdot V_{col} \cdot \frac{v_f \cdot C_f}{v_{St}} \qquad \ldots .\ \underline{9}$$

The total solute inventory in a dual process column is:

$$M_{(S,E)} = M_S + M_E$$

$$= \left(K_S \cdot V_S + K_E \cdot V_E\right) \cdot \frac{v_f \cdot C_f}{v_{St}} \qquad \ldots .\ \underline{10}$$

Considering the column volume:

$V_{col} = V_S + V_E$

and volume ratio:

$P_v = V_e/V_{col}$

The equation (10) obtains the form

$$M_{(S,E)} = \left[K_S(1 - P_V) + K_E \cdot P_V\right] \cdot V_{col} \cdot \frac{v_f \cdot C_f}{v_{St}}$$

$$= K_{S,E} \cdot V_{col} \cdot \frac{v_f \cdot C_f}{v_{St}} \qquad \ldots .\ \underline{11}$$

Theoretically, coefficients K_S, K_E, and $K_{S,E}$ are expected to be affected by operating and flow conditions in the respective column sections. The volume ratio (P_V) is given by the column design.

(2) Stripping Column (Figure 3-4)

Solute inventory can be expressed as:

$$M_{St} = V_{col} \cdot \left(1 - X_d\right) \cdot \overline{C}(A)_{St} + V_{col} \cdot X_{dSt} \cdot \overline{C}(O)_{St}$$

$$= V_{col} \cdot \left[\overline{C}(A)_{St} + X_d \cdot \left(\overline{C}(O)_{St} - \overline{C}(A)_{St}\right)\right] \quad \ldots\ldots \underline{12}$$

Assuming:

$$\overline{C}(A)_{St} = K_{1St} \cdot \frac{v_f \cdot C_f}{v_{St}}$$

and

$$\overline{C}(O)_{St} = K_{1St} \cdot \frac{v_f \cdot C_f}{v_f} = K_{2St} \cdot C_f,$$

then the equation (12) can be written in the form

$$M_{St} = \left[K_{1St} + X_d \left(K_{2St} \cdot \frac{v_f}{v_{St}} - K_{1St}\right)\right] \cdot V_{col} \cdot \frac{v_f \cdot C_f}{v_{St}}$$

$$= K_{St} \cdot V_{col} \cdot \frac{v_f \cdot C_f}{v_{St}} \quad \ldots\ldots \underline{13}$$

Coefficient

$$K_{St} = K_{1St} + X_d \left(K_{2St} \cdot \frac{v_f}{v_{St}} - K_{1St}\right)$$

is theoretically affected by operating and flow conditions in the column.

Derived Equations 11 and 13 show the effect of both the solute's feed rate and stripping stream (solvent) flow rate on the inventory as was observed during tests.

From the test results plotted in Figure 4-53 and shown in Table 4-28, empirical equations were derived from determination of the uranium inventory within the tested pulsed columns. The equations apply to the experimental range of operating conditions as shown in Tables 4-4 through 4-8. The equations are as follows:

(a) The 1C, 2E, 2B and 3B Stripping Columns:

$$M_{(U)} \approx 0.45\ V_{(col)} \cdot \frac{v_f}{v_{St}} \cdot C_{(U)_f} \qquad \pm 10\% \qquad \ldots.\ \underline{14}$$

The equation applies to the range of

$$\frac{v_f}{v_{St}} \cdot C_{(U)_f} = 30 \text{ to } 100 \text{ grams U/liter}$$

and stripping stream acidity of up to $0.3\underline{M}$ HNO_3.

(b) The HS Dual Column:

$$M_{(U)} \approx 0.44\ V_{(col)} \cdot \frac{v_f}{v_{St}} \cdot C_{(U)_f} \qquad \pm 4\% \qquad \ldots.\ \underline{15}$$

The equation applies to the range of

$$\frac{v_f}{v_{St}} \cdot C_{(U)_f} = 30 \text{ to } 95 \text{ grams U/liter}$$

and HSS scrubbing stream acidity of about $3.0\ \underline{M}$ HNO_3.

(c) The 2D Dual Column:

$$M_{(U)} \approx 1.26\ V_{(col)} \cdot \left(\frac{v_f}{v_{St}} \cdot C_{(U)_f} - 50\right) \qquad \pm 4\% \qquad \ldots.\ \underline{16}$$

The equation applies to the range of

$$\frac{v_f}{v_{St}} \cdot C_{(U)_f} = 75 \text{ to } 95 \text{ grams U/liter}$$

and 2DS scrubbing stream acidity of up to $0.01\underline{M}$ HNO_3.

(d) The 2A and 3A Dual Columns:

$$M_{(U)} \approx 0.84\ V_{(col)} \cdot \left(\frac{v_f}{v_{St}} \cdot C_{(U)_f} - 30\right) \qquad \pm 5\% \qquad \ldots.\ \underline{17}$$

The equation applies to the range of

$$\frac{v_f}{v_{St}} \cdot C_{(U)_f} = 55 \text{ to } 85 \text{ grams U/liter}$$

and scrubbing stream acidity of about $1.0\ \underline{M}$ HNO_3.

In these equations

$M_{(U)}$ = Uranium inventory in the column (grams)

$V_{(col)}$ = Column total liquid volume (liters)

v_f = Feed flow rate (liters/minute)

v_{St} = Stripping stream flow rate (liters/minute)

$C_{(U)_f}$ = Uranium concentration in the feeed stream (grams U/liter).

The above uncertainties of each equation indicate the difference between the calculated and measured value.

TABLE 4-1

OPERATIONAL LIQUID VELOCITY DATA

ORGANIC PHASE:	PROCESS:	CONTINUOUS PHASE:	TOTAL OPERATIONAL LIQUID VELOCITY: Maximum: U_{tot} (cm/sec)	TOTAL OPERATIONAL LIQUID VELOCITY: Recommended: $U_{(op)}$ (cm/sec)	FIGURES:
15 v/o TBP	Extraction	Organic	~2.4	~1.8	4-1
15 v/o TBP	Stripping	Aqueous	1.2	0.9	4-1
30 v/o TBP	Extraction	Organic	1.7	1.2	4-2
30 v/o TBP	Stripping	Aqueous	1.4	1.0	4-3 4-4

TABLE 4-2

DISPERSED PHASE HOLDUP DATA FOR SYSTEM 15 v/o TBP - 0.1 $\underline{M}$ HNO_3

Test No:	Dispersed Pulse:	Column Diameter: (cm)	Organic Flow Rate: L_O (ml/min)	Aqueous Flow Rate: L_A (ml/min)	Ratio L_O/L_A	Pulse Frequency: f (1/sec)	Pulse Amplitude: A_O (cm)	Dispersed Phase Holdup $\underline{X_d}$ (%):		
								Experimental (Volumetric Measurement)	Experimental: (Weight Recorder)	Calculated (Equation)
1	A	5.0	1250	500	2.5	1.25	2.0	~12.0	~13.0	11.3
2	A		500	1250	0.4	1.25	2.0	21.7	24.0	23.6
3	A		600	600	1.0	0.92	2.0	8.0	--	7.1
4	A		600	600	1.0	1.27	2.0	18.0	--	17.5
5	A		600	600	1.0	1.59	2.0	33.0	--	32.8
6	A		155	1545	0.1	1.00	2.0	19.6	--	18.3
7	A		600	300	2.0	1.42	1.6	11.0	--	10.9
8	A		300	600	0.5	1.42	1.6	14.8	--	15.0
9	A		120	600	0.2	1.42	1.6	16.0	--	16.4
10	A		600	120	5.0	1.42	1.6	7.7	--	9.8
11	A		160	600	0.3	1.42	1.8	22.0	--	21.8
12	A		600	150	4.0	1.42	2.0	19.1	--	19.6
13	0	5.0	600	600	1.0	1.27	2.0	17.9	--	17.5
14	0		800	400	2.0	1.27	2.0	21.4	--	21.0
15	0		400	800	0.5	1.27	2.0	12.6	--	14.3

TABLE 4-2 (CONTINUED)

DISPERSED PHASE HOLDUP DATA FOR SYSTEM 15 v/o TBP - 0.1 M HNO_3

Test No:	Dispersed Phase:	Column Diameter: (cm)	Organic Flow Rate: L_O (ml/min)	Aqueous Flow Rate: L_A (ml/min)	Ratio L_O/L_A	Pulse Frequency: f (1/sec)	Pulse Amplitude: A_O (cm)	Dispersed Phase Holdup X_d (%): Experimental (Volumetric Measurement)	Dispersed Phase Holdup X_d (%): Experimental: (Weight Recorder)	Dispersed Phase Holdup X_d (%): Calculated (Equation)
16	O	7.5	900	900	1.0	1.25	2.0	~17.6	--	16.7
17	O		450	900	0.5	1.25	2.0	13.1	--	15.2
18	O		900	450	2.0	1.25	2.0	17.3	--	18.4
19	O		200	1300	0.15	1.20	2.0	9.0	10.5	11.6
20	O		375	1125	0.33	1.20	2.0	11.6	12.0	12.6
21	O		750	750	1.0	1.20	2.0	14.2	15.5	14.9
22	O		1125	375	3.0	1.20	2.0	17.9	18.6	17.5
23	O		1300	200	6.5	1.20	2.0	20.5	20.0	18.9
24*	O		1050	1300	0.8	0.97	2.0	10.0	8.8	7.7
25**	O		1050	1300	0.8	0.97	2.0	9.2	8.8	7.7

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*Test HS-1

**Tests Hs-2, and HS-3

TABLE 4-3

DISPERSED PHASE HOLDUP DATA FOR SYSTEM 30 v/o TBP - 0.1 M HNO_3

Test No:	Dispersed Phase:	Column Diameter: (cm)	Organic Flow Rate: L_O (ml/min)	Aqueous Flow Rate: L_A (ml/min)	Ratio L_O/L_A	Pulse Frequency: f (1/sec)	Pulse Amplitude: A_O (cm)	Dispersed Phase Holdup X_d (%):		
								Experimental (Volumetric Measurement)	Experimental: (Weight Recorder)	Calculated (Equation)
1	A	5.0	800	800	1.0	1.2	2.0	~16.1	15.0	15.0
2	A		800	400	2.0	1.2	2.0	10.3	11.5	12.1
3	A		800	200	4.0	1.2	2.0	7.6	8.0	10.8
4	A		800	400	2.0	1.2	2.0	10.6	11.5	12.1
5	A		800	800	1.0	1.2	2.0	16.4	15.0	15.0
6	A		400	800	0.5	1.2	2.0	16.0	14.5	18.1
7	A		200	800	0.25	1.2	2.0	17.2	13.5	19.9
8	A		400	800	0.5	1.2	2.0	16.5	14.5	18.1
9	A		800	800	1.0	1.2	2.0	15.7	15.0	15.0
10	A		800	800	1.0	1.2	2.0	16.6	--	16.7
11	A		200	1300	0.15	1.2	2.0	22.6	--	24.8
12	A		375	1125	0.33	1.2	2.0	18.4	--	21.3
13	A		750	750	1.0	1.2	2.0	14.9	--	15.0
14	A		1125	375	3.0	1.2	2.0	9.8	--	9.9
15	A		1300	200	6.5	1.2	2.0	6.7	--	8.0

TABLE 4-3 (CONTINUED)

DISPERSED PHASE HOLDUP DATA FOR SYSTEM 30 v/o TBP - 0.1 M HNO_3

Test No:	Dispersed Phase:	Column Diameter: (cm)	Organic Flow Rate: L_O (ml/min)	Aqueous Flow Rate: L_A (ml/min)	Ratio L_O/L_A	Pulse Frequency: f (1/sec)	Pulse Amplitude: A_O (cm)	Dispersed Phase Holdup X_d (%): Experimental (Volumetric Measurement)	Experimental: (Weight Recorder)	Calculated (Equation)
16	A	5.0	250	1625	0.15	1.2	2.0	~27.1	26.0	27.8
17	A		470	1405	0.33	1.2	2.0	22.4	22.0	23.1
18	A		937	937	1.0	1.2	2.0	16.1	16.0	15.0
19	A		1405	470	3.0	1.2	2.0	9.7	10.5	8.9
20	A		1625	250	6.5	1.2	2.0	7.4	8.0	6.7
21	A		300	1950	0.15	1.25	2.0	38.0	--	33.9
22	A		560	1690	0.33	1.25	2.0	27.6	--	27.7
23	A		1125	1125	1.0	1.25	2.0	20.6	--	16.8
24	A		1690	560	3.0	1.25	2.0	9.0	--	9.0
25	A		1950	300	6.5	1.25	2.0	8.2	--	6.5
26	O	7.5	200	1300	0.15	1.20	2.0	9.7	10.0	11.6
27	O		375	1125	0.33	1.20	2.0	12.3	13.5	12.6
28	O		750	750	1.0	1.20	2.0	14.9	15.5	15.0
29	O		1125	375	3.0	1.20	2.0	18.0	--	17.6
30	O		1300	200	6.5	1.20	2.0	12.0	--	10.4

TABLE 4-3 (CONTINUED)

DISPERSED PHASE HOLDUP DATA FOR SYSTEM 30 v/o TBP - 0.1 M HNO_3

Test No:	Dispersed Phase:	Column Diameter: (cm)	Organic Flow Rate: L_O (ml/min)	Aqueous Flow Rate: L_A (ml/min)	Ratio L_O/L_A	Pulse Frequency: f (1/sec)	Pulse Amplitude: A_O (cm)	Dispersed Phase Holdup X_d (%):		
								Experimental (Volumetric Measurement)	Experimental: (Weight Recorder)	Calculated (Equation)
31	O	7.5	250	1625	0.15	0.95	2.0	~4.5	--	5.1
32	O		470	1400	0.33	0.95	2.0	7.0	--	5.9
33	O		300	1950	0.15	0.95	2.0	4.8	--	4.7
34	O		800	800	1.0	0.95	2.0	9.6	--	7.8
35	O		400	800	0.5	0.95	2.0	7.3	--	6.9
36	O		200	800	0.25	0.95	2.0	5.8	--	6.5
37	O		400	800	0.5	0.95	2.0	7.0	--	6.9
38	O		800	800	1.0	0.95	2.0	9.0	--	7.8
39	O		1050	1300	0.8	0.97	2.0	8.2	--	7.6
40	O		800	800	1.0	0.95	2.0	9.1	9.8	7.8
41	O		800	400	2.0	0.95	2.0	8.6	8.0	8.7
42	O		800	200	4.0	0.95	2.0	7.1	6.5	9.1
43	O		800	400	2.0	0.95	2.0	8.7	8.0	8.7
44	O		800	800	1.0	0.95	2.0	8.9	9.8	7.8
45	O		400	800	0.5	0.95	2.0	6.8	7.3	6.9

TABLE 4-3 (CONTINUED)

DISPERSED PHASE HOLDUP DATA FOR SYSTEM 30 v/o TBP - 0.1 M HNO_3

Test No:	Dispersed Phase:	Column Diameter: (cm)	Organic Flow Rate: L_O (ml/min)	Aqueous Flow Rate: L_A (ml/min)	Ratio L_O/L_A	Pulse Frequency: f (1/sec)	Pulse Amplitude: A_O (cm)	Dispersed Phase Holdup X_d (%):		
								Experimental (Volumetric Measurement)	Experimental: (Weight Recorder)	Calculated (Equation)
46	0	7.5	200	800	0.25	0.95	2.0	~4.6	5.0	6.5
47	0		400	800	0.5	0.95	2.0	7.3	7.9	6.9
48	0		800	800	1.0	0.95	2.0	8.9	9.8	7.8
49	0	5.0	240	1560	0.15	1.00	2.0	4.0	--	3.5
50	0		1560	240	6.5	1.00	2.0	18.2	--	18.1
51	0		200	1300	0.15	1.00	2.0	4.3	--	4.2
52	0		1300	200	6.5	1.00	2.0	17.0	--	16.3
53	0		300	900	0.33	1.13	2.0	8.0	--	9.0
54	0		600	600	1.0	1.13	2.0	13.0	--	12.6
55	0		900	300	3.0	1.13	2.0	17.8	--	17.2
56	0		1040	160	6.5	1.13	2.0	20.0	--	19.7
57	0		160	1040	0.15	1.13	2.0	6.8	--	7.6
58	0		800	800	1.0	1.00	2.0	10.2	~12.0	9.0
59	0		800	400	2.0	1.00	2.0	10.0	9.1	10.1
60	0		800	200	4.0	1.00	2.0	9.2	8.7	12.6

TABLE 4-3 (CONTINUED)

DISPERSED PHASE HOLDUP DATA FOR SYSTEM 30 v/o TBP - 0.1 M HNO_3

Test No:	Dispersed Phase:	Column Diameter: (cm)	Organic Flow Rate: L_O (ml/min)	Aqueous Flow Rate: L_A (ml/min)	Ratio L_O/L_A	Pulse Frequency: f (1/sec)	Pulse Amplitude: A_0 (cm)	Dispersed Phase Holdup X_d (%):		
								Experimental (Volumetric Measurement)	Experimental: (Weight Recorder)	Calculated (Equation)
61	O	5.0	800	400	2.0	1.0	2.0	~9.8	9.5	10.1
62	O		800	800	1.0	1.0	2.0	10.1	12.0	9.0
63	O		400	800	0.5	1.0	2.0	8.0	7.5	7.9
64	O		200	800	0.25	1.0	2.0	4.6	5.0	6.0
65	O		400	800	0.5	1.0	2.0	8.3	7.5	7.9
66	O		800	800	1.0	1.0	2.0	10.2	12.0	9.0

TABLE 4-4

RUN CONDITIONS AND DATA
(Runs: HS-1, HS-2, and HS-3)

Column:	Stream:	Phase:	Concentration:		Flow Rate: (ml/min)		
			U (g/ℓ)	HNO$_3$ (M)	Run HS-1	Run HS-2	Run HS-3
HS Column	HSS (1AS)	A	0.0	2.97	80	80	80
	HSF (1AF)	A	273.3	2.44	165	145	130
	HSX (1AX)	A	0.0	0.0	1050	1050	1050
1C Column	1CX (1BX)	A	0.0	0.0	1300	1300	1300
HS Column	Pulse Frequency: (c/min)				83	83	83
	Pulse Amplitude: (cm)				2.0	2.0	2.0
	Dispersed Phase Holdup: (%)		Scrubbing		(~7.6)	(7.6)	(7.6)
			Extraction		(~11.9)	(11.4)	(10.9)
			Average (Scrub and Extract)		~10.2	9.8	9.6
1C Column	Pulse Frequency: (c/min)				57	57	57
	Pulse Amplitude: (cm)				2.0	2.0	2.0
	Dispersed Phase Holdup: (%)				~10.4	10.1	11.0
HS and 1C Column	Temperature: (°C)				~24	24	24

NOTE: Holdup data in parenthesis were calculated using equation 5.

TABLE 4-5

RUN CONDITIONS AND DATA
(Runs: HS-4, HS-5, and HS-6)

Column:	Stream:	Phase:	Concentration:		Flow Rate: (ml/min)		
			U (g/ℓ)	HNO_3 (M)	Run HS-4	Run HS-5	Run HS-6
HS Column	HSS (1AS)	A	0.0	3.0	150	150	150
	HSF (1AF)	A	278.2	2.47	285	330	350
	HSX (1AX)	O	0.0	0.0	1030	1050	1050
1C Column	1CX (1BX)	A	0.0	0.0	1290	1300	1300
HS Column	Pulse Frequency: (c/min)				~84	84	84
	Pulse Amplitude: (cm)				2.0	2.0	2.0
	Dispersed Phase Holdup: (%)		Scrubbing		(~15.2)	(15.1)	(15.1)
			Extraction		(~17.4)	(17.9)	(18.1)
			Average (Scrub and Extract)		--	16.3	--
1C Column	Pulse Frequency: (c/min)				~60	60	60
	Pulse Amplitude: (cm)				2.0	2.0	2.0
	Dispersed Phase Holdup: (%)				(~8.4)	9.7	(8.4)
HS and 1C Column	Temperature: (°C)				~24	24	24

NOTE: Holdup data in parenthesis were calculated using equation 5.

TABLE 4-6

RUN CONDITIONS AND DATA
(Runs: 2D-1, 2D-2, and 2D-3)

Column:	Stream:	Phase:	Concentration:		Flow Rate: (ml/min)		
			U (g/ℓ)	HNO_3 (M)	Run 2D-1	Run 2D-2	Run 2D-3
2D Column	2DS (1AS)	A	0.0	0.01	145	145	145
	2DF (1AF)	A	272.6	2.5	310	310	310
	2DX (1AX)	O	0.0	0.0	1050	950	900
2E Column	2EX (1BX)	A	0.0	0.0	1130	1130	1130
2D Column	Pulse Frequency:	(c/min)			~84	84	82
	Pulse Amplitude:	(cm)			2.0	2.0	2.0
	Dispersed Phase Holdup: (%)	Scrubbing			(~15.0)	(14.7)	(15.1)
		Extraction			(~17.5)	(18.4)	(17.5)
		Average (Scrub and Extract)			--	17.6	16.4
2E Column	Pulse Frequency:	(c/min)			~60	60	60
	Pulse Amplitude:	(cm)			2.0	2.0	2.0
	Dispersed Phase Holdup:	(%)			(~8.8)	9.8	10.0
2D and 2E Column	Temperature:	(°C)			~ 24	24	24

NOTE: Holdup data in parenthesis were calculated using equation 5.

TABLE 4-7

RUN CONDITIONS AND DATA
(Runs: 2A-1, 2A-2, and 2A-3)

Column:	Stream:	Phase:	Concentration:		Flow Rate: (ml/min)		
			U (g/ℓ)	HNO_3 (M)	Run 2A-1	Run 2A-2	Run 2A-3
2A Column	2AS (1AS)	A	0.0	1.0	104	104	104
	2AF (1AF)	A	25.3	3.0	650	650	650
	2AX (1AX)	O	0.0	0.0	280	200	240
2B Column	2BX (1BX)	A	0.0	0.3	240	240	240
2A Column	Pulse Frequency:	(c/min)			~82	82	82
	Pulse Amplitude:	(cm)			2.0	2.0	2.0
	Dispersed Phase Holdup: (%)	Scrubbing			(~19.8)	(20.6)	(20.2)
		Extraction			(~26.3)	(27.2)	(26.8)
		Average (Scrub and Extract)			--	23.4	24.6
2B Column	Pulse Frequency:	(c/min)			~72	72	71
	Pulse Amplitude:	(cm)			2.0	2.0	2.0
	Dispersed Phase Holdup:	(%)			(~15.1)	16.1	14.4
2A and 2B Column	Temperature:	(°C)			~24	24	24

NOTE: Holdup data in parenthesis were calculated using equation 5.

TABLE 4-8

RUN CONDITIONS AND DATA
(Runs: 3A-1, 3A-2, and 3A-3)

Column:	Stream:	Phase:	Concentration:		Flow Rate: (ml/min)		
			U (g/ℓ)	HNO_3 (M)	Run 3A-1	Run 3A-2	Run 3A-3
3A Column	3AS (1AS)	A	0.0	1.0	100	100	100
	2AF (1AF)	A	41.8	3.0	400	400	400
	3AX (1AX)	O	0.0	0.0	260	200	230
3B Column	3BX (1BX)	A	0.0	0.2	260	260	260
3A Column	Pulse Frequency: (c/min)				~84	84	84
	Pulse Amplitude: (cm)				2.0	2.0	2.0
	Dispersed Phase Holdup: (%)		Scrubbing		(~21.4)	(22.0)	(21.6)
			Extraction		(~25.5)	(26.1)	(25.7)
			Average (Scrub and Extract)		--	24.1	23.3
3B Column	Pulse Frequency: (c/min)				~73	73	73
	Pulse Amplitude: (cm)				2.0	2.0	2.0
	Dispersed Phase Holdup: (%)				(~15.5)	16.7	16.3
3A and 3B Column	Temperature: (°C)				~24	24	24

NOTE: Holdup data in parenthesis were calculated using equation 5.

TABLE 4-9

CONCENTRATION PROFILE DATA
(Run: HS-1)

HS Column: (15 v/o TBP)				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(HSS) 0.1	(HSS) 2.97	(HSP) ~42.2	(HSP) ~0.12
A-1	~6.8	~2.95	42.3	0.12
A-2	16.3	3.03	42.6	0.12
A-3	20.1	3.04	43.3	0.12
A-4	21.0 20.8	3.10 3.0	43.4 43.2	0.13
A-5	19.2	3.15 3.10	43.0 43.3	0.13
A-6	18.4 17.1	3.16 3.0	43.0 42.2	0.14
A-7	9.1	3.05	27.6	0.25
A-8	2.6	3.30 3.12	8.8	0.33
A-9	0.4	3.30	1.8 1.9	0.34
A-10	0.2	2.84 2.94	0.2	0.32
A-11	0.1	2.20	0.1	0.08
End Stream	(HSW) (~0.2)	(HSW) ~2.18	(HSX) 0.0	(HSX) 0.0

1C Column: (15 v/o TBP)				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(1CX) <0.1	(1CX) <0.001	(1CW) 0.40	(1CW) 0.001
B-1	<0.1	0.002	<0.01	0.001
B-2	0.1	0.003	0.01	0.002
B-3	0.2	0.004	0.44	0.003
B-4	2.4	0.009	3.20	0.004
B-5	14.0	0.020	15.90	0.014
B-6	26.5 27.0	0.055 0.060	31.0 32.0	0.080 0.070
B-7	33.5 33.0	0.110 0.120	40.40 37.60	0.120 0.110
End Stream	(1CU) ~ 34.4	(1CU) ~ 0.120	(HSP) 42.20	(HSP) 0.120

TABLE 4-10

CONCENTRATION PROFILE DATA
(Run: HS-2)

HS Column: (15 v/o TBP)				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(HSS) 0.0	(HSS) 2.97	(HSP) ~ 34.7	(HSP) 0.16
A-1	~ 3.2	~2.96	34.8	0.16
A-2	8.5	3.09	35.5	0.16
A-3	12.6	2.98 3.20	35.7	0.16
A-4	14.6 15.2	3.10	35.9 36.2	0.16
A-5	14.1 13.6	3.05	35.6 36.0	0.18 0.17
A-6	12.6	3.10 2.97	34.3 34.0	0.36
A-7	8.1	3.14 3.0	22.8 21.9	0.36
A-8	2.6 2.0	3.46 3.51	8.5 9.3	0.34 0.33
A-9	0.3 0.3	3.50 3.47	2.3 2.6	0.32 0.34
A-10	0.2	2.90	1.2	0.27
A-11	0.2	2.10	0.1	0.08
End Stream	(HSW) ~ 0.2	(HSW) ~2.0	(HSX) 0.0	(HSX) 0.0

1C Column: (15 v/o TBP)				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(1CX) <0.01	(1CX) <0.001	(1CW) <0.1	(1CW) <0.001
B-1	<0.1	~ 0.003	<0.1	<0.001
B-2	0.03	0.003	<0.1	<0.001
B-3	0.16	0.003	0.1	<0.001
B-4	0.36	0.004	0.9	0.005
B-5	6.70 6.0	0.020 0.016	8.6 8.1	0.010 0.012
B-6	18.60 18.0	0.060 0.063	21.2 23.7	0.050 0.070
B-7	28.20 28.0	0.140 0.145	33.6 33.3	0.139 0.130
End Stream	(1CU) ~ 29.0	(1CU) ~ 0.120	(HSP) 34.7	(HSP) 0.155

TABLE 4-11

CONCENTRATION PROFILE DATA
(Run: HS-3)

HS Column: (15 v/o TBP)				
	Aqueous:		Organic:	
Sample:	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(HSS) 0.0	(HSS) 2.97	(HSP) ~ 33.1	(HSP) ~ 0.14
A-1	~2.0	2.98	33.1 32.2	0.15
A-2	4.8 5.0	2.96 3.10	33.4 33.0	0.16 0.17
A-3	9.0 9.8	2.95 3.02	33.4 32.9	0.16 0.17
A-4	9.5	3.0 3.20	33.9 33.1	0.17
A-5	10.3 9.8	3.10 3.15	32.9 32.8	0.17
A-6	9.0 9.1	3.10 3.18	32.4 32.7	0.17 0.16
A-7	6.6	3.0 2.97	24.7 25.2	0.21 0.20
A-8	2.6	2.98 3.0	13.2 13.4	0.25 0.26
A-9	0.4 0.6	2.80 2.90	4.6 6.3	0.245 0.25
A-10	0.3	2.70	1.4	0.20
A-11	0.1	2.10	0.1	0.07
End Stream	(HSW) (~0.2)	(HSW) 2.01	(HSX) 0.0	(HSX) 0.0

1C Column: (15 v/o TBP)				
	Aqueous:		Organic:	
Sample:	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(1CX) 0.0	(1CX) <0.01	(1CW) (~0.2)	(1CW) <0.001
B-1	0.2	<0.01	<0.1	<0.001
B-2	0.2	<0.001	0.3	0.002
B-3	0.3 0.4	0.01	0.5	0.003
B-4	0.7	0.01	0.6	0.040
B-5	5.2	0.01 0.01	5.9 5.5	0.050
B-6	19.0 18.4	0.02	23.2 22.9	0.061
B-7	26.0 25.1	0.15 0.14	31.6 30.7	0.145 0.140
End Stream	(1CU) ~ 26.9	(1CU) ~ 0.13	(HSP) 33.1	(HSP) 0.140

TABLE 4-12

CONCENTRATION PROFILE DATA
(Run: HS-4)

HS Column:

Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(HSS) 0.0	(HSS) 3.0	(HSP) ~ 73.2	(HSP) ~0.29
A-1	~ 5.0	2.98	73.4	0.28
A-2	12.1	3.10	74.1	0.28
A-3	15.1	3.13	74.2	0.30
A-4	16.4 16.6	3.30	74.2 74.6	0.30
A-5	17.1 17.3	3.35	75.2 74.9	0.28
A-6	17.0 16.7	3.40	74.5 74.3	0.26
A-7	11.6 12.1	3.47	54.4 54.0	0.41
A-8	4.4 4.6	3.50	21.0 20.6	0.64
A-9	0.9	3.50	4.1	0.68
A-10	0.2	3.34	0.8	0.66
A-11	0.1	2.70	0.2	0.40
End Stream	(HSW) ~ 0.1	(HSW) ~2.20	(HSX) 0.0	(HSX) 0.0

1C Column:

Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(1CX) <0.1	(1CX) <0.01	(1CW) ~ 0.1	(1CW) <0.001
B-1	~ 0.1	<0.01	0.1	<0.001
B-2	0.4	<0.01	0.2	<0.001
B-3	5.0 4.8	<0.01	0.3 0.3	<0.001
B-4	15.9 16.2	0.02	11.0 11.2	<0.001
B-5	34.1 33.8	0.04	39.1 38.8	0.014
B-6	47.6 47.5	0.10	59.2 58.9	0.030
B-7	56.4 56.1	0.23	72.8 72.5	0.160
End Stream	(1CU) ~ 57.0	(1CU) ~ 0.23	(HSP) 73.2	(HSP) 0.290

TABLE 4-13

CONCENTRATION PROFILE DATA
(Run: HS-5)

HS Column:				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(HSS) 0.0	(HSS) 3.0	(HSP) ~ 85.0	(HSP) ~0.20
A-1	~ 7.1	2.97	85.1	0.20
A-2	15.0	3.01	85.4	0.20
A-3	16.4	3.05	85.7	0.20
A-4	17.5 17.9	3.11 3.07	86.7 87.3	0.21 0.22
A-5	18.6 18.3	3.21 3.26	88.7 88.2	0.21 0.23
A-6	18.2 17.8	3.30 3.34	87.8 87.5	0.22 0.26
A-7	12.2 12.5	3.57 3.61	72.8 73.5	0.31 0.35
A-8	5.6 5.2	3.69 3.60	31.9 32.4	0.54 0.59
A-9	1.0 0.8	3.60 3.51	5.7 6.1	0.70 0.63
A-10	0.3	3.08	0.2	0.66
A-11	0.1	2.60	0.1	0.35
End Stream	(HSW) ~ 0.1	(HSW) ~2.26	(HSX) 0.0	(HSX) 0.0

1C Column:				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(1CX) <0.1	(1CX) <0.01	(1CW) ~ 0.0	(1CW) <0.001
B-1	~ 0.1	<0.01	0.1	<0.001
B-2	0.5	<0.01	0.3	<0.001
B-3	5.1 5.3	<0.01	1.0 0.8	0.012
B-4	19.0 19.2	0.01	14.4 14.7	0.015
B-5	38.4 39.0	0.02	45.6 46.0	0.021
B-6	54.3 54.0	0.08	68.6 69.0	0.030
B-7	63.0 63.3	0.18	83.6 84.0	0.110
End Stream	(1CU) ~ 63.9	(1CU) ~ 0.17	(HSP) 85.0	(HSP) 0.204

TABLE 4-14

CONCENTRATION PROFILE DATA
(Run: HS-6)

HS Column: (30 v/o TBP)				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(HSS) 0.0	(HSS) 3.01	(HSP) ~ 91.1	(HSP) ~ 0.175
A-1	~ 5.4	2.94	91.4	0.175
A-2	17.1 15.6	2.97	93.3	0.170
A-3	22.3 21.6	3.15	93.6	0.170
A-4	26.3 27.0	3.11	93.7 94.0	0.165
A-5	27.1 26.6	3.10 3.05	94.2 94.8	0.180
A-6	22.6 23.7	2.98 3.10	93.1 93.4	0.240
A-7	17.6 18.1 16.2	3.20 3.24	82.1 82.7	0.30 0.340
A-8	4.8 5.1	3.40 3.35	20.4 21.4	0.60 0.630
A-9	<0.1	3.30	2.3	0.650
A-10	<0.1	2.90	<0.1	0.50
A-11	<0.1	2.40	<0.1	0.370
End Stream	(HSW) <0.01	(HSW) ~2.35	(HSX) 0.0	(HSX) 0.0

1C Column: (30 v/o TBP)				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(1CX) <0.1	(1CX) <0.001	(1CW) <0.1	(1CW) ~ 0.001
B-1	<0.1	~ 0.001	<0.1	0.002
B-2	<0.1	0.001	<0.1	0.002
B-3	0.3 0.3	0.002	0.1 0.1	0.002
B-4	4.7 5.1	0.003	1.8 2.1	0.002
B-5	36.8 37.5	0.003	44.1 43.5	0.020
B-6	61.5 60.9	0.070	74.6 74.0	0.060
B-7	72.0 71.7	0.085	88.1 88.5	0.110
End Stream	(1CU) ~ 73.5	(1CU) ~ 0.094	(HSP) 91.1	(HSP) 0.175

TABLE 4-15

CONCENTRATION PROFILE DATA
(Run: 2D-1)

2D Column				
	Aqueous:		Organic:	
Sample:	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2DS) 0.0	(2DS) 0.01	(2DU) ~ 79.8	(2DU) 0.08
A-1				
A-2	~31.0	~0.08	83.1	0.06
A-3	50.8	0.14	86.2	0.07
A-4	62.9 63.7	0.40	86.8 88.1	0.12
A-5	72.1 72.4	1.90	87.1 89.1	0.15
A-6	71.9 72.5	2.30	87.1 89.0	0.19
A-7	42.7 43.2	2.94	67.1 68.0	0.41
A-8	8.7	2.91	18.6 19.7	0.54
A-9	3.8	2.83	8.9	0.54
A-10	1.7	2.68	3.9	0.48
A-11	1.1	1.80	1.5	0.18
End Stream	(2DW) (~1.4)	(2DW) ~1.50	(2DX) 0.0	(2DX) 0.0

2E Column				
	Aqueous:		Organic:	
Sample:	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2EX) 0.0	(2EX) <0.01	(2EW) (~0.2)	(2EW) <0.001
B-1	~ 0.1	<0.01	~0.1	<0.001
B-2	0.3	<0.01	0.1	<0.001
B-3	4.4 4.6	<0.01	0.2 0.4	<0.001
B-4	12.0 5.1	<0.01	4.3 2.1	<0.001
B-5	32.8 33.0	0.01	28.7 29.1	0.015
B-6	59.6 59.9	0.02	62.6 63.0	0.030
B-7	72.1 72.4	0.06	78.2 78.5	0.070
End Stream	(2EU) ~ 72.6 73.9	(2EU) ~ 0.07	(2DU) 79.8	(2DU) 0.079

TABLE 4-16

CONCENTRATION PROFILE DATA
(Run: 2D-2)

2D Column				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2DS) 0.0	(2DS) 0.01	(2DU) ~ 88.5	(2DU) ~ 0.06
A-1	~ 14.1	~0.02	89.3	0.04
A-2	70.0	0.04	97.1	0.06
A-3	100.1	0.09	104.0	0.07
A-4	114.2 116.6	0.70	108.2 109.8	0.10
A-5	120.2 126.7	1.70	111.6 112.2	0.16
A-6	121.9 127.2	2.10	111.8 112.3	0.19
A-7	120.8 125.0	2.40	110.6 111.5	0.23
A-8	108.0 109.7	2.43	104.1 106.6	0.20
A-9	53.0	2.40	74.2	0.20
A-10	3.1	2.10	10.7	0.37
A-11	0.4	1.80	0.7	0.30
End Stream	(2DW) (~0.1)	(2DW) 1.56	(2DX) 0.0	(2DX) 0.0

2E Column				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2EX) 0.0	(2EX) <0.001	(2EW) ~ 0.1	(2EW) <0.001
B-1	0.3	<0.001	0.2	<0.001
B-2	0.4	<0.001	0.25	<0.001
B-3	1.9	<0.001	0.70	<0.001
B-4	24.1 24.6	0.001	20.7 21.1	<0.001
B-5	45.4 46.0	0.009	50.3 50.6	0.001
B-6	64.6 65.1	0.016	75.1 75.5	0.007
B-7	72.8 73.2	0.035	85.8 86.3	0.030
End Stream	(2EU) ~ 74.4	(2EU) ~ 0.044	(2DU) 88.5	(2DU) 0.060

TABLE 4-17

CONCENTRATION PROFILE DATA
(Run: 2D-3)

2D Column				
	Aqueous:		Organic:	
Sample:	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2DS) 0.0	(2DS) 0.01	(2DU) ~ 92.8	(2DU) 0.03
A-1				
A-2	~ 53.4	0.02	99.3	0.02
A-3	79.0	0.02	104.1	0.02
A-4	99.5 101.8	0.40	107.6 108.0	0.05
A-5	111.0 114.3	1.80	112.0 112.7	0.11
A-6	114.0 116.2	2.10	112.4 113.0	0.16
A-7	116.8 118.4	2.20	111.9 112.7	0.16
A-8	114.8 115.6	2.27	110.8 112.0	0.19
A-9	103.0	2.0	104.6 105.7	0.18
A-10	65.6	2.0	90.2	0.21
A-11	2.3	1.83	9.1	0.15
End Stream	(2DW) ~ 2.1	(2DW) ~1.60	(2DX) 0.0	(2DX) 0.0

2E Column				
	Aqueous:		Organic:	
Sample:	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2EX) <0.1	(2EX) <0.001	(2EW) ~ 0.2	(2EW) <0.001
B-1	0.3	<0.001	0.2	<0.001
B-2	0.5	<0.001	0.3	<0.001
B-3	3.4	<0.001	0.7	<0.001
B-4	15.7 16.2	0.001	12.1 12.9	<0.001
B-5	42.1 42.7	0.001	47.8 48.1	0.001
B-6	63.9 64.2	0.010	79.0 79.4	0.001
B-7	72.8 73.3	0.025	90.8 91.5	0.010
End Stream	(2EU) ~ 73.8	(2EU) ~ 0.033	(2DU) 92.8	(2DU) 0.028

TABLE 4-18

CONCENTRATION PROFILE DATA
(Run: 2A-1)

2A Column				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2AS) 0.0	(2AS) 1.0	(2AP) ~ 57.6	(2AP) ~ 0.11
A-1	~ 3.4	0.99	57.9	0.09
A-2	10.2	1.0	59.6	0.10
A-3	15.1	1.10	60.3	0.12
A-4	18.8 19.1	1.32	61.1 61.4	0.16
A-5	19.6 20.5	1.71	61.7 63.6	0.20
A-6	19.3 19.8	2.84	61.6 62.2	0.40
A-7	5.4 5.9	2.91	23.0 24.1	0.39
A-8	1.0 1.2	2.90	4.7 5.9	0.53
A-9	0.2	2.87	1.1	0.51
A-10	0.1	2.81	0.6	0.40
A-11	0.1	2.70	0.3	0.40
End Stream	(2AW) (~0.4)	(2AW) ~2.62	(2AX) 0.0	(2AX) 0.0

2B Column				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2BX) 0.0	(2BX) 0.30	(2BW) (~15.0)	(2BW) ~ 0.030
B-1	~ 14.7 12.8	0.29	~25.4 24.3	0.028
B-2	20.8	0.29	31.8 34.7	0.028
B-3	27.8	0.30	40.6	0.030
B-4	32.1 32.9	0.30	45.7 46.3	0.030
B-5	36.1 36.7	0.30	50.6 51.1	0.030
B-6	38.8 39.3	0.30	55.8 56.3	0.033
B-7	40.6 40.9	0.31	57.1 57.4	0.060
End Stream	(2BP) ~41.4	(2BP) ~0.33	(2AP) 57.6	(2AP) 0.113

TABLE 4-19

CONCENTRATION PROFILE DATA
(Run: 2A-2)

2A Column				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2AS) 0.0	(2AS) 1.0	(2AP) ~64.1	(2AP) ~0.11
A-1	~3.1	0.96	64.3	0.10
A-2	15.9	1.0	67.1	0.10
A-3	29.8	1.10	75.1	0.11
A-4	39.4 40.0	1.30	84.3 85.5	0.13
A-5	41.8 41.2	1.95	90.0 90.5	0.16
A-6	42.0 41.9	2.57	90.3 91.1	0.21
A-7	38.0 37.8	2.63	88.3 89.1	0.20
A-8	32.0 32.4	2.71	85.4 86.2	0.30
A-9	26.9	2.73	81.0	0.33
A-10	18.3	2.70	69.0	0.40
A-11	4.6	2.70	24.5 26.9	0.30
End Stream	(2AW) (~1.4)	(2AW) ~2.62	(2AX) 0.0	(2AX) 0.0

2B Column				
Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2BX) 0.0	(2BX) 0.30	(2BW) ~4.6	(2BW) <0.001
B-1	~3.0	0.29	6.0	0.030
B-2	7.5	0.29	10.6	0.023
B-3	13.9	0.30	18.1	0.023
B-4	19.6 20.1	0.29	24.6 25.5	0.025
B-5	27.6 28.3	0.30	34.1 35.5	0.025
B-6	36.1 37.0	0.30	47.4 48.5	0.025
B-7	48.2 48.7	0.30	63.2 63.6	0.050
End Stream	(2BP) ~49.6	(2BP) ~0.31	(2AP) 64.1	(2AP) 0.113

TABLE 4-20

CONCENTRATION PROFILE DATA
(Run: 2A-3)

2A Column					2B Column				
Sample:	Aqueous:		Organic:		Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)		U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(2AS) 0.0	(2AS) 1.0	(2AP) ~ 60.9	(2AP) ~ 0.09	End Stream	(2BX) 0.0	(2BX) 0.30	(2BW) ~15.4	(2BW) ~ 0.025
A-1	~ 5.1	0.95	63.4	0.09	B-1	~ 6.9 8.1	0.29	16.8	0.025
A-2	19.5	0.99	69.4	0.10	B-2	12.6 13.3	0.29	21.3 22.0	0.025
A-3	36.0	1.12	78.3	0.13	B-3	18.9 19.7	0.29	30.1 30.6	0.024
A-4	44.9 46.4	1.40	82.2 83.0	0.16	B-4	28.6 29.2	0.30	40.4 40.6	0.025
A-5	45.6 47.2	2.10	83.5 84.1	0.18	B-5	33.7 34.2	0.30	46.6 46.9	0.026
A-6	45.4 47.4	2.64	83.9 84.2	0.22	B-6	40.3 40.6	0.30	55.3 55.7	0.028
A-7	26.3 27.0	2.83	73.2 75.3	0.21	B-7	44.1 44.7	0.30	60.0 60.4	0.050
A-8	9.1	2.80	36.4 37.0	0.28	End Stream	(2BP) ~ 45.5	(2BP) ~ 0.31	(2AP) 60.9	(2AP) 0.092
A-9	4.0	2.80	11.8	0.30					
A-10	2.4	2.76	3.8	0.35					
A-11	1.7	2.70	0.6	0.33					
End Stream	(2AW) (~ 0.2)	(2AW) ~2.59	(2AX) 0.0	(2AX) 0.0					

TABLE 4-21

CONCENTRATION PROFILE DATA
(Run: 3A-1)

3A Column					3B Column				
Sample:	Aqueous:		Organic:		Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)		U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(3AS) 0.0	(3AS) 1.0	(3AP) ~ 62.7	(3AP) 0.09	End Stream	(3BX) <0.1	(3BX) 0.20	(3BW) ~ 12.0	(3BW) ~ 0.012
A-1	~ 7.3	1.0	64.3	0.10	B-1	~ 6.6	0.19	13.3 14.5	0.010
A-2	19.7	1.10	71.1	0.10	B-2	18.9 20.2	0.20	27.4 28.0	0.010
A-3	23.8	1.21	76.2	0.12	B-3	28.8 29.1	0.20	36.7 37.0	0.015
A-4	25.6 26.1	1.34	76.4 77.4	0.14	B-4	36.3 38.0	0.20	46.3 48.0	0.015
A-5	26.9 27.7	1.60	79.1 80.8	0.19	B-5	46.2 46.8	0.20	56.8 57.0	0.015
A-6	27.8 28.6	2.70	80.3 81.0	0.28	B-6	49.8 50.1	0.22	61.6 62.2	0.030
A-7	11.4 12.1	2.90	52.4 53.1	0.35					
A-8	3.7	2.94	11.2	0.41	End Stream	(3BP) ~ 50.8	(3BP) ~ 0.26	(3AP) 62.7	(3AP) 0.087
A-9	1.3	2.91	3.6	0.44					
A-10	1.0	2.80	2.1	0.40					
A-11	0.6	2.73	0.8	0.31					
End Stream	(3AW) (~0.9)	(3AW) ~2.70	(3AX) 0.0	(3AX) 0.0					

TABLE 4-22

CONCENTRATION PROFILE DATA

(Run: 3A-2)

3A Column				
Sample:	Aqueous: U (g/ℓ)	Aqueous: HNO_3 (M)	Organic: U (g/ℓ)	Organic: HNO_3 (M)
End Stream	(3AS) 0.0	(3AS) 1.00	(3AP) ~ 66.9	(3AP) ~ 0.08
A-1	~ 10.4	0.99	67.8	0.07
A-2	29.2	1.12	72.7	0.09
A-3	39.3	1.33	80.7	0.10
A-4	47.9 49.3	1.67	90.3 91.0	0.13
A-5	52.6 54.9	1.96	98.6 99.8	0.17
A-6	52.2 53.4	2.83	99.7 100.7	0.22
A-7	52.2 52.8	2.90	100.3 101.1	0.26
A-8	50.5 51.4	2.92	98.5 99.3	0.32
A-9	41.2 42.6	2.94	91.0 92.8	0.36
A-10	24.4	2.90	70.4	0.34
A-11	7.0	2.81	12.1	0.30
End Stream	(3AW) (~ 0.5)	(3AW) ~ 2.78	(3AX) 0.0	(3AX) 0.0

3B Column				
Sample:	Aqueous: U (g/ℓ)	Aqueous: HNO_3 (M)	Organic: U (g/ℓ)	Organic: HNO_3 (M)
End Stream	(3BX) 0.0	(3BX) 0.20	(3BW) ~ 5.3	(3BW) 0.007
B-1	~ 2.6	0.19	6.0	0.020
B-2	6.1	0.19	10.5	0.020
B-3	11.1 12.2	0.20	15.7 16.2	0.019
B-4	20.4 21.0	0.20	27.0 27.5	0.019
B-5	33.5 34.1	0.20	45.6 46.3	0.020
B-6	46.8 47.1	0.21	64.8 65.6	0.040
End Stream	(3BP) ~ 47.3	(3BP) ~ 0.23	(3AP) 66.9	(3AP) 0.082

TABLE 4-23

CONCENTRATION PROFILE DATA
(Run: 3A-3)

3A Column

Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(3AS) 0.0	(3AS) 1.0	(3AP) ~64.3	(3AP) ~ 0.10
A-1	8.7	0.98	66.2	0.09
A-2	21.4	1.0	76.6	0.10
A-3	30.3	1.18	86.1	0.11
A-4	30.9 32.2	1.50	91.0 89.2	0.16
A-5	33.9 34.5	2.20	94.6 95.3	0.20
A-6	34.2 35.1	2.79	94.8 96.1	0.26
A-7	31.3 32.0	2.98	91.5 92.2	0.24
A-8	21.6 22.9	2.99	75.4 76.0	0.35
A-9	12.6	2.93	42.0 42.7	0.36
A-10	8.0	2.93	42.0	0.36
A-11	4.1	2.69	3.6	0.34
End Stream	(3AW) (~0.1)	(3AW) ~2.62	(3AX) 0.0	(3AX) 0.0

3B Column

Sample:	Aqueous:		Organic:	
	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
End Stream	(3BX) 0.0	(3BX) 0.20	(3BW) ~ 7.0	(3BW) ~ 0.025
B-1	~ 4.3	0.19	7.6	0.023
B-2	12.1 13.0	0.19	16.5	0.024
B-3	22.4 23.0	0.19	27.6 28.1	0.025
B-4	30.3 31.3	0.20	37.4 38.8	0.023
B-5	41.2 42.4	0.20	53.2 53.9	0.025
B-6	49.8 50.2	0.22	62.6 63.3	0.040
End Stream	(3BP) ~ 50.7	(3BP) ~ 0.26	(3AP) 64.3	(3AP) 0.100

TABLE 4-24

TRANSIENT URANIUM CONCENTRATION DATA BETWEEN RUNS HS-4 AND HS-5

Sampler:	Phase:	Uranium Concentration (grams/liter) at Sampling Time:				
		0 min.	5-10 min.	20-25 min.	35-40 min.	~100-110 min.
		Run HS-4 at steady state:				Run HS-5 at steady state
A-4	O	74.2	~76.3	79.7	82.4	86.7
		74.6				87.3
	A	16.4	16.6	16.8	17.7	17.5
		16.6				17.9
A-5	O	74.9	78.8	81.7	84.5	88.2
		75.2				88.7
	A	17.1	17.5	17.6	18.5	18.3
		17.3				18.6
A-6	O	74.3	79.0	82.1	84.3	87.5
		74.5				87.8
	A	16.7	17.5	17.7	18.1	17.8
		17.0				18.2
A-7	O	54.0	58.8	66.3	69.9	72.8
		54.4				73.5
	A	11.6	12.2	12.1	12.5	12.2
		12.1				12.5

TABLE 4-25

TRANSIENT URANIUM CONCENTRATION DATA BETWEEN RUNS 2D-1 AND 2D-2

Sampler:	Phase:	Uranium Concentration (grams/liter) at Sampling Time:				
		0 min.	5-10 min.	20-25 min.	35-40 min.	~110-120 min.
		Run 2D-1 at steady state:				Run 2D-2 at steady state
A-4	0	86.7	~93.4	98.9	103.0	108.1
		88.1				109.8
	A	62.9	73.8	90.1	100.7	114.2
		63.7				116.6
A-5	0	87.1	96.9	102.0	105.0	111.6
		89.1				112.2
	A	72.1	82.1	97.6	107.6	120.2
		72.3				126.7
A-6	0	87.1	97.4	102.6	104.7	111.8
		89.0				112.3
	A	71.9	82.4	97.7	108.4	121.9
		72.4				127.2
A-7	0	67.1	85.4	94.3	99.1	111.5
		68.0				110.6
	A	42.7	64.2	87.9	106.3	120.8
		43.2				125.0

TABLE 4-26

TRANSIENT URANIUM CONCENTRATION DATA BETWEEN RUNS 2A-1 AND 2A-2

Sampler:	Phase:	Uranium Concentration (grams/liter) at Sampling Time:				
		0 min.	5-10 min.	20-25 min.	35-40 min.	~ 110-120 min.
		Run 2A-1 at steady state:				Run 2A-2 at steady state
A-4	0	61.0 61.4	~ 63.4	71.5	76.7	84.3 85.5
	A	18.8 19.1	21.2	25.5	29.7	39.4 40.0
A-5	0	61.7 63.6	67.5	79.6	84.3	90.0 90.5
	A	19.6 20.5	22.9	29.4	33.8	41.2 41.8
A-6	0	61.6 62.2	68.2	80.6	83.0	90.3 91.1
	A	19.3 19.8	23.3	29.8	33.5	42.0
A-7	0	23.0 24.0	47.7	66.1	71.8	88.3 89.1
	A	5.4 5.9	12.1	19.7	26.3	38.0 38.9

TABLE 4-27

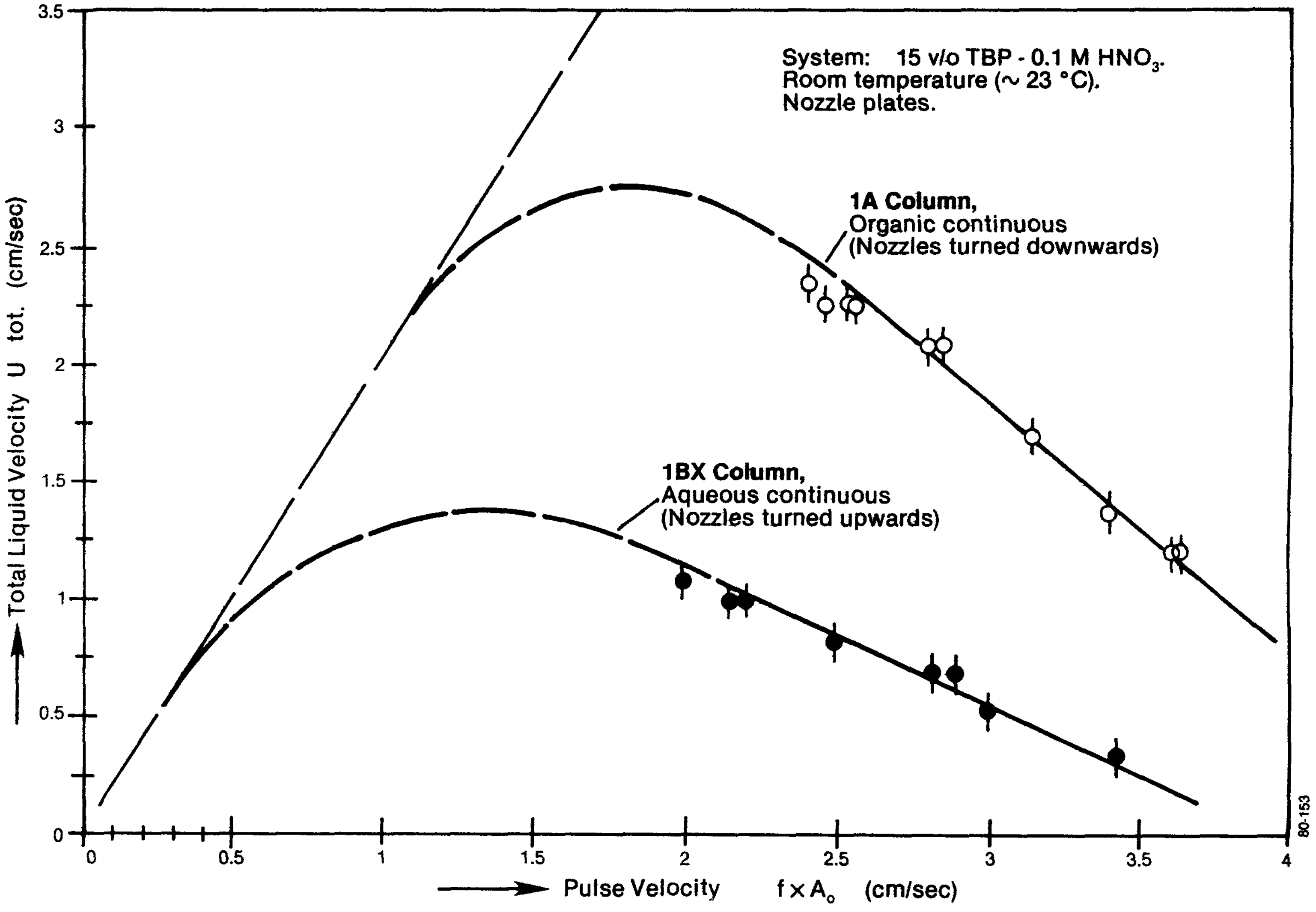
TRANSIENT URANIUM CONCENTRATION DATA BETWEEN RUNS 3A-1 AND 3A-2

Sampler:	Phase:	Uranium Concentration (grams/liter) at Sampling Time:				
		0 min. Run 3A-1 at steady state:	5-10 min.	20-25 min.	35-40 min.	~110-120 min. Run 3A-2 at steady state
A-4	0	76.4 77.4	~78.6	82.8	88.1	90.3 91.0
	A	26.1 25.6	28.3	36.9	40.8	47.9 49.3
A-5	0	79.1 80.8	82.7	90.9	95.4	98.6 99.8
	A	26.9 27.7	31.9	40.7	46.7	52.6 54.9
A-6	0	80.3 81.0	83.0	91.3	95.1	99.7 100.7
	A	27.8 28.6	32.2	41.4	46.1	52.2 53.4
A-7	0	52.4 53.1	61.0	79.2	89.5	100.3 101.1
	A	11.4 12.1	19.1	30.4	40.3	52.2 52.8

TABLE 4-28

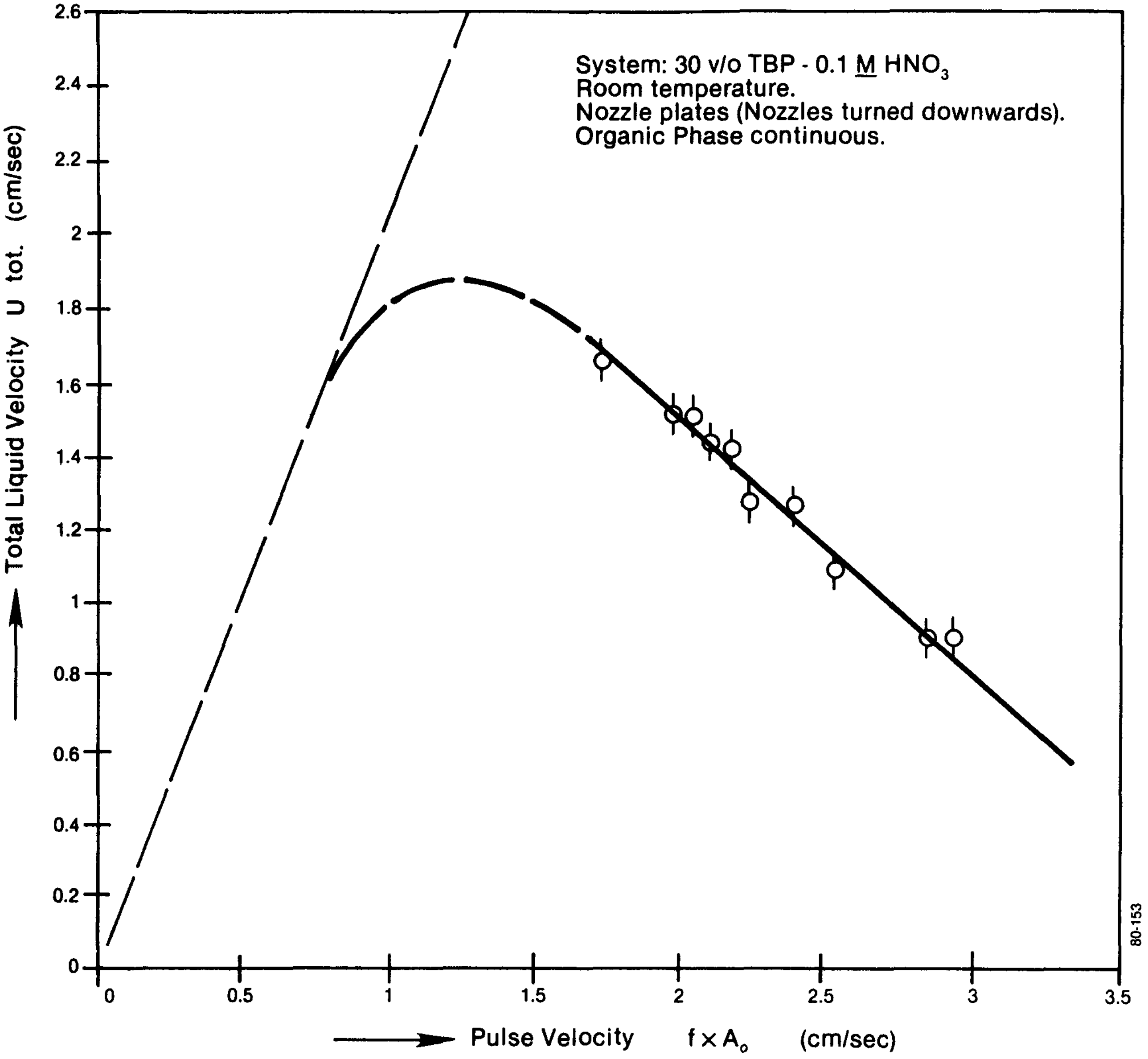
URANIUM INVENTORY IN TESTED COLUMNS

	1A Column (extraction & scrubbing)				1BX & 1BS Columns (stripping)			
	U Inventory (grams)			$V_{col}\frac{V_f}{V_{st}}C(U)_f$ (grams)	U Inventory (grams)			$V_{col}\frac{V_f}{V_{st}}C(U)_f$ (grams)
	From Concentration Profile and Hold-up Data:	From Volume and Concentration Measurement:	Calculated From Equations 15 Through 17: (grams)		From Concentration Profile and Hold-up Data:	From Volume and Concentration Measurement:	Calculated From Equation 14: (grams)	
HS-1	~560	---	570	~1290	~540	---	594	~1320
HS-2	490	---	497	1130	450	---	490	1090
HS-3	460	---	450	1020	430	---	470	1040
HS-4	1010	---	1012	2300	990	---	1030	2290
HS-5	1190	~1140	1144	2630	1150	~1190	1206	2680
HS-6	1280	---	1223	2780	1210	---	1290	2870
2D-1	1140	---	1150	2410	1190	---	1305	2900
2D-2	1510	1430	1474	2670	1290	1315	1310	2910
2D-3	1690	1610	1650	2810	1380	1330	1300	2890
2A-1	730	---	722	1760	1160	---	1180	2620
2A-2	1310	1260	1320	2470	870	940	940	2090
2A-3	990	960	974	2060	1050	1090	1070	2380
3A-1	860	830	865	1930	970*	---	855	1900
3A-2	1370	1320	1344	2500	760*	715*	700	1550
3A-3	1130	1060	1075	2180	880*	820*	775	1720



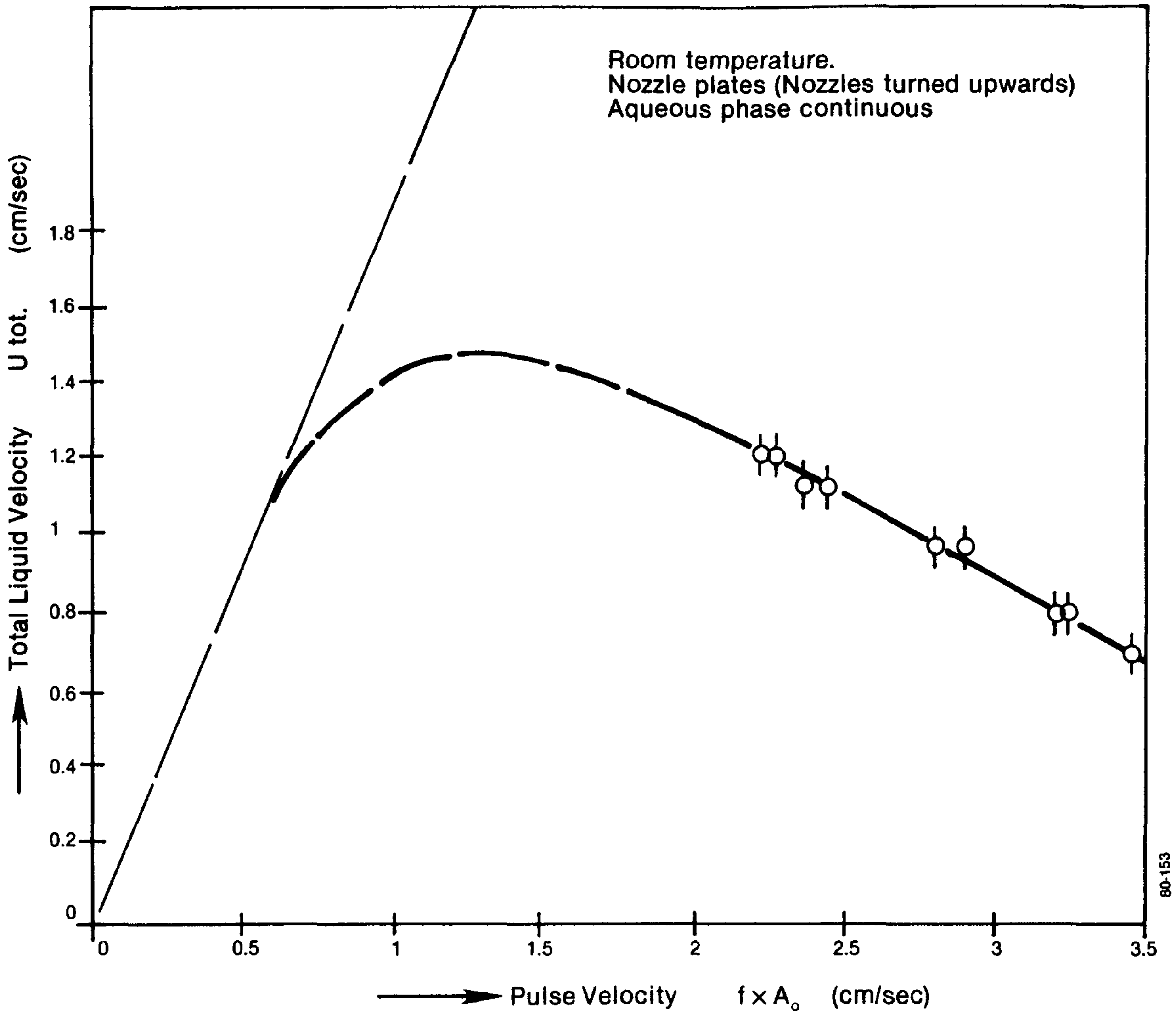
THE 1A and 1BX COLUMNS FLOODING CURVE
(WITH 15 v/o TBP - 0.1 M HNO3)

FIGURE 4-1



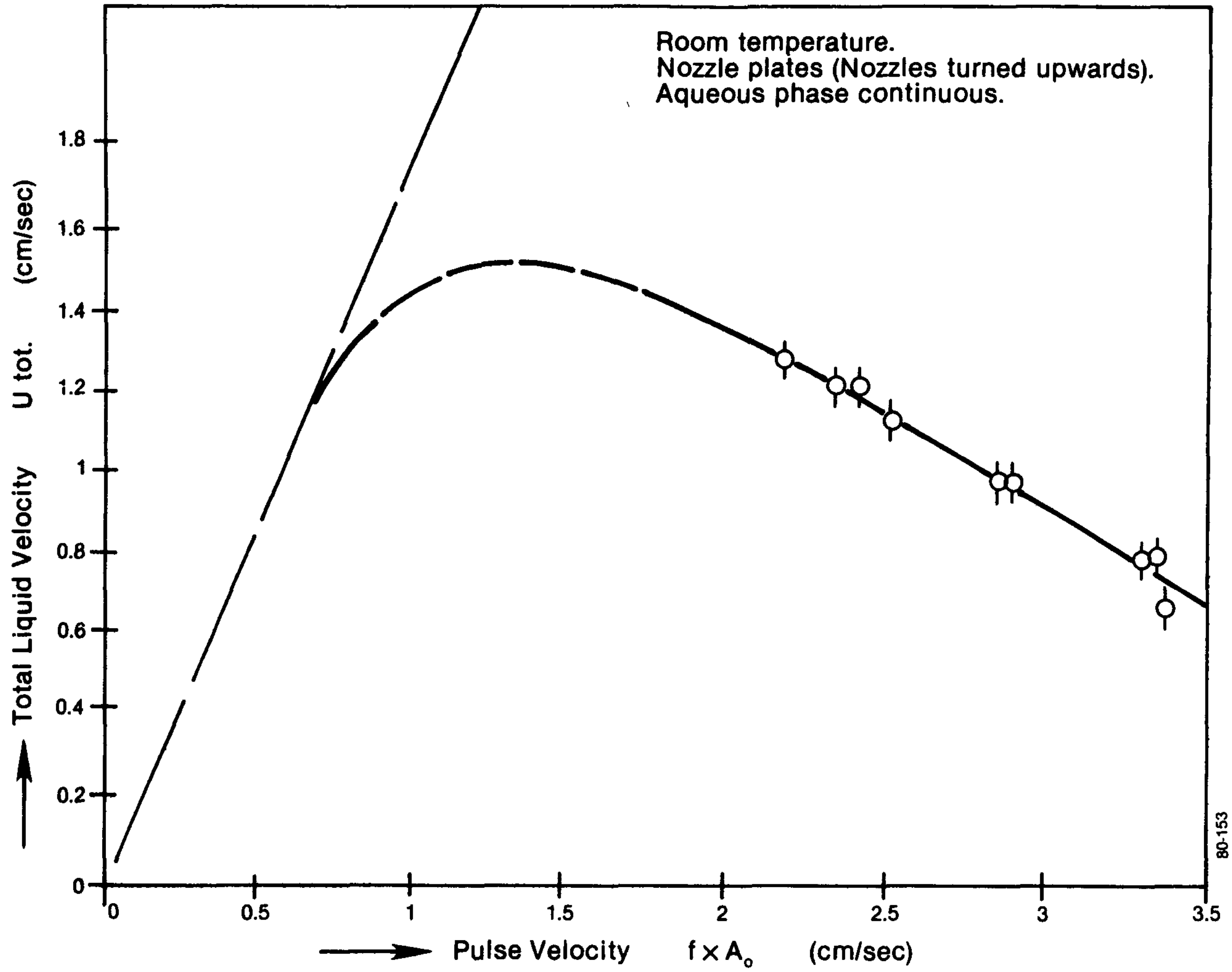
THE 1A COLUMN FLOODING CURVE
(WITH 30 v/o TBP - 0.1 M HNO_3)

FIGURE 4-2



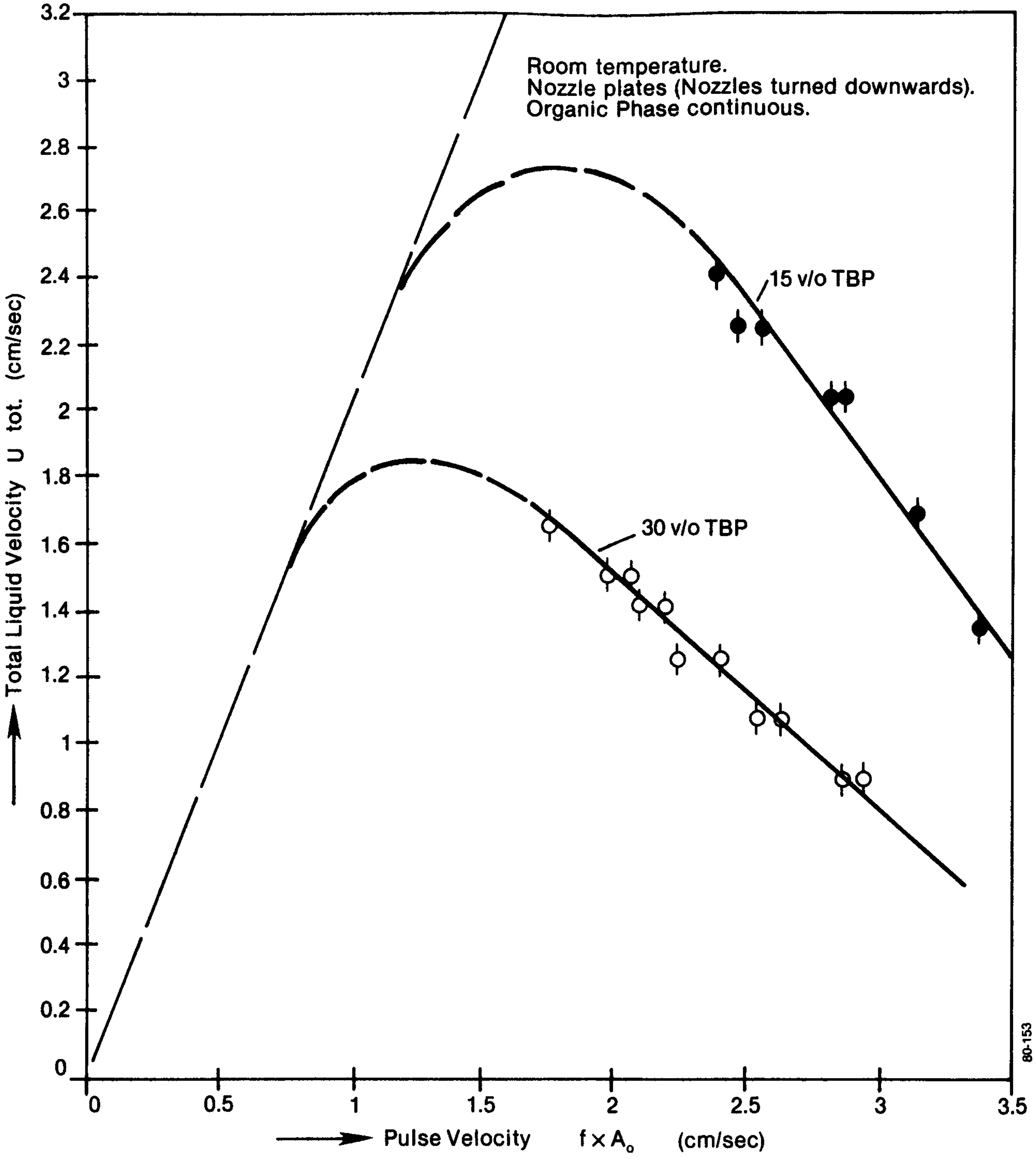
THE 1BX COLUMN FLOODING CURVE
(WITH 30 v/o TBP - 0.1 M HNO_3)

FIGURE 4-3



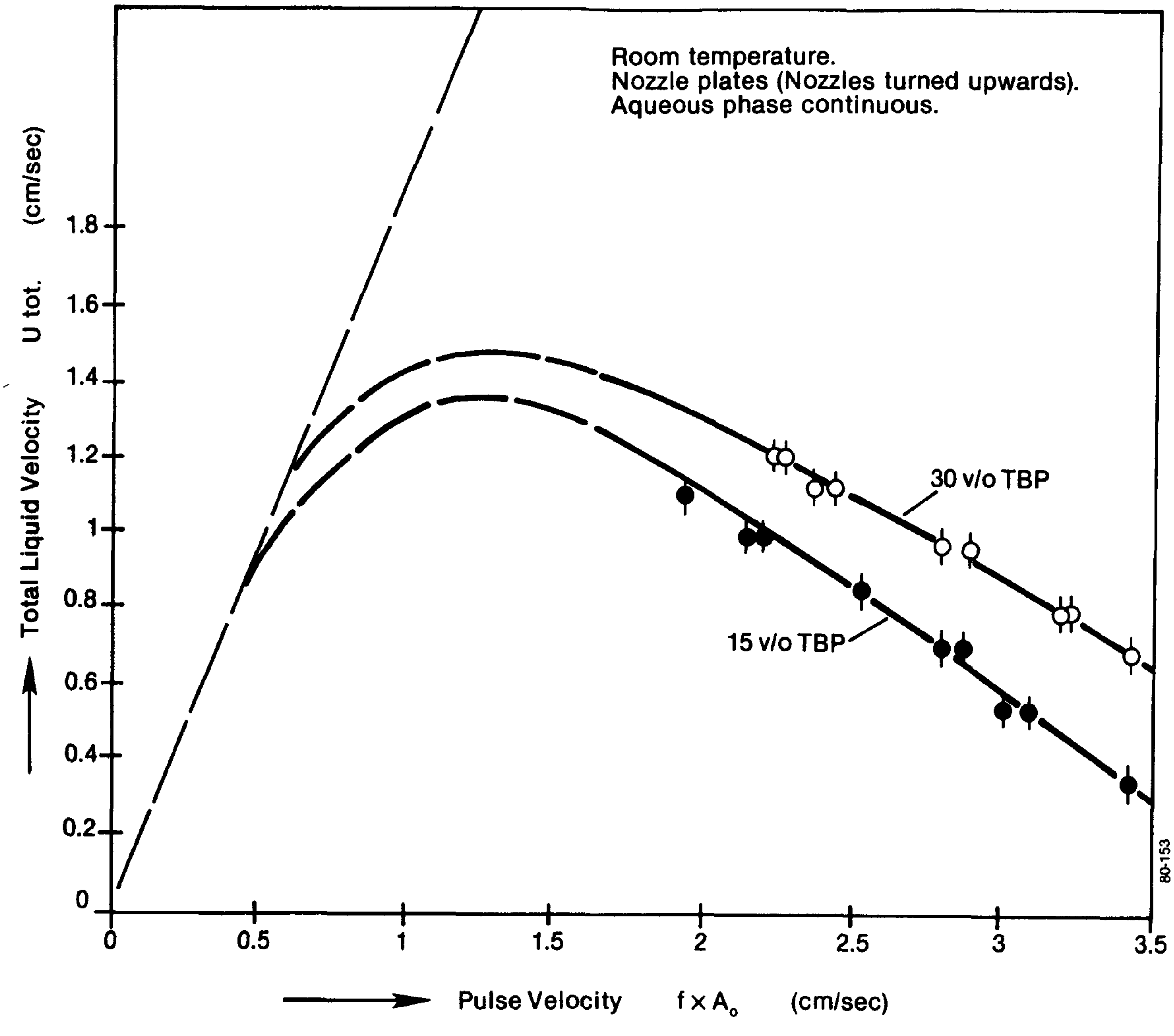
THE 1BS COLUMN FLOODING CURVE
(WITH 30 v/o TBP - 0.1 M HNO_3)

FIGURE 4-4



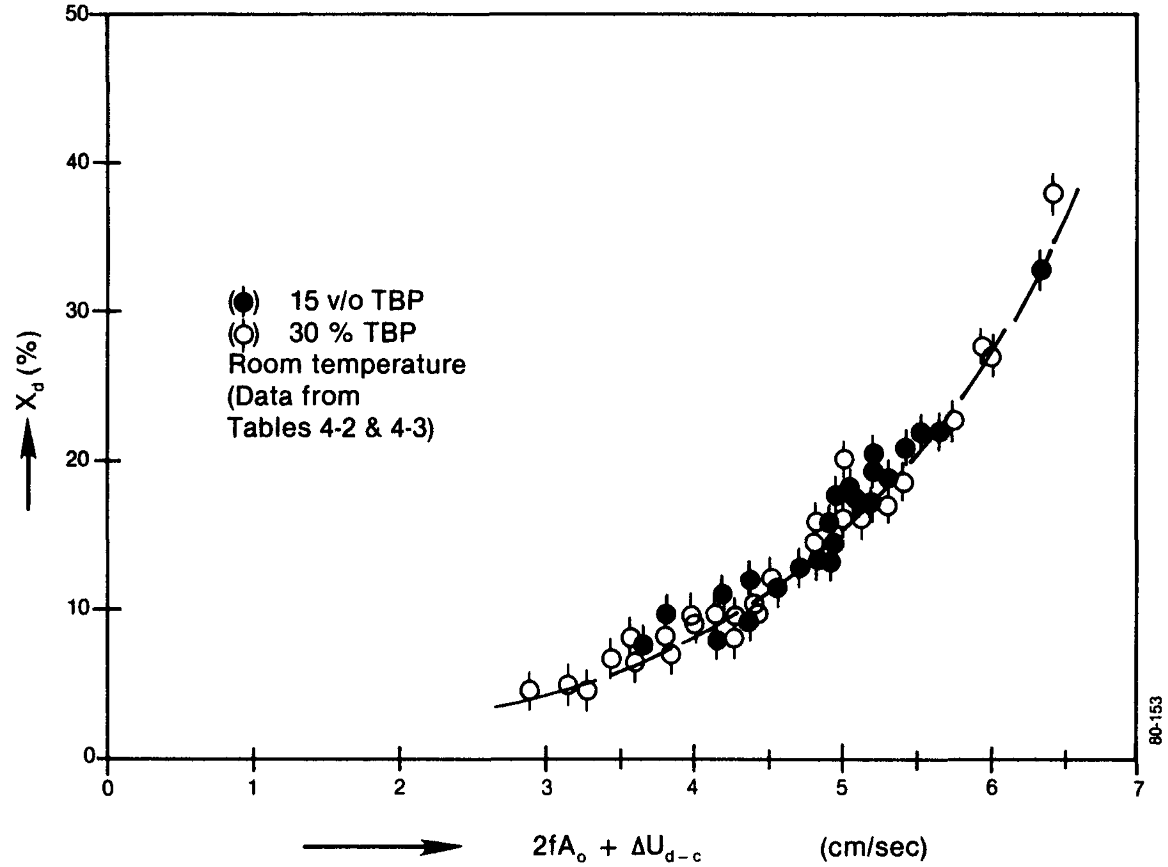
COMPARISON OF 1A COLUMN
FLOODING CURVES FOR 15 v/o AND 30 v/o TBP

FIGURE 4-5



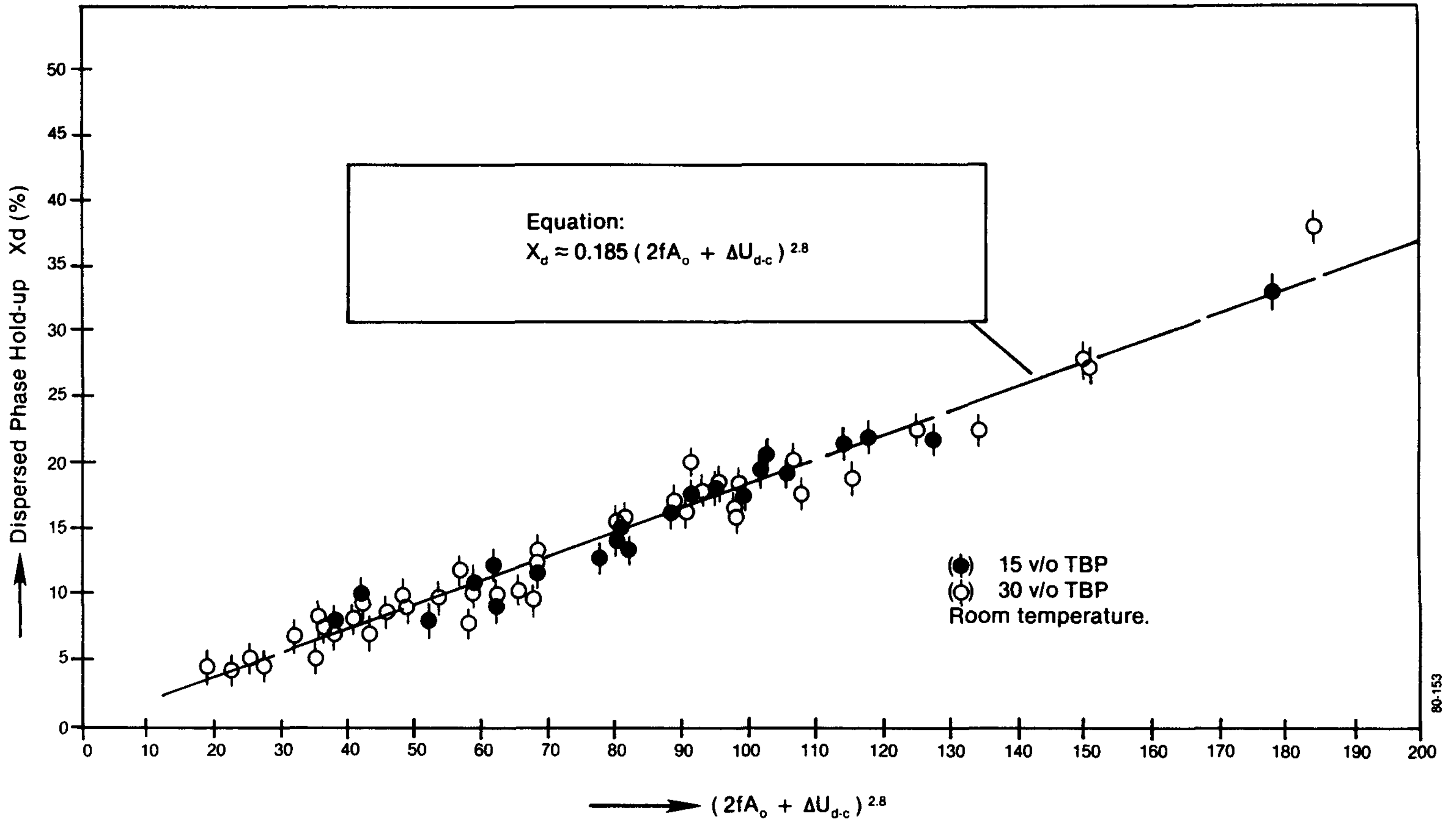
COMPARISON OF 1BX COLUMN
FLOODING CURVES FOR 15 v/o AND 30 v/o TBP

FIGURE 4-6



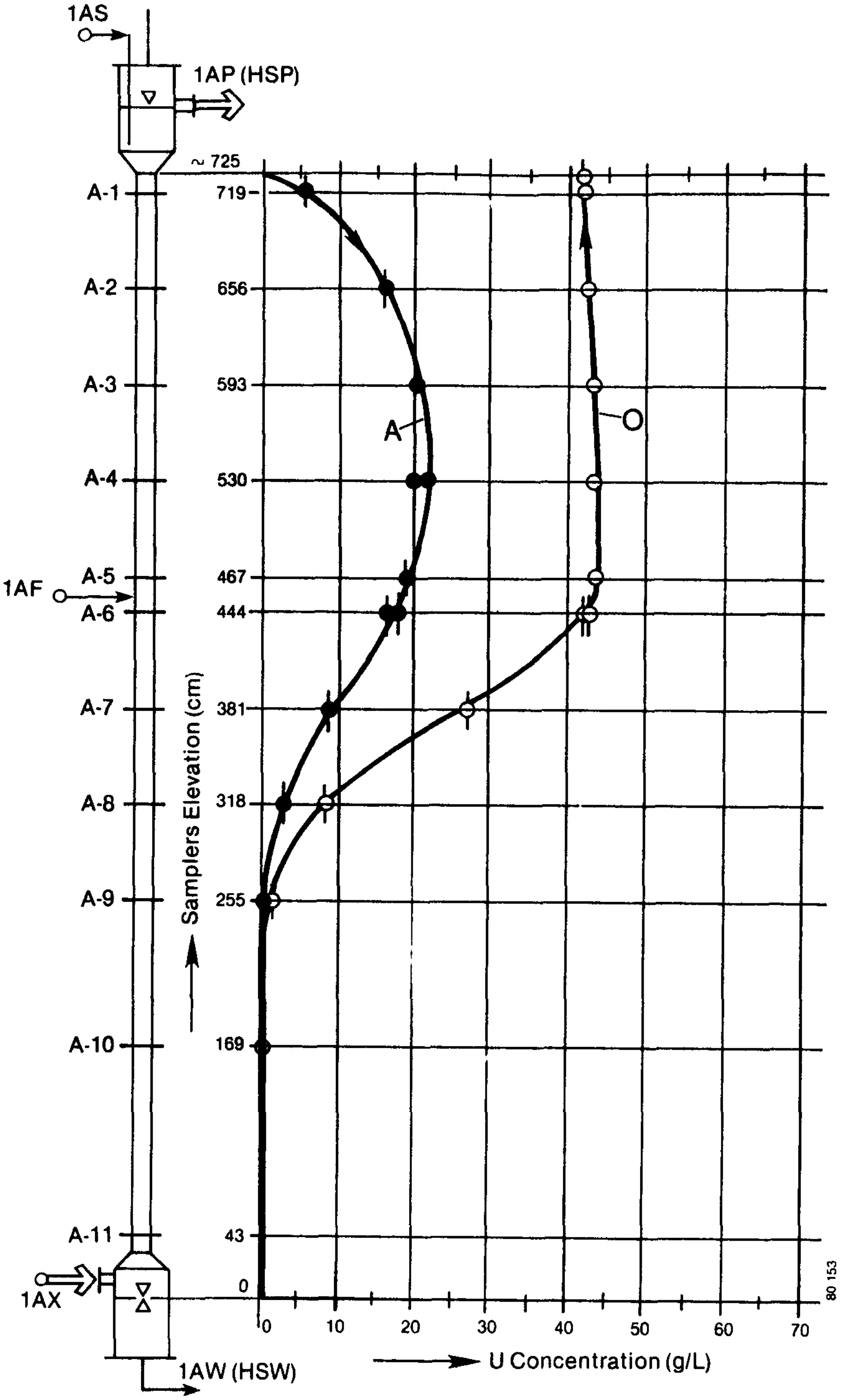
DISPERSED PHASE HOLDUP VERSUS $2fA_o + \Delta U_{d-c}$

FIGURE 4-7



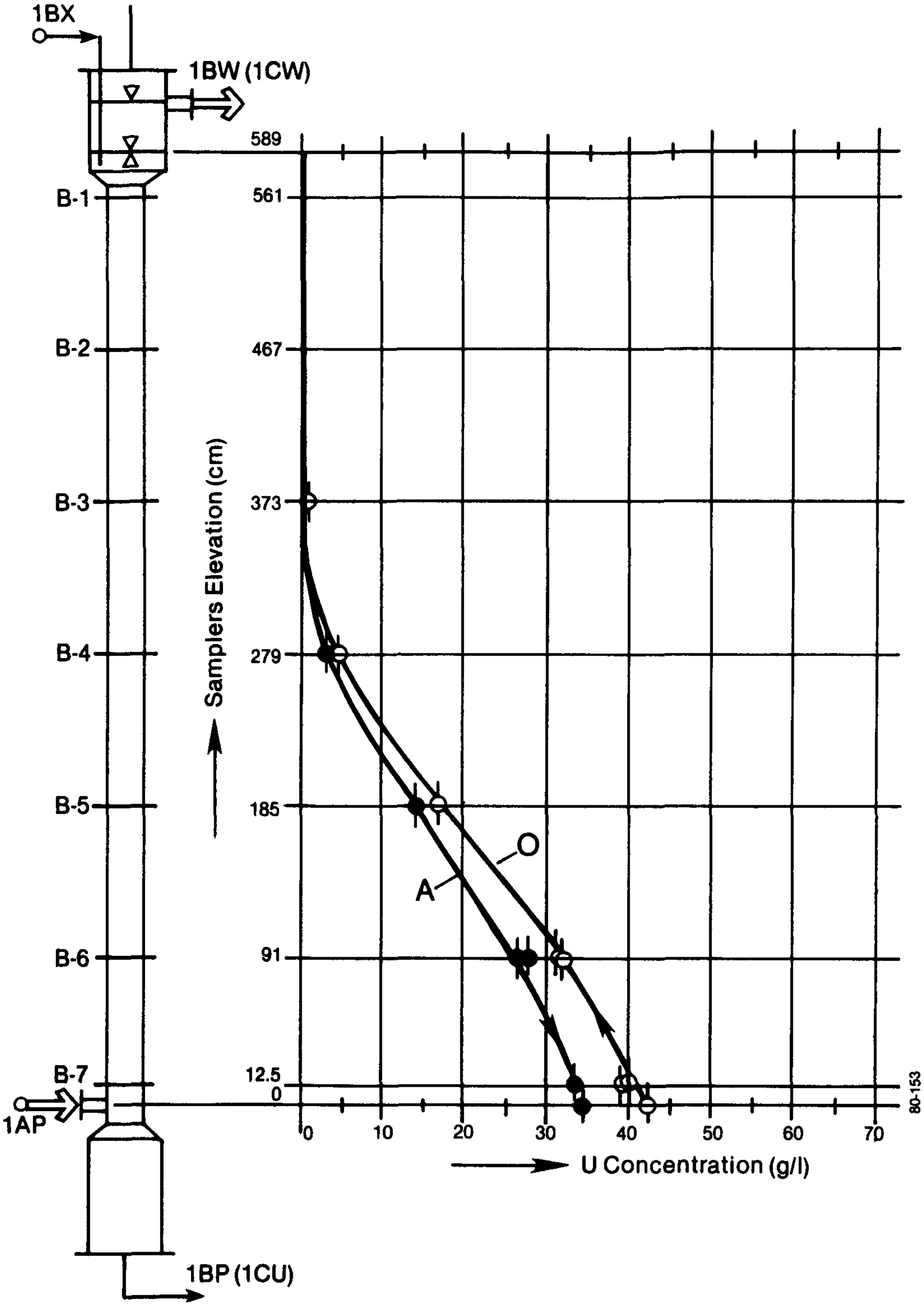
DISPERSED PHASE HOLDUP VERSUS $(2fA_o + \Delta U_{d-c})^{2.8}$

FIGURE 4-8



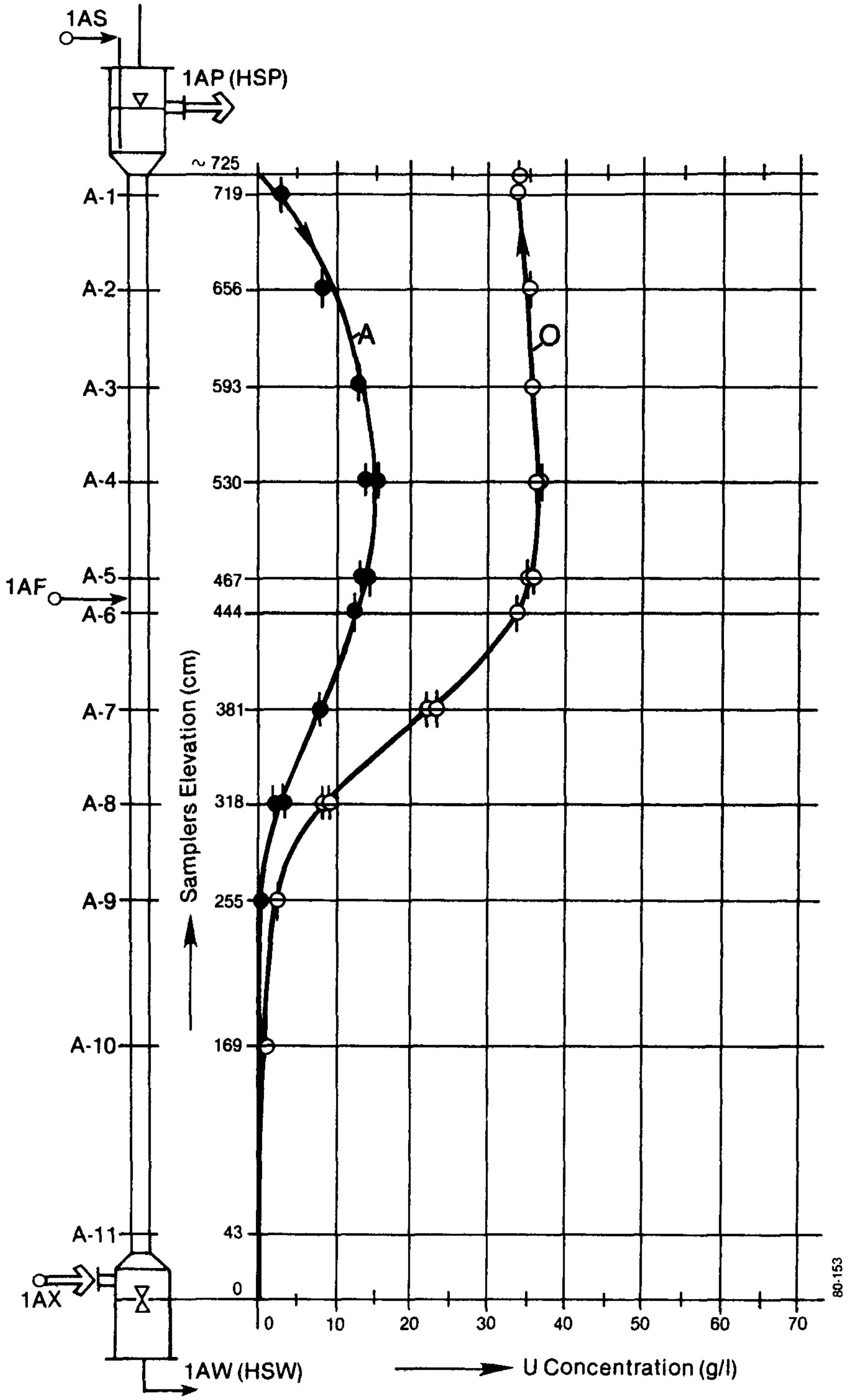
THE HS COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-1 (15 v/o TBP)

FIGURE 4-9



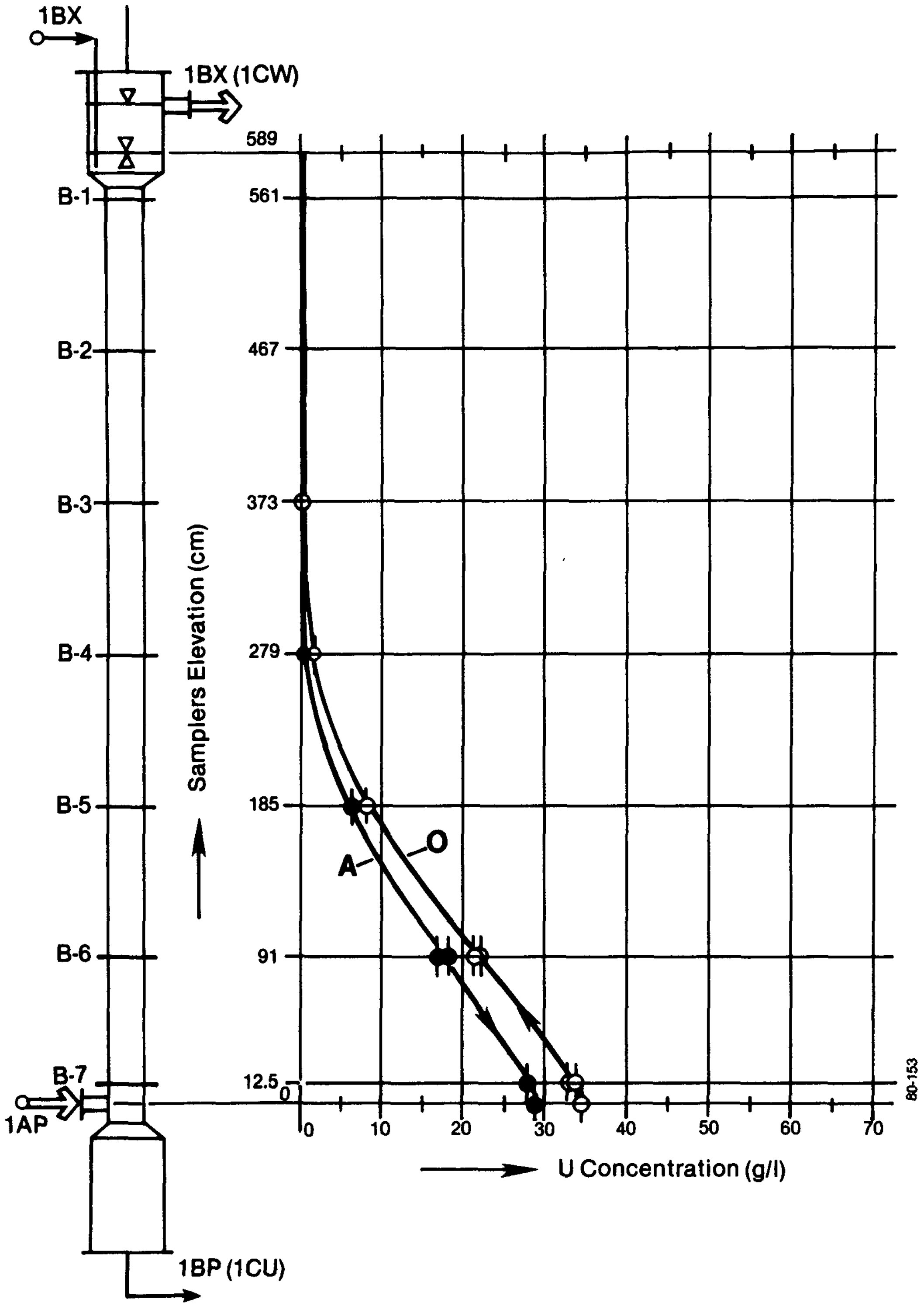
THE 1C COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-1 (15 v/o TBP)

FIGURE 4-10



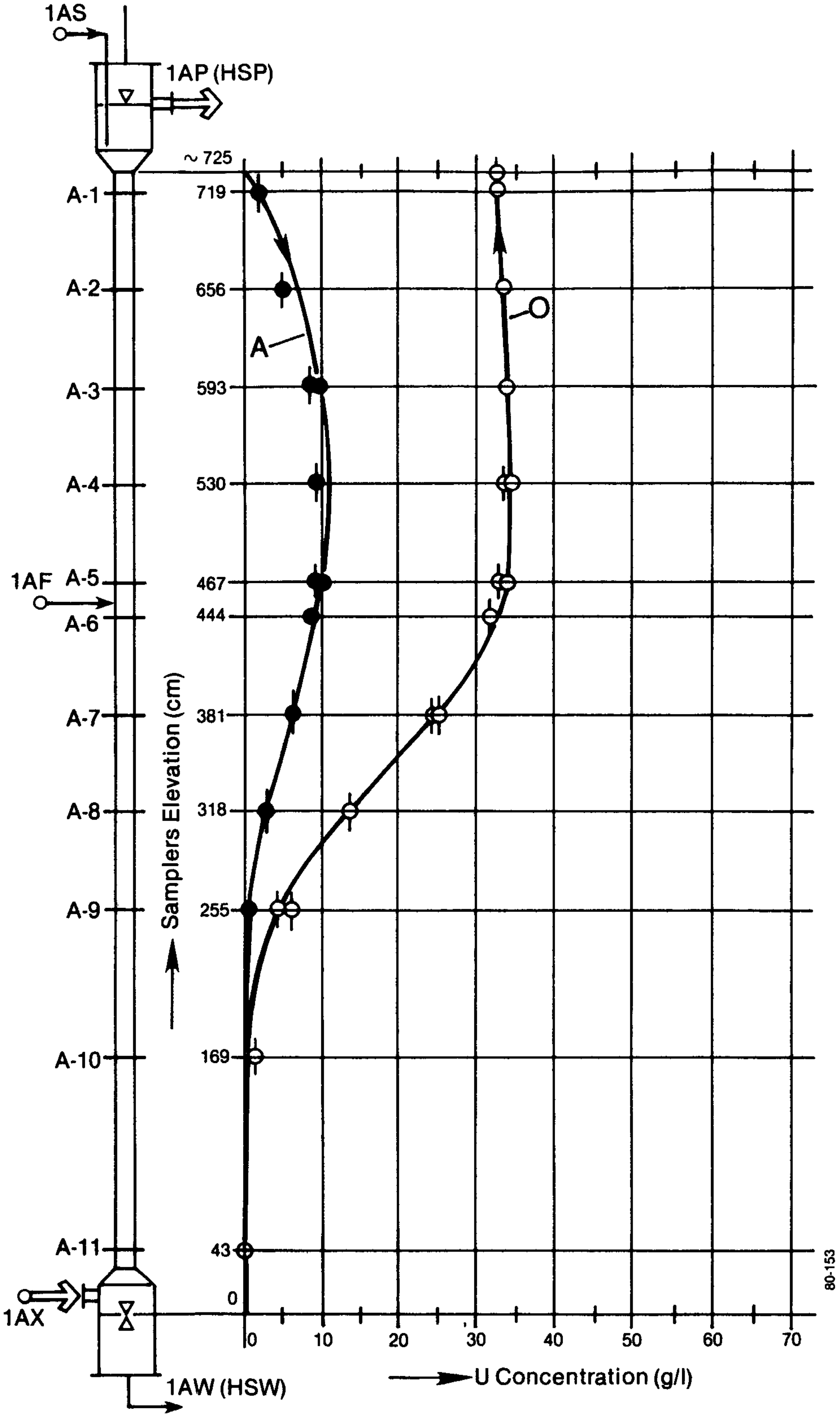
THE HS COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-2 (15 v/o TBP)

FIGURE 4-11



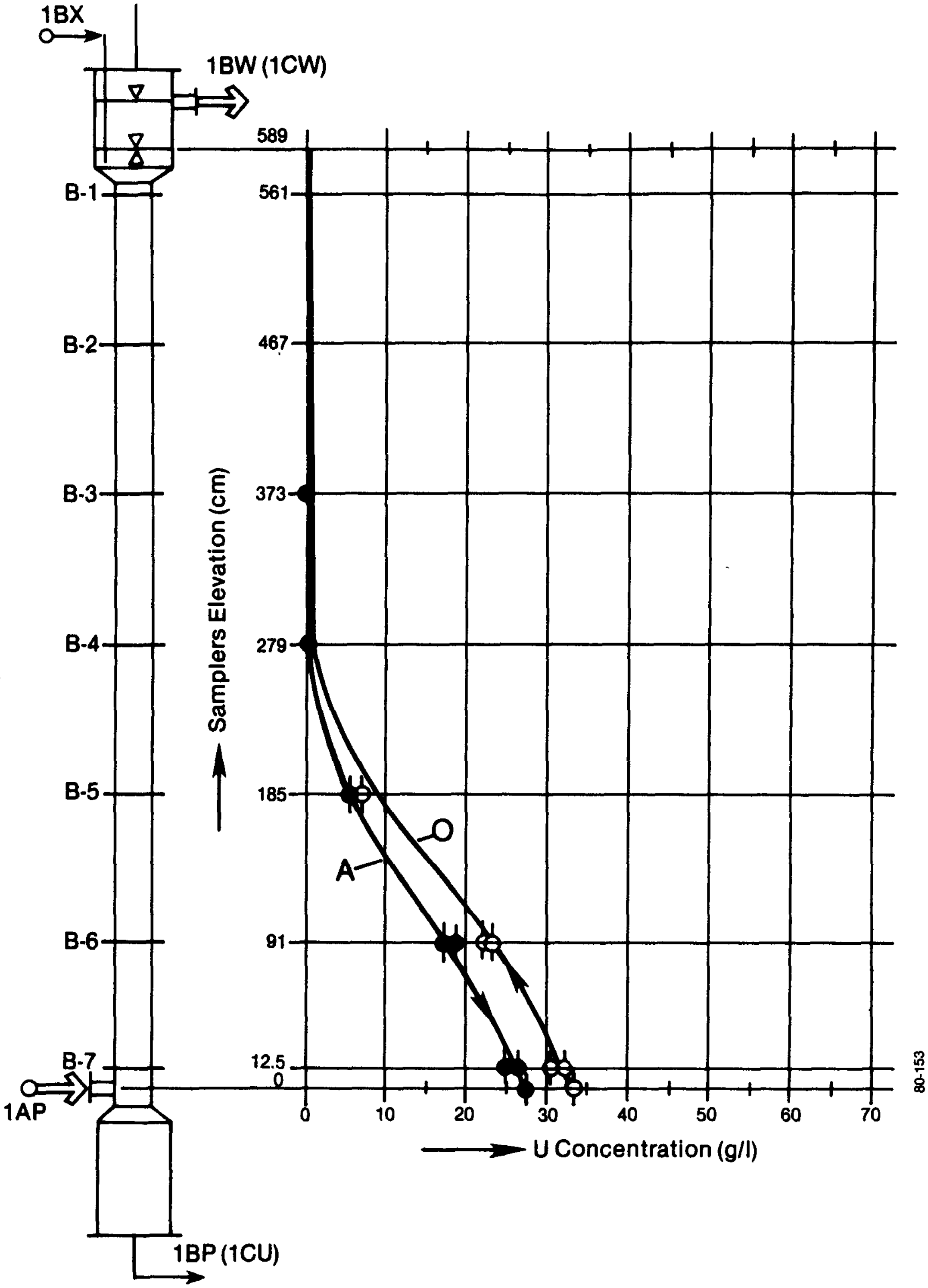
THE 1C COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-2 (15 v/o TBP)

FIGURE 4-12



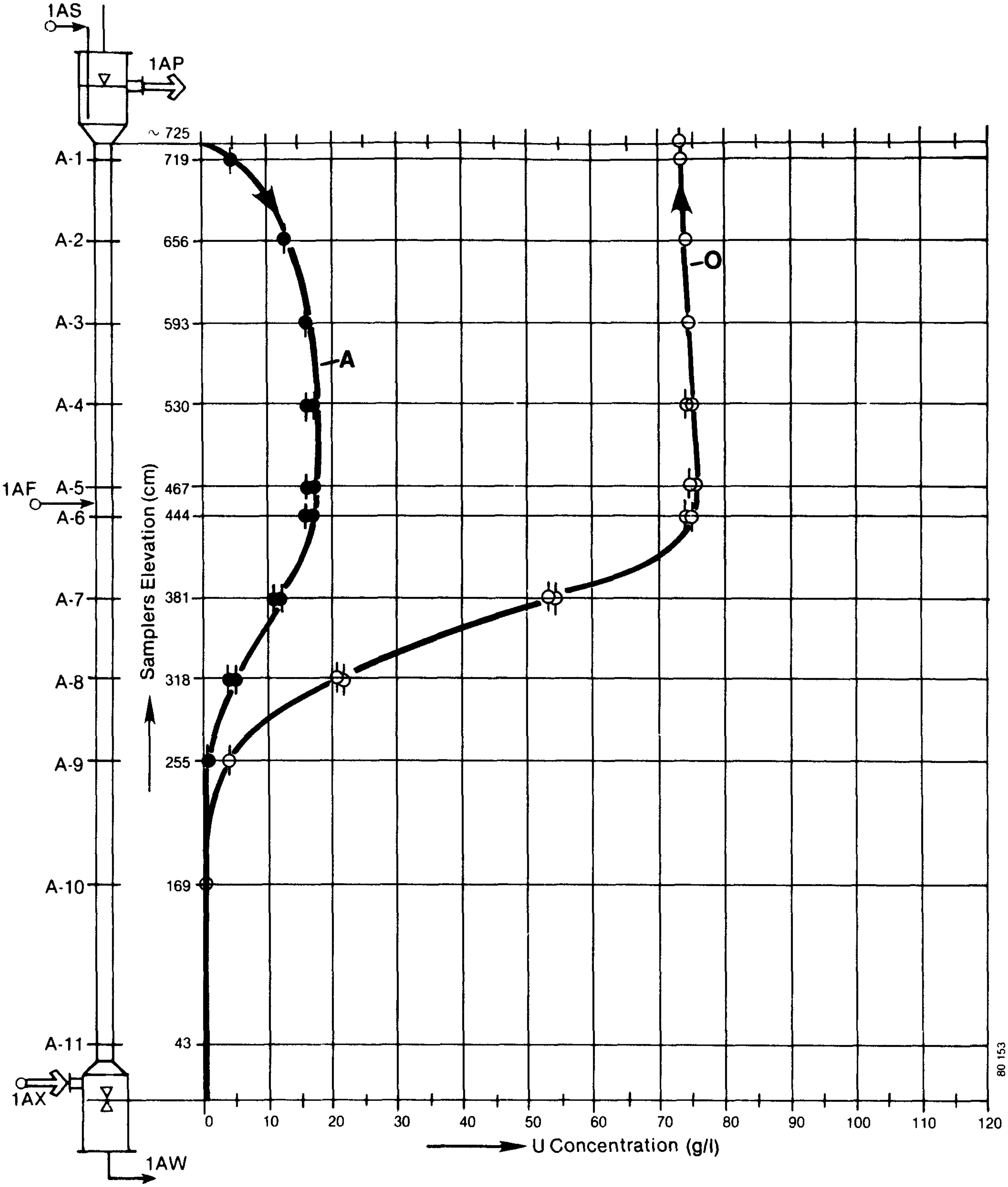
THE HS COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-3 (15 v/o TBP)

FIGURE 4-13



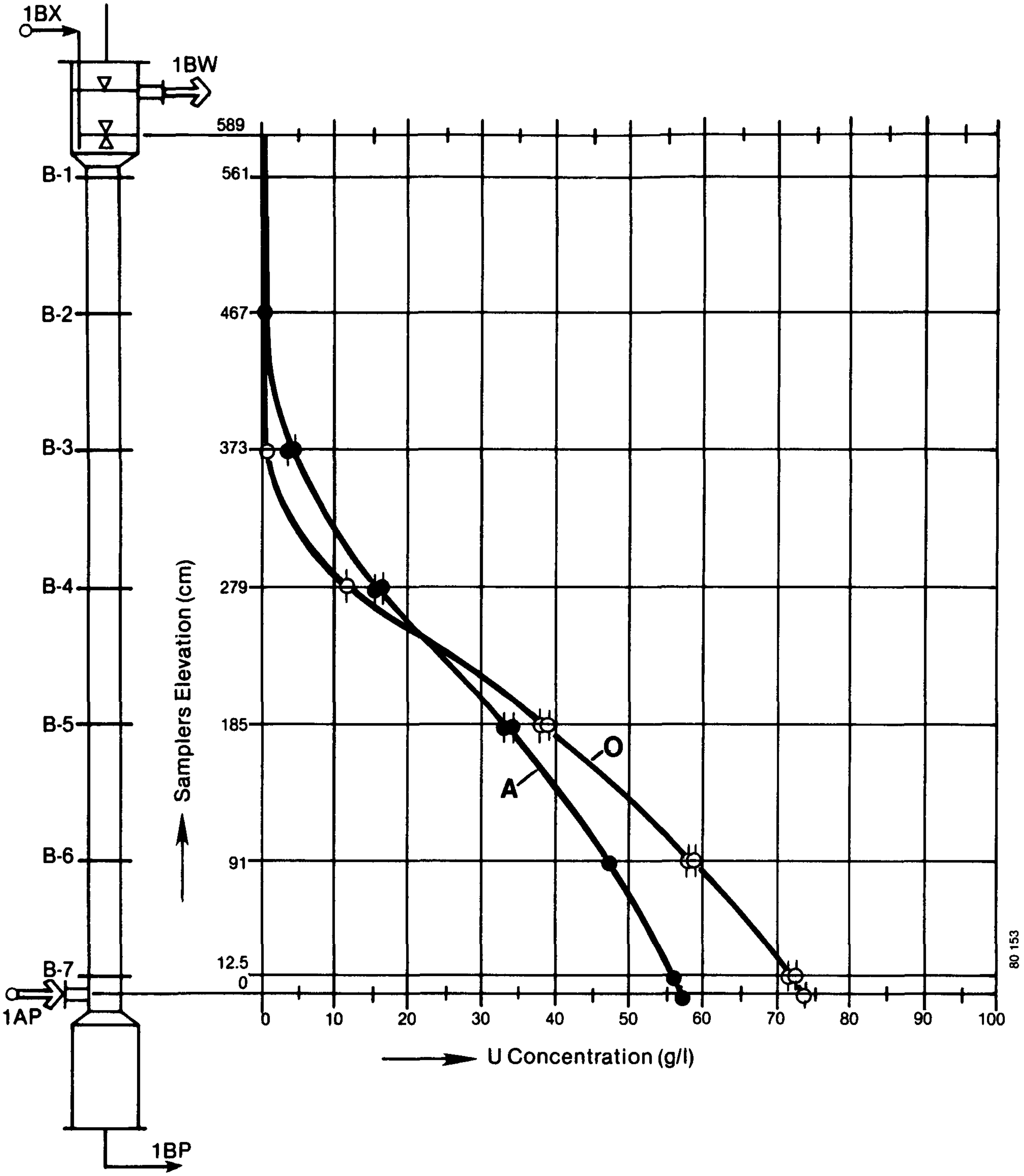
THE 1C COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-3 (15 v/o TBP)

FIGURE 4-14



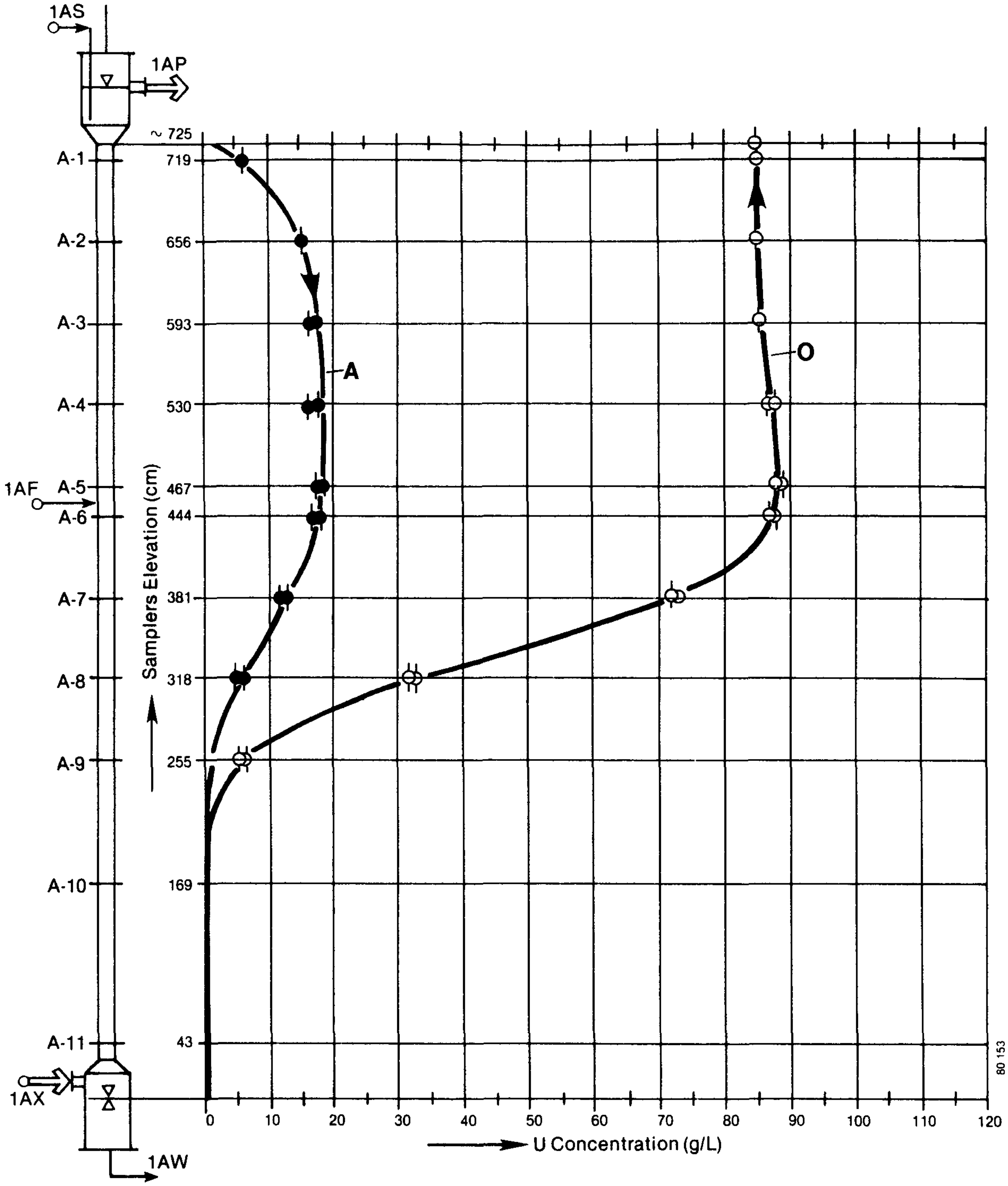
THE HS COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-4 (30 v/o TBP)

FIGURE 4-15



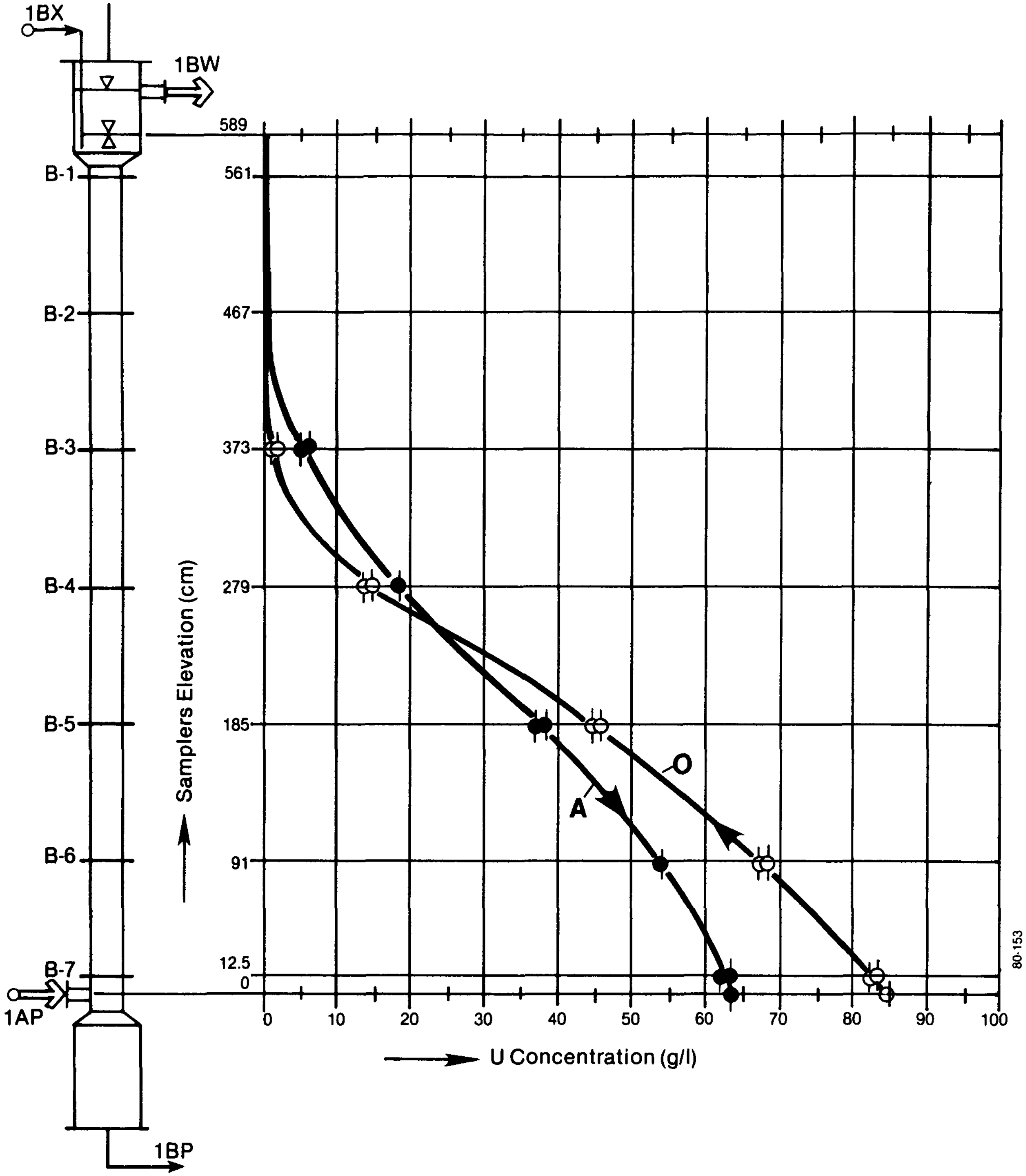
THE 1C COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-4

FIGURE 4-16



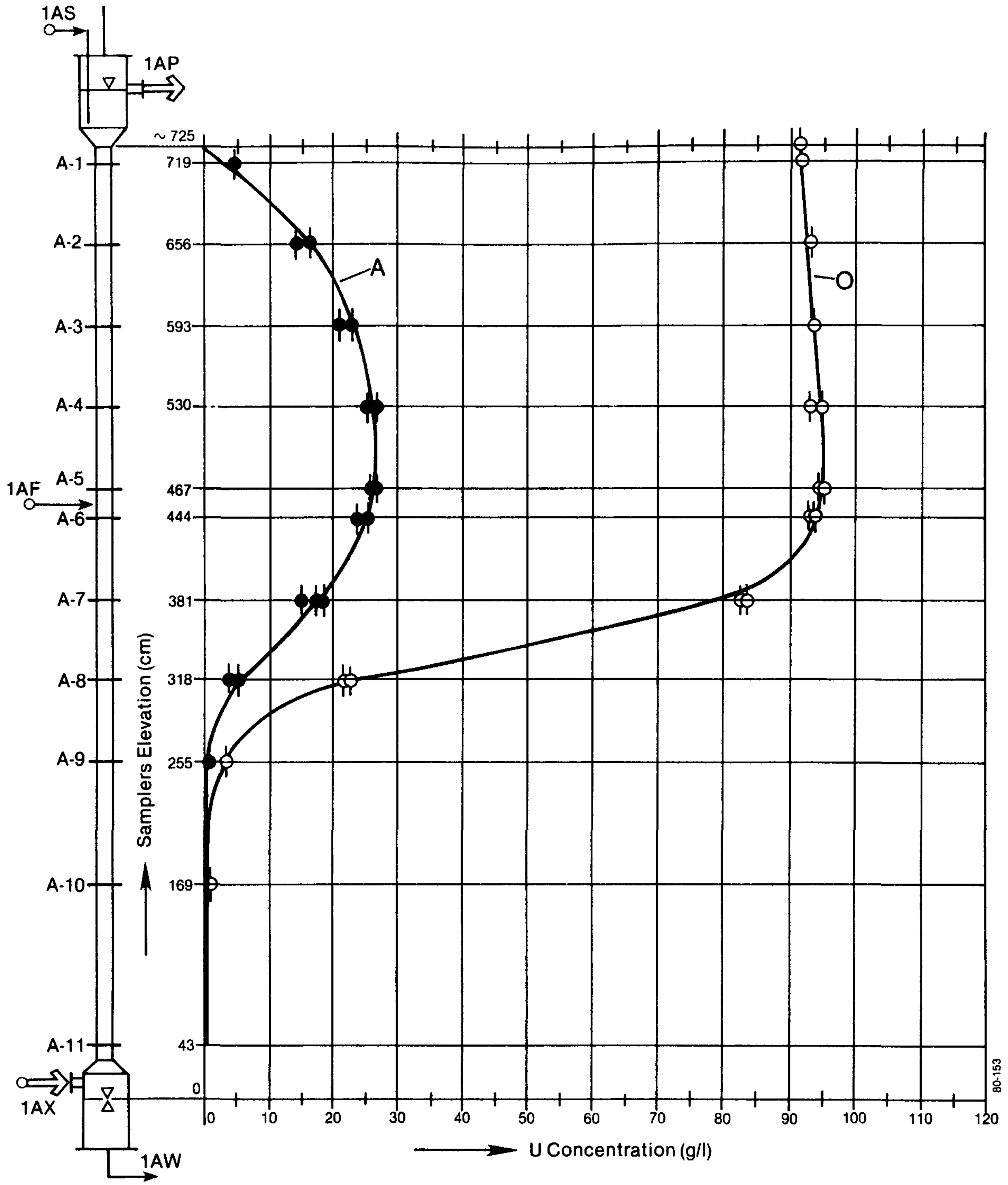
THE HS COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-5 (30 v/o TBP)

FIGURE 4-17



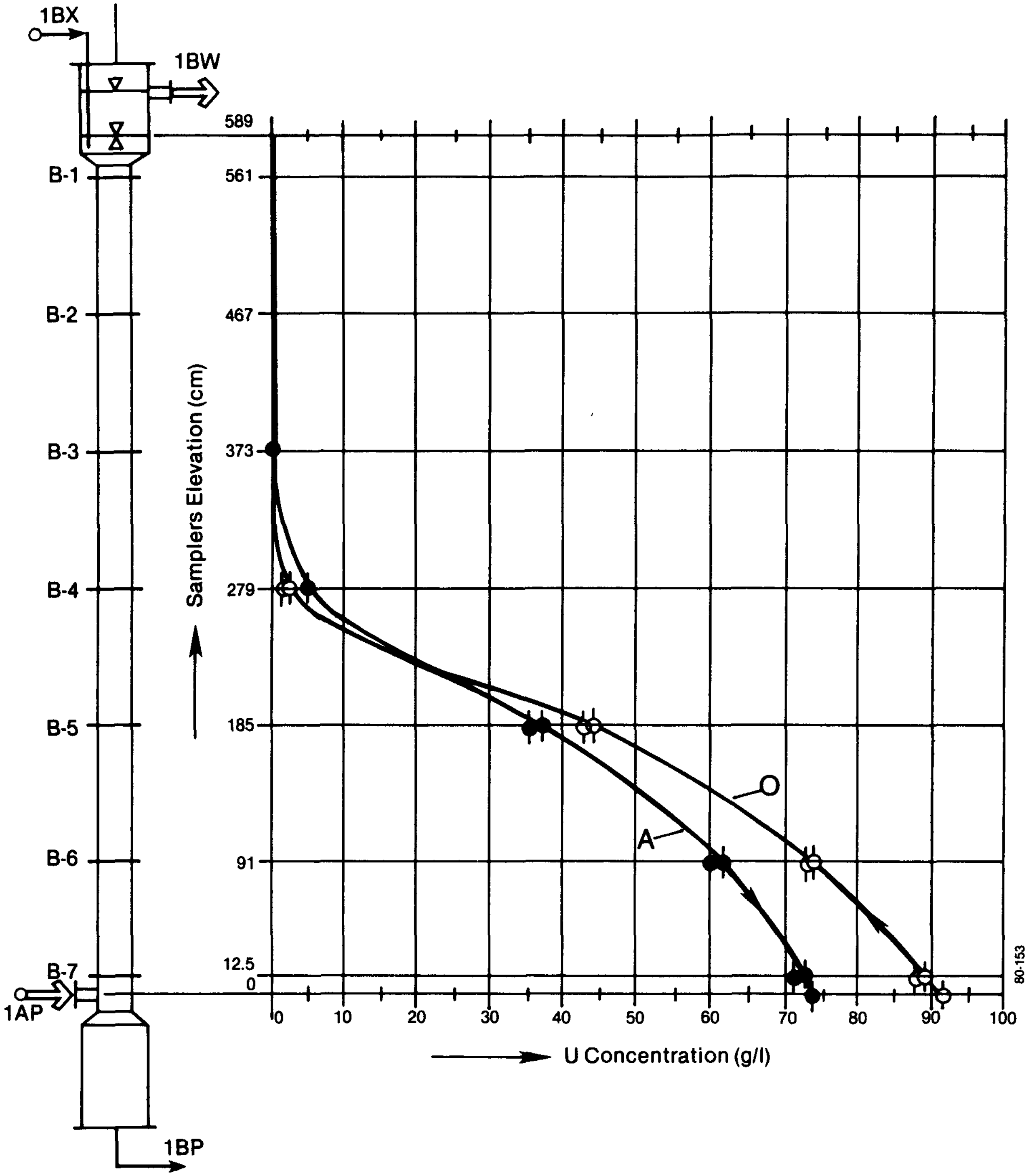
THE 1C COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-5

FIGURE 4-18



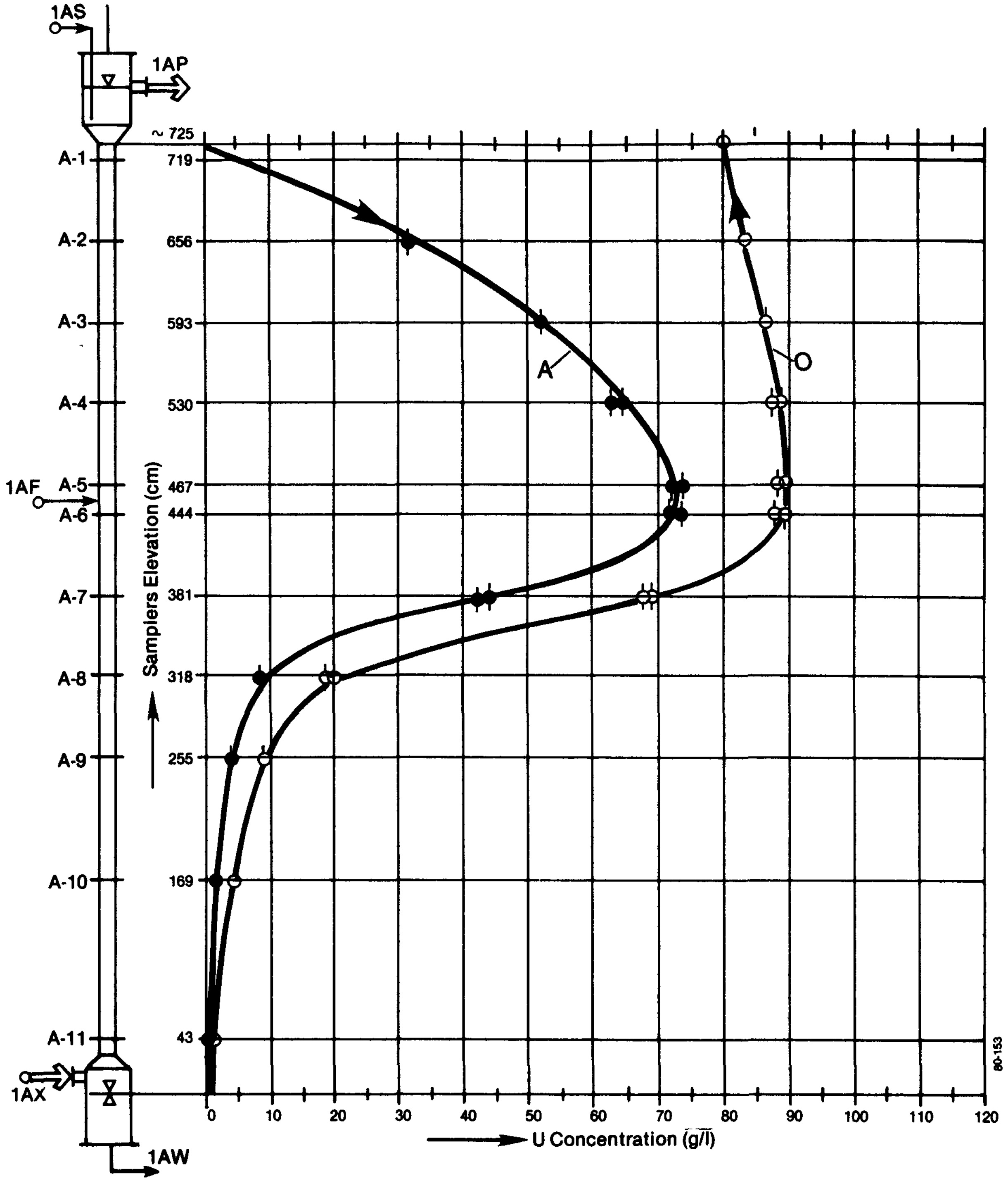
THE HS COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-6 (30 v/o TBP)

FIGURE 4-19



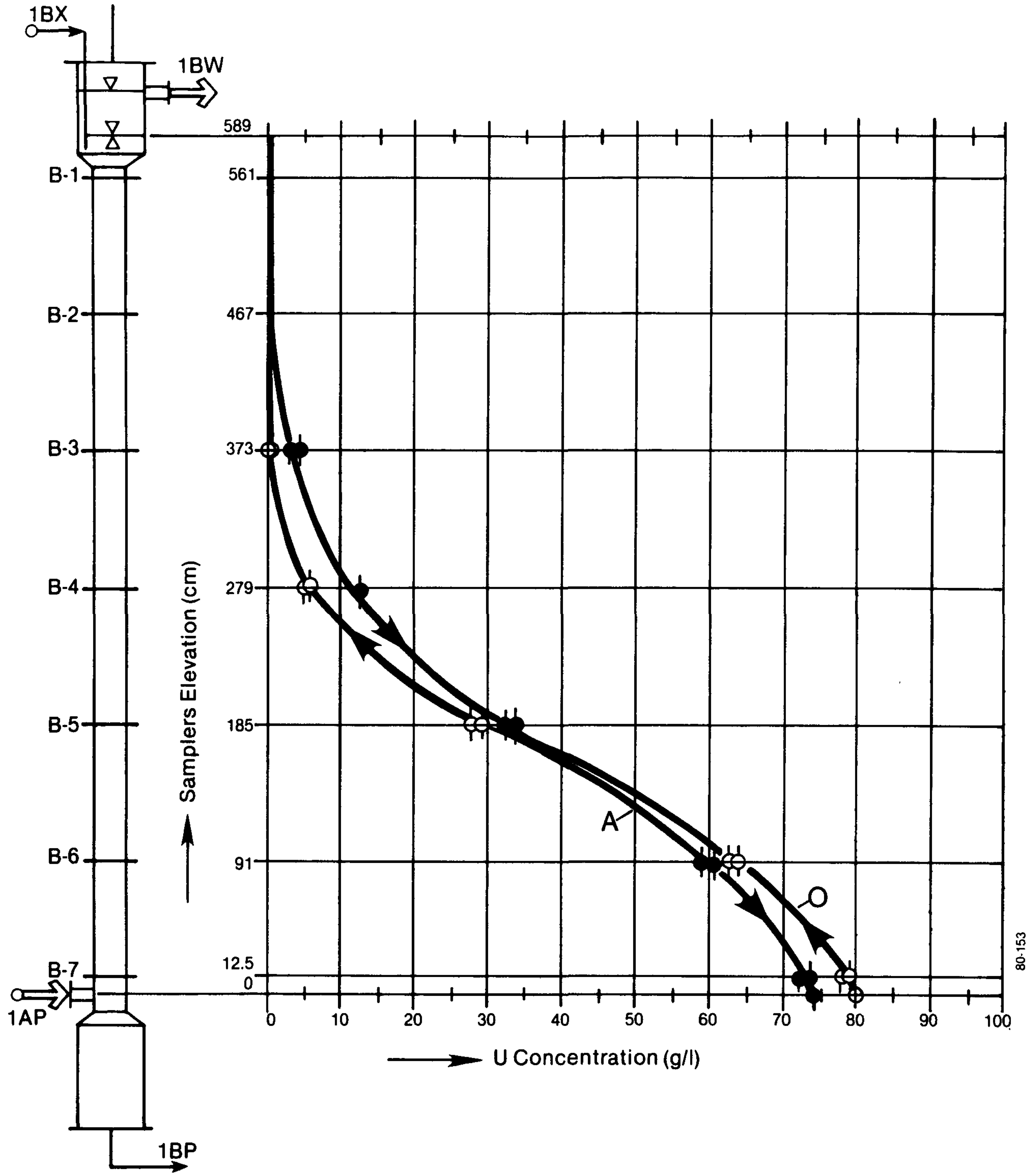
THE 1C COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN HS-6

FIGURE 4-20



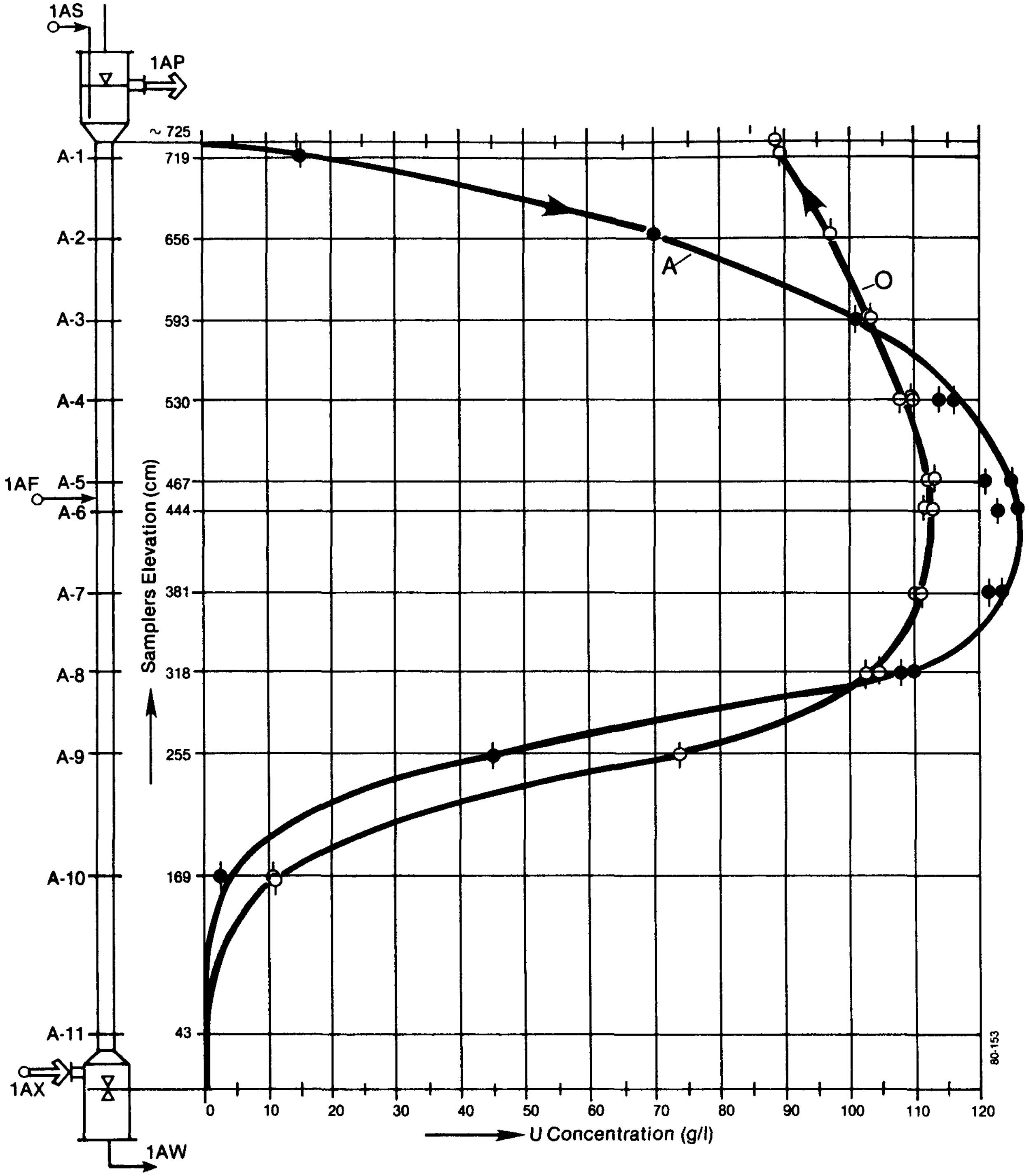
THE 2D COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 2D-1 (30 v/o TBP)

FIGURE 4-21



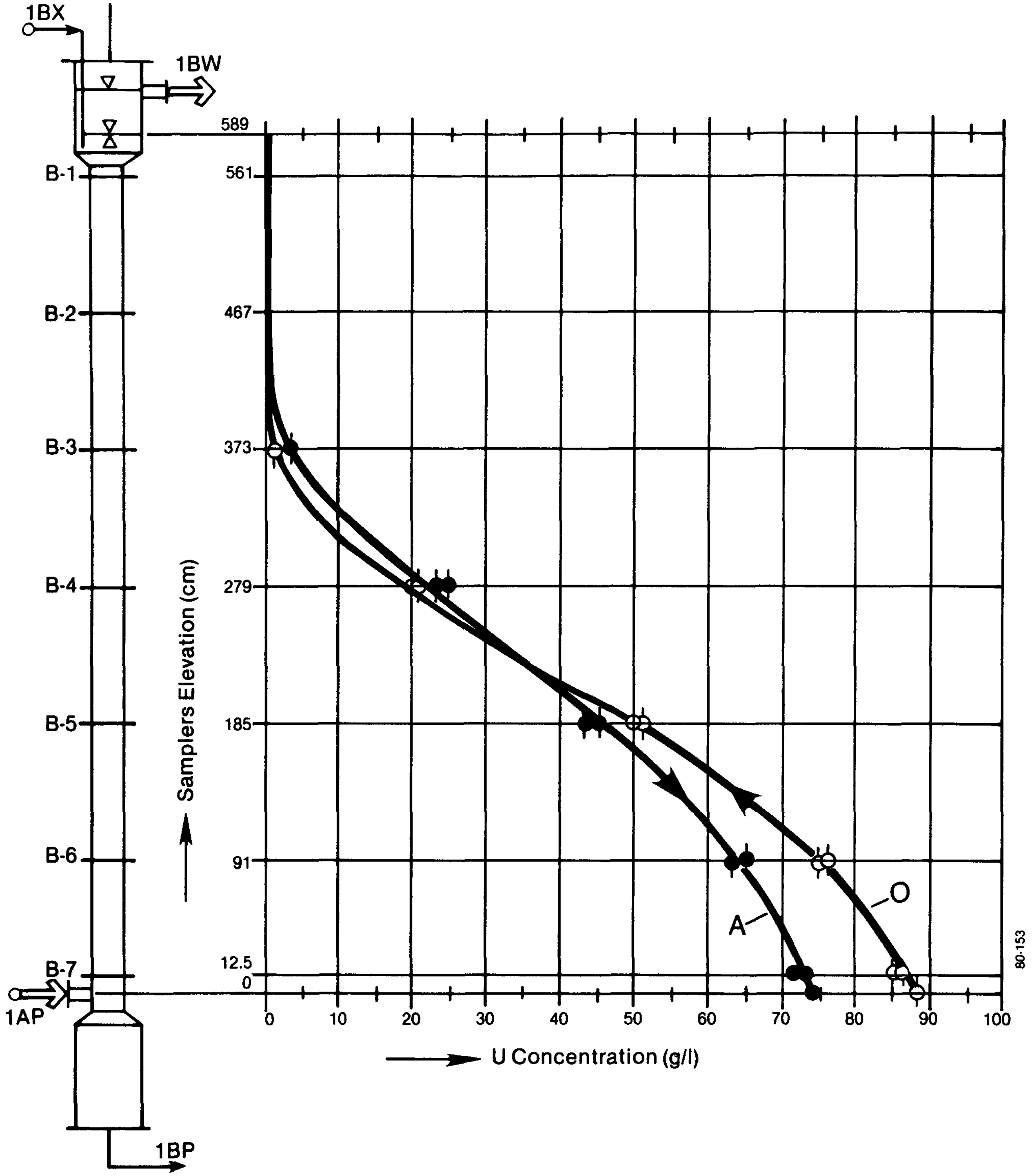
THE 2E COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 2D-1

FIGURE 4-22



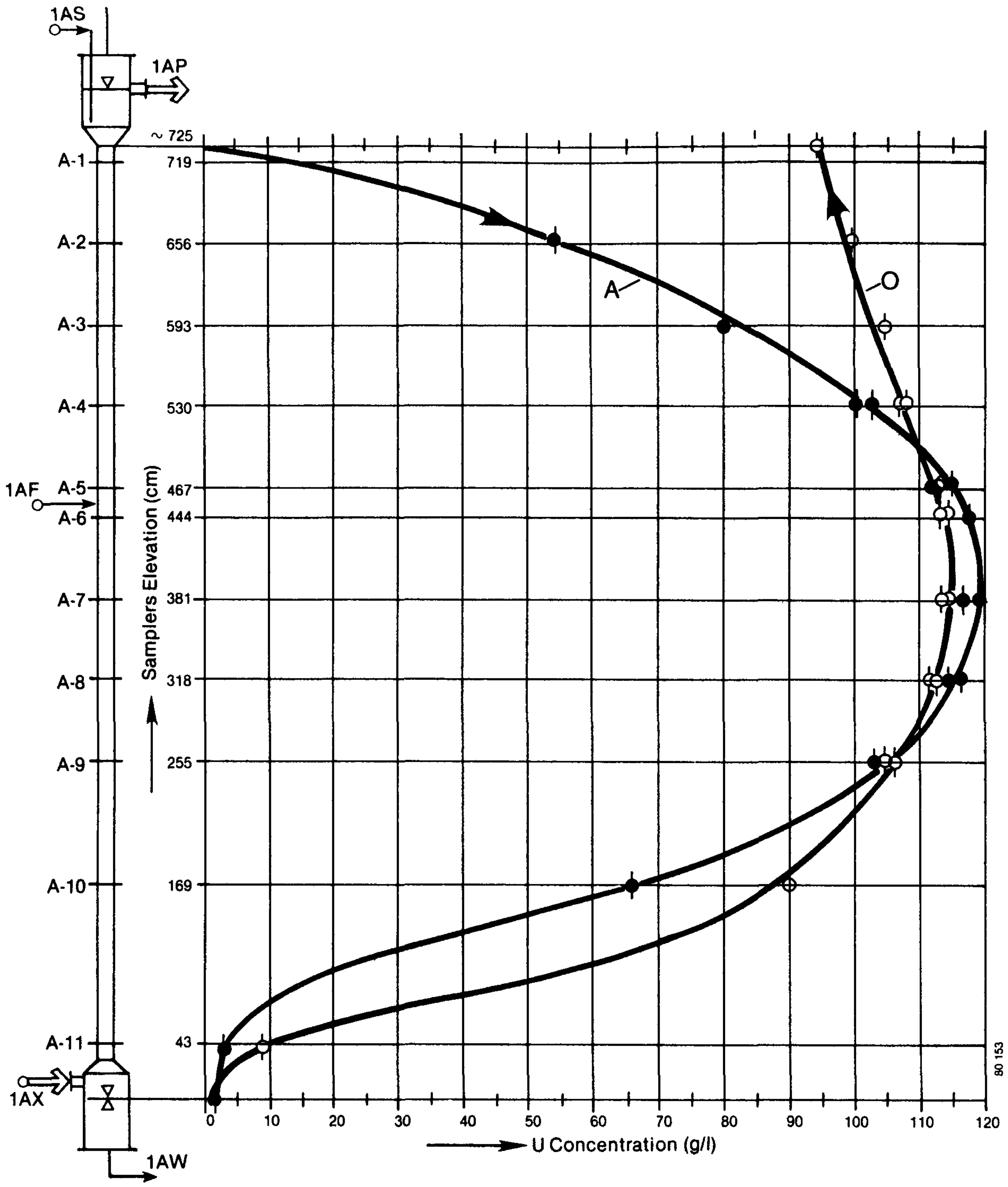
THE 2D COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 2D-2 (30 v/o TBP)

FIGURE 4-23



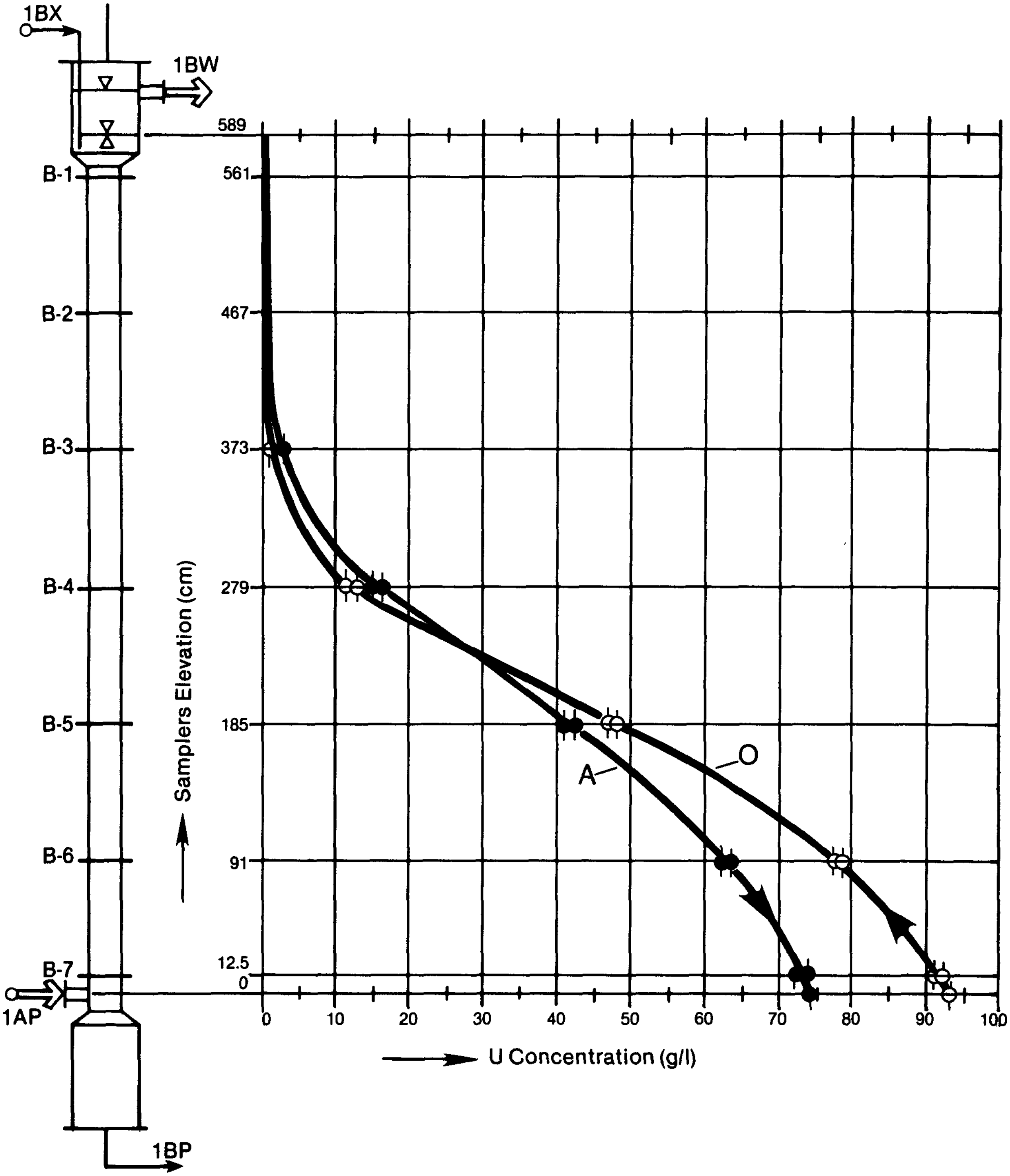
THE 2E COLUMN EXPERIMENTAL
CONCENTRATION PROFILES FOR RUN 2D-2

FIGURE 4-24



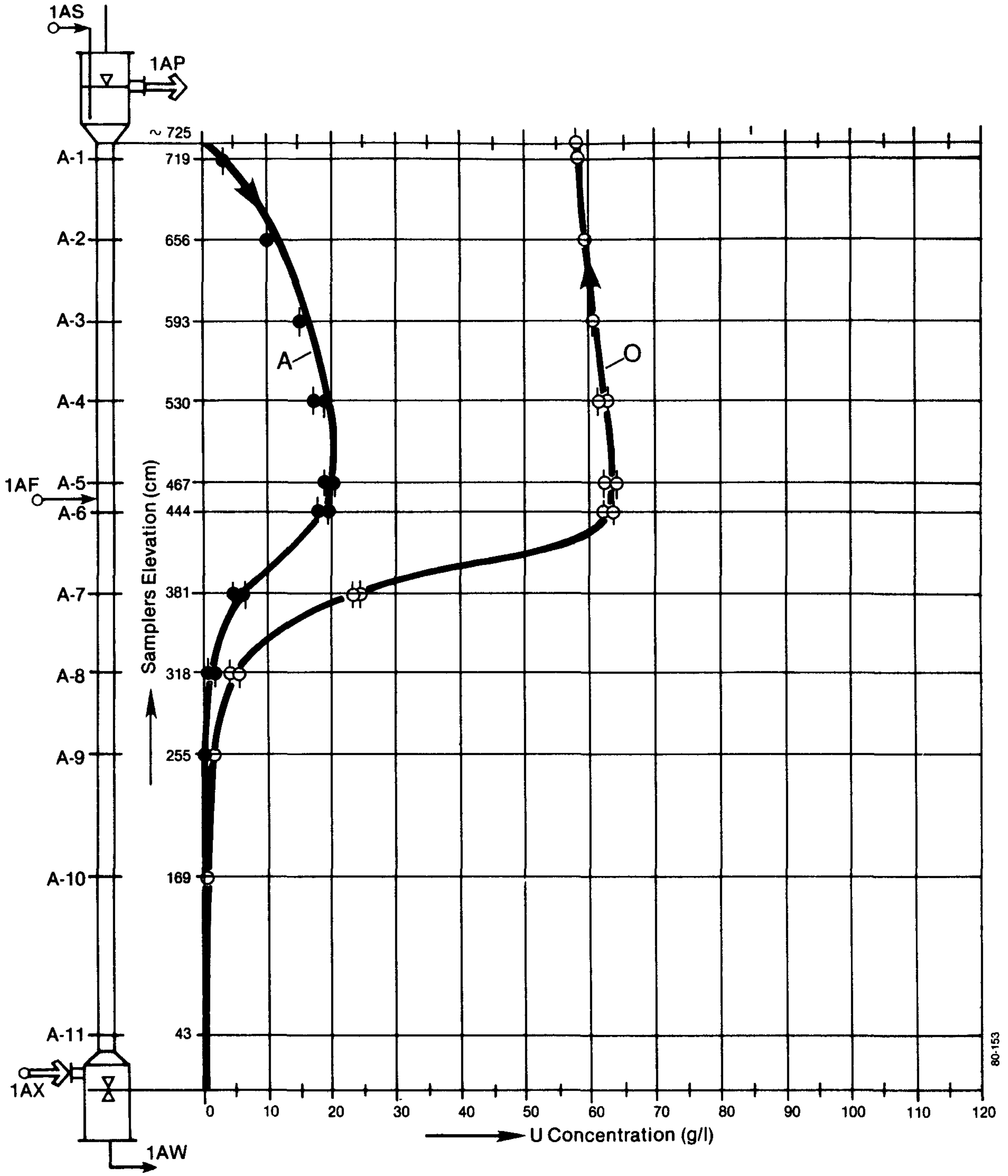
THE 2D COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 2D-3 (30 v/o TBP)

FIGURE 4-25



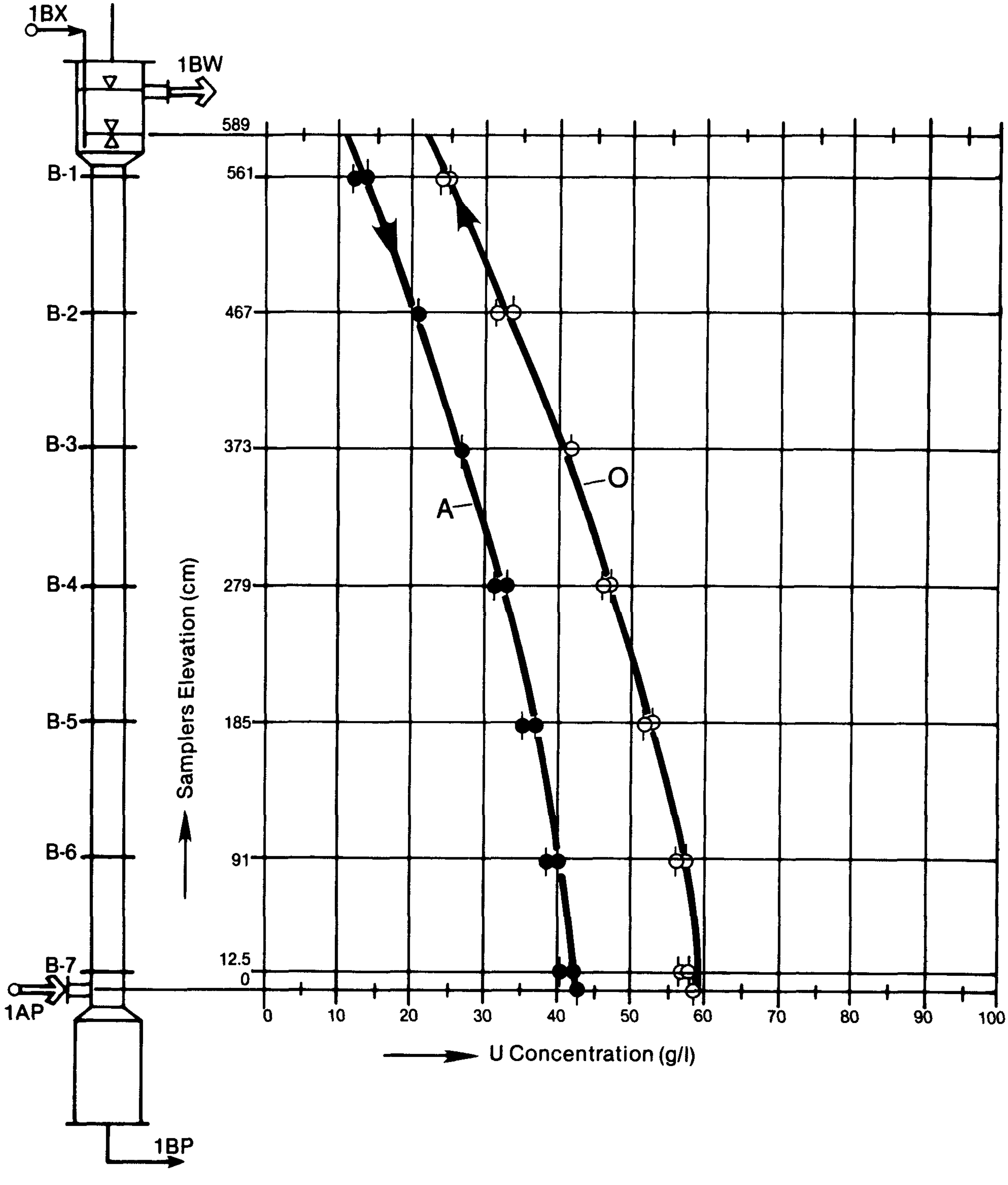
THE 2E COLUMN EXPERIMENTAL
CONCENTRATION PROFILES FOR RUN 2D-3

FIGURE 4-26



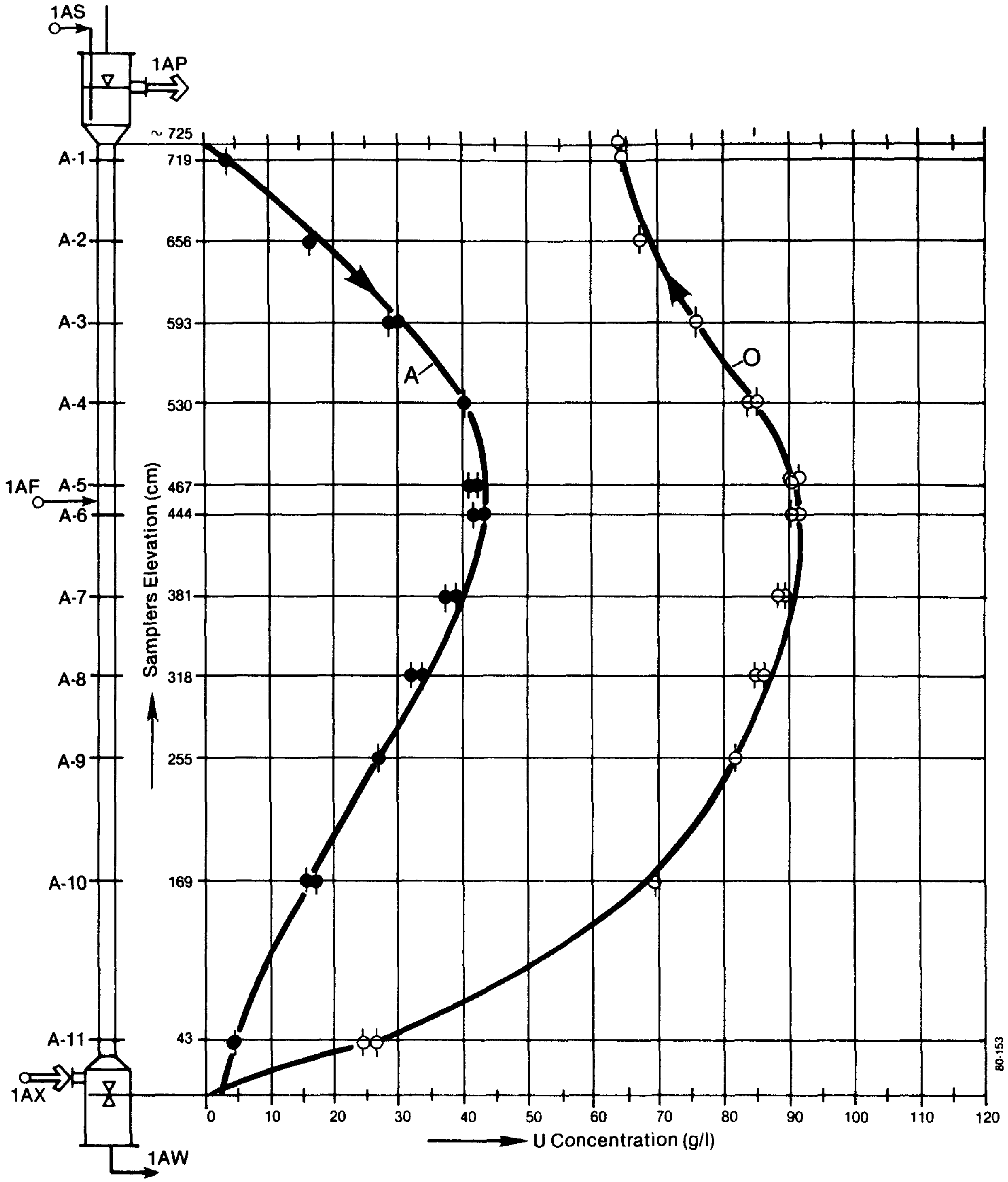
THE 2A COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 2A-1 (30 v/o TBP)

FIGURE 4-27



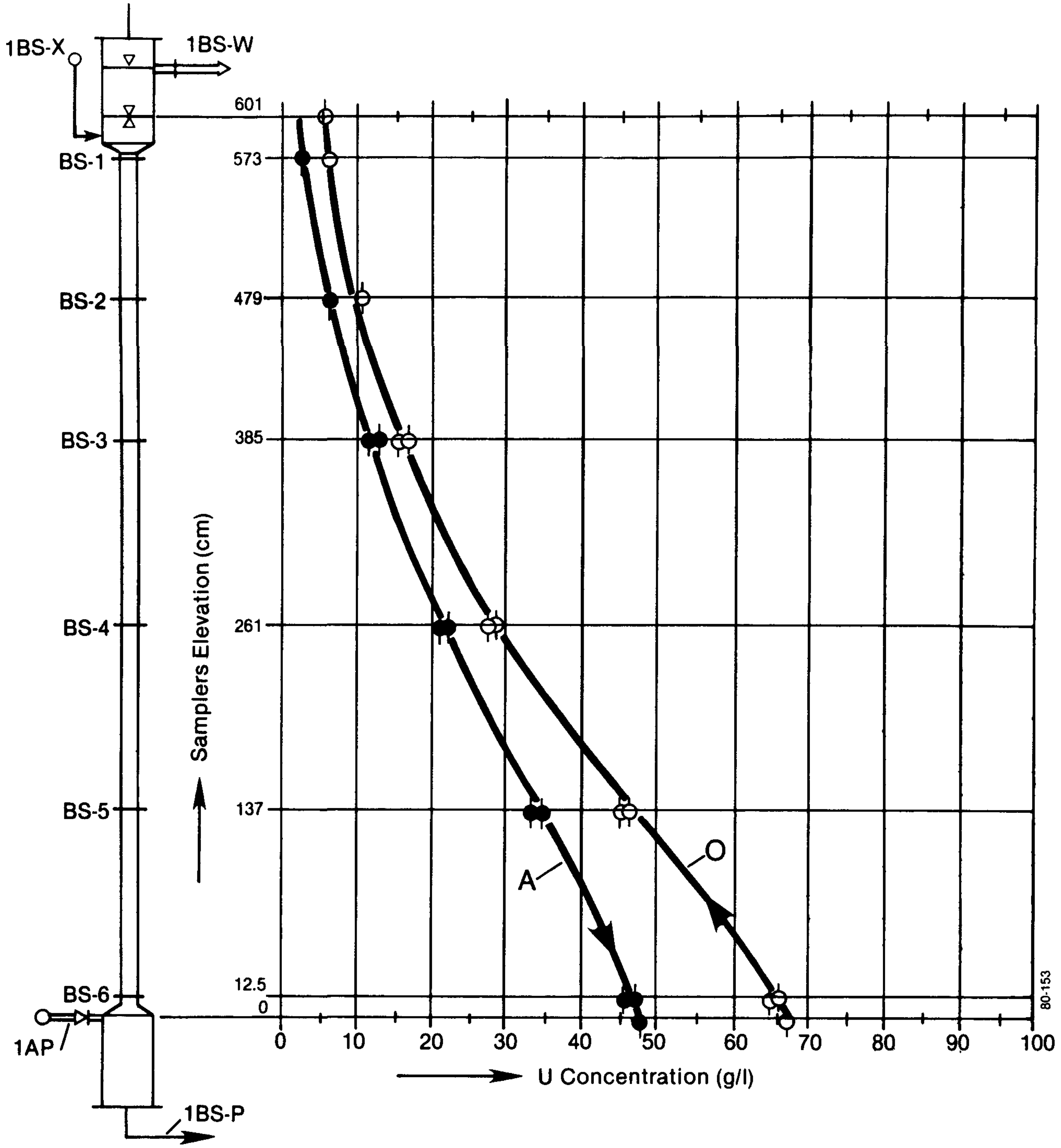
THE 2B COLUMN EXPERIMENTAL
CONCENTRATION PROFILES FOR RUN 2A-1

FIGURE 4-28



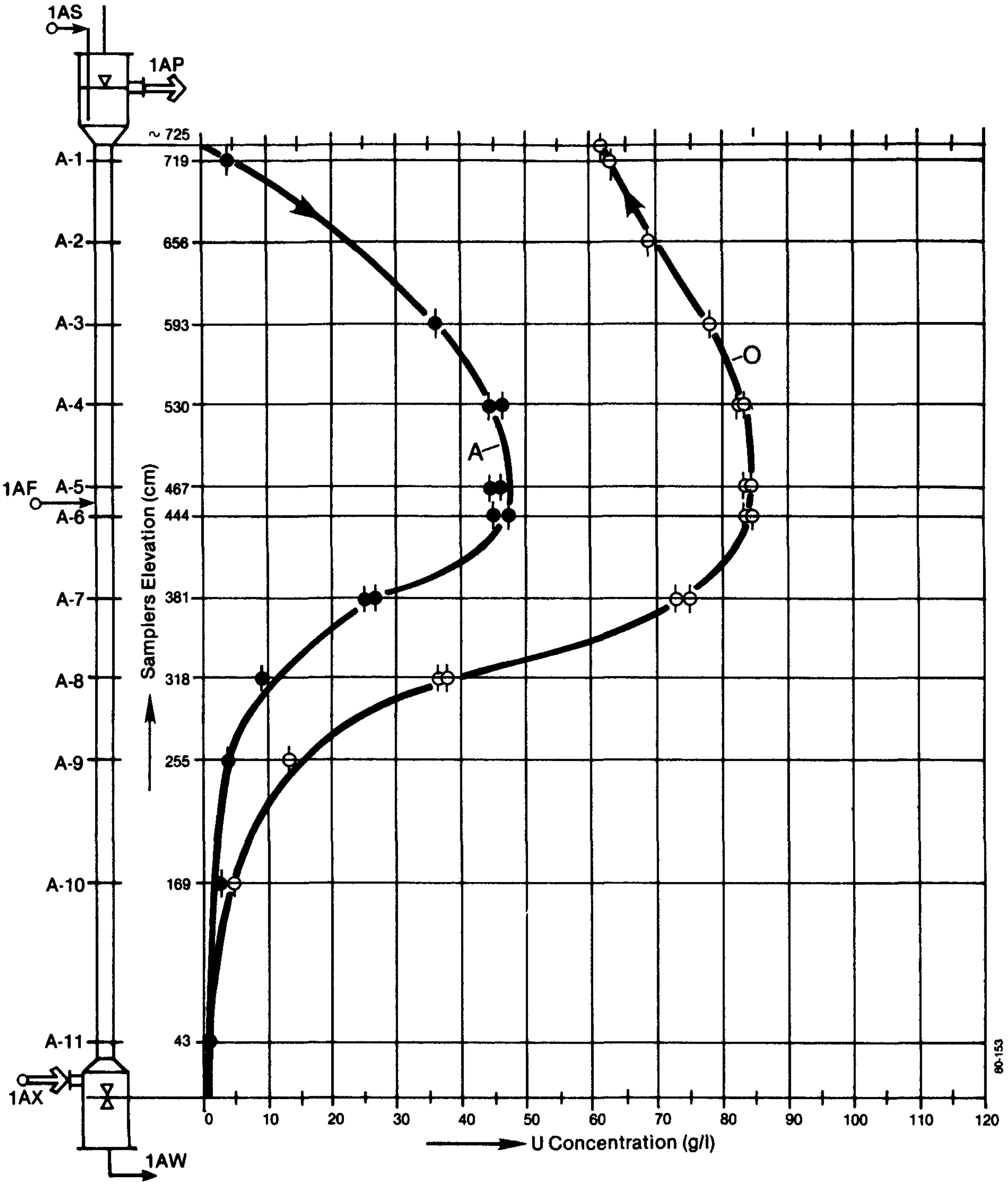
THE 2A COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 2A-2 (30 v/o TBP)

FIGURE 4-29



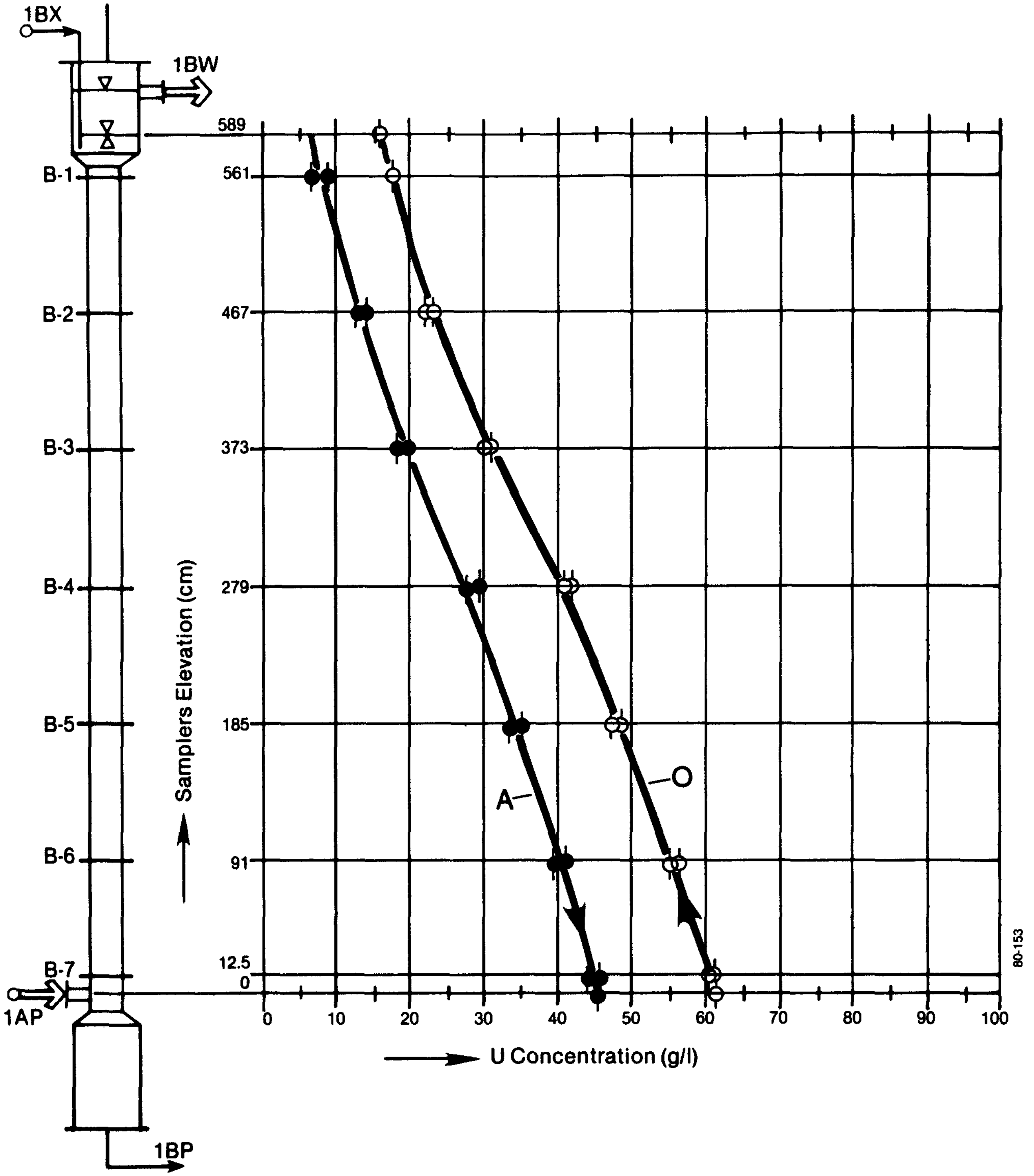
THE 2B COLUMN EXPERIMENTAL
CONCENTRATION PROFILES FOR RUN 2A-2

FIGURE 4-30



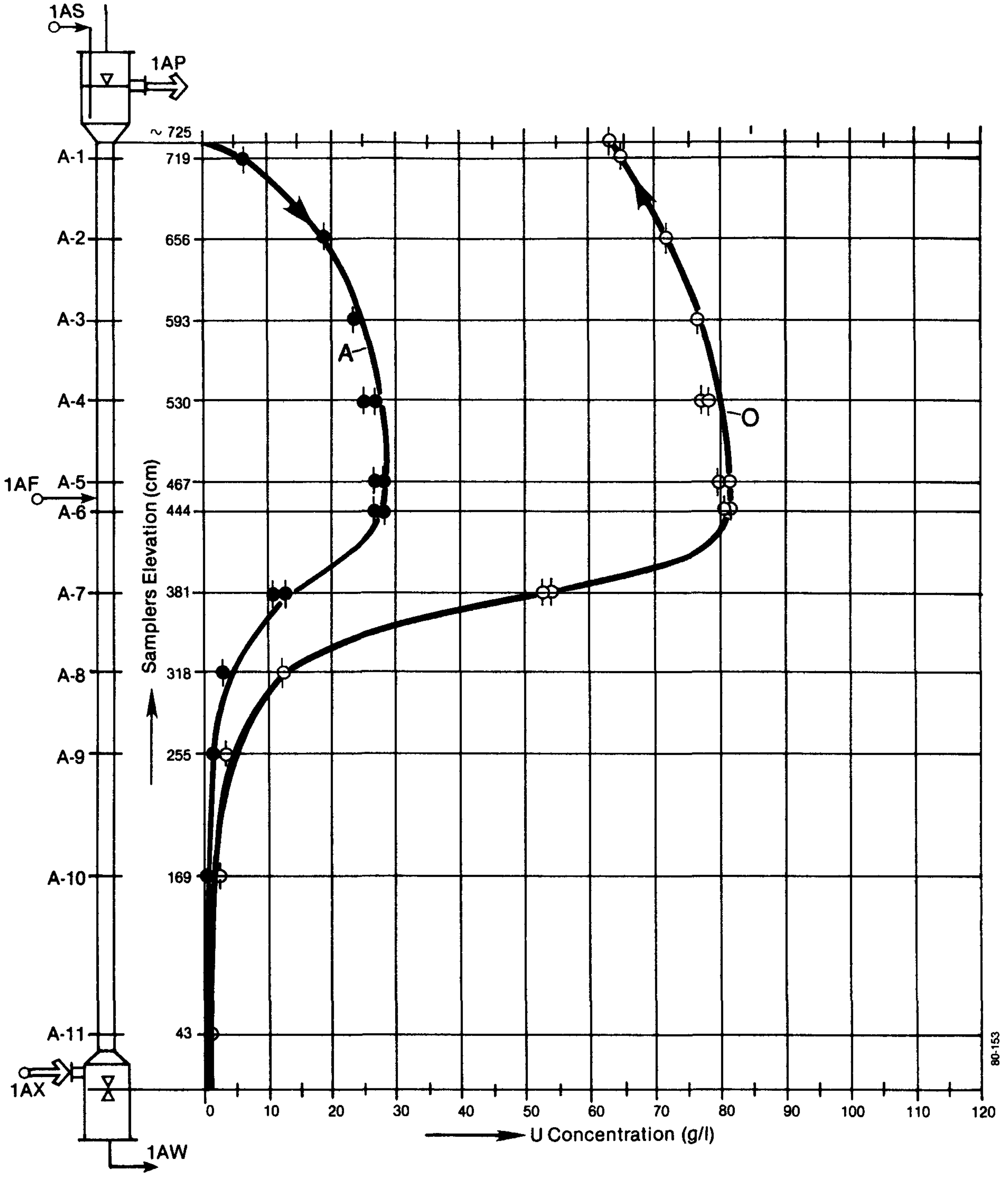
THE 2A COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 2A-3 (30 v/o TBP)

FIGURE 4-31



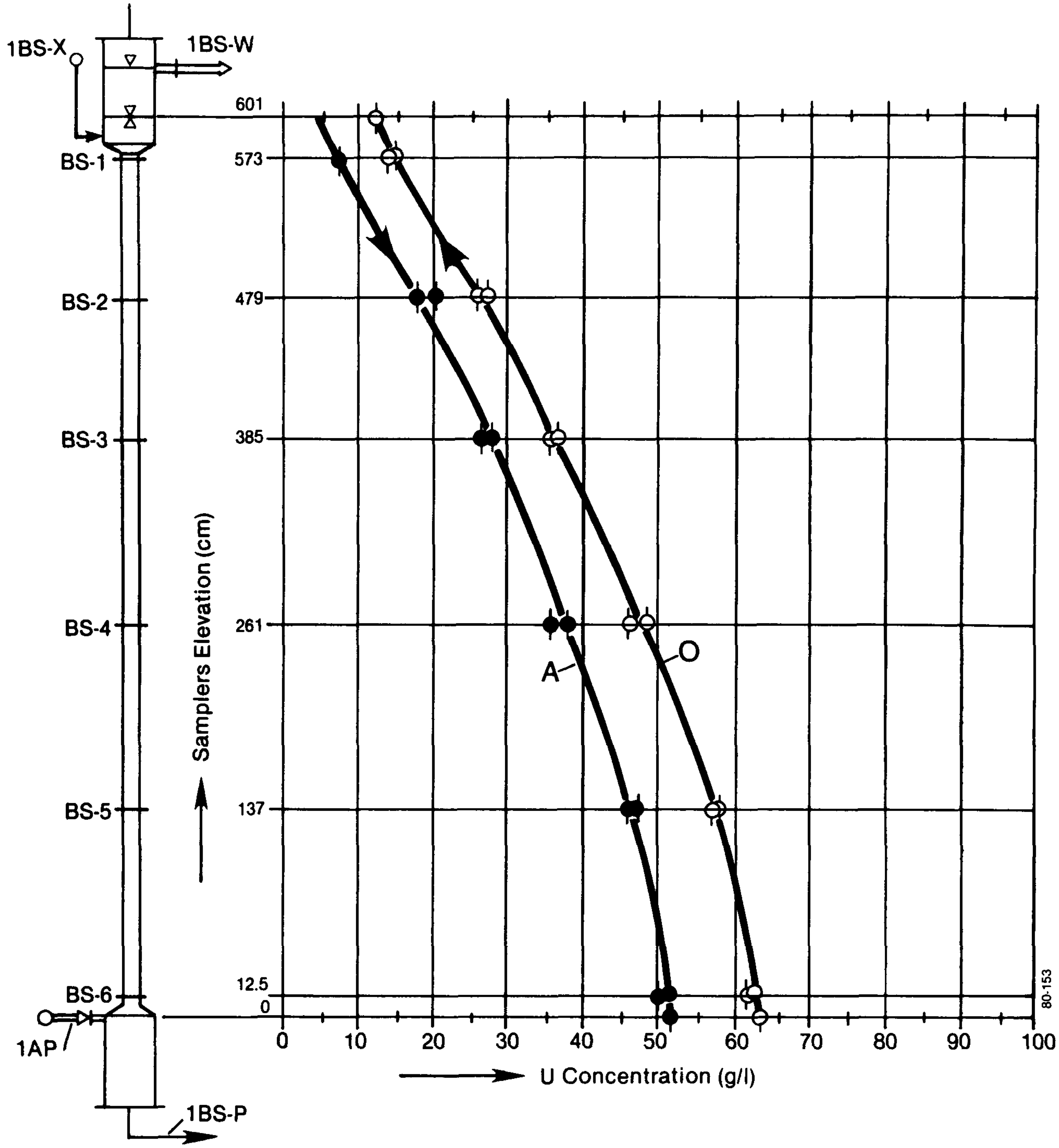
THE 2B COLUMN EXPERIMENTAL
CONCENTRATION PROFILES FOR RUN 2A-3

FIGURE 4-32



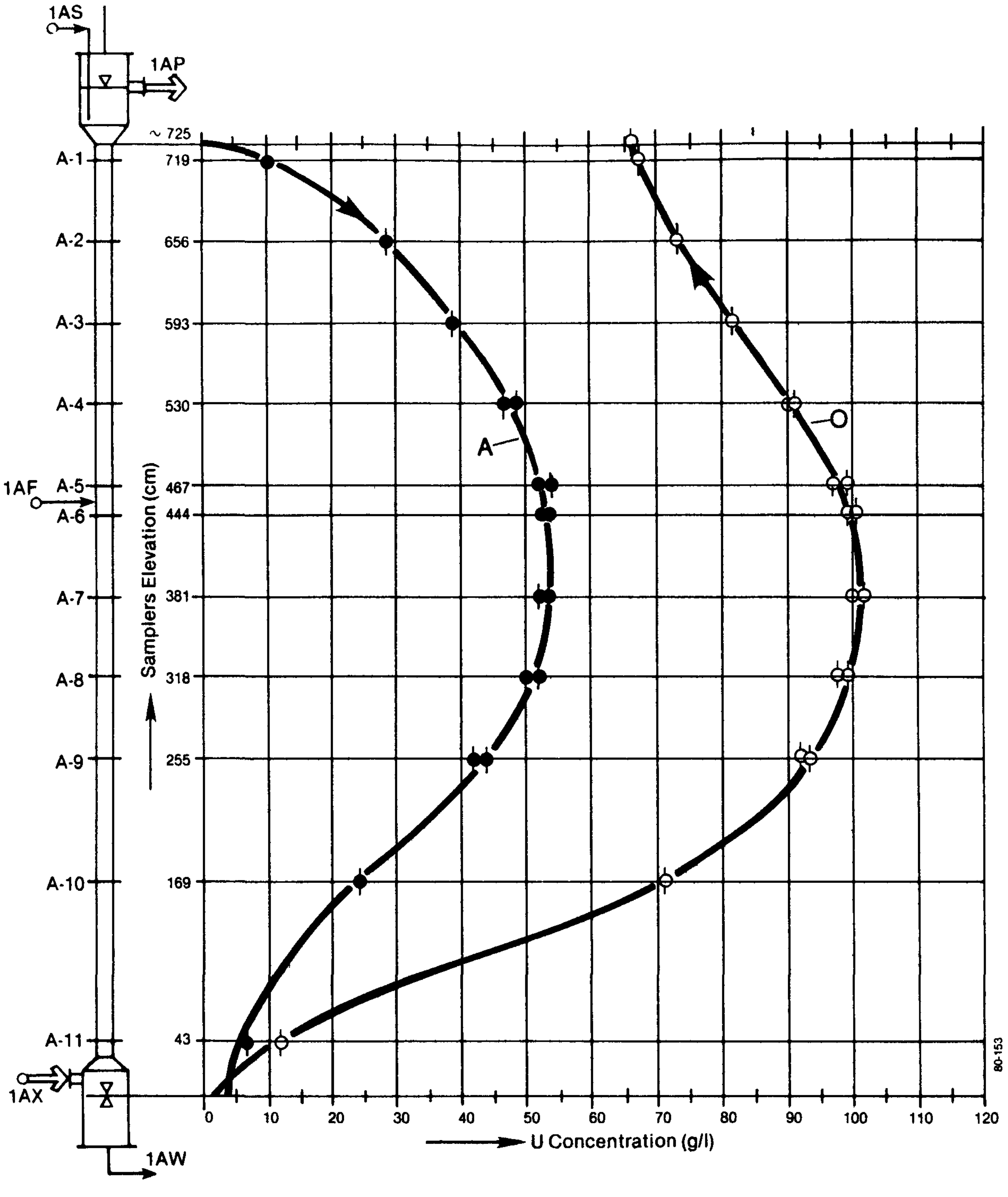
THE 3A COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 3A-1 (30 v/o TBP)

FIGURE 4-33



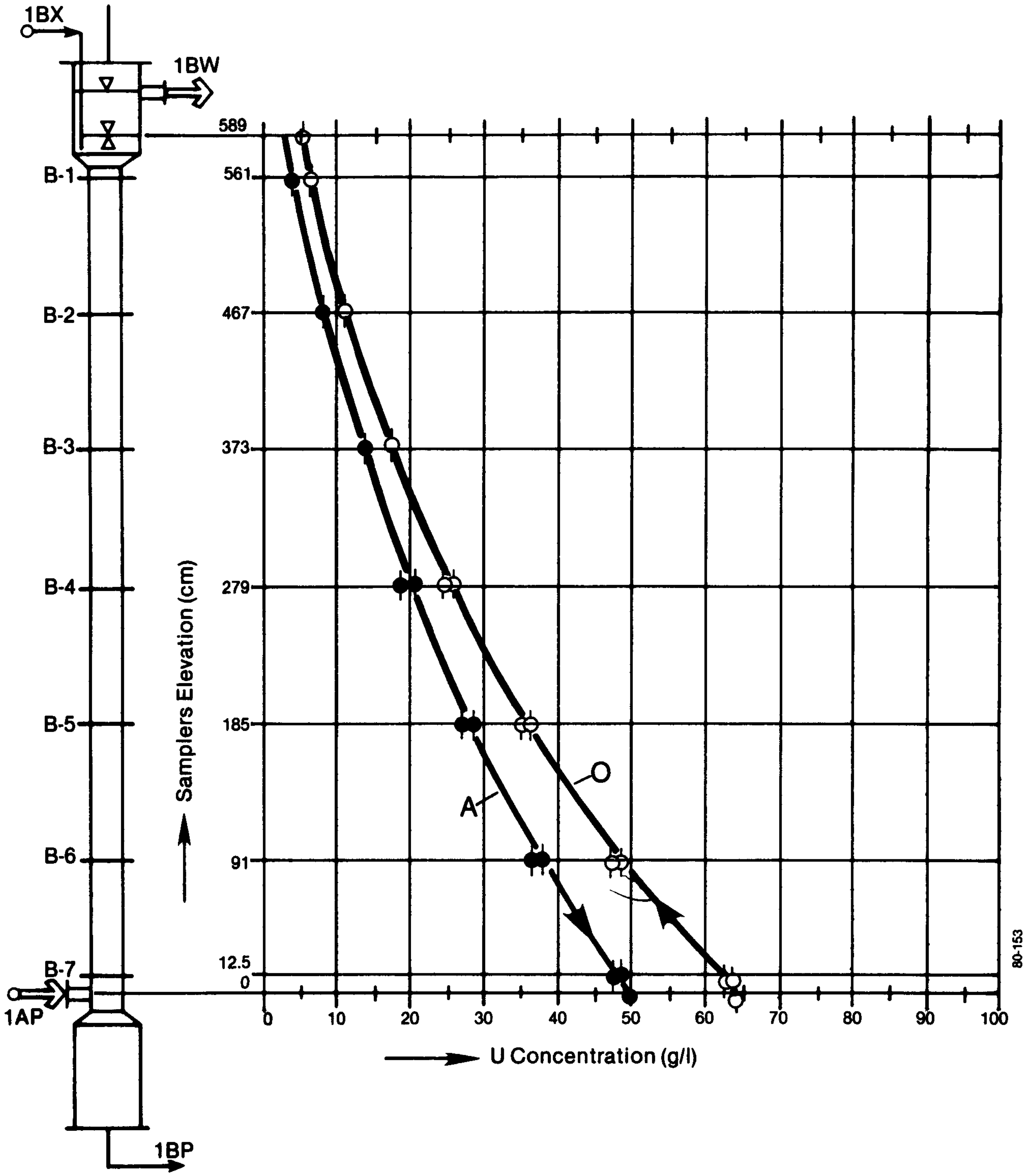
THE 3B COLUMN EXPERIMENTAL
CONCENTRATION PROFILES FOR RUN 3A-1

FIGURE 4-34



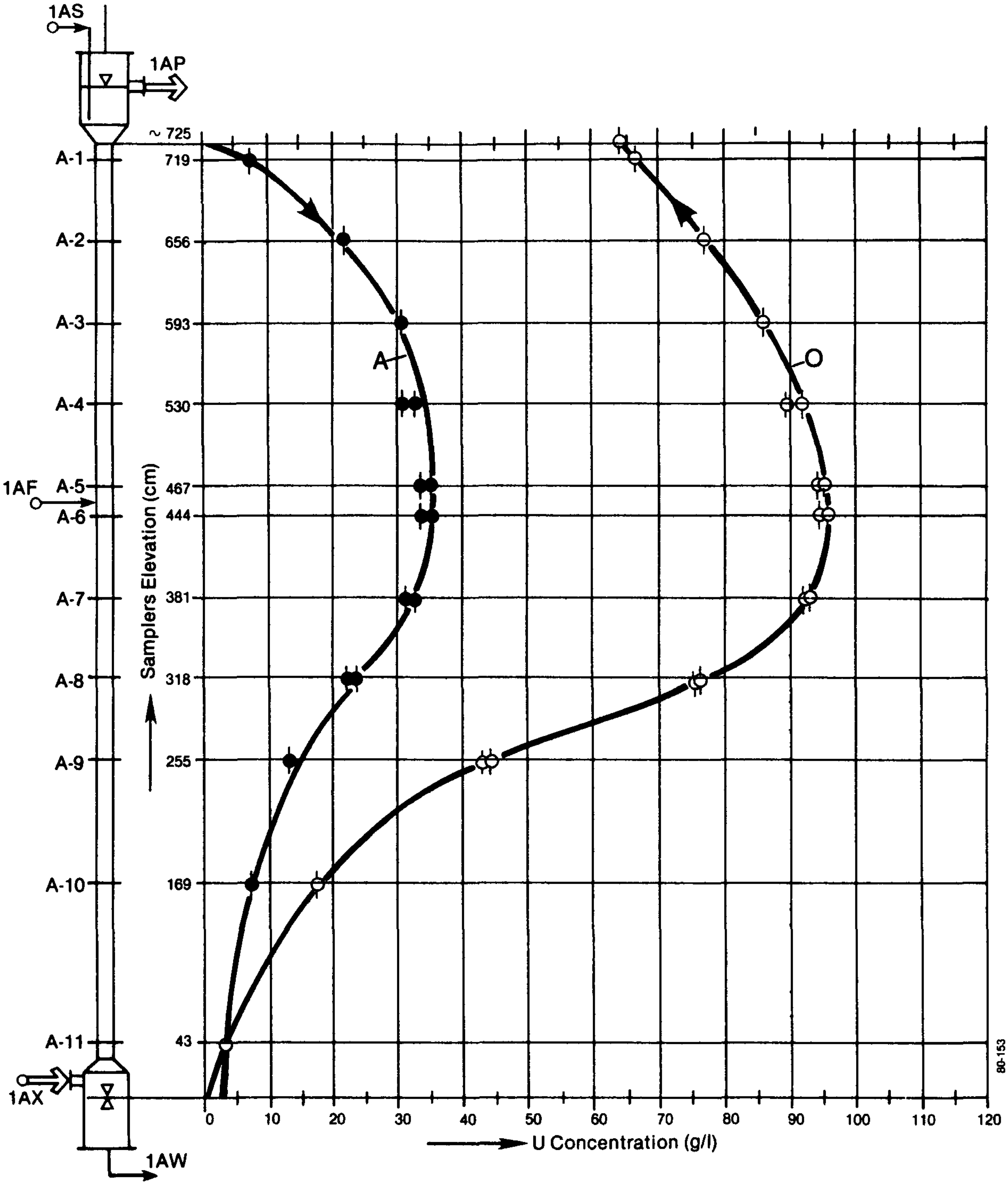
THE 3A COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 3A-2 (30 v/o TBP)

FIGURE 4-35



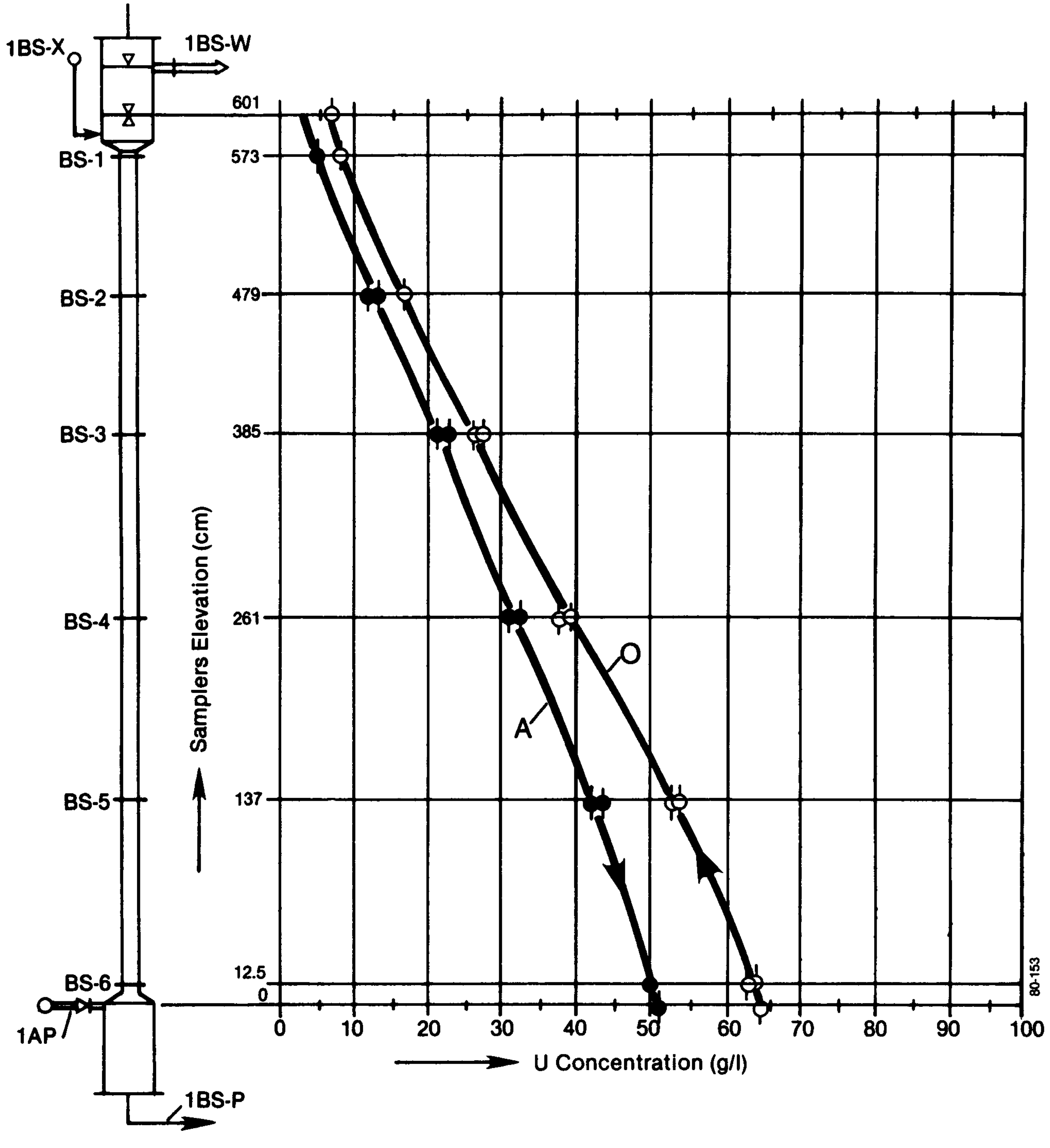
THE 3B COLUMN EXPERIMENTAL
CONCENTRATION PROFILES FOR RUN 3A-2

FIGURE 4-36



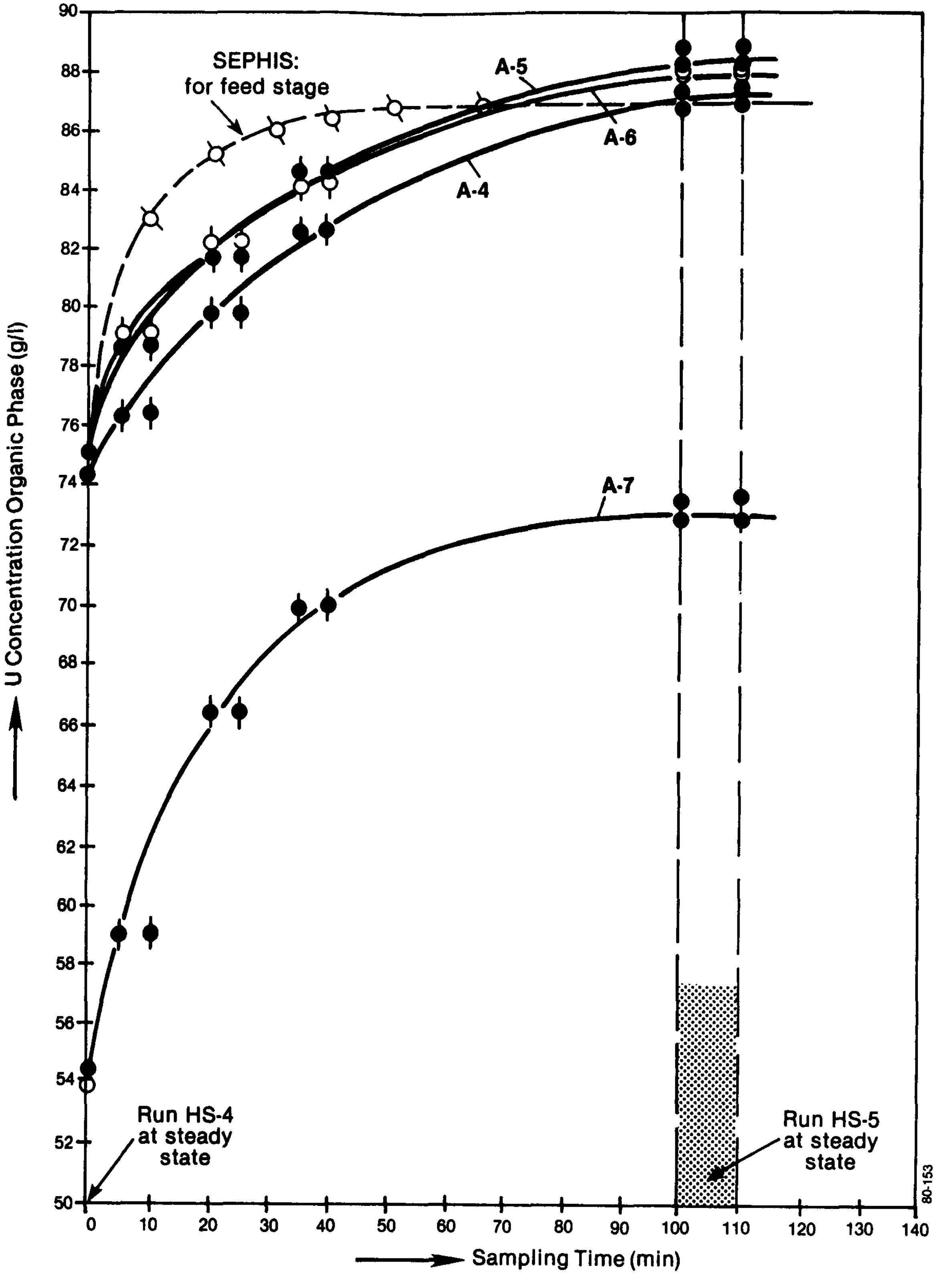
THE 3A COLUMN EXPERIMENTAL CONCENTRATION PROFILES FOR RUN 3A-3 (30 v/o TBP)

FIGURE 4-37



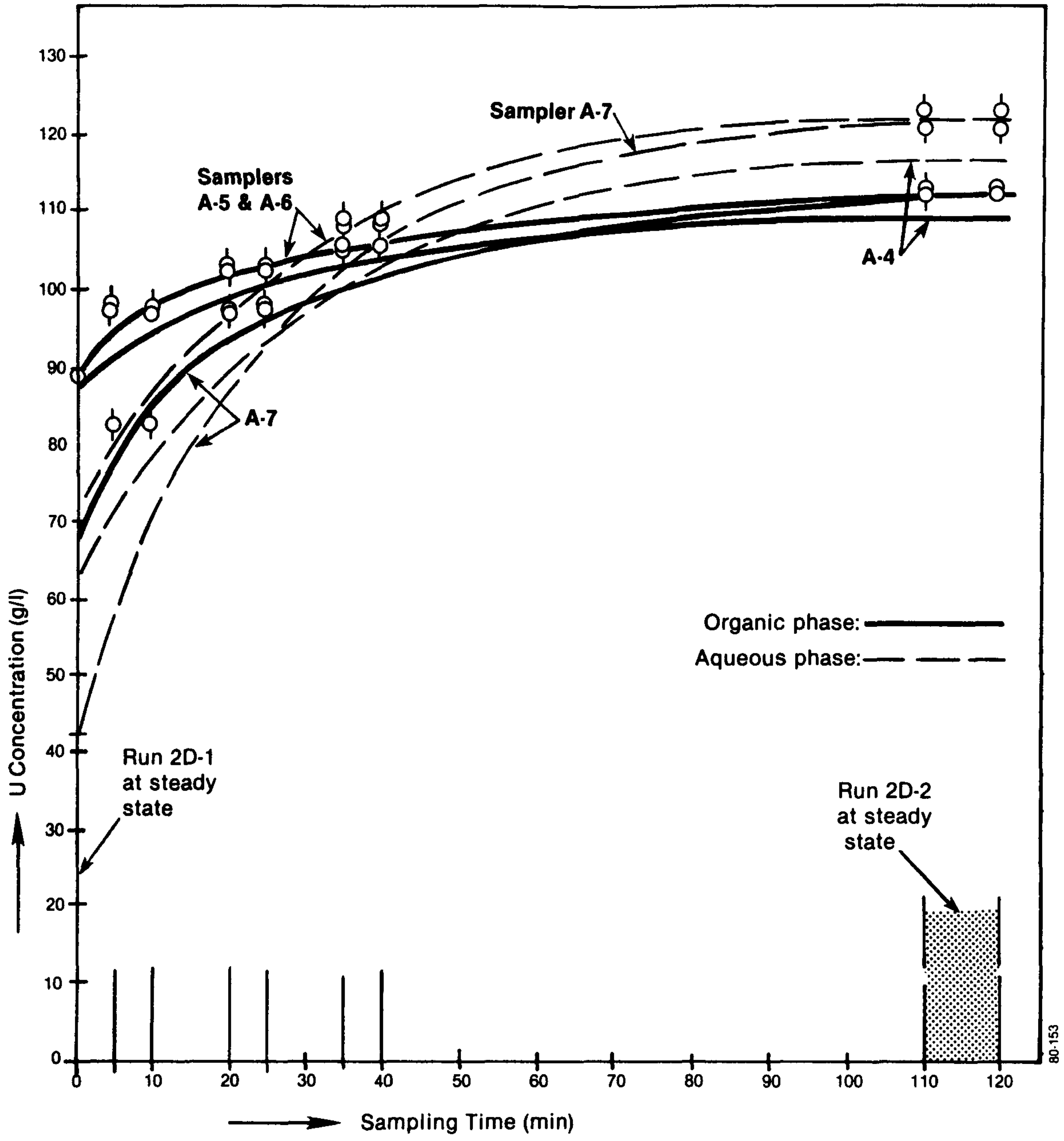
THE 3B COLUMN EXPERIMENTAL
CONCENTRATION PROFILES FOR RUN 3A-3

FIGURE 4-38



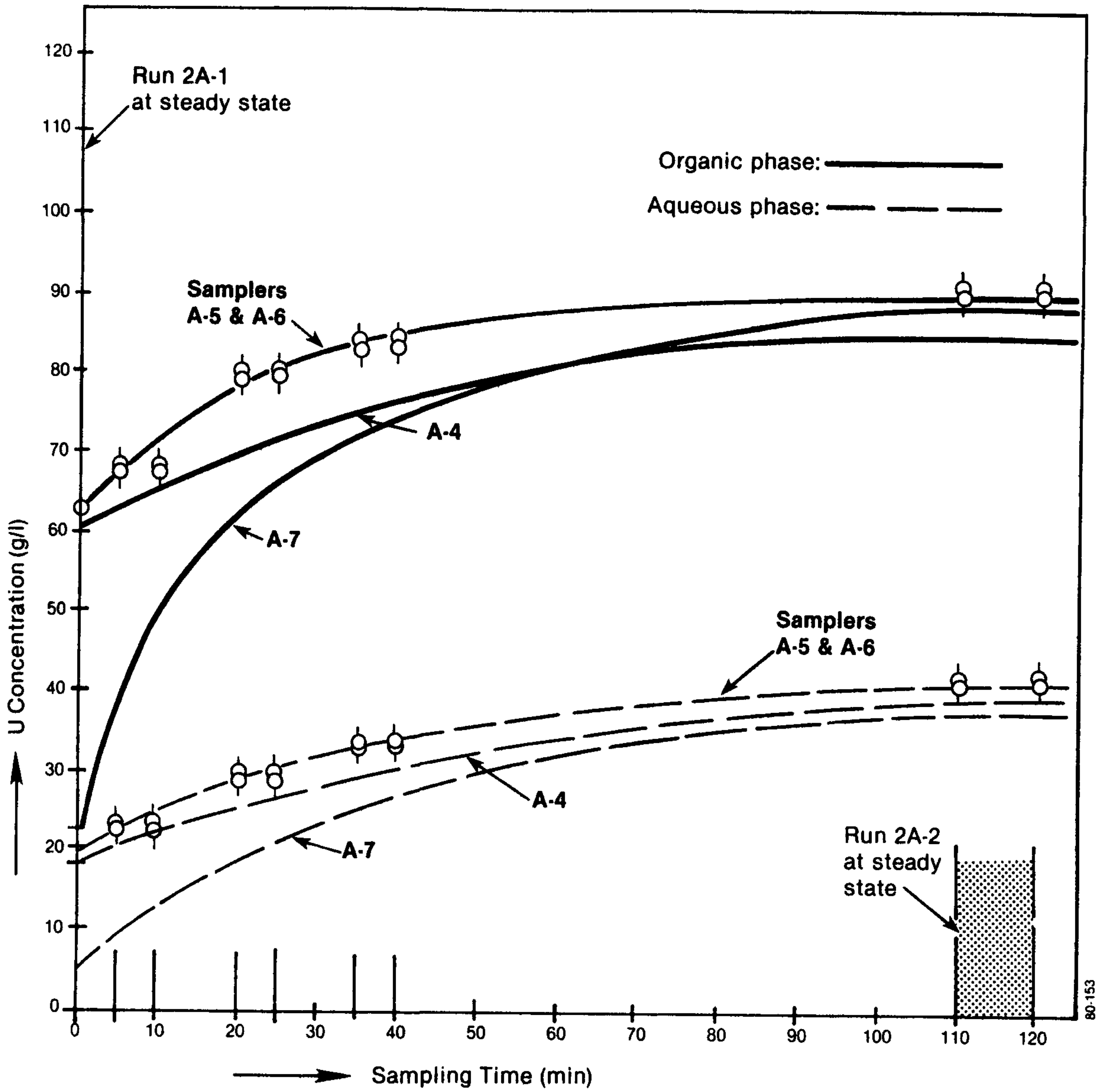
TRANSIENT URANIUM CONCENTRATION IN THE
HS COLUMN BETWEEN RUNS HS-4 AND HS-5

FIGURE 4-39



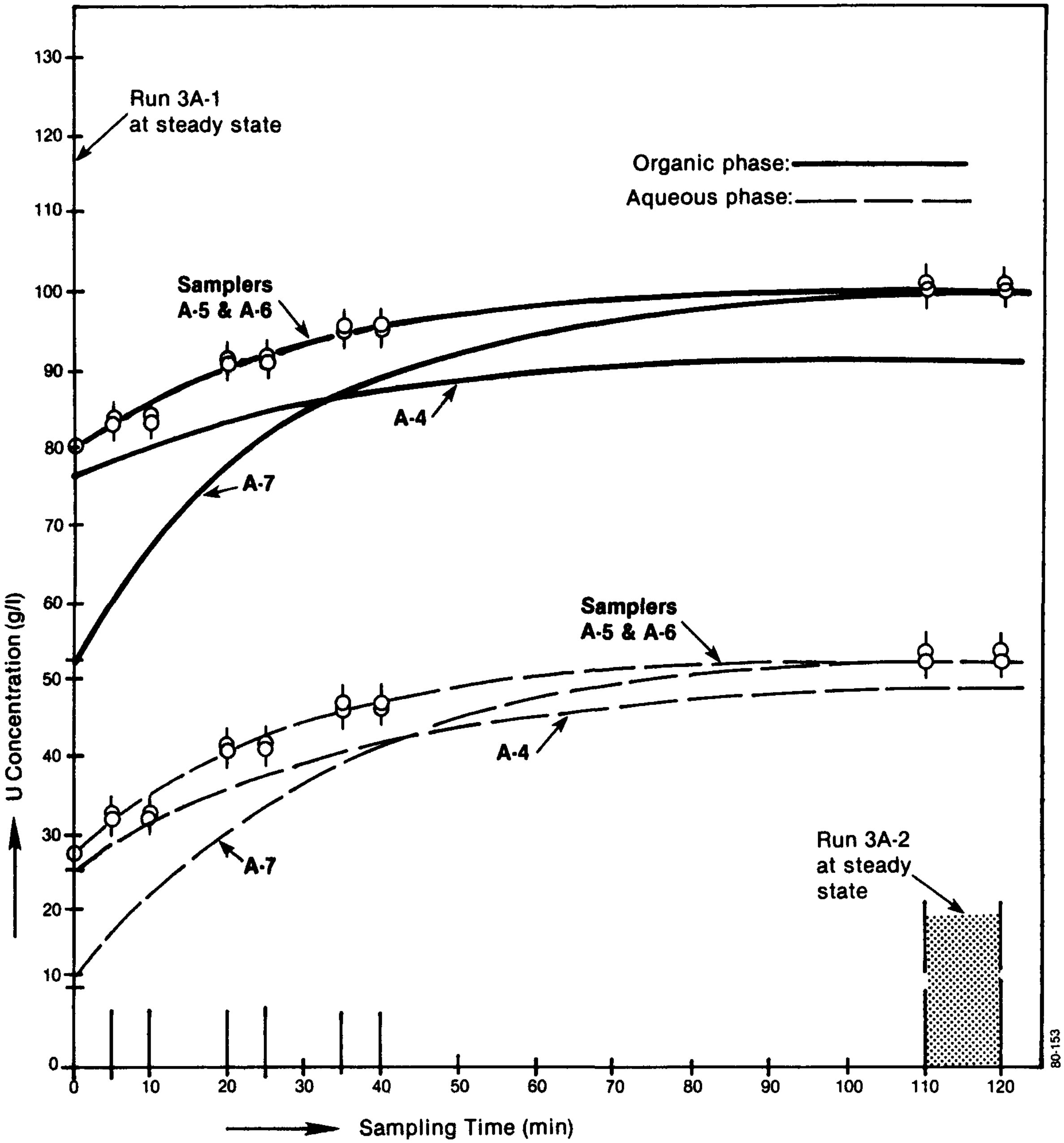
TRANSIENT URANIUM CONCENTRATION IN THE 2D COLUMN BETWEEN RUNS 2D-1 and 2D-2

FIGURE 4-40



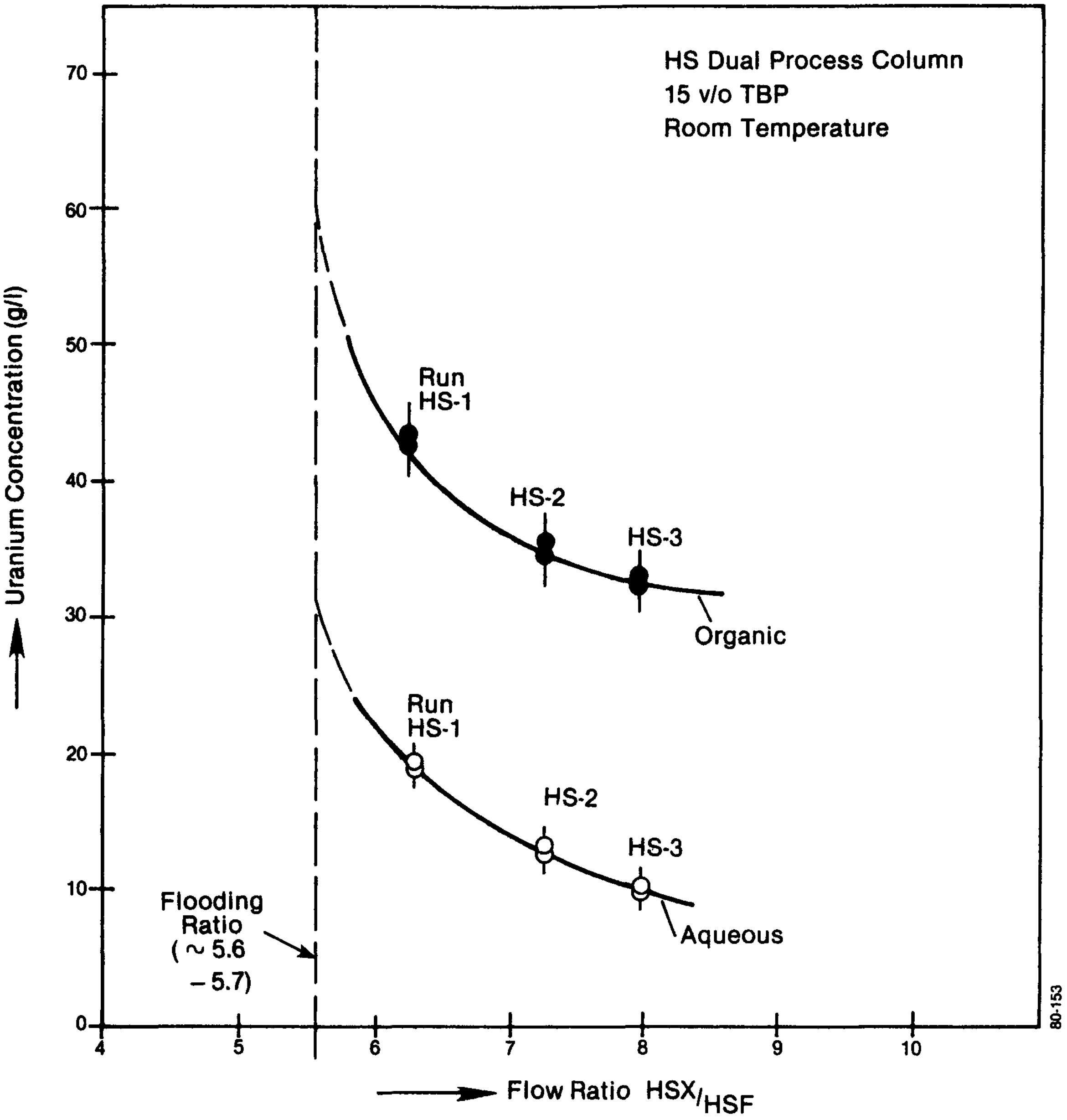
TRANSIENT URANIUM CONCENTRATION IN THE 2A COLUMN BETWEEN RUNS 2A-1 and 2A-2

FIGURE 4-41



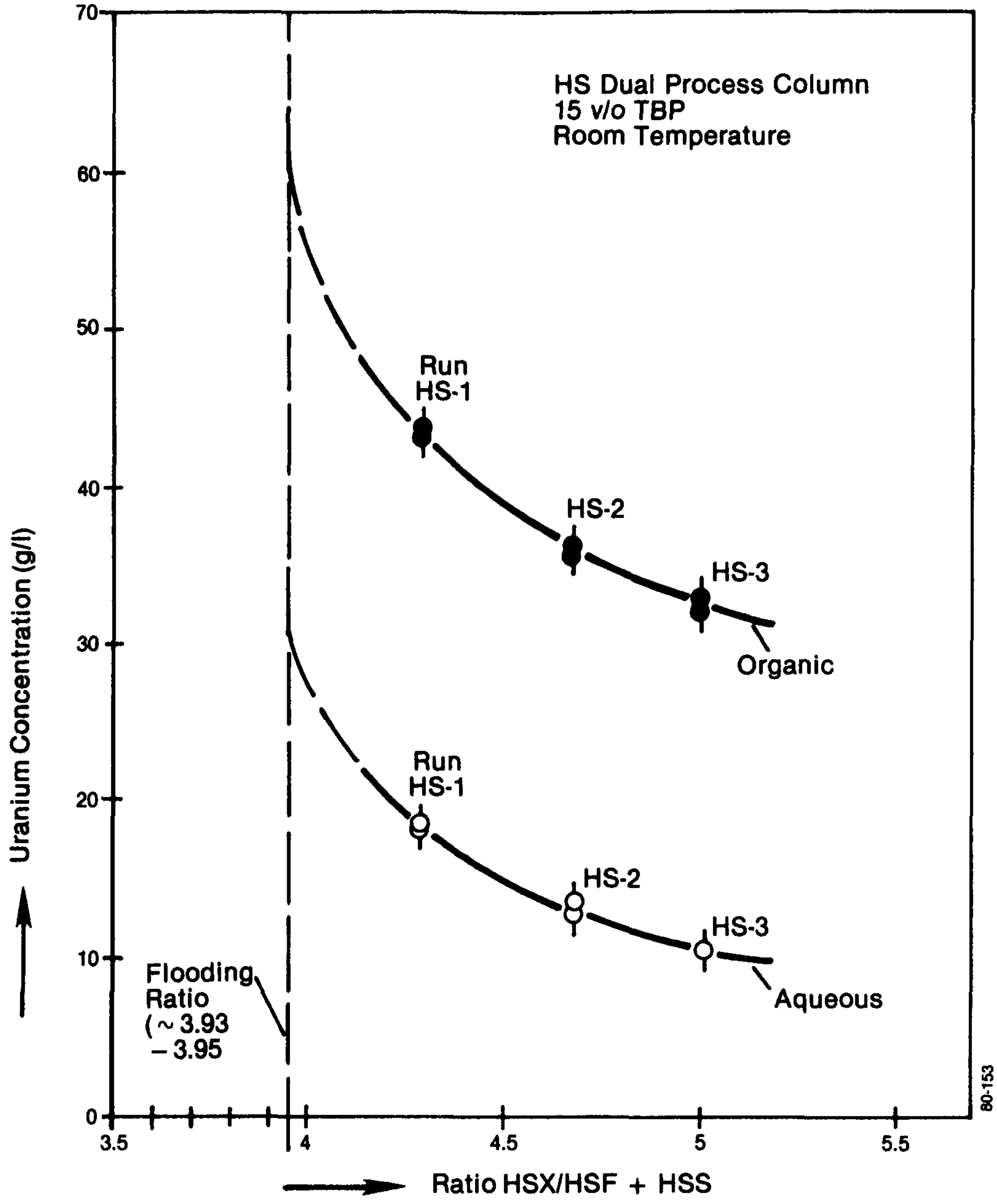
TRANSIENT URANIUM CONCENTRATION IN THE 3A COLUMN BETWEEN RUNS 3A-1 and 3A-2

FIGURE 4-42



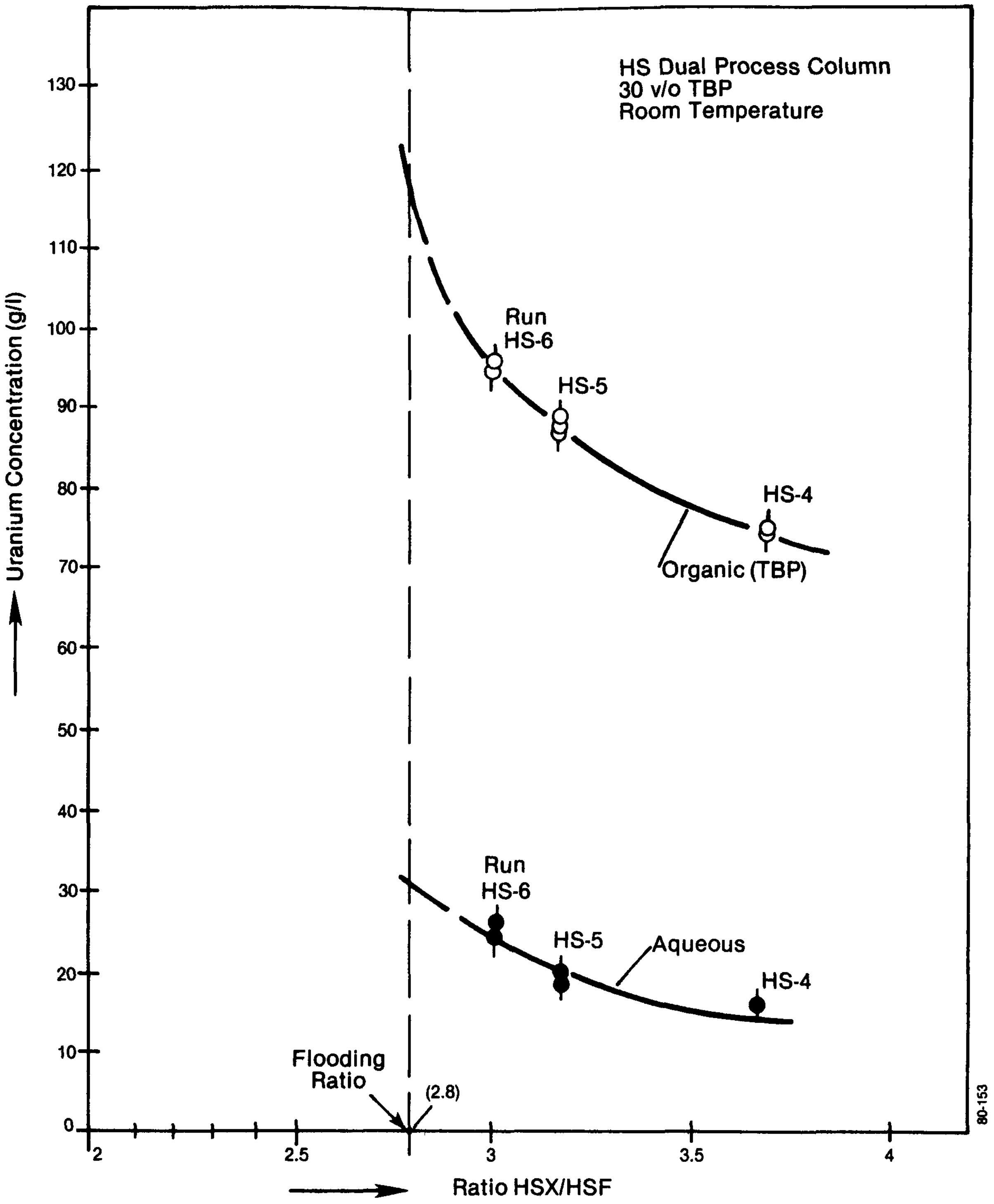
URANIUM CONCENTRATION AT HSF FEED INLET RELATED TO HSX/HSF FLOW RATIO (FOR RUNS HS-1, HS-2, AND HS-3)

FIGURE 4-43



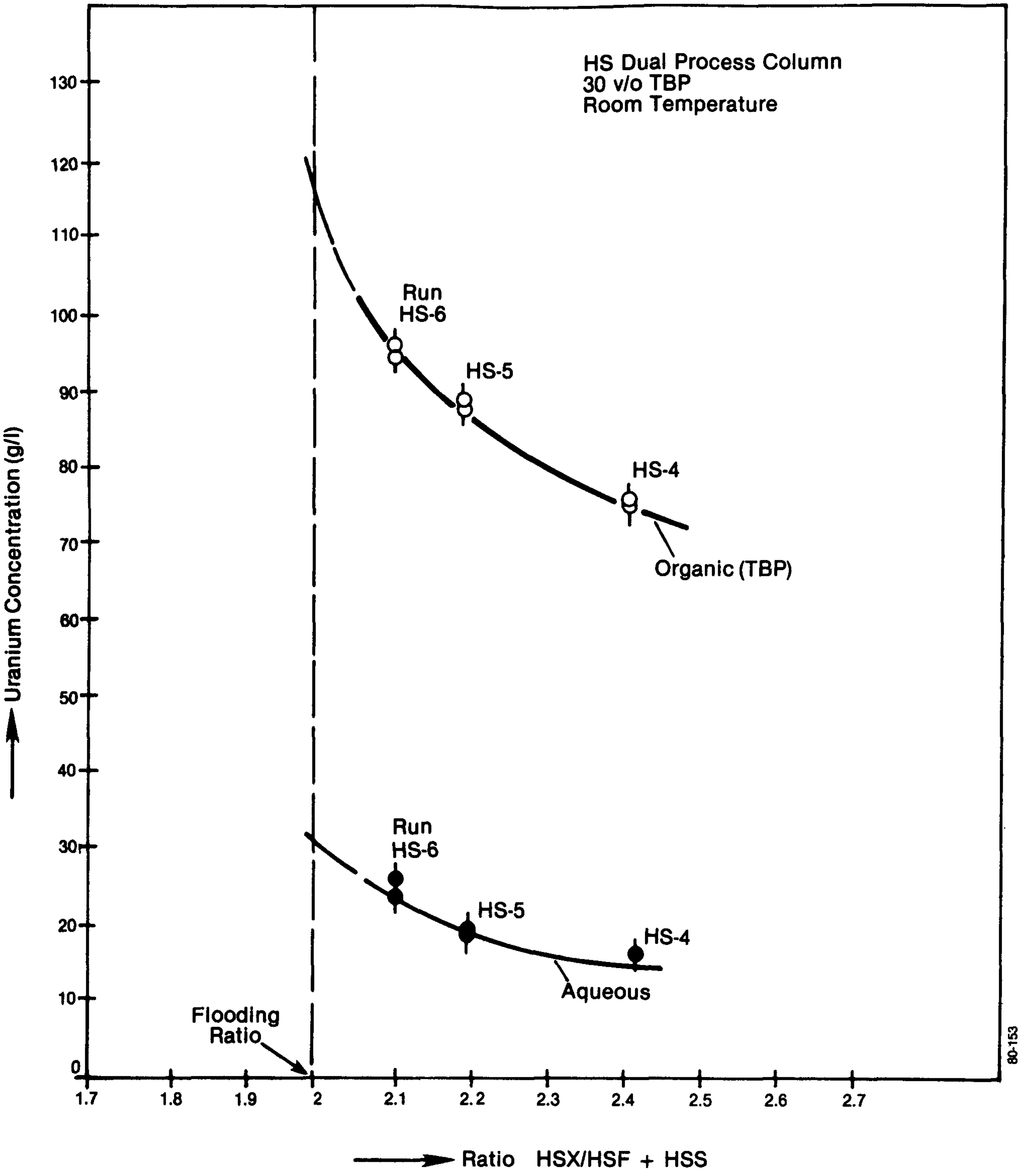
URANIUM CONCENTRATION AT HSF FEED INLET RELATED TO HSX/HSF + HSS FLOW RATIO (FOR RUNS HS-1, HS-2, AND HS-3)

FIGURE 4-44



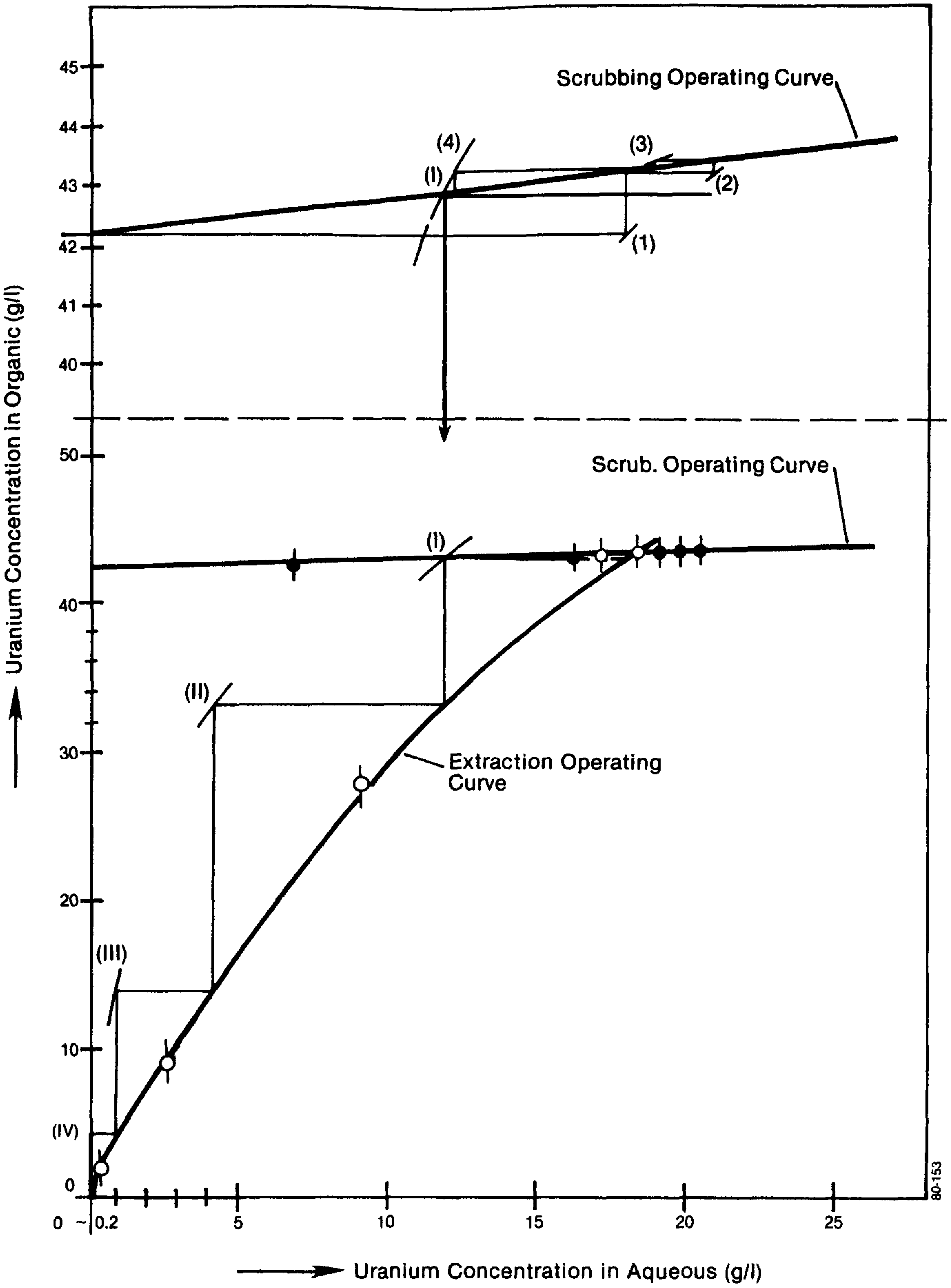
URANIUM CONCENTRATION AT HSF FEED INLET RELATED
TO HSX/HSF FLOW RATIO (FOR RUNS HS-4, HS-5, AND HS-6)

FIGURE 4-45



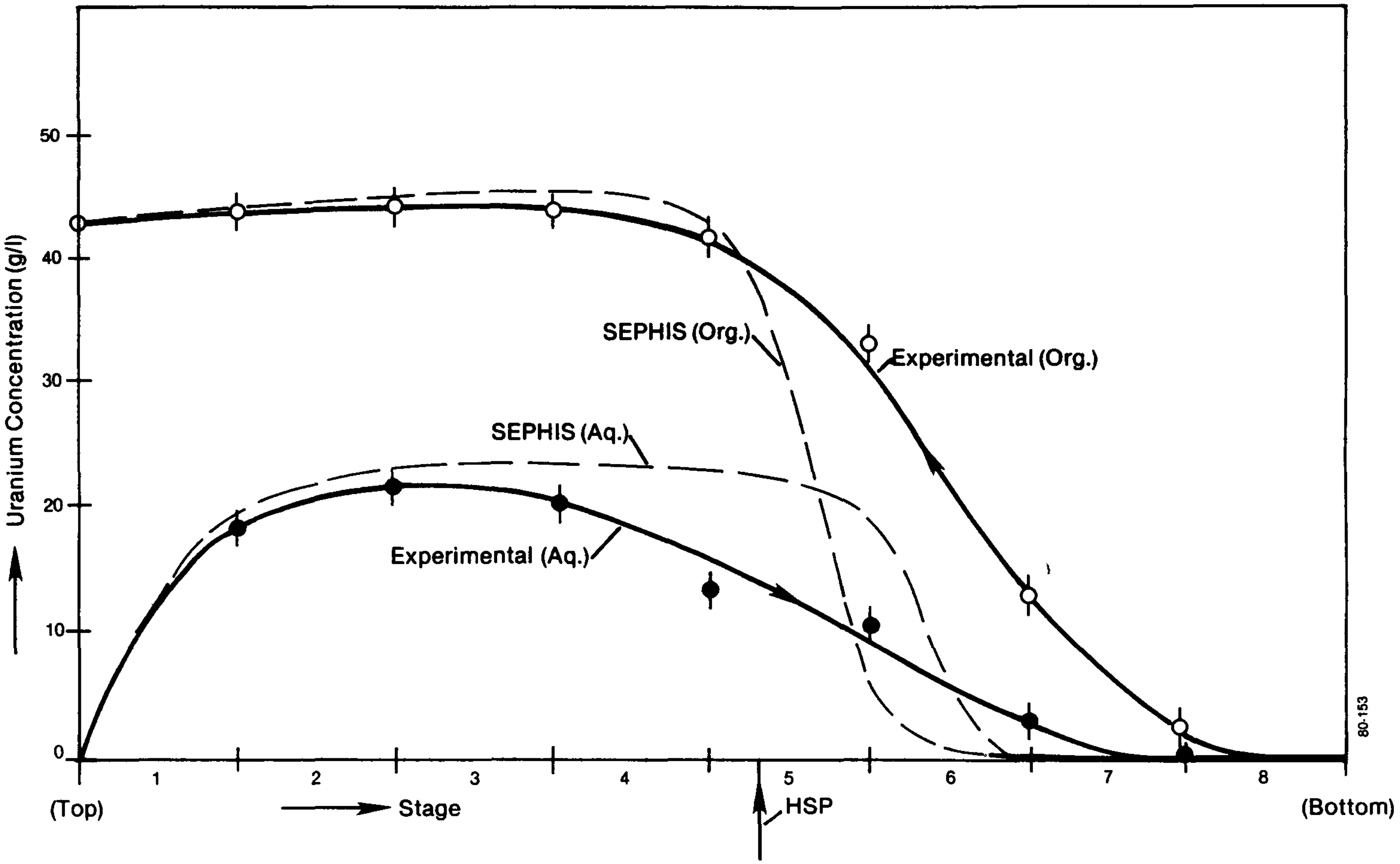
URANIUM CONCENTRATION AT HSF FEED INLET RELATED TO HSX/HSF + HSS FLOW RATIO (FOR RUNS HS-4, HS-5, AND HS-6)

FIGURE 4-46



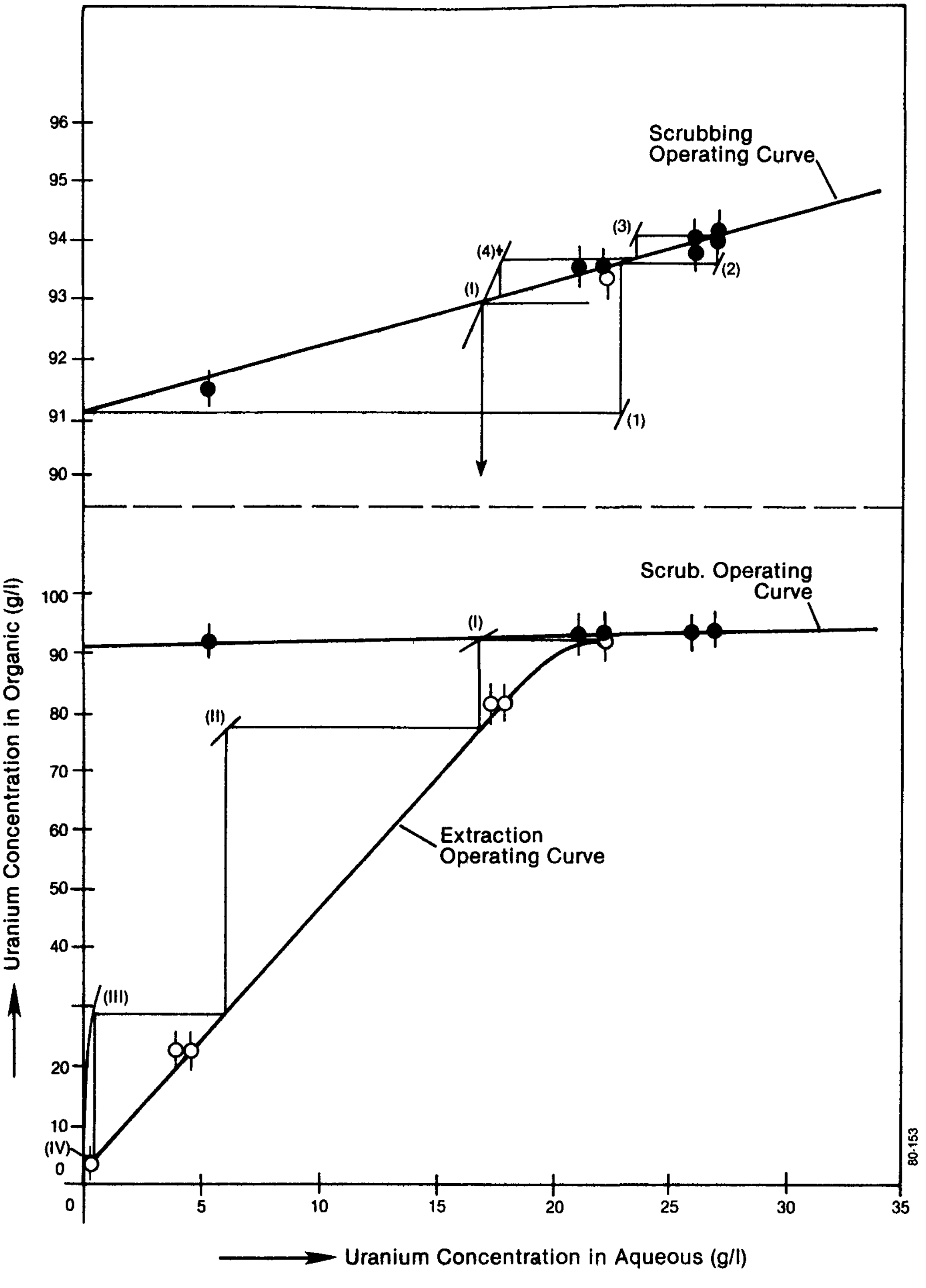
THE HS COLUMN OPERATING DIAGRAM FOR RUN HS-1

FIGURE 4-47



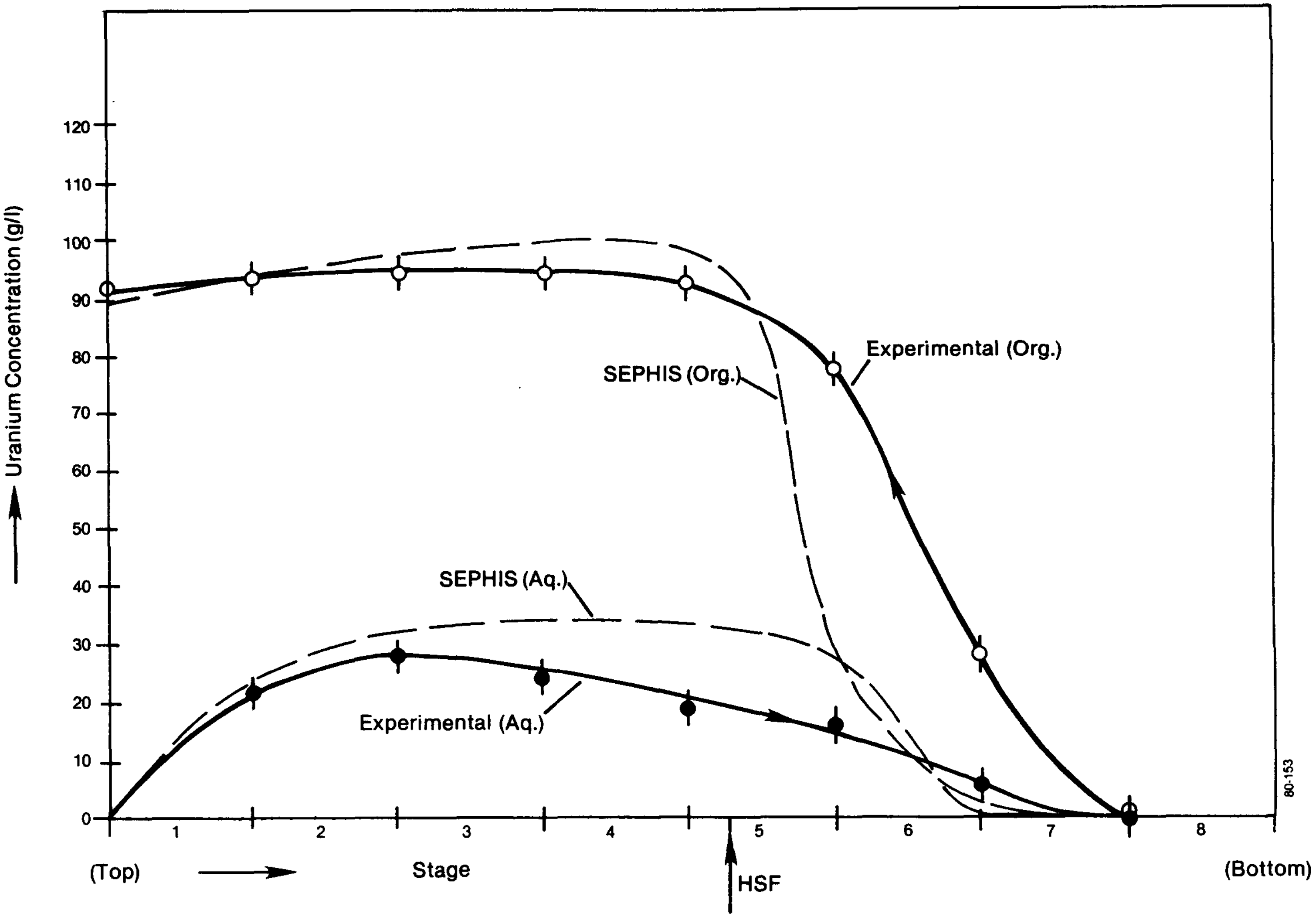
COMPARISON OF THE HS COLUMN EXPERIMENTAL CONCENTRATION PROFILE WITH THAT OBTAINED FROM SEPHIS PROGRAM (RUN HS-1)

FIGURE 4-48



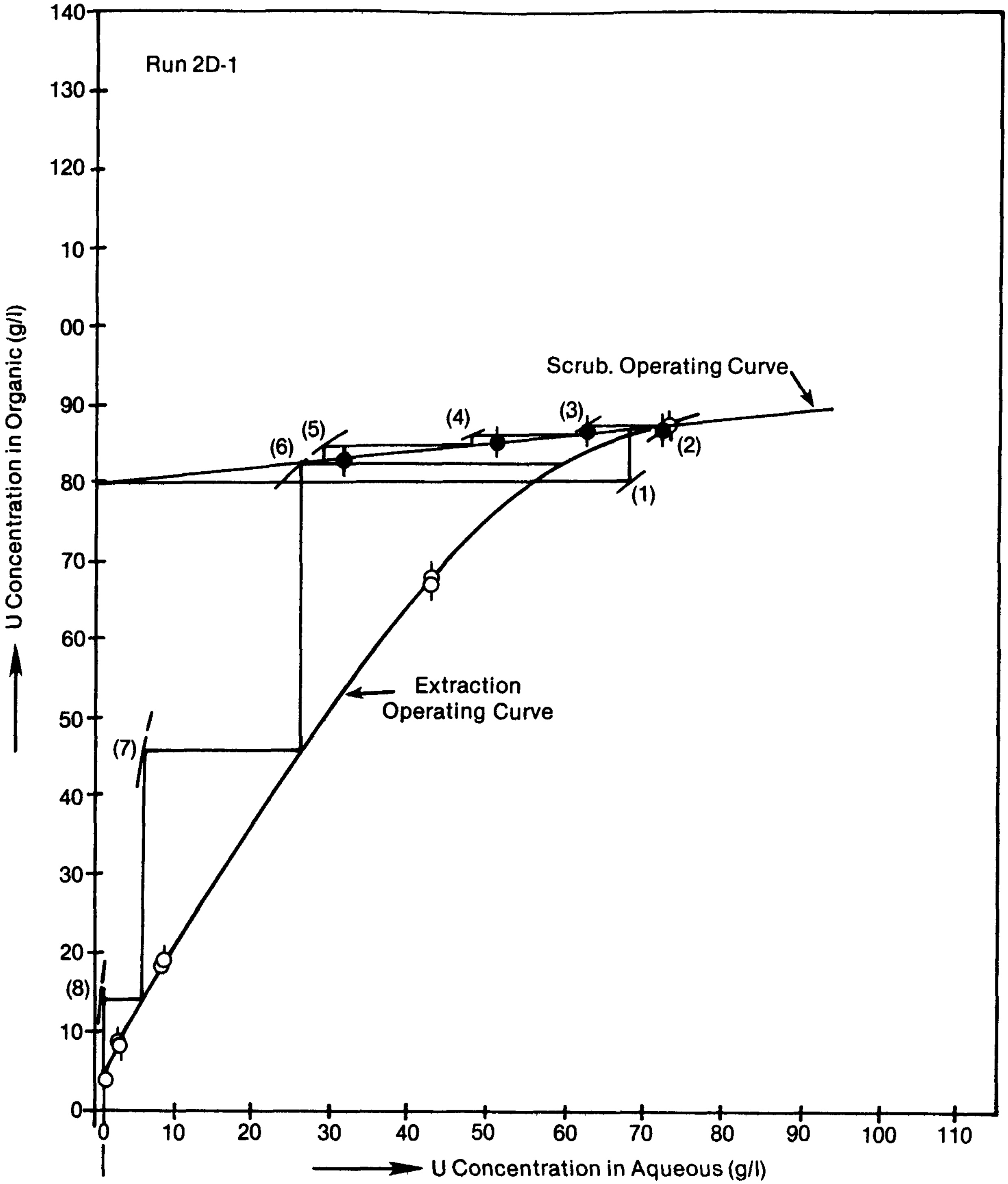
THE HS COLUMN OPERATING DIAGRAM FOR RUN HS-6

FIGURE 4-49



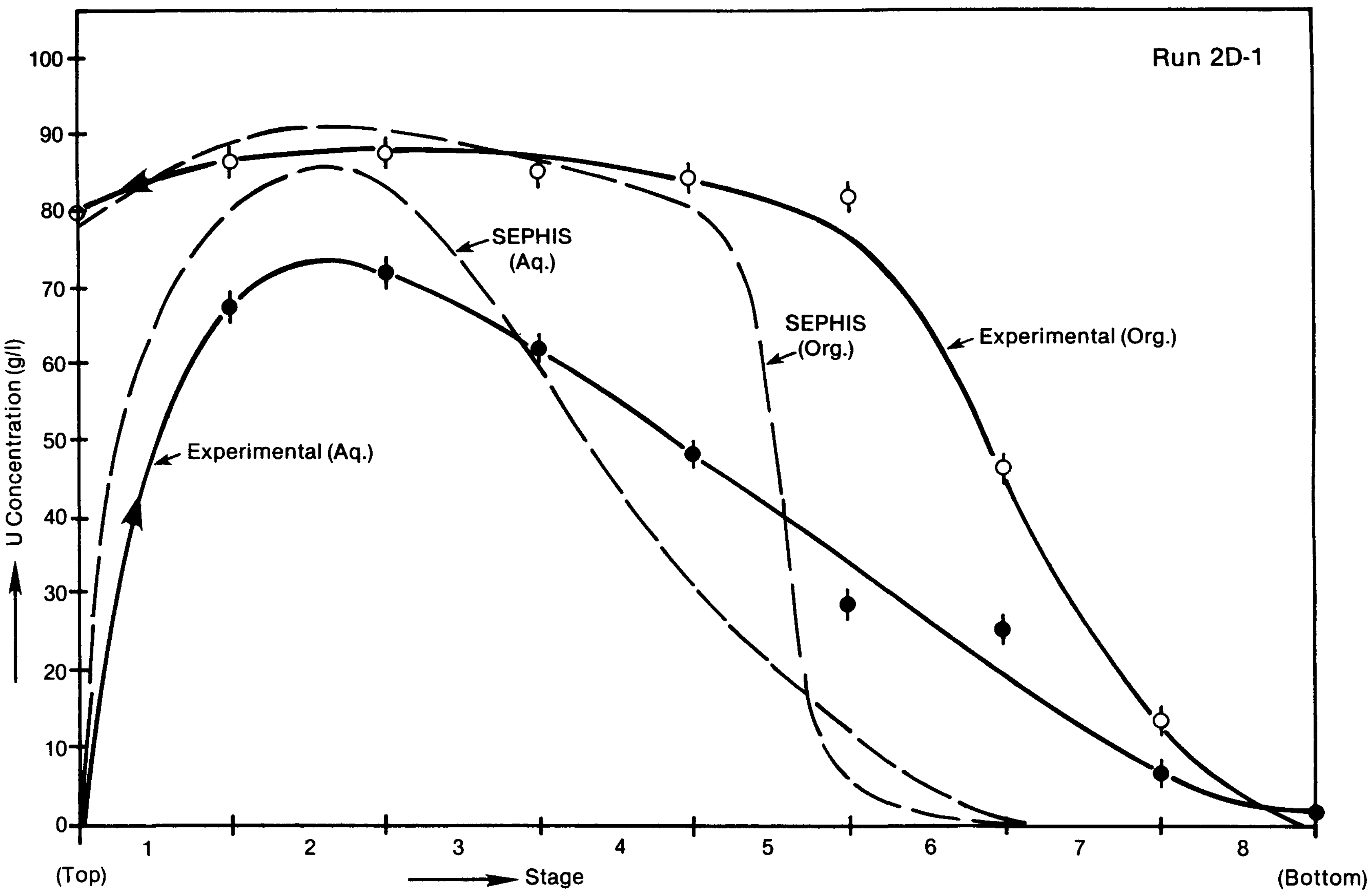
COMPARISON OF THE HS COLUMN EXPERIMENTAL CONCENTRATION PROFILE WITH THAT OBTAINED FROM SEPHIS PROGRAM (RUN HS-6)

FIGURE 4-50



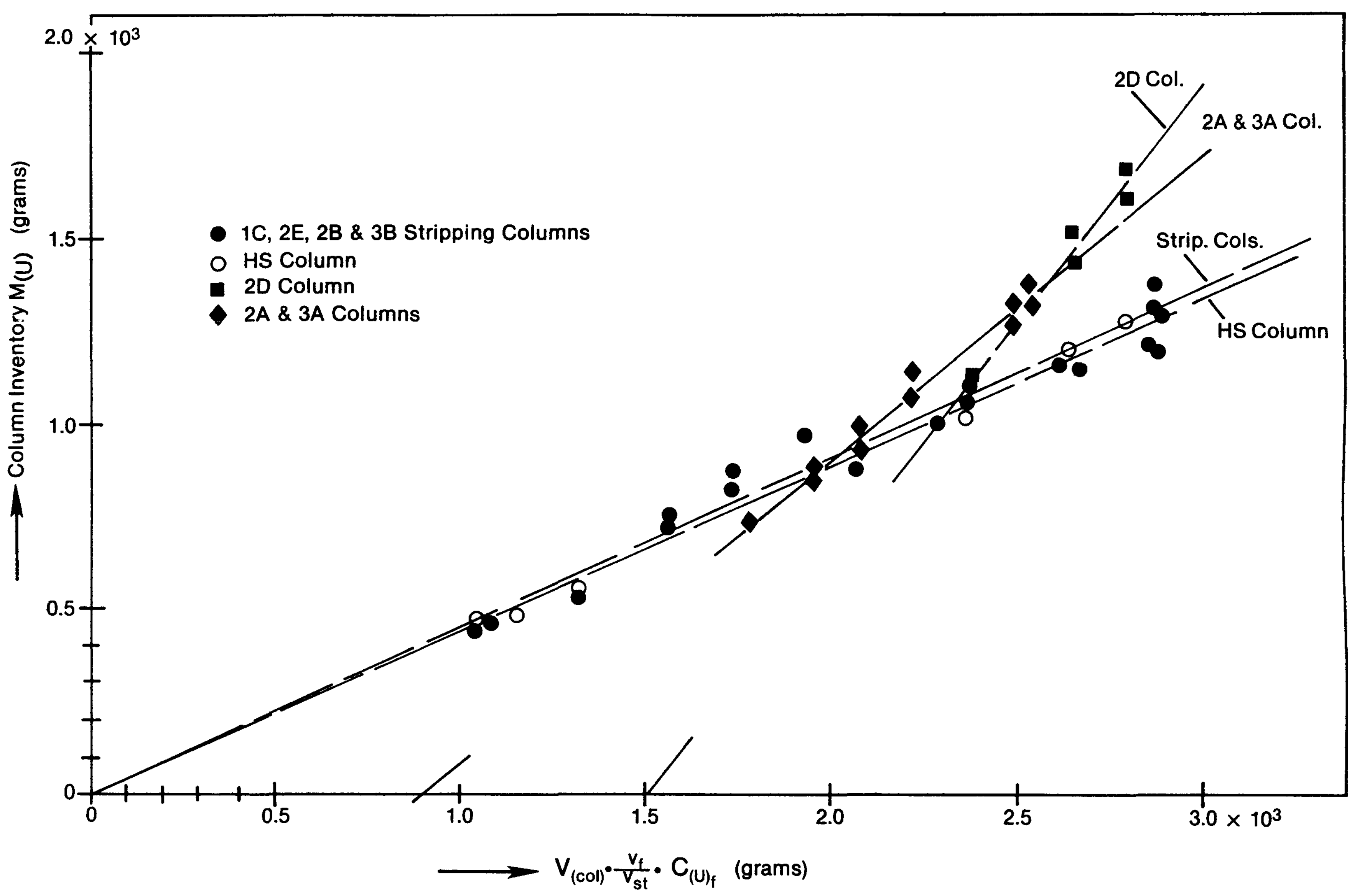
THE 2D COLUMN OPERATING DIAGRAM FOR RUN 2D-1

FIGURE 4-51



COMPARISON OF THE 2D COLUMN EXPERIMENTAL CONCENTRATION PROFILE WITH THAT OBTAINED FROM SEPHIS PROGRAM (RUN 2D-1)

FIGURE 4-52



URANIUM INVENTORY $M_{(U)}$ IN TESTED COLUMNS VERSUS FUNCTION $V_{(col)} \cdot \frac{v_f}{v_{St}} \cdot C_{(U)_f}$

FIGURE 4-53

5.0 CONCLUSIONS AND RECOMMENDATIONS

The major objectives of this work were: (1) to determine the dispersed phase holdup within a pulsed column, (2) the column throughput capacity, (3) the uranium concentration profile along columns operating under different conditions, and (4) to develop a method for determination of the uranium inventory during operation.

Evaluation of data obtained during holdup tests resulted in development of the empirical equation $x_d \approx 0.185\ (2fA_o + \Delta U_{d-c})^{2.8}$ (see equation 5). This equation is recommended for calculating the dispersed phase holdup in pulsed columns operating under similar conditions as tested. Experimental data from these tests and from previous tests(4) confirm the practicality of the method developed by AGNS for the determination of dispersed phase holdup based on data obtained by means of a weight recorder.

The total column throughput (capacity) is generally determined by knowing the column diameter and the total liquid velocity considered for the process. The recommended liquid velocities, determined from flooding tests, are shown in Table 4-1. They can be also used for calculating the column diameter, knowing the liquid phases flow rate from the flowsheet.

The 1A column, simulating the HS dual process column, was flooded when the HSX organic phase (TBP) to HSF feed solution flow ratio dropped below 5.8 (at 15 v/o TBP) and 2.8 (at 30 v/o TBP), operating with constant organic and aqueous scrubbing stream flows as shown in Tables 4-4 and 4-5, respectively. This observation also applies to the 2D column which was flooded when operated with a 2DX/2DF flow ratio lower than 2.8.

Concentration profiles shown in this report indicate that the uranium concentration increased around the feed inlet and in the dual process column scrubbing section with either an increase in the feed solution flow rate, or a decrease in the solvent (organic phase) flow rate while keeping the other stream flow rates constant.

Comparison of the experimental concentration profiles with those obtained from the SEPHIS code (Figures 4-48, 4-50, and 4-52) shows differences, which are caused by the axial mixing (back-mixing) in the continuous phase within the pulsed column.

Transient uranium concentration curves between two subsequent runs (Figures 4-39 through 4-42) show no concentration peaks at four sampling points around the feed solution inlet of the dual process column.

Evaluation of the experimentally determined uranium inventory (Table 4-28 and Figure 4-53) resulted in developing empirical equations 14 through 17 suitable for predicting and calculating the inventory in pulsed columns, with respect to test flow ratios, acidity, and the applicable range of the $\frac{v_f \cdot C_{(U)_f}}{v_{St}}$ value.

It is recommended that the applicability of the above empirical inventory equations be verified through tests performed on full-scale pulsed columns.

It is also recommended to proceed with this type of inventory experiment on pilot-plant or laboratory equipment, in order to verify the reproducibility of solutes inventory, concentration profile, and dispersed phase holdup data.

6.0 REFERENCES

(1) Hakkila, E. A., et al, Materials Management in an Internationally Safeguarded Fuels Reprocessing Plant, Los Alamos Scientific Laboratory, LA-8042 (April 1980).

(2) Ibid, Estimation of In-Process Inventory in Solvent Extraction Contactors, Volume III, Appendix J.

(3) Mitchell, A. D., SEPHIS-Mod 4: A User's Manual to a Revised Model of the Purex Solvent Extraction System, Oak Ridge National Laboratory, ORNL-5471 (May 1979).

(4) Cermak, A. F., Neace, J. C., and Spaunburgh, R. G., Coprocessing Tests with Uranium on the Electropulse Column and Pilot-Scale Pulse Columns Simulating the Second and Third Plutonium Process Cycles, AGNS-35900-4.1-20 (November 1979).

(5) Cermak, A. F., Two-Inch Diameter Pulsed Column, Dispersed Phase Hold-up Tests, AGNS report (1975) (unpublished).

(6) Cermak, A. F., Techniques for Determination of the Dispersed Phase Hold-up in Pulsed Columns Used in a Nuclear Fuel Reprocessing Plant, paper presented on the International Solvent Extraction Conference, Liege, Belgium (September 1980).

(7) Cobb, D. D., and Ostenak, C. A., Dynamic Materials Accounting for Solvent Extraction Systems, Los Alamos Scientific Laboratory, LA-UR-79-3221 (1979).

(8) Hall, J. C., Evaluation of Alternatives for Processing Uranium-Based LWR Fuels, AGNS-1040-3.1-15 (May 1978).

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PILOT-SCALE PULSED COLUMNS COLUMN PROFILE AND HOLDUP STUDIES

APPENDIX A

METHODS FOR CHEMICAL ANALYSES

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November 1980

ALLIED-GENERAL NUCLEAR SERVICES
POST OFFICE BOX 847
BARNWELL, SOUTH CAROLINA 29812

1.0 METHODS FOR CHEMICAL ANALYSES

1.1 Density

Density determinations were made by means of an Anton-Paar DMA-10 Densimeter. This instrument operates on the principle of measuring changes in resonant frequency of a hollow mechanical oscillator when it is filled with liquids of different density. Data reported here were obtained while the oscillator cell was held at a temperature of 25.0 ± 0.1°C by means of a thermostated water bath. Air and distilled water were used for calibration of the oscillator cell.

1.2 Free Acid Concentration

The method of Booman(1) was used for free acid determination. A 10-fold excess of oxalate ion, preadjusted to pH 5.55, was added to the sample to complex uranium and so prevent its hydrolysis and the consequent introduction of a positive error through consumption of standard NaOH. The acid concentration in the sample was then determined by titration with standard (0.100N) NaOH until a pH of 5.55 was reached as measured by an Orion 701 pH meter.

1.3 Titrimetric Uranium Determination

The New Brunswick modification of the Davies-Gray method(2) was used throughout this experimental program where titrimetric uranium determinations were made. The method, as reported by Rodden,(2) was further modified as follows:

(1) To eliminate possible interference by hydrazine, the samples were pretreated with 0.1 ml of a 10% solution of $NaNO_3$

(2) To solubilize organic phase samples in the aqueous reagents, all organic phase samples were combined with an equal volume of acetone before analysis

(3) A colorimetric end point, based on sodium diphenyamine sulfonate, was substituted for the potentiometric end point.

1.4 Densimetric Uranium Determination

The large number and rapid turnover of samples involved in this study made the time-consuming titrimetric uranium determinations impractical. Therefore, densimetric uranium determinations were made where applicable. The use of this method was reported in the early fifties,(3) but only after the advent of electronic instrumentation, based on resonance principles (see Section 1.1) for rapid and accurate density measurements, has this method become practical.

Methods described above (Sections 1.1, 1.2, and 1.3) were used to measure density (d) acid concentration $[H^+]$, and uranium content (U) of prepared solutions of uranium plus HNO_3 in H_2O, 15%TBP, and 30%TBP. The make-up of these prepared solutions was distributed so as to cover the range of interest for all components. Typically, the design was a full three-level factorial with selected replication. A full quadratic polynomial model was fit to these data to form predictor equations for uranium.

1.4.1 Low-Level Aqueous Uranium (Limits: 0.1 to 3.5M$[H^+]$, 10-90 Grams-Uranium/Liter)

$U = (30.889848\ X + 48.795328)d$ gU/liter at t°C

Where d = density at t°C,

$$X = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

$A = 0.00199196$,

$B = 0.04978369 + 0.00168559y - 0.00013578z$,

$C = 1.12670857 - d + 0.04793604y - 0.00209437z$
$\quad - 0.00050179yz - 0.00042916(y^2) - 0.00000964(z^2)$,

$y = ([H^+] - 1.76)/1.400565$,

$z = (t - 29.96)/4.178783$, and

t = temperature in °C at which d was measured.

1.4.2 U in 15%TBP (Limits: 0.1 to 0.9<u>M</u> $[H^+]$, 0.2 to 60gU/liter.)

1.4.2.1 Where d< = 0.7983

$U = (d - 0.77915 - 0.026407[H^+]/0.00154465$ gU/liter at 25°C.

1.4.2.2 Where d> 0.7983

$U = (d - 0.77898 - 0.027809[H^+]/0.0013706$ gU/liter at 25°C.

Where d = density at 25.0 ± 0.1°C (see Section 1.1), and

$[H^+]$ = free HNO_3 concentration, <u>M</u> (see Section 1.2).

1.4.3 U in 30%TBP (Limits: 0.1 to 0.9M[H^+], 0.3 to 110 gU/liter.)

1.4.3.1 Where d< = 0.84395

U = (d −0.81379 −0.027034[H^+])/0.00130016 gU/liter at 25°C.

1.4.3.2 Where d> = 0.84395

U = (d −0.81442 −0.027131[H^+])/0.00131169 gU/liter at 25°C

Where d = density at 25.0 ± 0.1°C (see Section 1.1), and

[H^+] = free HNO_3 concentration M (see Section 1.2).

Note: Titrimetric U determinations were made on all samples not within the stated limits for the methods in Section 1.4.

The multiple correlation coefficient (γ^2) and residual standard deviation densimetric U determination methods were:

Method	Mult. γ^2	Res. Std. Dev.
1.4.1	0.99995	0.00053
1.4.2.1	0.95752	0.00115
1.4.2.2	0.99944	0.00047
1.4.3.1	0.99592	0.00059
1.4.3.2	0.99959	0.00090

2.0 REFERENCES

(1) Booman, G. L., et al, Determination of Free Acid in the Presence of Hydrolyzable Tons, Anal. Chem., 30, 284, (1958).

(2) Rodden, C. J., ed., Selected Measurement Methods for Plutonium and Uranium in the Nuclear Fuel Cycle, TID-7029 (2nd Ed.), (1972).

(3) Codding, J. W., et al, "Equilibrium Data for Purex Systems," KAPL-602, p. 8, (Nov. 1951).

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PILOT-SCALE PULSED COLUMNS
COLUMN PROFILE AND HOLDUP STUDIES

APPENDIX B

ANALYSIS OF HOLDUP VERSUS PULSE VELOCITY DATA

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November 1980

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ANALYSIS OF HOLDUP VERSUS PULSE VELOCITY DATA

Analysis of data presented in Tables 4-2 and 4-3, relating pulse column holdup (X_d) to the pulse velocity ($Ƶ$), confirms previous estimates (see equation 5) of the parameters in the empirical relation:

$$\hat{X}_d = b_o Ƶ^{b_1} = .19Ƶ^{2.78}$$

These estimates ($B_o = .19$, $b_1 = 2.78$) result from least-squares estimation based on the linearized (logarithmic) form of the equation:

$$(\ln \hat{X}_d) = \ln b_o + b_1 \ln Ƶ$$

with the presumption that all the random error is contained in the X_d measurement. Reasonable uncertainty bounds (95% confidence limits) about the fitted line which likely bracket the "true" line are:

±9% of $\hat{X}_d$ at low values of $\hat{X}_d$,

±5.5% of $\hat{X}_d$ at middle values of $\hat{X}_d$, and

±13.3% of $\hat{X}_d$ at high values of $\hat{X}_d$.

These bounds result from transforming the bounds on $(\ln \hat{X}_d)$ which result from standard straight-line theory to exp $(\ln \hat{X}_d)$, or $\hat{X}_d$.

Also, there are a continuum of possible least-squares lines that can be fit to the data depending upon whether it is presumed "all-error-in-X_d-none-in-$Ƶ$," "all-error-in-$Ƶ$-none-in-X_d," or any of the infinite number of possibilities in between. The parameter ^, the ratio of error variances of X_d and $Ƶ$, determines which line is appropriate. It is thus far assumed ^ = ∞. The model analysis follows.

(1) Model:

$$\hat{X}_d = b_o(2f A_o + \Delta U_{d-c})^{b_1}$$

Independent variables:

f: pulse frequency

A_o: pulse amplitude

ΔU_{d-c}:

$Ƶ$: $2f A_o + \Delta U_{d-c}$: pulse velocity

Dependent variable:

X_d: observed column holdup

Parameters to be estimated:

b_o: column holdup at unit pulse velocity

b_1: normalized slope of $\hat{X}_d$ versus Z relationship at unit pulse velocity

Linearized form:

$$(\ln \hat{X}_d) = \ln b_o + b_1 \ln Z$$

or

$$y = B_o + B_1 X$$

x: $\ln Z$

y: $\ln \hat{X}_d$

B_o: $\ln b_o$

B_1: b_1

(2) General MLE of b_1:

Let $y = \ln X_d$

$x = \ln Z$

$\wedge = S_y^2 / S_x^2$

$$\hat{b}_1(\wedge) = \frac{S_y^2 - \wedge S_x^2 + \sqrt{\left(S_y^2 - \wedge S_x^2\right)^2 + 4 \wedge S_{x,y}^2}}{2 S_{x,y}}$$

All-error-in-x, none-in-y:

$$\underset{\wedge \to o}{\text{line}} \; \hat{b}_1(\wedge) = \frac{S_y^2}{S_{x,y}}$$

All-error-in-y, none-in-x:

$$\underset{\wedge \to \infty}{\text{line}} \; \hat{b}_1(\wedge) = \underset{\wedge \to \infty}{\text{line}} \; \frac{d\hat{b}_1(\wedge)}{d\wedge} = \frac{S_{x,y}}{S_x^2}$$

(3) <u>95% confidence limits on line:</u>

$$\hat{y}_i \pm S_r \sqrt{2f_{.95}\ (2,\ n-2)\left[\frac{1}{n} + \frac{\left(x_i - \overline{x}\right)^2}{\sum_i \left(x_i - \overline{x}\right)^2}\right]}$$

n: number of data points

f: f-statistic

$\hat{y}_i$: prediction at $X = X_i$

S_r: residual standard deviation

(4) <u>Results:</u>

Error Structure	$\hat{b}_1$	$\hat{b}_0$	95% CL's
All in $\ln X_d$ (^ = ∞)	2.7820	.1863	±9.1% X_d low ±5.5% X_d mid ±13.3% X_d high
Equal in both (^ = 1)	2.9860	.1350	
All in lnZ (^ = 0)	3.0105	.1299	±4.0% Ƶ low ±1.9% Ƶ mid ±4.6% Ƶ high

$S_y^2 = .131831458$

$S_x^2 = .015740391$

$S_{x,y} = .043790286$

$r_{x,y} = .9613$

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