GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: __8/7/78__

Project Title: Powerhouse Penstock and Tunnel Junctions

Project No: E-20-638 (Co-project w/E-20-637/Mayer/CE)

Dr. CM

Project Director: Dr. C. S. Martin

Sponsor: Southern Company Services

Agreement Period: From __6/30/78__ Until __7/1/80__ ~~5/1/79~~

Type Agreement: Standard Industrial Research Agreement dated 7/24/78

Amount: $58,500

Reports Required: Initial Results, Final Report

Sponsor Contact Person (s):

Technical Matters | Contractual Matters
(thru OCA)

Mr. G. B. Dougherty, Manager
Hydro-Projects Department
Southern Company Services
P. O. Box 2625
Birmingham, AL 35202

Defense Priority Rating: None

Assigned to: __Civil Engineering__ (School/Laboratory)

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CA—3 (3/76)

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: __10/3/80__

Project Title: Powerhouse Penstock and Tunnel Junctions

Project No: E-20-638 (Co-project w/E-20/637/Mayer/CE)

Project Director: Dr. C.S. Martin

Sponsor: Southern Company Services

Effective Termination Date: ___7/31/80___

Clearance of Accounting Charges: ___7/31/80___

Grant/Contract Closeout Actions Remaining:

x Final Invoice and Closing Documents

_ Final Fiscal Report

_ Final Report of Inventions

_ Govt. Property Inventory & Related Certificate

_ Classified Material Certificate

_ Other _____

Assigned to: ___Civil Engineering___ (School/L̶a̶b̶o̶r̶a̶t̶o̶r̶y̶)

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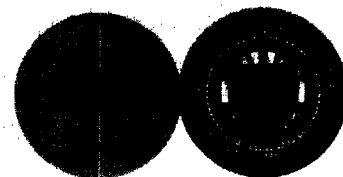Project File (OCA)
Project Code (GTRI)
Other C. E. Smith

CA—4 (1/79)

HYDRAULIC MODEL STUDY — POWER TUNNEL BIFURCATION ROCKY MOUNTAIN PROJECT GEORGIA POWER COMPANY

By

C. S. Martin

Prepared for

SOUTHERN COMPANY SERVICES, INC.
Birmingham, Alabama 35202

March 1980

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL ENGINEERING
ATLANTA, GEORGIA 30332

HYDRAULIC MODEL STUDY – POWER TUNNEL BIFURCATION

ROCKY MOUNTAIN PROJECT

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SOUTHERN COMPANY SERVICES, INC.
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School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

FOREWORD

Hydraulic model studies of the Power Tunnel Bifurcation of the Rocky Mountain Project were conducted in the Old Hydraulics Laboratory, School of Civil Engineering, Georgia Institute of Technology for the Georgia Power Company under the administration of Southern Company Services, Inc.

Dr. C. S. Martin, Professor of Civil Engineering, was the principal investigator for the project. Mr. Frank D. Lewis of the Lockheed-Georgia Corporation supervised the design and construction of the initial model scheme. Mr. Homer J. Bates, Senior Laboratory Technician, fabricated and installed the remaining three schemes. Mr. D. E. Tamplin assisted in the construction of the model and the collection of data. Most of the data exhibits were prepared by Mr. M. E. Blalock with the aid of a digital plotter.

The guidance and advice of Mr. Gale B. Dougherty of Southern Company Services, Inc. throughout the conduct of the project is appreciated. The assistance of Dr. C. S. Chiou of the same organization is likewise acknowledged. The writer also would like to recognize the able advice and assistance of Mr. A. W. Elkins of the Georgia Power Company.

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SUMMARY

A hydraulic model study of four bifurcation schemes of the Rocky
Mountain Pumped Storage Project was conducted. For each design the head
losses and the hydraulic performance of the three-penstock bifurcation were
determined. Head loss coefficients were based upon the extrapolation of
the energy grade lines from the straight tunnel and three straight pen-
stocks to the bifurcation itself. Careful measurement of the linear
HGLs in each straight leg allowed for the construction and extrapolation
of representative EGLs to the bifurcation. By means of observing tuft
glued to the inside walls of the trunk of the bifurcation and air bubbles
injected into the flowing water flow patterns in the model were photographed
and studied.

Based upon an extensive research program that included 14 tests for
each configuration, Scheme A-1 was judged to be the best overall.
Although for several modes of operation this scheme was outperformed by
one of the others, Scheme A-1 is recommended as having the lowest overall
hydraulic losses and the best hydraulic performance.

CHAPTER I

INTRODUCTION

The Rocky Mountain Project is a pumped storage development of the Georgia Power Company. This hydroelectric facility is to be located some ten miles northwest of Rome, Georgia. Hydraulic model studies were conducted at the Georgia Institute of the following three main components of the project: Lower Reservoir Main Spillway, Upper Reservoir Intake Structure, and Power Tunnel Bifurcation. This report includes only the results of the hydraulic model investigation of the Power Tunnel Bifurcation. The results of the other hydraulic model studies of the Rocky Mountain Project are contained in companion reports.

The purpose of this model study was to evaluate the head losses and hydraulic performance of three-tunnel bifurcation schemes. The vertical shaft, tunnel, bifurcations, and penstocks were modeled with a pressurized piping system that did not include the upper reservoir and its intake. The model was constructed at a scale ratio of 39.6:1, corresponding to a ten-inch conduit representing the model tunnel and vertical shaft.

The model was constructed so that flow in both the generating and pumping modes could be investigated. By the use of pumps, and control valves on each penstock, various combinations of one, two, or three unit operation in either mode could be established.

Four schemes were extensively tested for energy efficiency and flow distribution in the bifurcations. Exhibit 1 shows the shape of the four geometries, which are referred to as Schemes C-1, B-2, B-1,(Modified) and A-1. In the Appendix the detailed designs of Schemes B-1, B-2, and A-1 are compared with the actual scaled cross sections of the model as built.

1

Exhibit 1. Geometries of Four Bifurcation Schemes Tested.
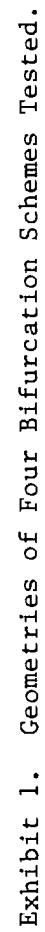
CHAPTER II

DESCRIPTION OF MODEL

The entire hydraulic model was built at an undistorted scale of 1:39.6. Although gravity does not affect the flow patterns in a pressurized flow of the type present in tunnel bifurcations, the Froude law was used to establish the model flows. From the length scale L_R = 39.6, the prototype-to-model ratios of velocity V_R, discharge Q_R, and head H_R are

$$V_R = \sqrt{L_R} = 6.29 \tag{1}$$

$$Q_R = L_R^{5/2} = 9868 \tag{2}$$

$$H_R = L_R = 39.6 \tag{3}$$

The above relationships were used in specifying model flows and in the conversion of model data to prototype conditions. Testing was frequently conducted at flows higher than those dictated by equation (2) in order to create greater differences in head for ease of measurement. For the range of Reynolds numbers covered in the test program the flow was always turbulent. The bifurcation losses, which are mainly a result of turbulence caused by separated flow, should vary as the velocity squared. All flow rates and heads are reported in prototype units.

The free-surface condition and the intake of the upper reservoir were not simulated in this model as the principal objective was the hydraulic performance of the various bifurcation schemes, which should not have been influenced measurably by the entrance flow patterns in the generation mode. A schematic of the model layout is shown in Exhibit 2. Because of the limitation in space both the vertical shaft and the tunnel had to be foreshortened somewhat. In order to improve the flow conditions in the

3

generating mode straightening vanes were installed in the upper elbow of the model. The lower elbow shown in the background of Exhibit 3 was fabricated to scale out of clear plastic.

The entire bifurcation model was made out of clear plastic, as shown in the photograph in Exhibit 4. Standard size commercial piping was used for the three penstocks, which were connected to PVC elbows and piping, terminating with the three pinch valves, which simulated the pump-turbines. By closing the discharge valve on the pump situated in the laboratory sump flow could be produced in the generating mode from the constant head tank outside the laboratory. In this mode the dump valve at the sump was open, allowing the flow through the respective units to be controlled by the three pinch valves.

By closing the dump valve and opening the pump discharge valve the sump pump produced flow in the pumping mode to the head tank. The flow rate in each unit could be systematically set to a prescribed value.

Flow Measurement

As shown in Exhibit 2 a bend meter was installed on each unit. Each bend meter was connected to an air-water manometer for direct reading. By use of the large laboratory weighing tank the discharge coefficient of each meter was accurately determined for flow in both directions. Based upon calibration and the accuracy of reading the manometer it is estimated that the uncertainty in flow measurement is no more than $\pm$ 100 cfs for each bend meter. In order to simulate the identical approach flow conditions to the meters the entire PVC pipe assembly upstream and downstream of each meter was in place during calibration.

Piezometric Head Measurement

Piezometer taps were installed in the walls of the vertical shaft, the tunnel, and the penstocks for the determination of the head loss

characteristics of the model. Exhibits 5 and 6 illustrate the location of the piezometer taps for Schemes B-1 and B-2, and A-1, respectively. The only difference between the two is the location of piezometers 4, 8, 12 and 13 relative to the bifurcation model. During measurement each of the piezometer tubes was connected to a 20-tube manometer board, where the water level could be read to 0.1 inch model units.

For bifurcation schemes B-1, B-2, and A-1 the piezometric-head distribution in the trunk of the model, which is defined by cross hatching on Exhibits 7, 8, and 9 for Schemes B-1, B-2, and A-1, respectively, was also measured using the 20-tube air-water manometer board. The exact location of the various piezometers are also indicated on the exhibits.

Test Conditions

For each of the schemes there were fourteen possible combinations of flow for the three-unit system operating in either the generating or pumping mode, as listed in Table 1.

5

PENSTOCKS

TUNNEL

BIFUR-
CATION
MODEL

PINCH VALVES

BEND
METERS

GENERATING

PLAN

VANES

TO HEAD
TANK

PUMP

PUMPING

SUMP

VERTICAL
SHAFT

TUNNEL

BIFUR-
CATION
MODEL

PROFILE
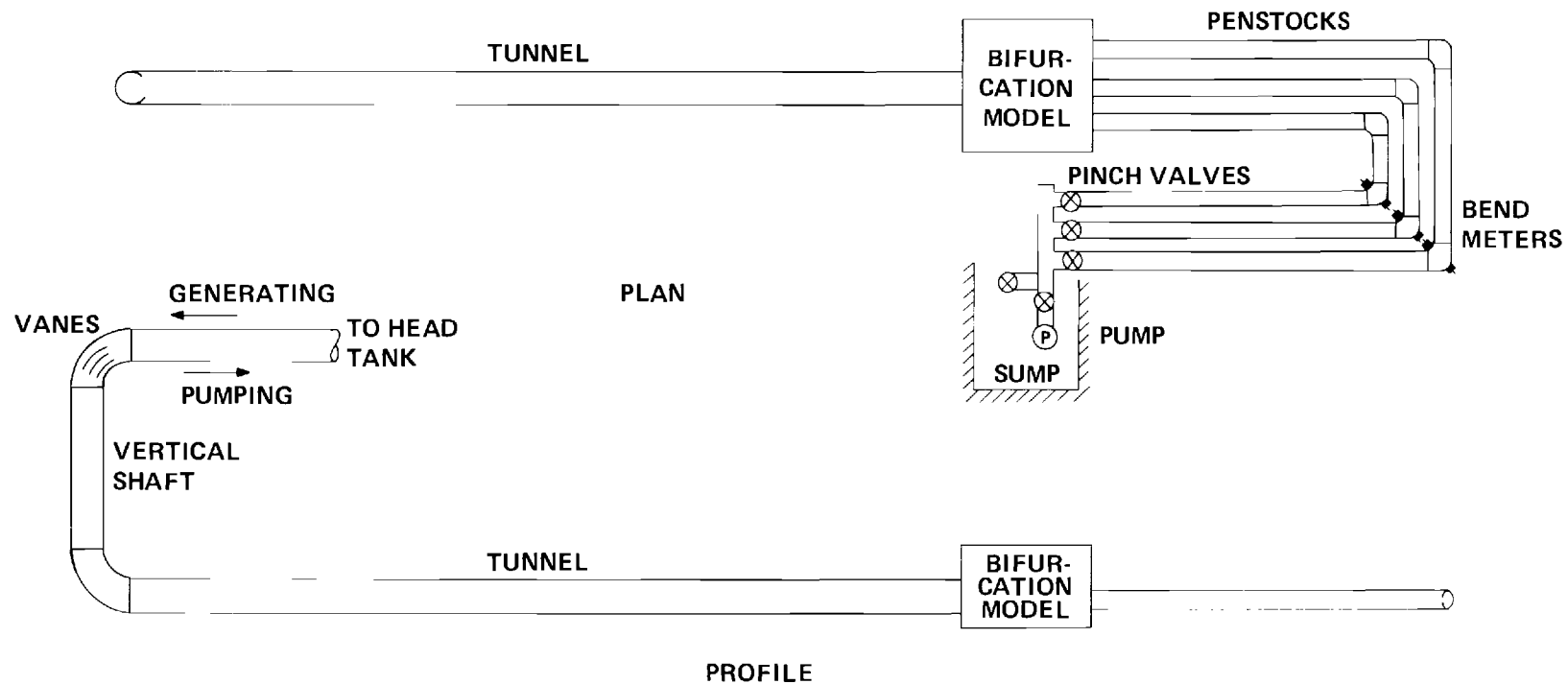
Exhibit 2.   Layout of Model in Laboratory.
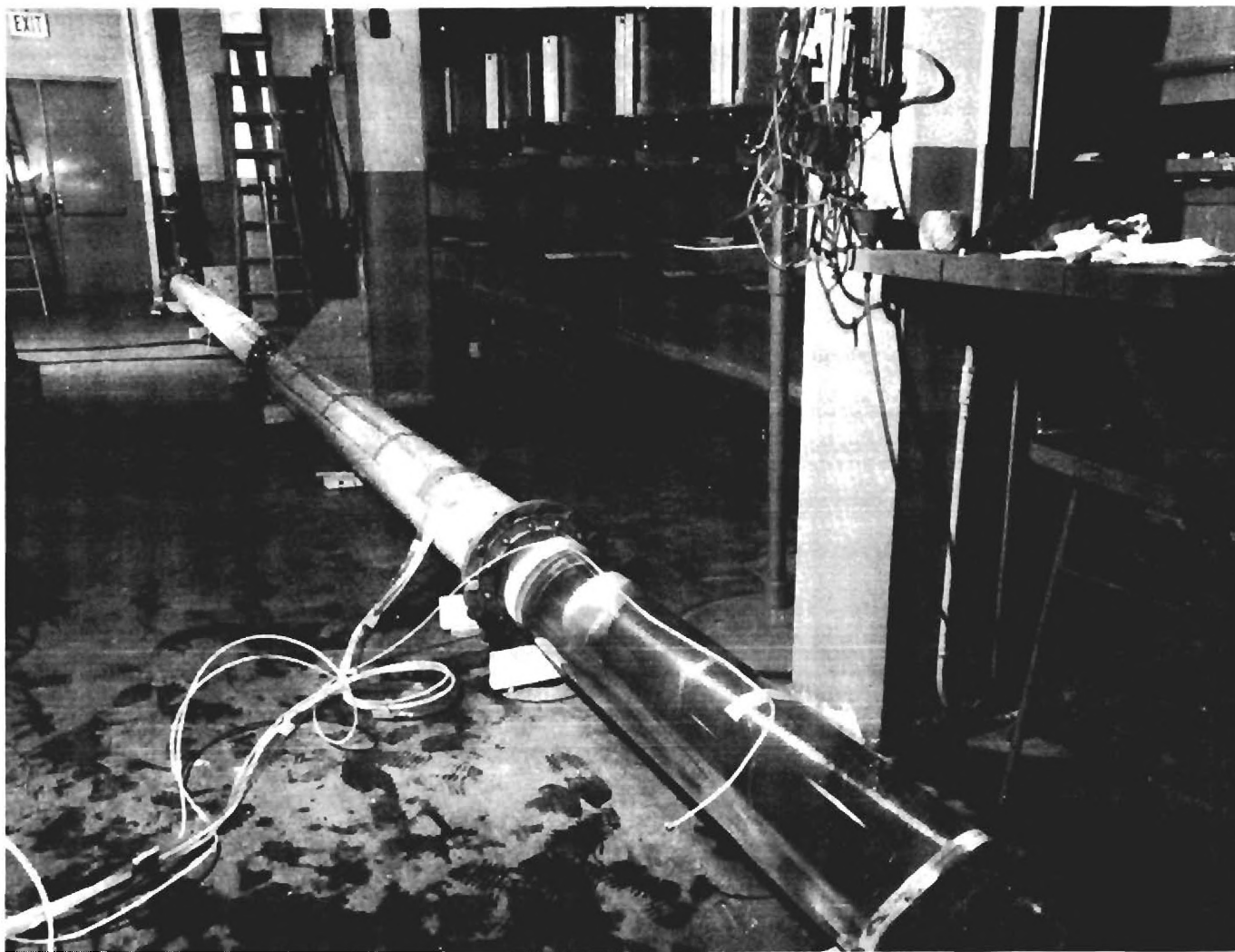
Exhibit 3.   View of Model Tunnel and Vertical Shaft.
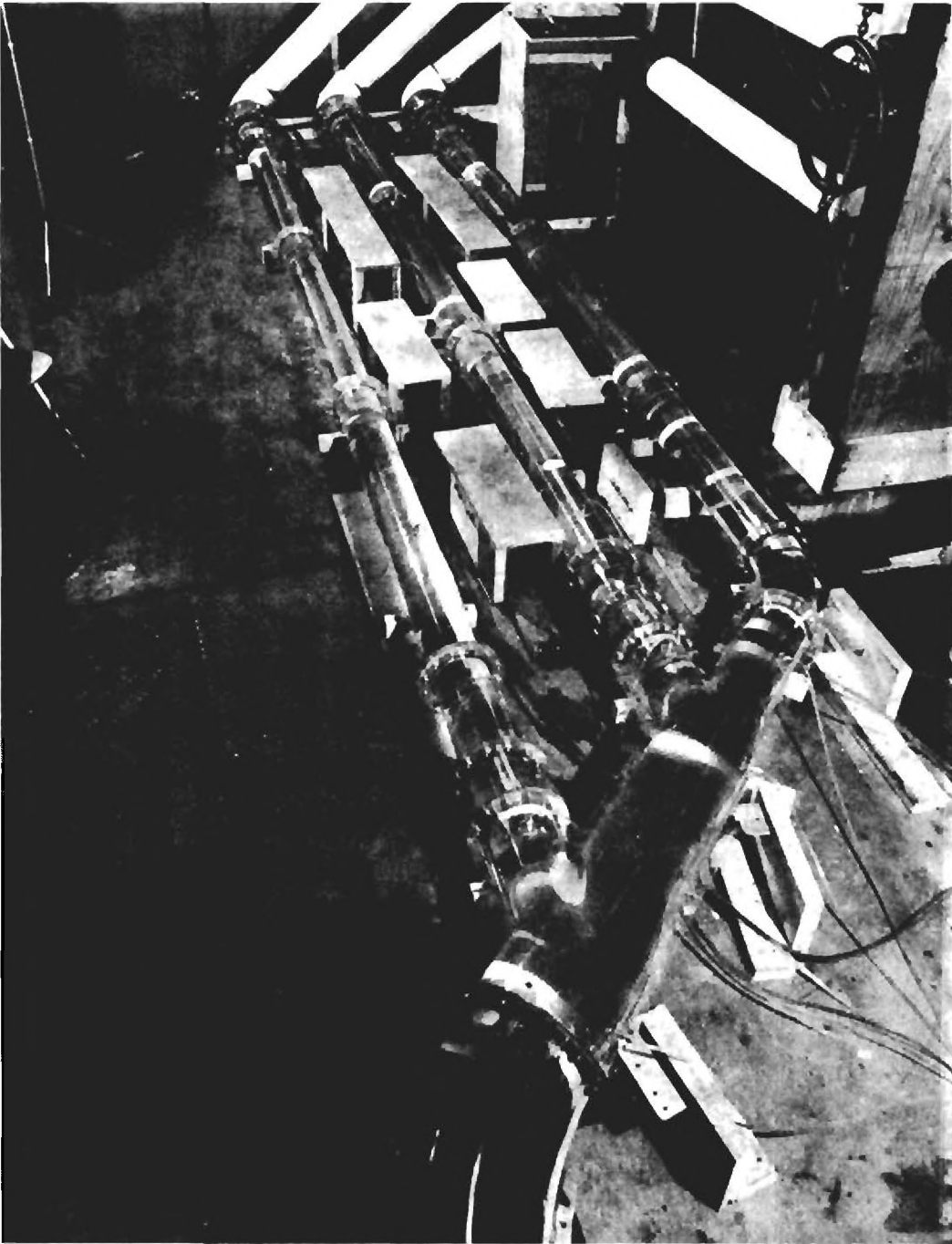
Exhibit 4. View of Model Trunk and Penstocks.

8

DIMENSIONS IN FEET

D-LINE

U-LINE

UNIT

80

12   11   10   9   3
8   7   6   5   2
4   3   2   1   1

PLAN

23

79
79
79
69

0
19
18
17   16   15   14   13

R = 95

BIFUR-
CATION
MODEL

79   396   396   396   264   40   244   30   158   158   158 20

PROFILE
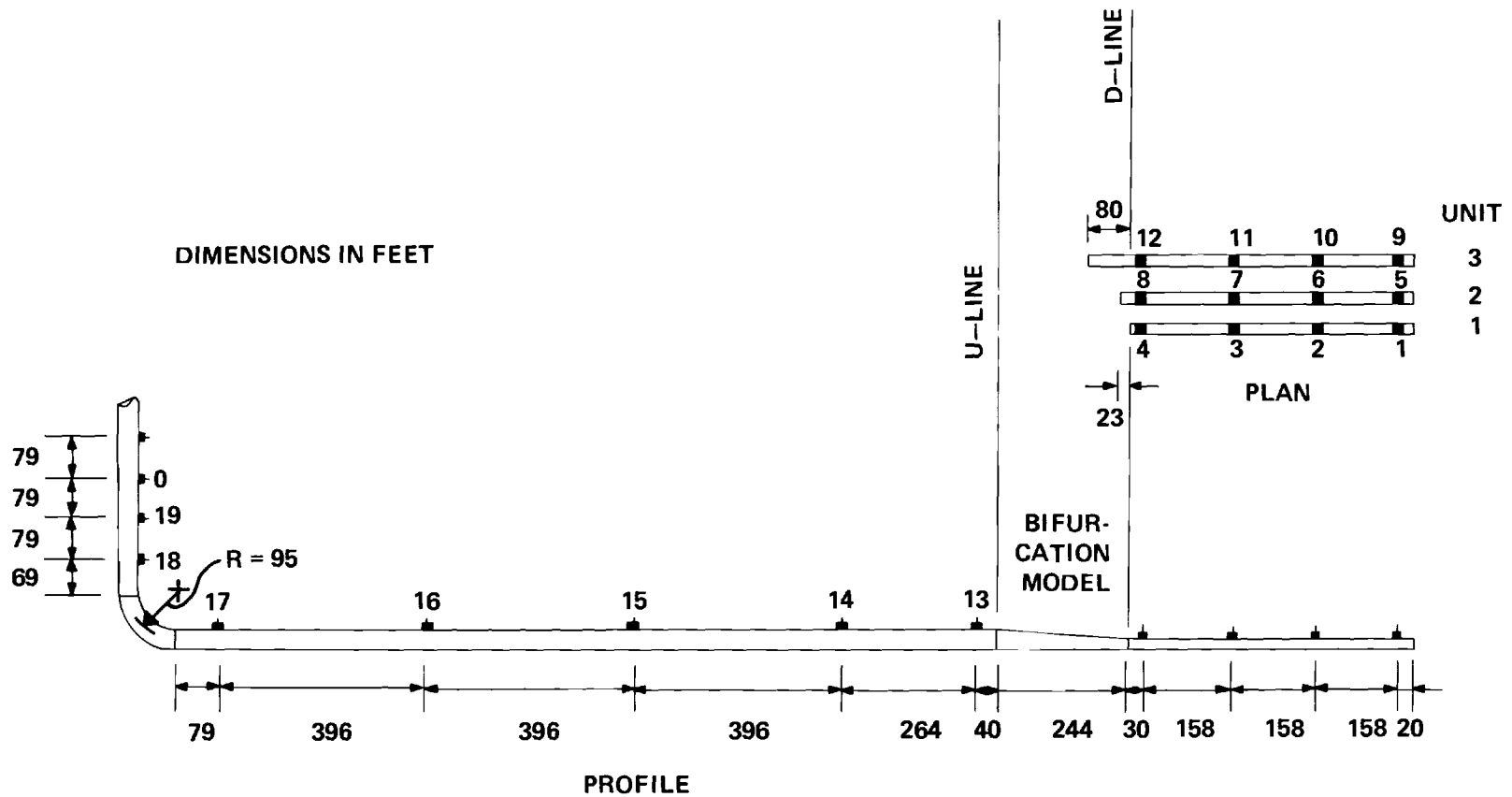
Exhibit 5.   Location of Pressure Taps in Straight Legs of
Schemes B-1 and B-2.

9

DIMENSIONS IN FEET

D-LINE

33

UNIT

12   11   10   9

3

2

U-LINE

8   7   6   5

1

4   3   2   1

PLAN

23

**BIFUR-
CATION
MODEL**

79
79
79
69

0

19

18

17   R = 95

16   15   14   13

79   396   396   396   264   120 165 35 158   158   158 20

PROFILE
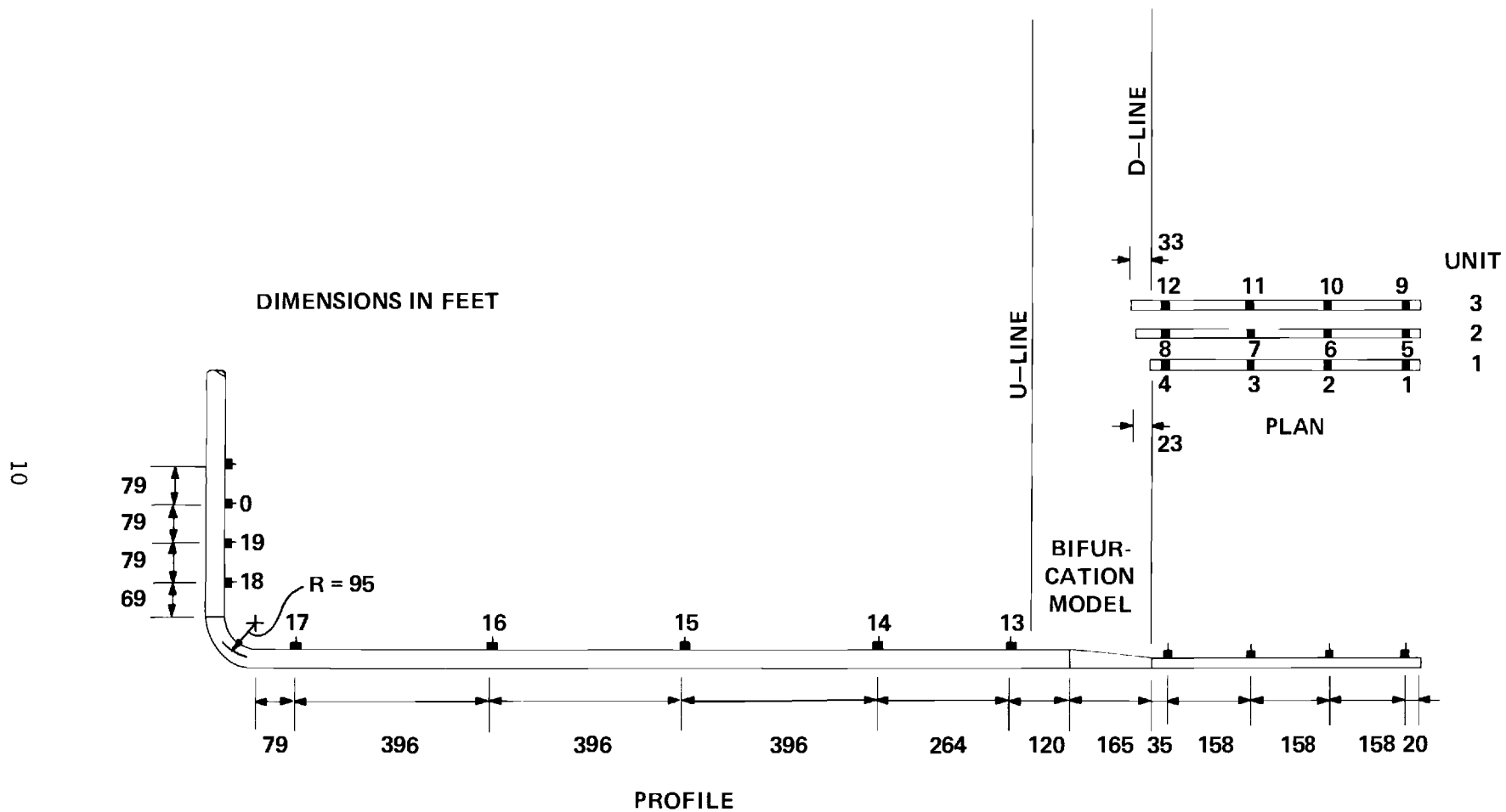
Exhibit 6. Location of Pressure Taps in Straight Legs of
Scheme A-1.

47.6

TRUNK IS IDENTIFIED
BY CROSS HATCHING

D3—LINE

D2—LINE

D1—LINE

45°

45°

UNIT 1   UNIT 2   UNIT 3
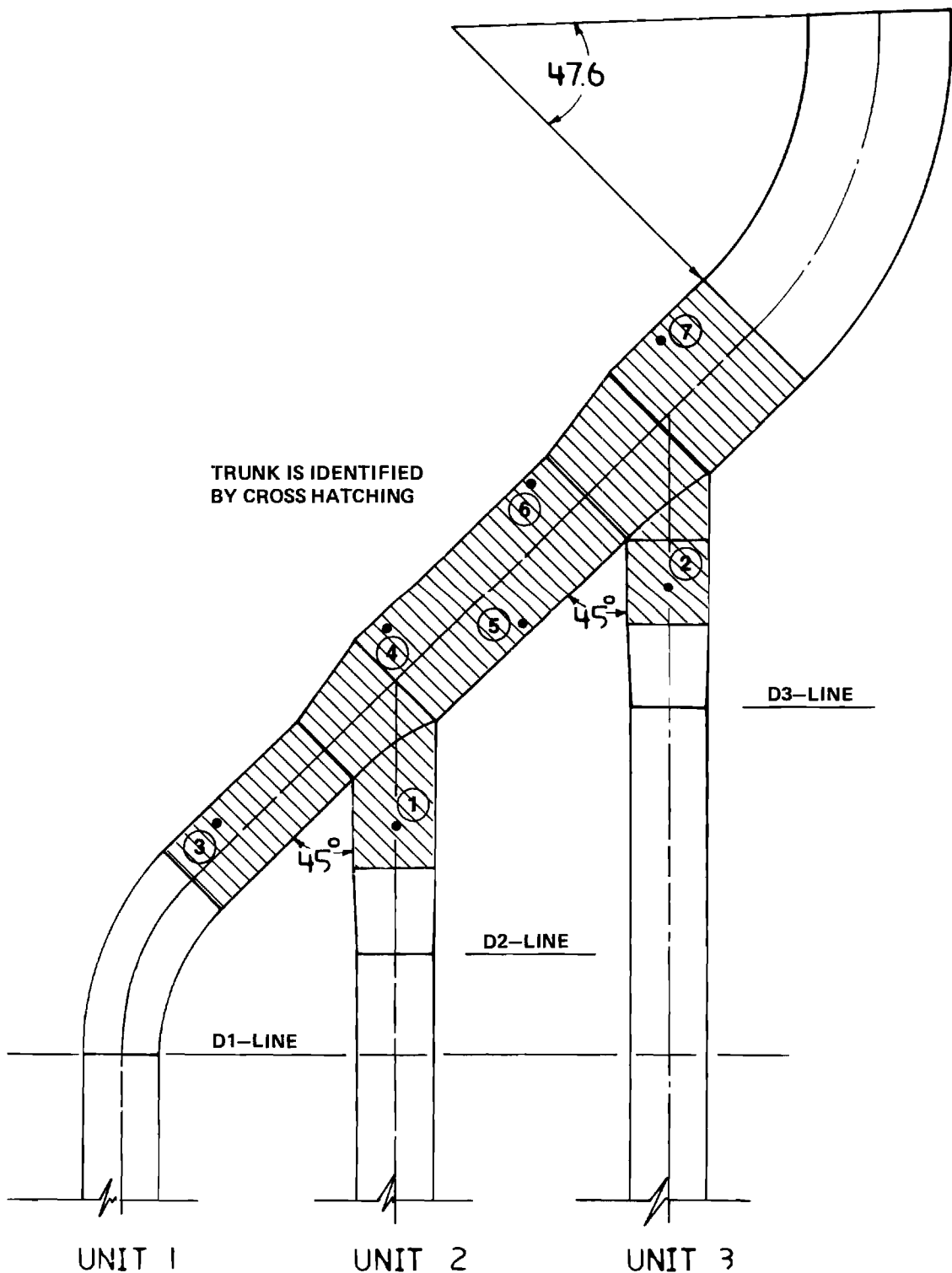
Exhibit 7. Location of Pressure Taps in Trunk of Modified
            Scheme B-1.

11

TRUNK IS IDENTIFIED
BY CROSS HATCHING

D3—LINE

D2—LINE

D1—LINE

UNIT 1   UNIT 2   UNIT 3
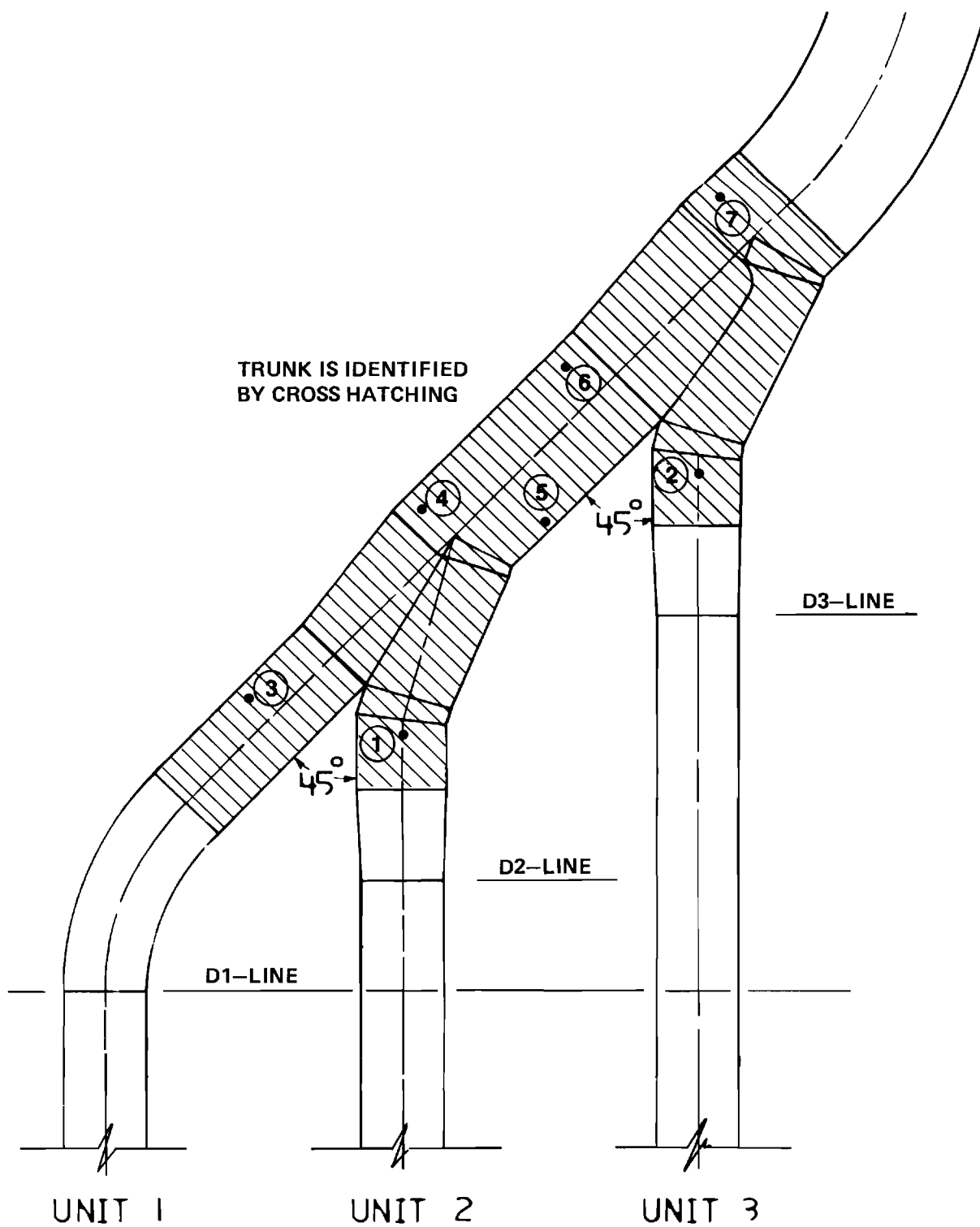
Exhibit 8. Location of Pressure Taps in Trunk of Scheme B-2.

12

TRUNK IS IDENTIFIED
BY CROSS HATCHING

D3—LINE

D2—LINE

D1—LINE

17.5'

PENSTOCK

UNIT 1   UNIT 2   UNIT 3
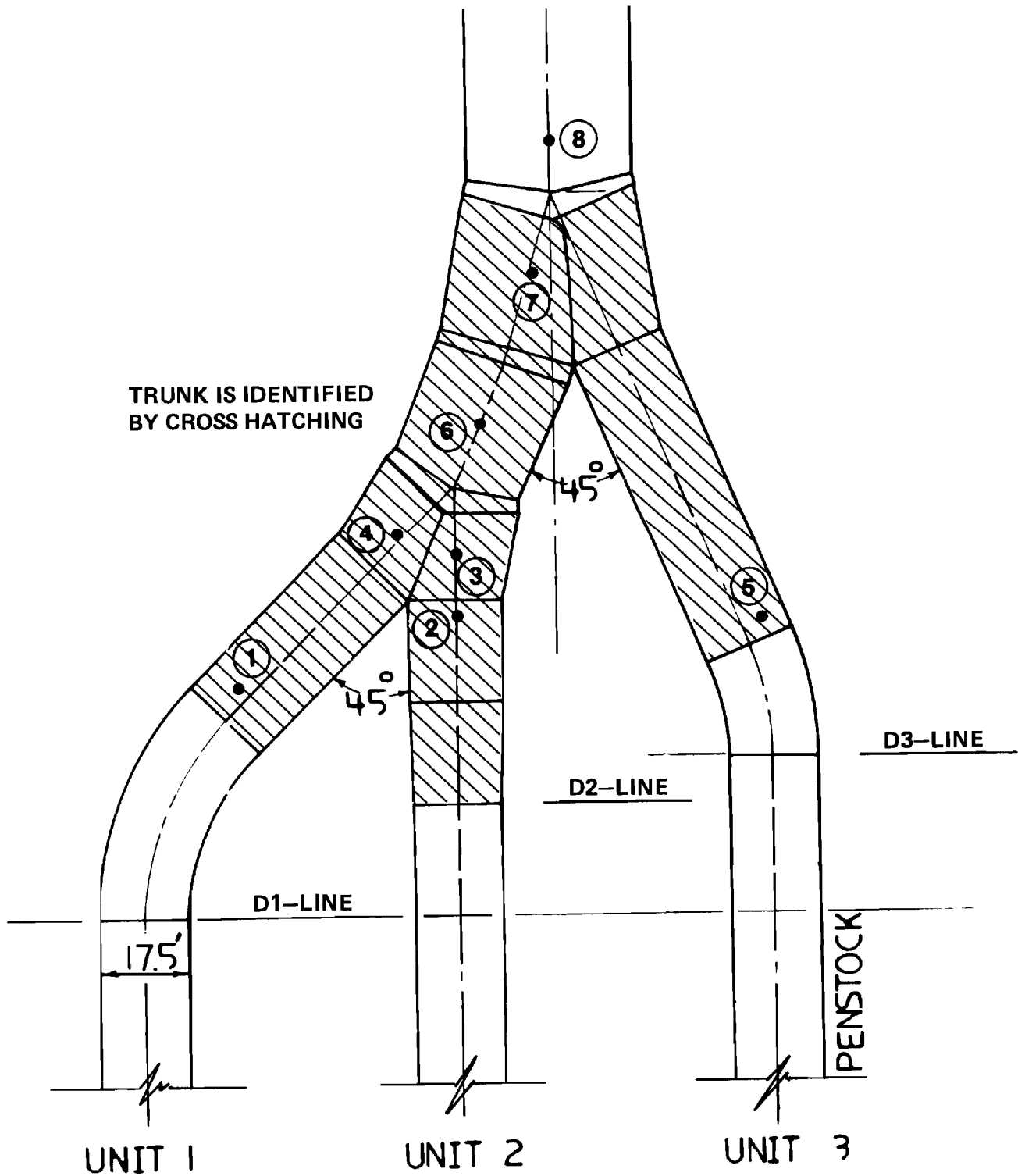
Exhibit 9. Location of Pressure Taps in Trunk of Scheme A-1.

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TABLE 1

LIST OF POSSIBLE TEST CONDITIONS

Mode	Units Operating
Generating	1, 2 and 3
Generating	1 and 2
Generating	1 and 3
Generating	2 and 3
Generating	1
Generating	2
Generating	3
Pumping	1, 2 and 3
Pumping	1 and 2
Pumping	1 and 3
Pumping	2 and 3
Pumping	1
Pumping	2
Pumping	3

CHAPTER III

TEST RESULTS FOR MODIFIED B-1 SCHEME

The B-1 Scheme as tested is referred to as a modified scheme as the transition from the trunk to the penstock of Unit 3 was not fabricated precisely according to design drawings. In order to produce a more streamlined flow in that region the transition was improved somewhat by grinding and reforming the model, the result of which can be seen on some of the following photographs. Exhibit 82 in the Appendix illustrates more precisely the actual difference between the model as tested and the bifurcation as designed.

Head-Loss Data

The fourteen possible test conditions for the three-unit system operating in either the generating or pumping mode listed in Table 1 were tested for Scheme B-1. Maximum possible model flows rather than design flows were produced in each case in order to improve the accuracy of measurement. The results for each test are plotted along the straight portions of the vertical shaft, tunnel, and penstocks of the comprehensive model in Exhibits 10-19. For ease of reference and for the sole purpose of comparison of head loss between schemes, the value of the HGL at piezometer number 0 in Exhibit 5 is arbitrarily assigned a value of 1000 ft. Therefore, the values of the HGL throughout the system are not actual, but relative.

As shown in Exhibit 10, which corresponds to three units generating, the piezometric-head line or hydraulic grade line (HGL) is essentially a straight line in the various legs of the model for this test condition. For each leg a best fit straight line is drawn through the points on the HGL which appear to be in a developed flow region. Using the measured discharge through the respective conduit the energy grade line (EGL) is then drawn parallel to the HGL one velocity head higher.

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The elbow head loss is determined by extrapolating the EGL's from
the vertical shaft and the tunnel to the bend, which is assumed to have
no length in this analysis. The loss coefficient K_L for the elbow is
defined by

$$H_L = K_L \frac{V^2}{2g} \tag{4}$$

in which V is the mean velocity in the tunnel and in the shaft. As shown
in Exhibit 10 the difference in EGL's at the location of the elbow is
defined as the bend head loss, which was 3.4 ft in this instance. Based
upon the velocity head in the tunnel, which is the same as that in the
shaft, the loss coefficient is 0.15.

The head loss coefficients for the tunnel bifurcation are defined on
the basis of the velocity head in the respective penstock. The actual head
loss is defined as the difference in the extrapolated EGL at the right
end of the tunnel (beginning of bend) and the extrapolated EGL at the
left end of the 17.5 ft diameter penstock (Lines D1, D2, or D3 in Exhibit 7)
in question, as shown by Exhibit 5. For each penstock the actual head loss
coefficient is   defined by:

$$H_{L_1} = K_{L_1} \frac{V_1^2}{2g} \tag{5}$$

$$H_{L_2} = K_{L_2} \frac{V_2^2}{2g} \tag{6}$$

$$H_{L_3} = K_{L_3} \frac{V_3^2}{2g} \tag{7}$$

in which V_1, V_2, and V_3 are the mean velocities in the penstocks for Units
1, 2, and 3, respectively.

In Exhibits 10-19 the values of the HGL are plotted relative to the
beginning of the penstocks in order to calculate the actual head loss
across the model. The relative loss coefficients, which are useful in

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comparing performance of the three units, are instead referred to the head loss between the common locations designated by the U-Line and D-Line shown on Exhibit 1, and are defined by

$$H_{R_1} = K_{R_1} \frac{V_1^2}{2g} \tag{8}$$

$$H_{R_2} = K_{R_2} \frac{V_2^2}{2g} \tag{9}$$

$$H_{R_3} = K_{R_3} \frac{V_3^2}{2g} \tag{10}$$

in which K_{R_1}, K_{R_2}, and K_{R_3} are the relative head loss coefficients.

The head-loss coefficients tabulated on Exhibits 10-19 are based upon the actual head loss across the bifurcation model. Tables 2 and 3 provide a summary of the actual and relative loss coefficients for the fourteen test conditions for the Modified B-1 Scheme, respectively. Since the D-Line crosses the plane of the beginning of the penstock of Unit 1 there is no difference in the actual and relative loss coefficients K_{L_1} and K_{R_1} for this unit. The rather abrupt transition from the penstocks of Units 2 and 3, especially that of Unit 3, created unusually bad flow conditions, particularly in the pumping mode.

Flow Patterns in Bifurcation Model

The flow patterns in the model were determined by (1) observing the direction of tuft glued to the inside wall of the trunk and penstocks and (2) by photographing air bubbles that were injected upstream of the model.

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For scheme B-1 the air bubbles clearly illustrated the severe turbulence under several modes of operation.

Exhibit 20 shows both the orientation of the various tuft and a time exposure of air bubbles which were injected into the flow for the case of three units generating. The bad flow condition at the juncture of penstock #3 and the trunk is illustrated by the tuft swirling in the eddy caused by the flow separation at that location. Exhibit 21 shows the flow pattern for Units 1 and 2 in the generating mode. The values of the loss coefficients listed in Tables 2 and 3 indicate lower losses for single unit flow than for multiple unit flow in the generating mode. Exhibit 22 clearly shows, in comparison with Exhibit 20, that the eddy at the beginning of penstock #3 is quite weak for flow through that unit alone.

The flow patterns in the model were more clearly exhibited in the pumping mode by the air bubbles because of the ability to inject air into each penstock. Moreover, the severe turbulence generated in the expanded flow regions at the junction of penstocks #2 and #3 with the trunk could be easily observed. Exhibit 23 clearly illustrates the turbulence in the trunk for the condition of all three units pumping. Even when Unit 3 is not pumping the fairly sudden expansion in the trunk area creates a considerable amount of turbulence, as shown by Exhibit 24 for Units 1 and 2 pumping. The flow pattern changes considerably when Units 1 and 3 are pumping (Exhibit 25) or Units 2 and 3 (Exhibit 26). The corresponding redistribution of the head losses is reflected by the changes in the loss coefficients (Tables 2 and 3).

For single unit pumping the loss coefficients for Units 2 and 3 increase significantly because of the steep expansion angle from the penstocks to the trunk. Exhibits 27 and 28 show the flow patterns for

the cases of Unit 1 pumping and Unit 2 pumping, respectively. The worst

flow condition of the entire set of test conditions is shown by Exhibit 29 --

Unit 3 pumping. In this case the turbulence, as marked by the air bubbles,

persisted as a strong vortex core up the tunnel for a number of diameters.

This nonuniform flow condition is reflected by the much higher values of

the HGL in the tunnel for Unit 1 pumping than for either Unit 2 or Unit 3

pumping, as clearly shown by Exhibit 19.

Pressure Distribution in Trunk

For the seven piezometer locations indicated on Exhibit 7 the piezo-

metric head was measured for all of the pumping conditions and one of the

generating conditions listed in Table 1. The results are listed in Table 4

relative to the same 1000 ft datum for piezometer number 0 in the vertical

shaft. The differences in pressure throughout the trunk are not significant

from a design standpoint. The values of the piezometric head at piezometers

4 and 7 in the pumping mode are in particular greater than at the remaining

locations because of a stagnation effect as the flow enters the trunk from

penstocks 2 and 3, respectively.
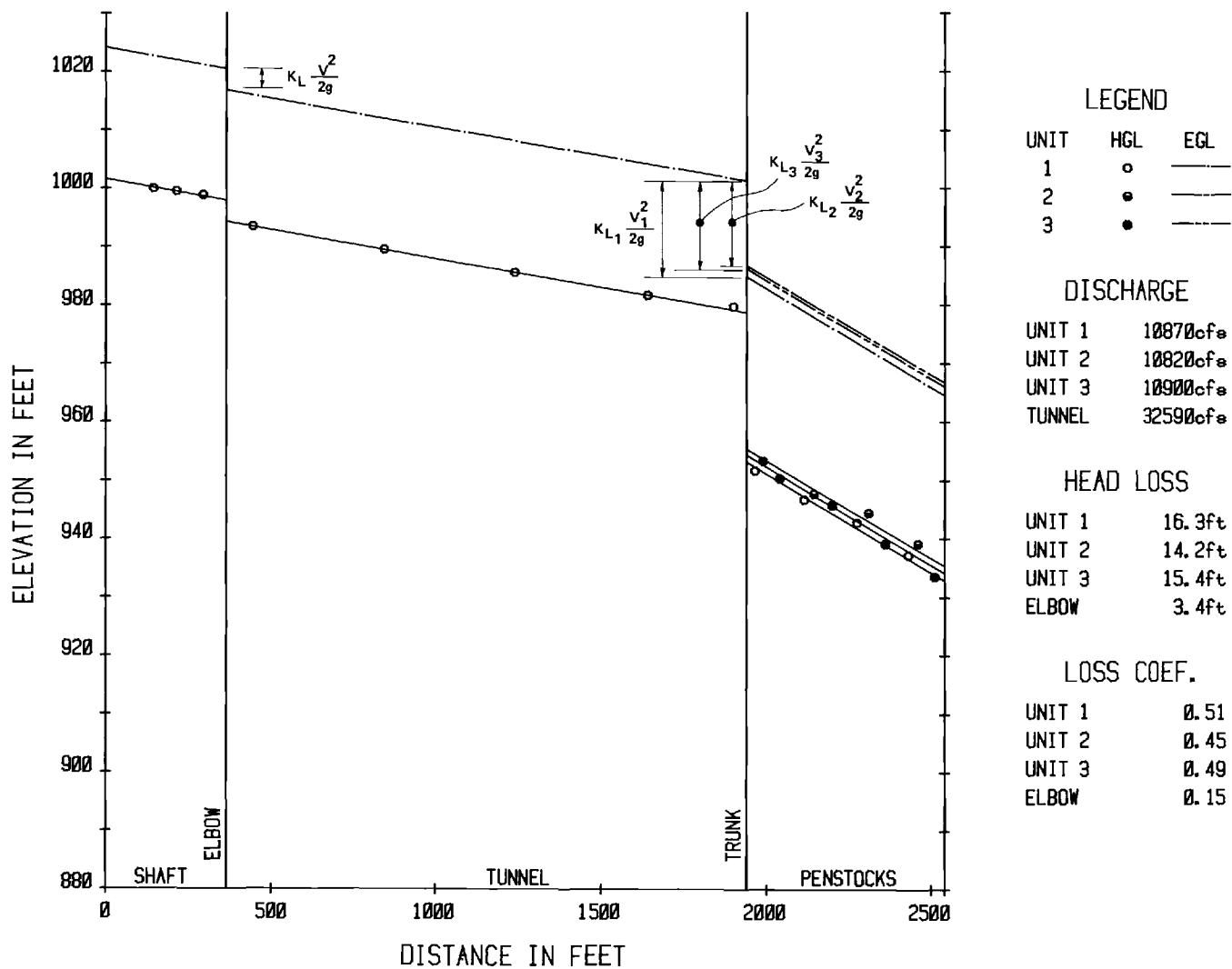
Exhibit 10. Hydraulic and Energy Grade Lines in Modified Scheme
B-1 for Three Units Generating.
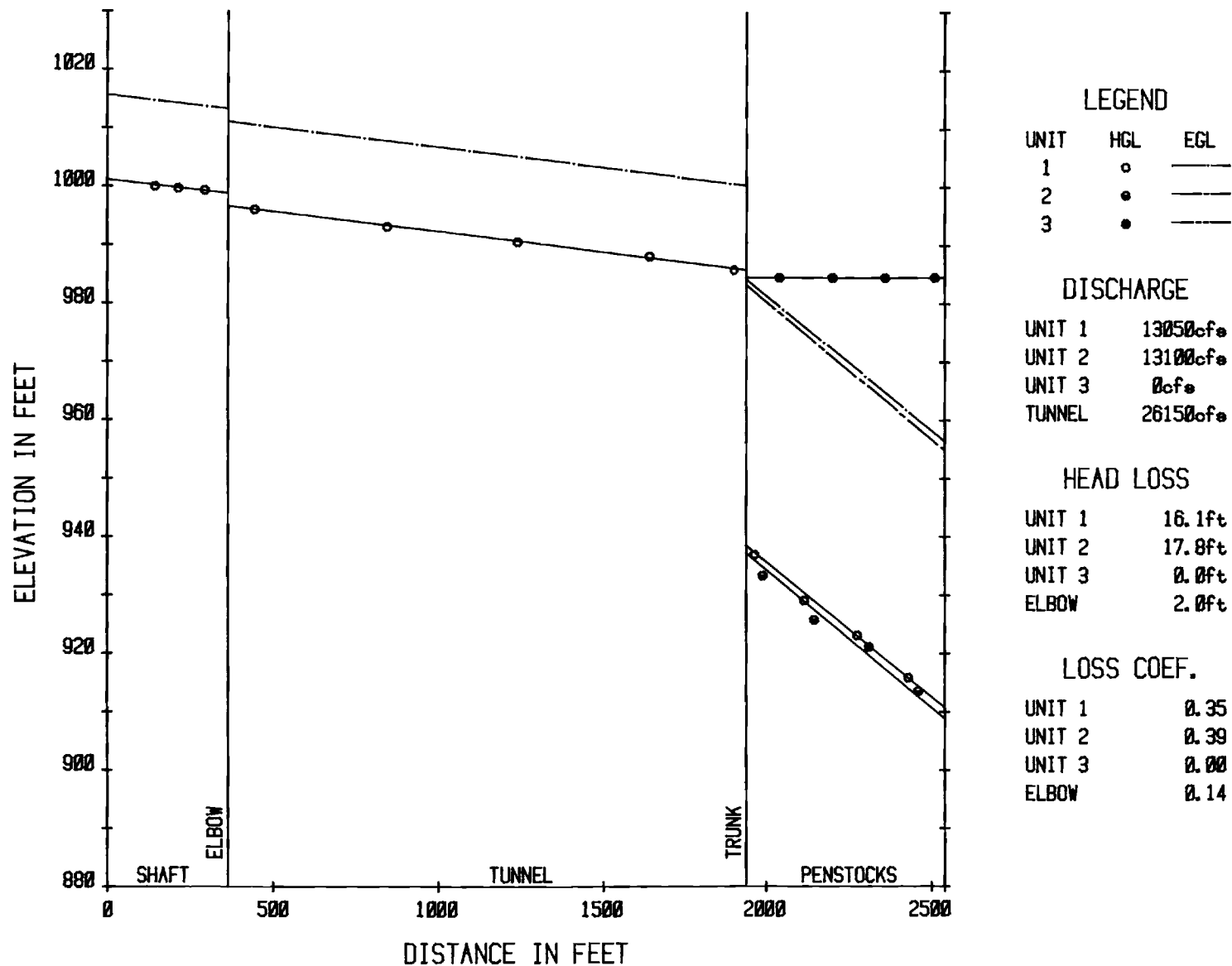
Exhibit 11.   Hydraulic and Energy Grade Lines in Modified Scheme
              B-1 for Units 1 and 2 Generating.

ELEVATION IN FEET

DISTANCE IN FEET

1020

1000

980

960

940

920

900

880

0   500   1000   1500   2000   2500

SHAFT   ELBOW   TUNNEL   TRUNK   PENSTOCKS

LEGEND

UNIT	HGL	EGL
1	o	———
2	•	———
3	•	—·—·—

DISCHARGE

UNIT 1	12940cfs
UNIT 2	0cfs
UNIT 3	13240cfs
TUNNEL	26180cfs

HEAD LOSS

UNIT 1	18.8ft
UNIT 2	0.0ft
UNIT 3	16.1ft
ELBOW	2.8ft

LOSS COEF.

UNIT 1	0.42
UNIT 2	0.00
UNIT 3	0.34
ELBOW	0.19
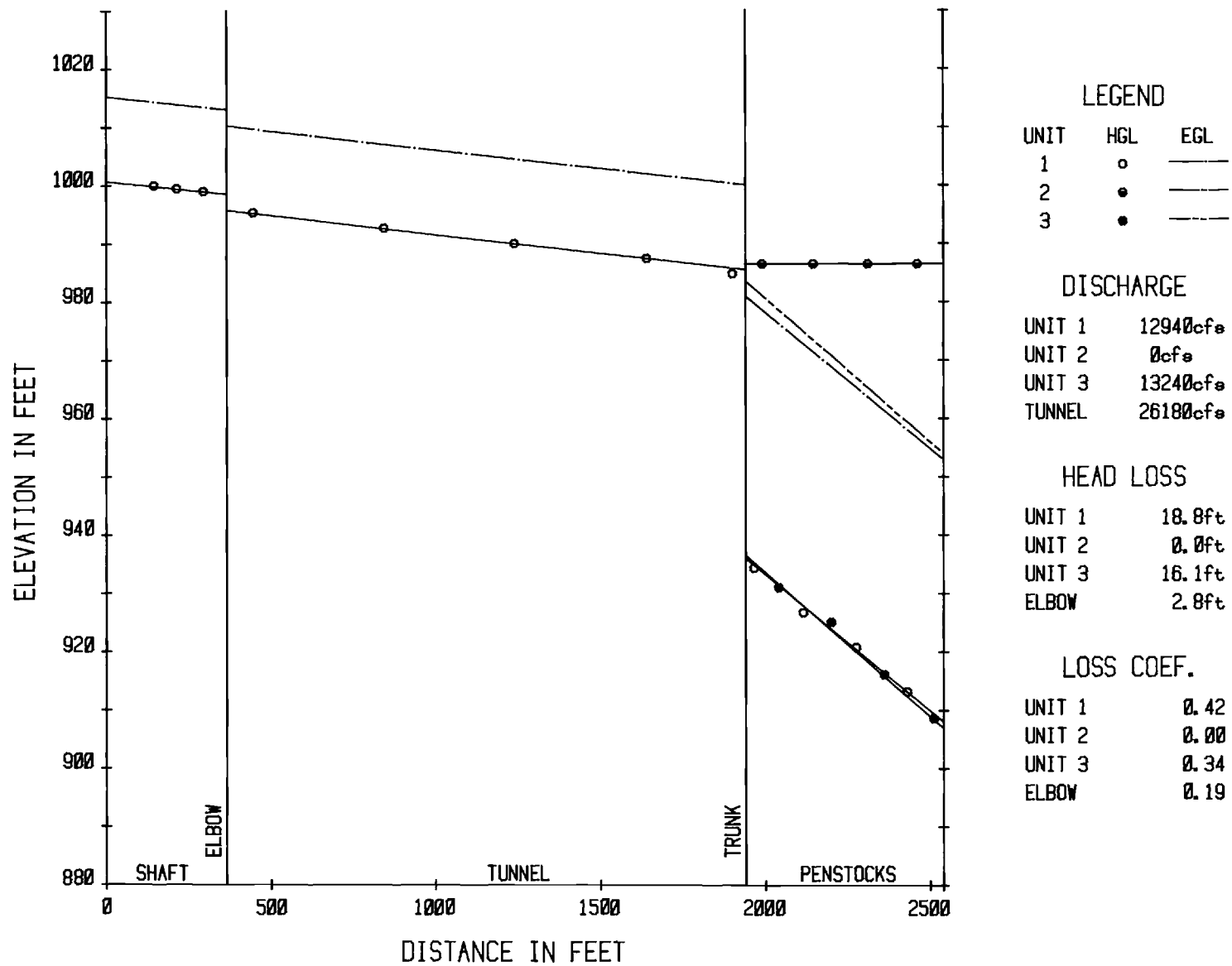
Exhibit 12.   Hydraulic and Energy Grade Lines in Modified Scheme
B-1 for Units 1 and 3 Generating.
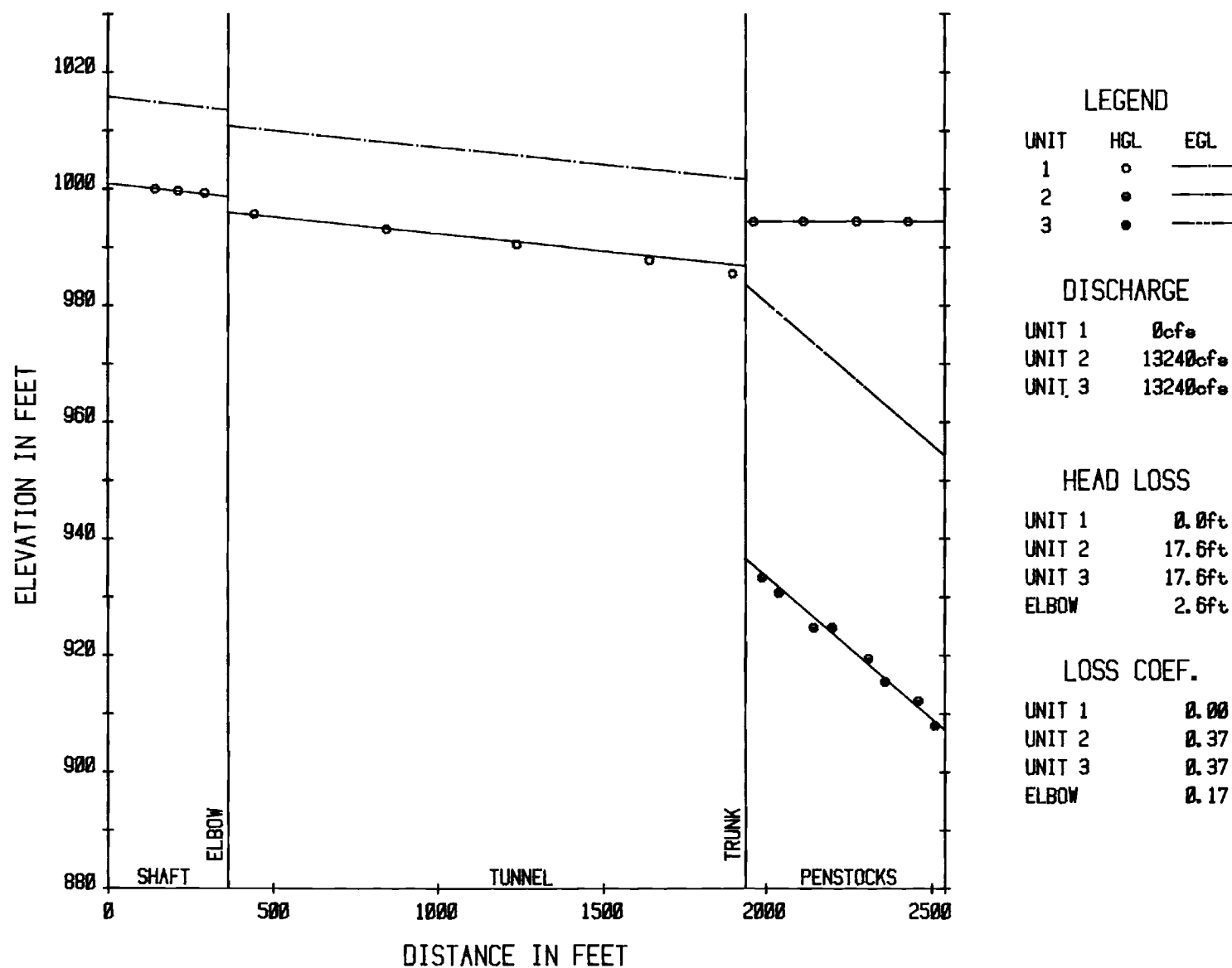
Exhibit 13. Hydraulic and Energy Grade Lines in Modified Scheme
B-1 for Units 2 and 3 Generating.

ELEVATION IN FEET

1020

1000

980

960

940

920

900

880

0   500   1000   1500   2000   2500

DISTANCE IN FEET

SHAFT   ELBOW   TUNNEL   TRUNK   PENSTOCKS

LEGEND

UNIT	HGL	EGL
1	o	————
2	●	— — —
3	●	—·—·—

DISCHARGE

UNIT 1   13400cfs
UNIT 2   13300cfs
.UNIT 3   13400cfs

HEAD LOSS

UNIT 1   13.9ft
UNIT 2   11.6ft
UNIT 3   15.3ft

LOSS COEF.

UNIT 1   0.29
UNIT 2   0.24
UNIT 3   0.32

24
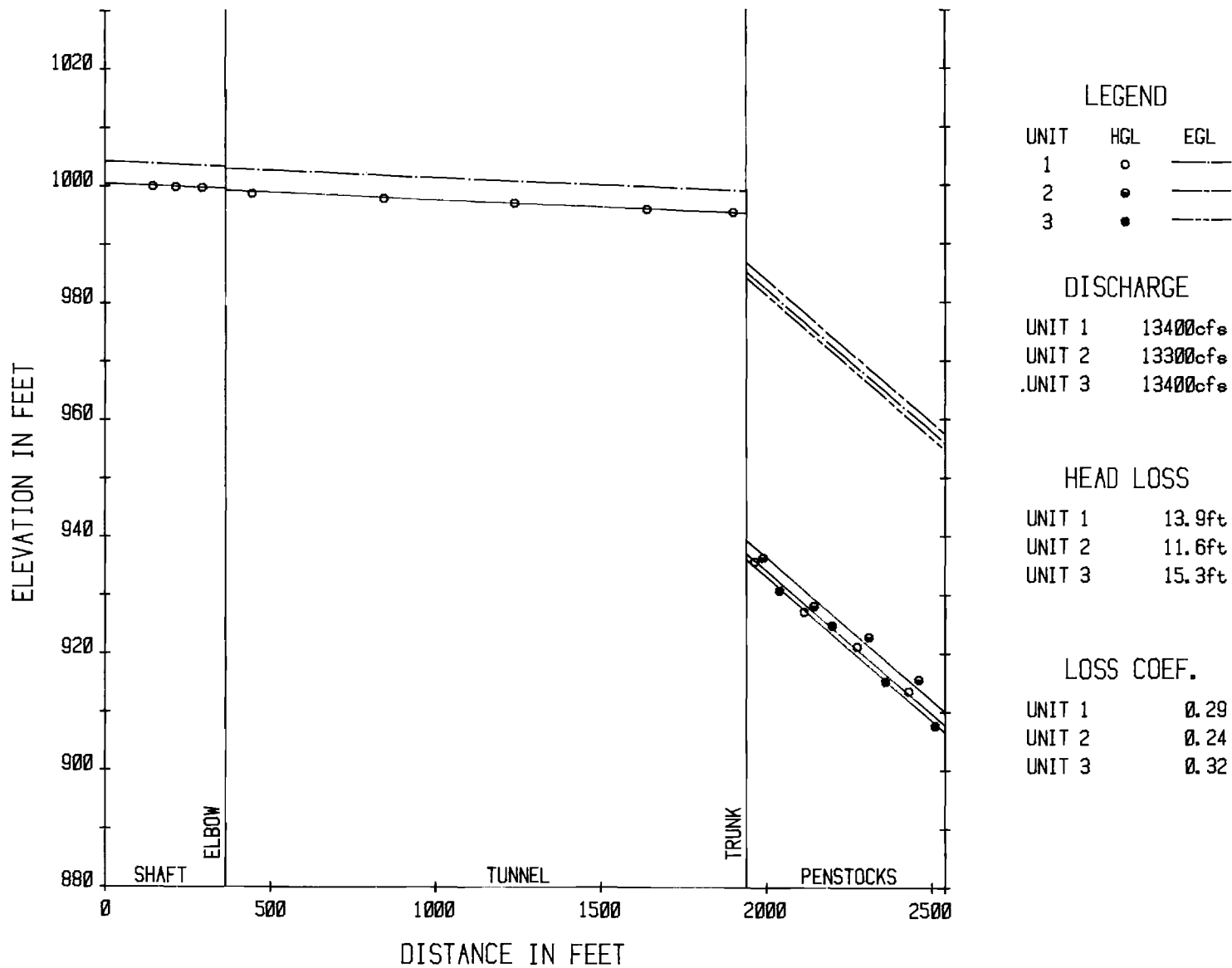
Exhibit 14.   Hydraulic and Energy Grade Lines in Modified Scheme
B-1 for Single Unit Generating.
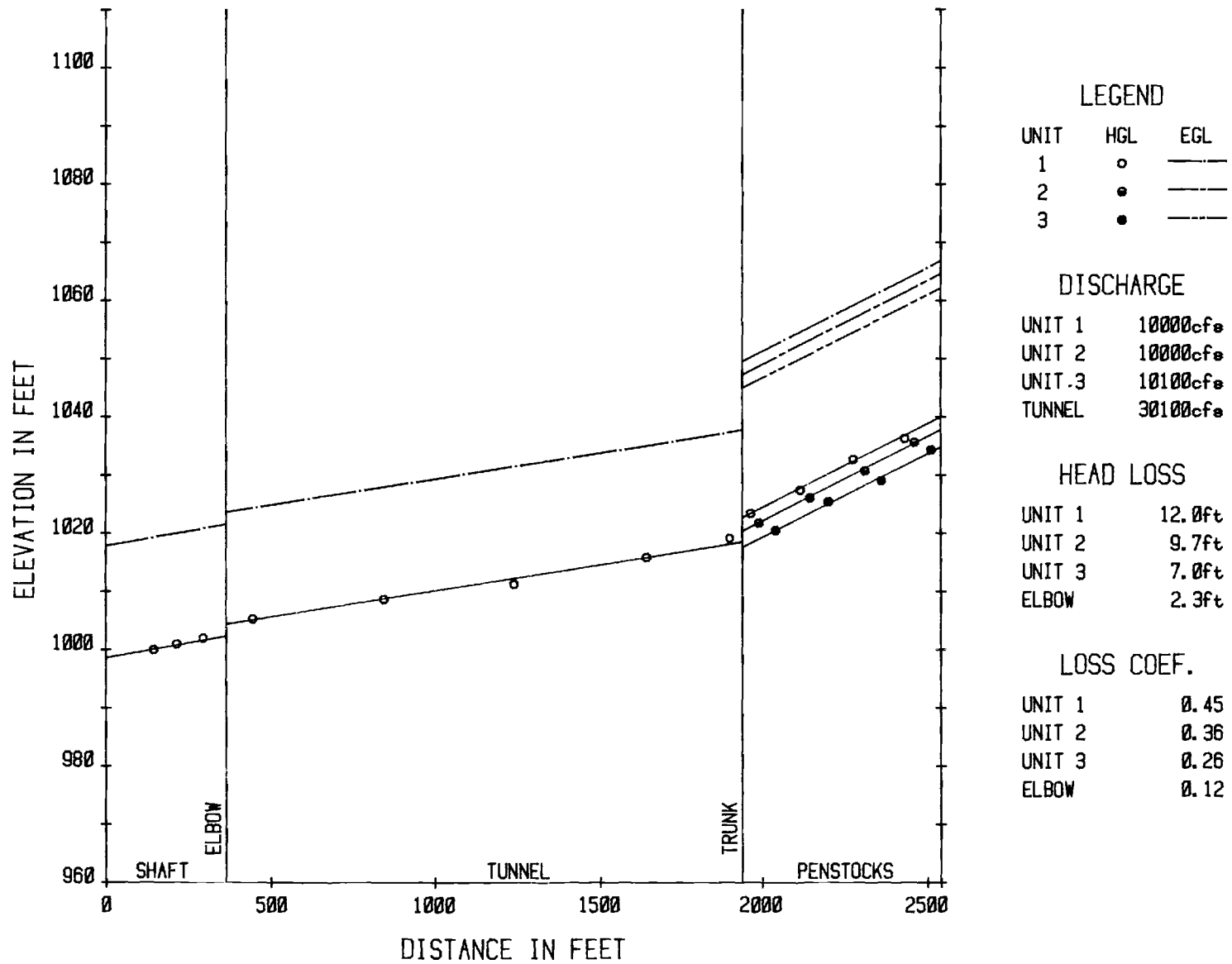
Exhibit 15. Hydraulic and Energy Grade Lines in Modified Scheme
B-1 for Three Units Pumping.
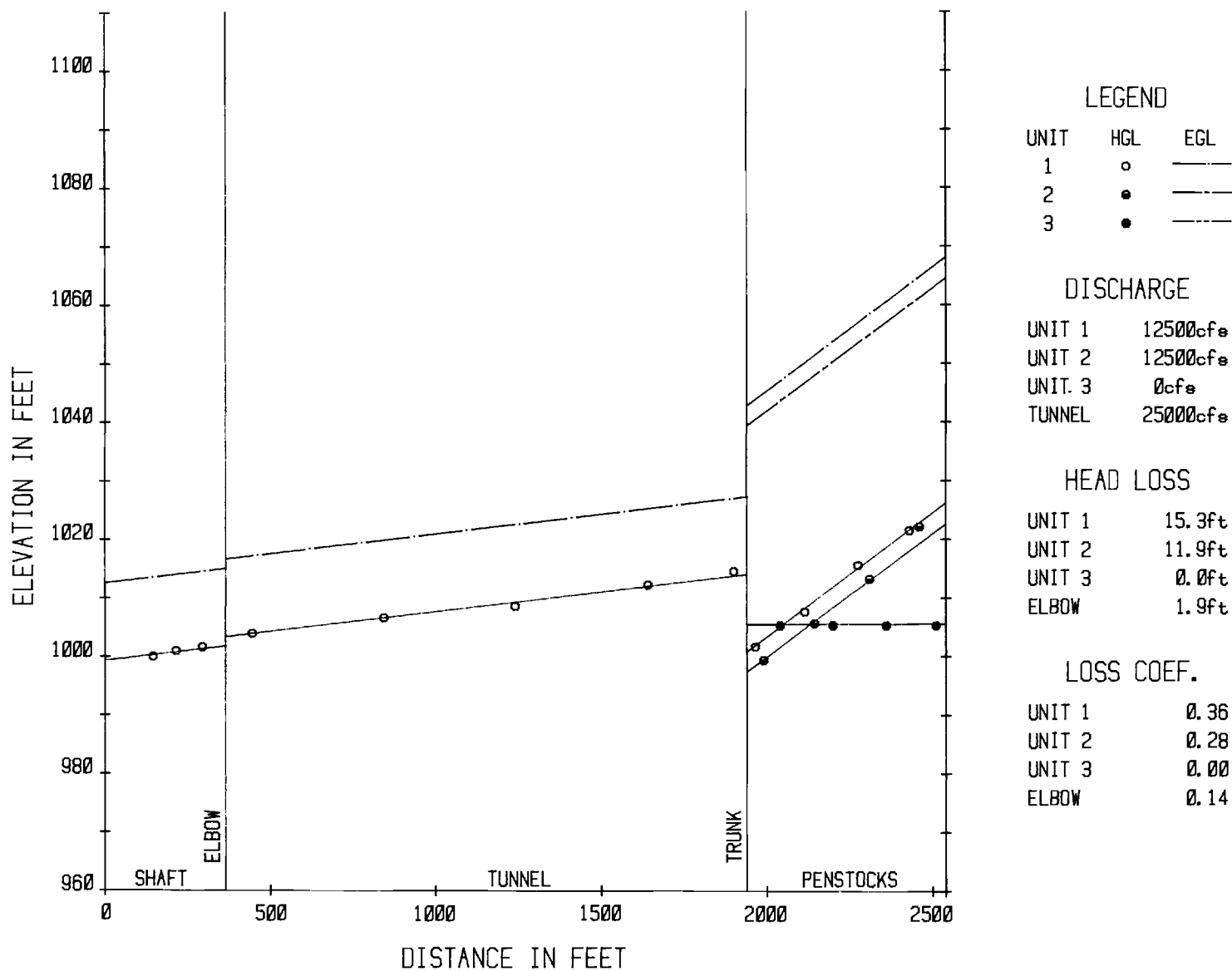
Exhibit 16.   Hydraulic and Energy Grade Lines in Modified Scheme
             B-1 for Units 1 and 2 Pumping.
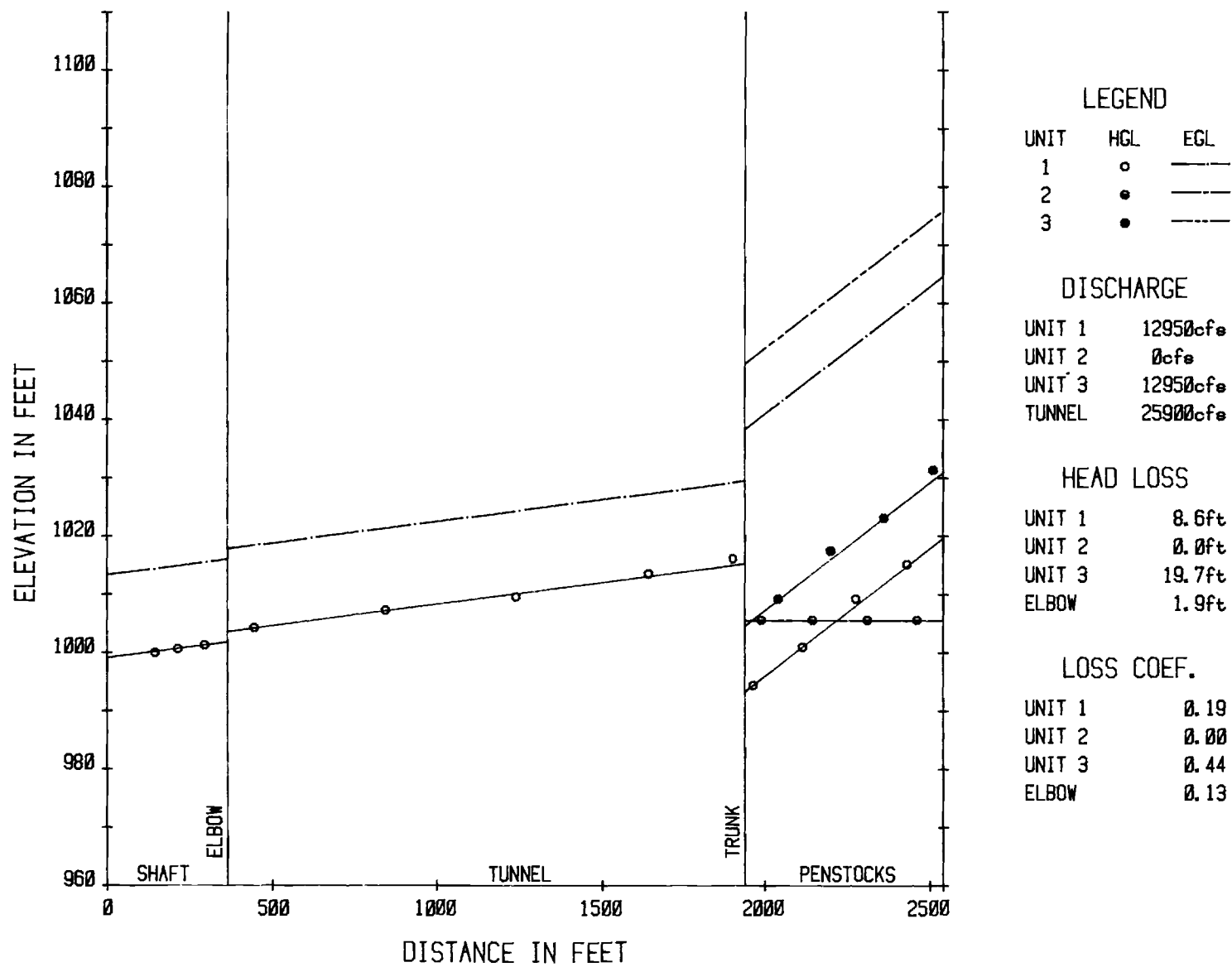
Exhibit 17.   Hydraulic and Energy Grade Lines in Modified Scheme
B-1 for Units 1 and 3 Pumping.
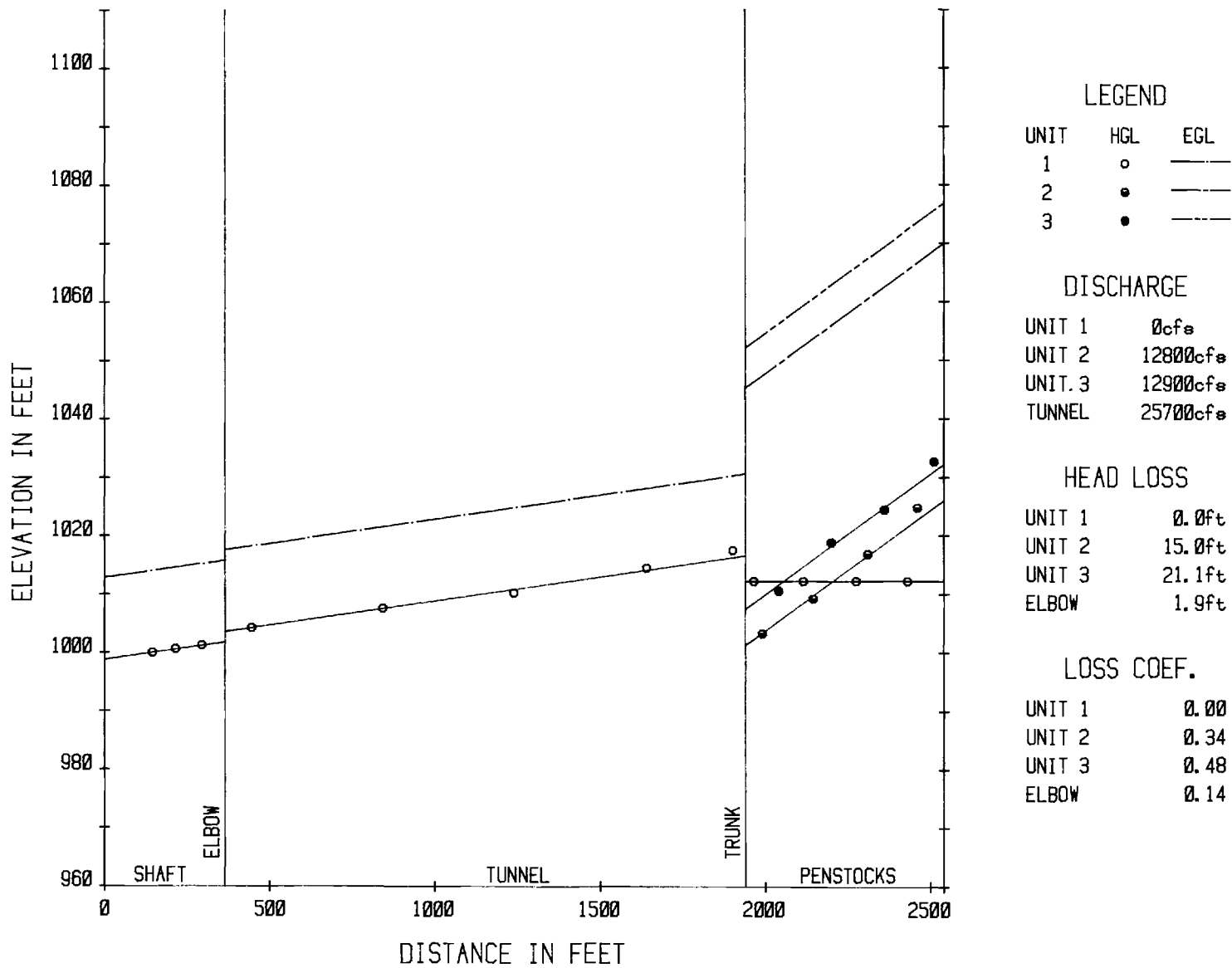
Exhibit 18.   Hydraulic and Energy Grade Lines in Modified Scheme
B-1 for Units 2 and 3 Pumping.

ELEVATION IN FEET

1100

1080

1060

1040

1020

1000

980

960

SHAFT | ELBOW | TUNNEL | TRUNK | PENSTOCKS

0   500   1000   1500   2000   2500

DISTANCE IN FEET

LEGEND

UNIT	HGL	EGL
1	o	—·—
2	◐	——
3	●	—··—

DISCHARGE

UNIT 1   13000cfs
UNIT 2   12700cfs
UNIT 3   13000cfs

HEAD LOSS

UNIT 1   14.1ft
UNIT 2   19.9ft
UNIT 3   30.9ft

LOSS COEF.

UNIT 1   0.31
UNIT 2   0.46
UNIT 3   0.68
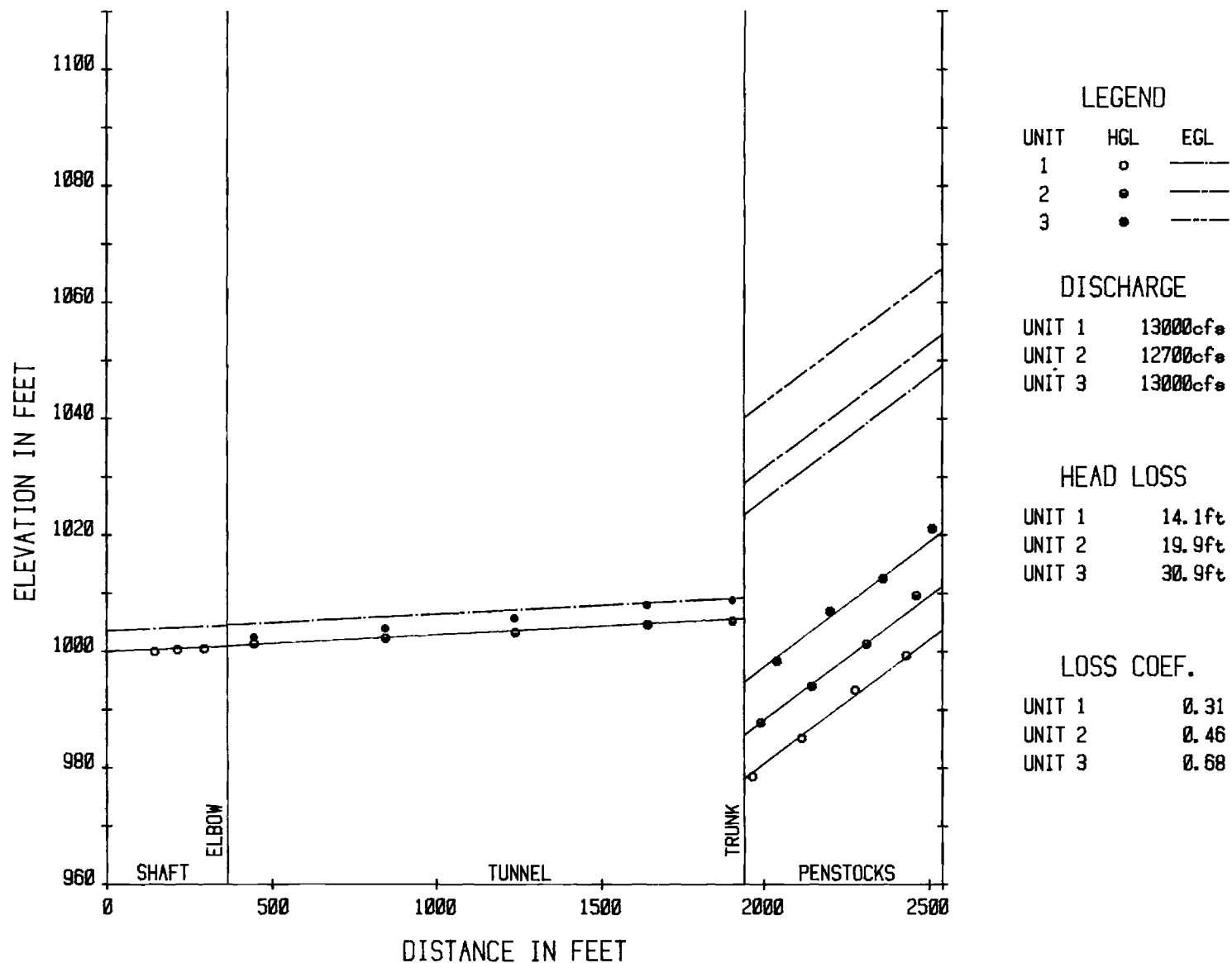
Exhibit 19. Hydraulic and Energy Grade Lines in Modified Scheme
B-1 for Single Unit Pumping.

TABLE 2

SUMMARY OF ACTUAL LOSS COEFFICIENTS

FOR MODIFIED B-1 SCHEME

MODE	K_{L_1} (UNIT 1)	K_{L_2} (UNIT 2)	K_{L_3} (UNIT 3)
Three Units Generating	0.51	0.45	0.49
Units 1 and 2 Generating	0.35	0.39	--
Units 1 and 3 Generating	0.42	--	0.34
Units 2 and 3 Generating	--	0.37	0.37
Single Unit Generating	0.29	0.24	0.32
Three Units Pumping	0.45	0.36	0.26
Units 1 and 2 Pumping	0.36	0.28	--
Units 1 and 3 Pumping	0.19	--	0.44
Units 2 and 3 Pumping	--	0.34	0.48
Single Unit Pumping	0.31	0.46	0.68

TABLE 3

SUMMARY OF

RELATIVE LOSS COEFFICIENTS

FOR MODIFIED B-1 SCHEME

MODE	K_{R_1} (UNIT 1)	K_{R_2} (UNIT 2)	K_{R_3} (UNIT 3)
Three Units Generating	0.51	0.47	0.57
Units 1 and 2 Generating	0.35	0.41	--
Units 1 and 3 Generating	0.42	--	0.42
Units 2 and 3 Generating	--	0.39	0.45
Single Unit Generating	0.29	0.26	0.40
Three Units Pumping	0.45	0.38	0.34
Units 1 and 2 Pumping	0.36	0.30	--
Units 1 and 3 Pumping	0.19	--	0.52
Units 2 and 3 Pumping	--	0.36	0.56
Single Unit Pumping	0.31	0.48	0.74

Exhibit 20. View of Tuft and Air Bubble Patterns in Trunk of Modified
Scheme B-1 for Three Units Generating.

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Exhibit 21. View of Tuft Pattern in Trunk of Modified Scheme B-1 for
Units 1 and 2 Generating.

Exhibit 22. View of Tuft Pattern in Trunk of Modified Scheme B-1
for Unit 3 Generating.

Exhibit 23. View of Tuft and Air Bubble Patterns in Trunk of Modified Scheme B-1 for Three Units Pumping.

Exhibit 24. View of Tuft and Air Bubble Patterns in Trunk of Modified
Scheme B-1 for Units 1 and 2 Pumping.
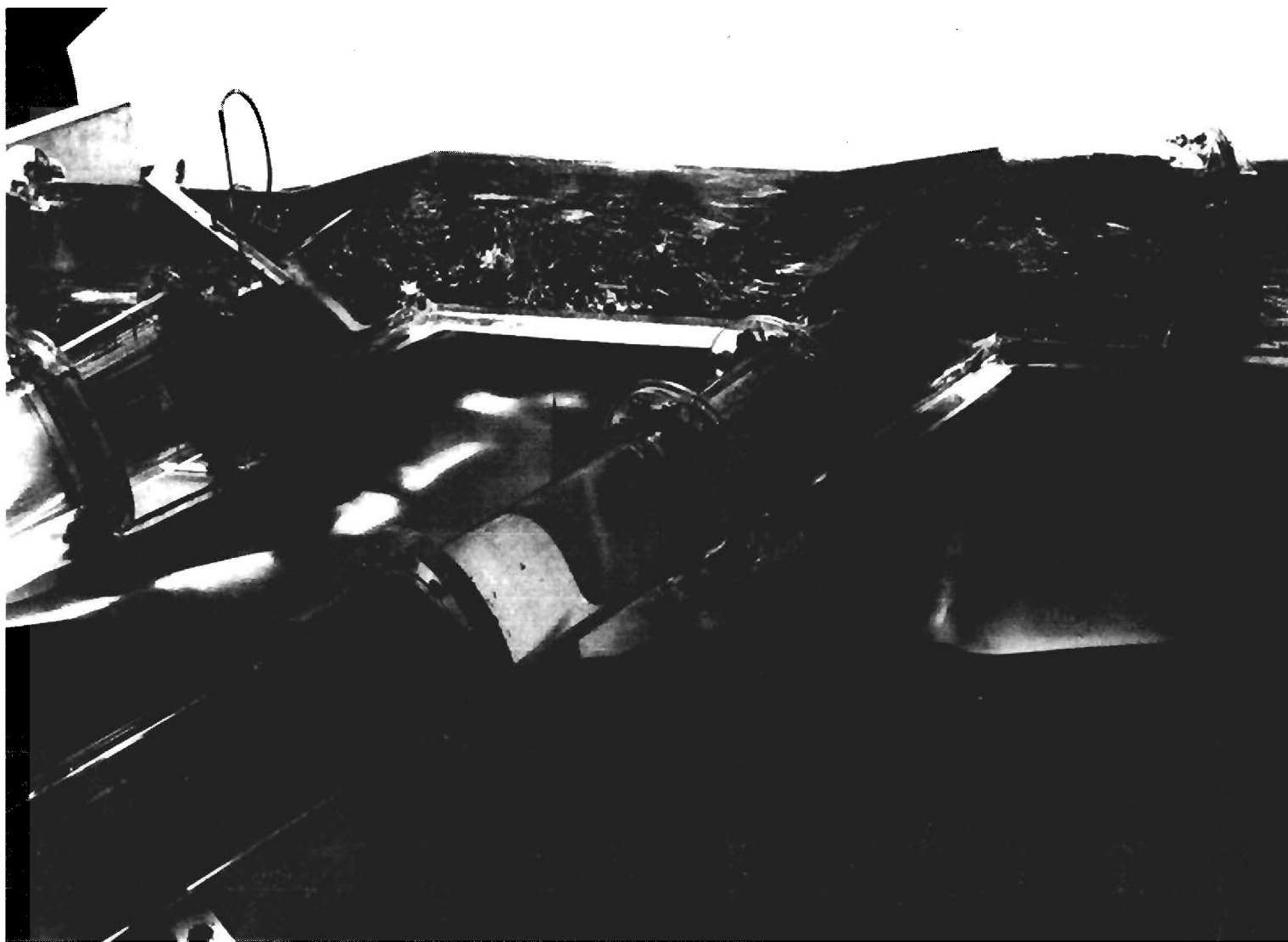
Exhibit 25. View of Tuft and Air Bubble Patterns in Trunk of Modified
Scheme B-1 for Units 1 and 3 Pumping.

Exhibit 26. View of Tuft and Air Bubble Patterns in Trunk of Modified
Scheme B-1 for Units 2 and 3 Pumping.

Exhibit 27. View of Tuft and Air Bubble Patterns in Trunk of Modified Scheme B-1 for Unit 1 Pumping.

Exhibit 28.   View of Tuft and Air Bubble Patterns in Trunk of Modified
Scheme B-1 for Unit 2 Pumping.

Exhibit 29. View of Tuft and Air Bubble Patterns in Trunk of Modified
Scheme B-1 for Unit 3 Pumping.

Table 4. Values of Relative Hydraulic Grade
Line in Trunk of Modified B-1 Scheme.

TRUNK HYDRAULIC GRADE LINE
SCHEME B-1 (MOD)

UNIT 1	UNIT 2	UNIT 3	PIEZOMETER NUMBER
(cfs)	(cfs)	(cfs)	1	2	3	4	5	6	7
PUMPING MODE
10000	9990	10010	1027.7	1025.4	1028.7	1031.7	1024.1	1023.1	1023.4
9950	9990	9970	1027.4	1025.1	1028.7	1031.4	1023.8	1023.1	1023.4
12710	0	0	990.8	1002.3	983.8	998.0	998.4	1000.0	1004.6
0	12580	0	993.1	1001.3	995.1	1022.4	999.7	1001.3	1003.3
0	0	16110	1002.3	1003.6	1001.7	1003.0	1003.6	1002.0	1041.6
12310	12360	0	1006.9	1008.9	1008.9	1013.2	1002.0	1002.0	1015.8
12280	12360	0	1007.3	1008.9	1008.9	1013.2	1002.0	1001.3	1015.2
12440	0	12550	1006.3	1013.2	1001.0	1014.9	1014.9	1016.2	1018.2
0	12690	12800	1008.6	1015.5	1011.9	1039.3	1017.2	1018.5	1019.5
6030	3220	6060	1011.9	1010.6	1011.9	1012.9	1009.9	1009.9	1009.6
GENERATING MODE
10870	10790	10760	965.0	970.0	968.0	976.2	972.3	972.3	975.6

HYDRAULIC GRADE LINE ELEVATIONS ARE IN FEET

CHAPTER IV

TEST RESULTS FOR SCHEME B-2

The B-2 Scheme, shown on Exhibit 1, is more streamlined than the
Modified Scheme B-1 at the junction of penstocks 2 and 3 and the bifurca-
tion trunk. Hence in general the flow patterns were better and the head
losses were smaller for Scheme B-2 than for Modified Scheme B-1.

Head-Loss Data

The hydraulic grade lines for the fourteen test conditions outlined
in Table 1 are plotted in Exhibits 30-39. Again the piezometer scheme of
Exhibit 5 applies, and the head at piezometer number 0 in the vertical
shaft is assigned an arbitrary value of 1000 ft for all test results.
The actual and relative loss coefficients are summarized in Tables 5
and 6, respectively. The performance of Scheme B-2 relative to the Modi-
fied Scheme B-1 will be discussed later.

Flow Patterns in Bifurcation Model

During initial stages of the testing of this scheme the trunk of
the model failed structurally. It was subsequently repaired by means of
reinforcing bands and pieces of clear plastic glued to the body of the
trunk along the failure line, as shown by the photograph of Exhibit 40,
which illustrates somewhat poorly the flow pattern for the case of three
units generating. Exhibit 41 shows the flow in the approach to Unit 3
when it is the sole unit generating.

The flow in the pumping mode is still fairly turbulent, as illustrated
by the air bubbles of Exhibits 42-44, which correspond to three units
pumping, Units 2 and 3 pumping, and Unit 3 pumping, respectively.

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Pressure Distribution in Trunk

For the seven piezometer locations shown on Exhibit 8 the values of
the hydraulic grade line in trunk of Scheme B-2 are listed in Table 7.
The greatest value of the HGL occurs at piezometer number 4 for Units 2
and 3 pumping because of the effect of stagnation from the flow out of
penstock number 2.

Exhibit 30. Hydraulic and Energy Grade Lines in Scheme B-2 for Three
Units Generating.

Exhibit 31.   Hydraulic and Energy Grade Lines in Scheme B-2 for Units
1 and 2 Generating.

ELEVATION IN FEET

1020

1000

980

960

940

920

900

880

LEGEND

UNIT	HGL	EGL
1	o	—— · —
2	◉	———
3	●	—— · ——

DISCHARGE

UNIT 1   13000cfs
UNIT 2   0cfs
UNIT 3   13000cfs
TUNNEL   26000cfs

HEAD LOSS

UNIT 1   18.7ft
UNIT 2   0.0ft
UNIT 3   3.6ft
ELBOW   2.5ft

LOSS COEF.

UNIT 1   0.41
UNIT 2   0.00
UNIT 3   0.08
ELBOW   0.17

ELBOW

TRUNK

SHAFT   TUNNEL   PENSTOCKS

0   500   1000   1500   2000   2500

DISTANCE IN FEET

Exhibit 32.   Hydraulic and Energy Grade Lines in Scheme B-2 for Units
1 and 3 Generating.

Exhibit 33.   Hydraulic and Energy Grade Lines in Scheme B-2 for Units
2 and 3 Generating.

ELEVATION IN FEET

1020

1000

980

960

940

920

900

880

SHAFT

ELBOW

TUNNEL

TRUNK

PENSTOCKS

0   500   1000   1500   2000   2500

DISTANCE IN FEET

LEGEND

UNIT	HGL	EGL
1	o	———
2	◐	———
3	●	—·—

DISCHARGE

UNIT 1   13500cfs
UNIT 2   13600cfs
UNIT 3   13500cfs

HEAD LOSS

UNIT 1   15.9ft
UNIT 2   7.9ft
UNIT 3   9.4ft

LOSS COEF.

UNIT 1   0.33
UNIT 2   0.16
UNIT 3   0.19

Exhibit 34.   Hydraulic and Energy Grade Lines in Scheme B-2 for Single
Unit Generating.

Exhibit 35. Hydraulic and Energy Grade Lines in Scheme B-2 for Three
Units Pumping.
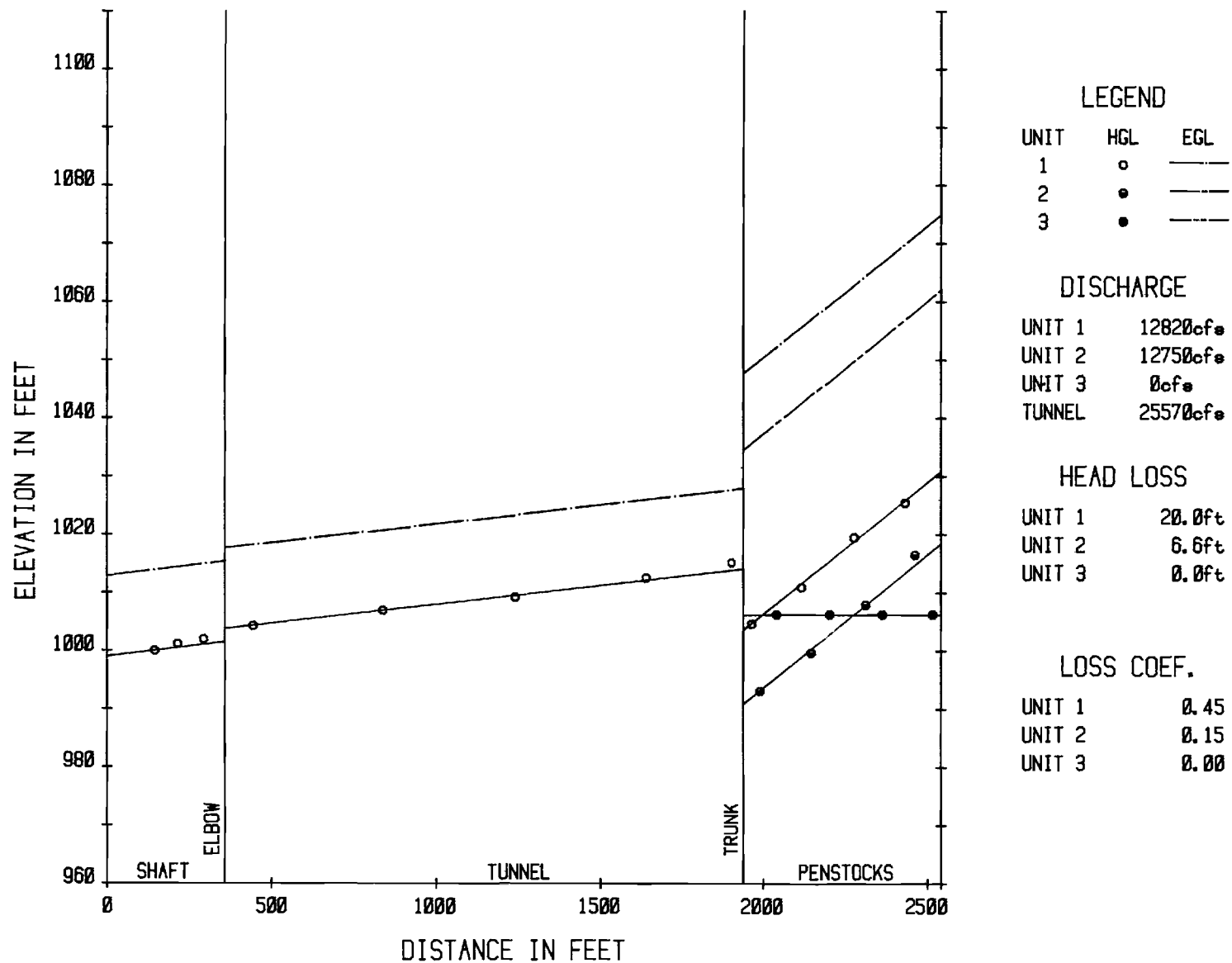
Exhibit 36.   Hydraulic and Energy Grade Lines in Scheme B-2 for
Units 1 and 2 Pumping.
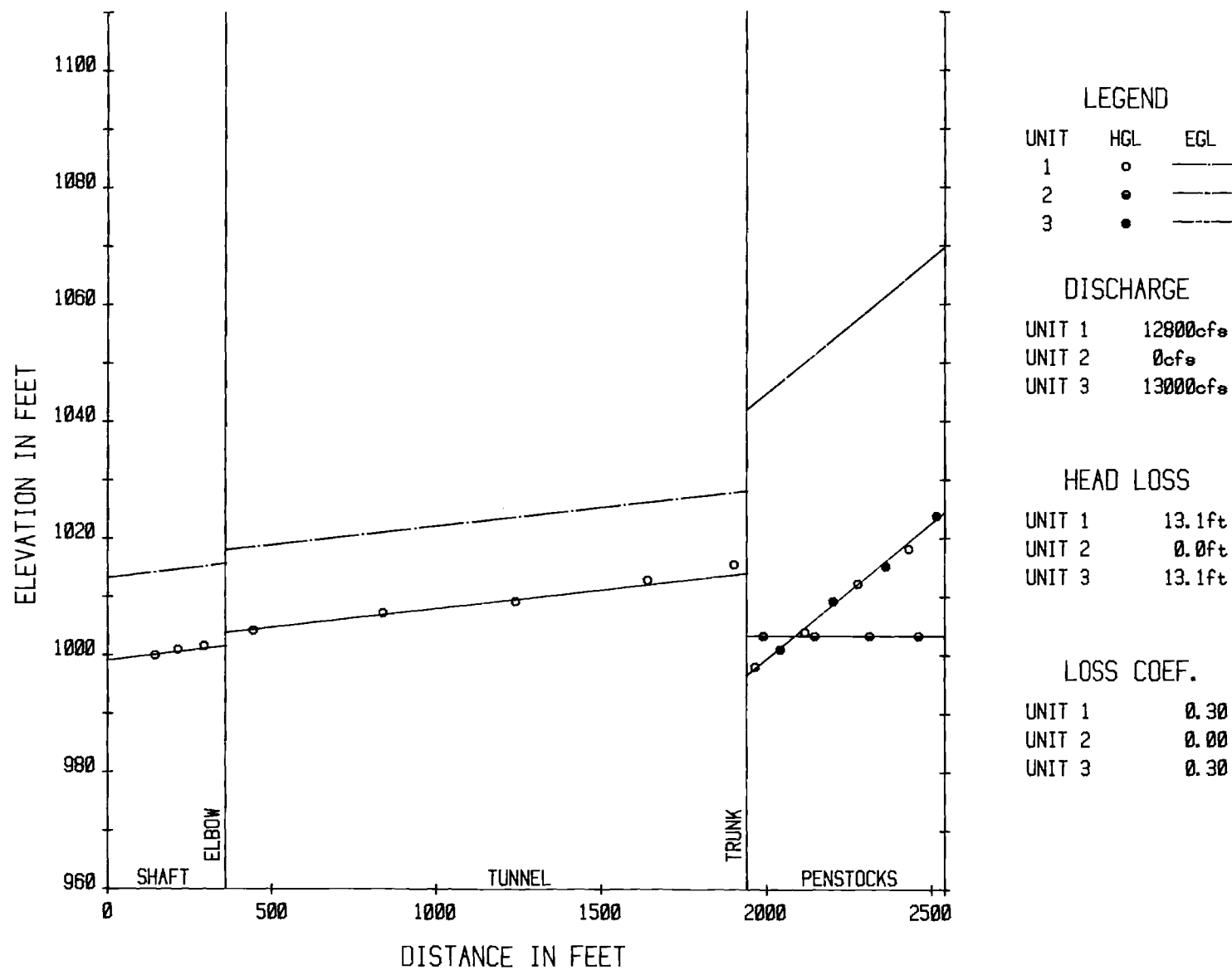
Exhibit 37. Hydraulic and Energy Grade Lines in Scheme B-2 for Units 1 and 3 Pumping.

ELEVATION IN FEET

1100

1080

1060

1040

1020

1000

980

960

LEGEND

UNIT	HGL	EGL
1	o	———
2	⊜	— — —
3	●	—·—·—

DISCHARGE

UNIT 1	0cfs
UNIT 2	12800cfs
UNIT 3	12900cfs
TUNNEL	25700cfs

HEAD LOSS

UNIT 1	0.0ft
UNIT 2	11.4ft
UNIT 3	14.1ft

LOSS COEF.

UNIT 1	0.00
UNIT 2	0.26
UNIT 3	0.32

SHAFT   ELBOW   TUNNEL   TRUNK   PENSTOCKS

0   500   1000   1500   2000   2500

DISTANCE IN FEET
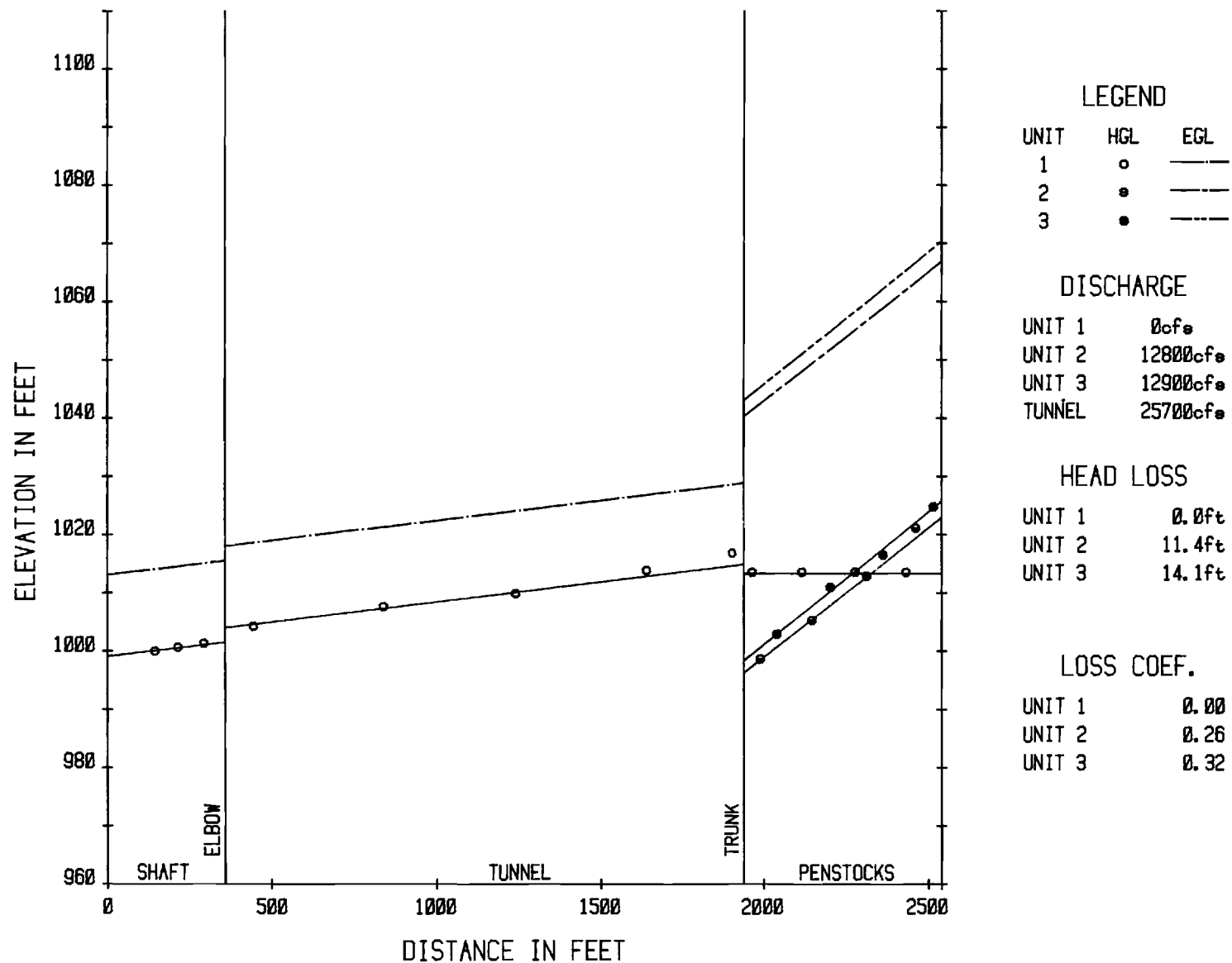
Exhibit 38. Hydraulic and Energy Grade Lines in Scheme B-2 for
Units 2 and 3 Pumping.

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LEGEND

UNIT	HGL	EGL
1	o	———
2	◑	— — —
3	●	—·—·—

DISCHARGE

UNIT 1   12950cfs
UNIT 2   12840cfs
UNIT 3 .   0cfs

HEAD LOSS

UNIT 1   20.5ft
UNIT 2   15.4ft
UNIT 3   0.0ft

LOSS COEF.

UNIT 1   0.46
UNIT 2   0.35
UNIT 3   0.00

1100

1080

1060

1040

1020

1000

980

960

ELEVATION IN FEET

ELBOW

TRUNK

SHAFT   TUNNEL   PENSTOCKS

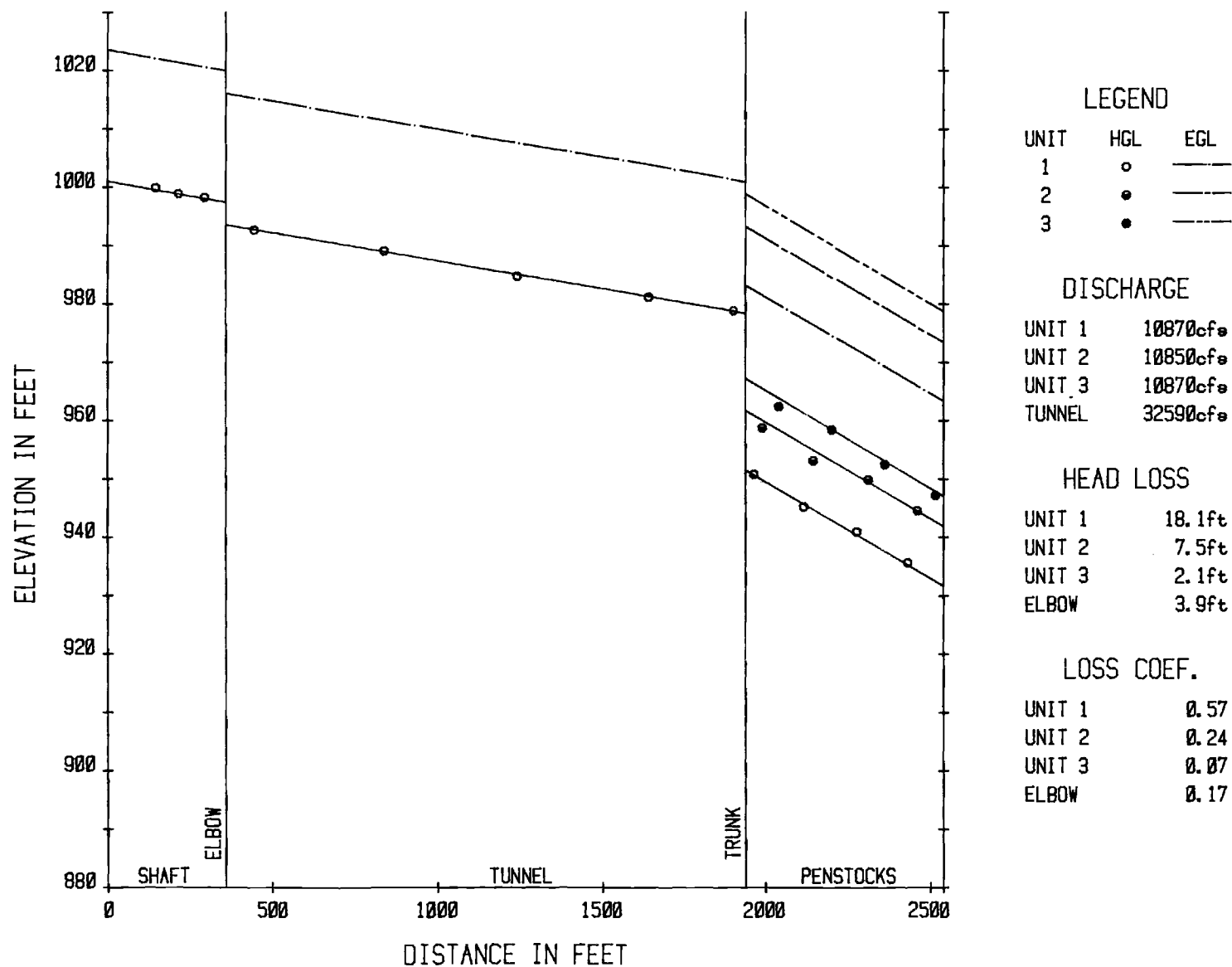0   500   1000   1500   2000   2500
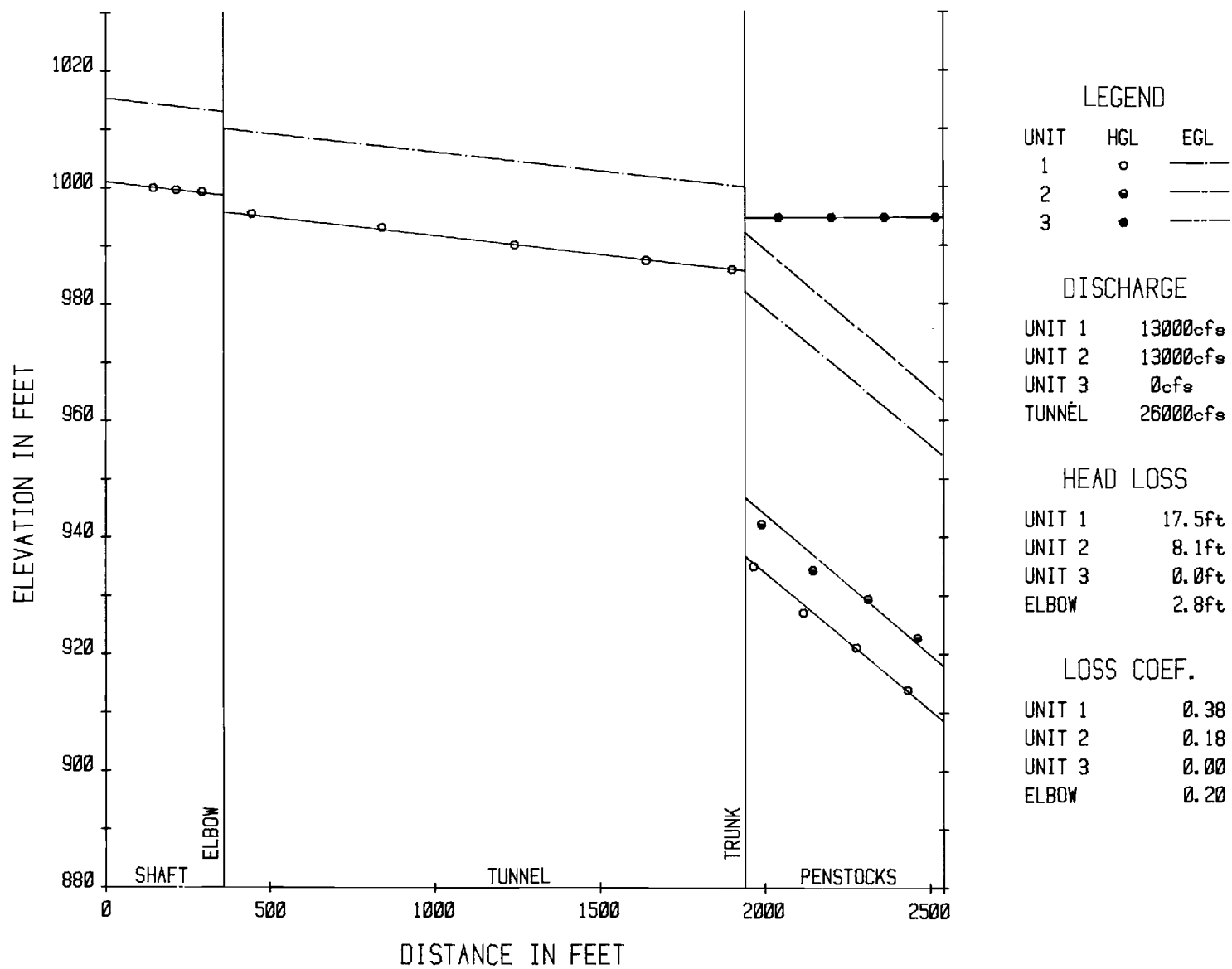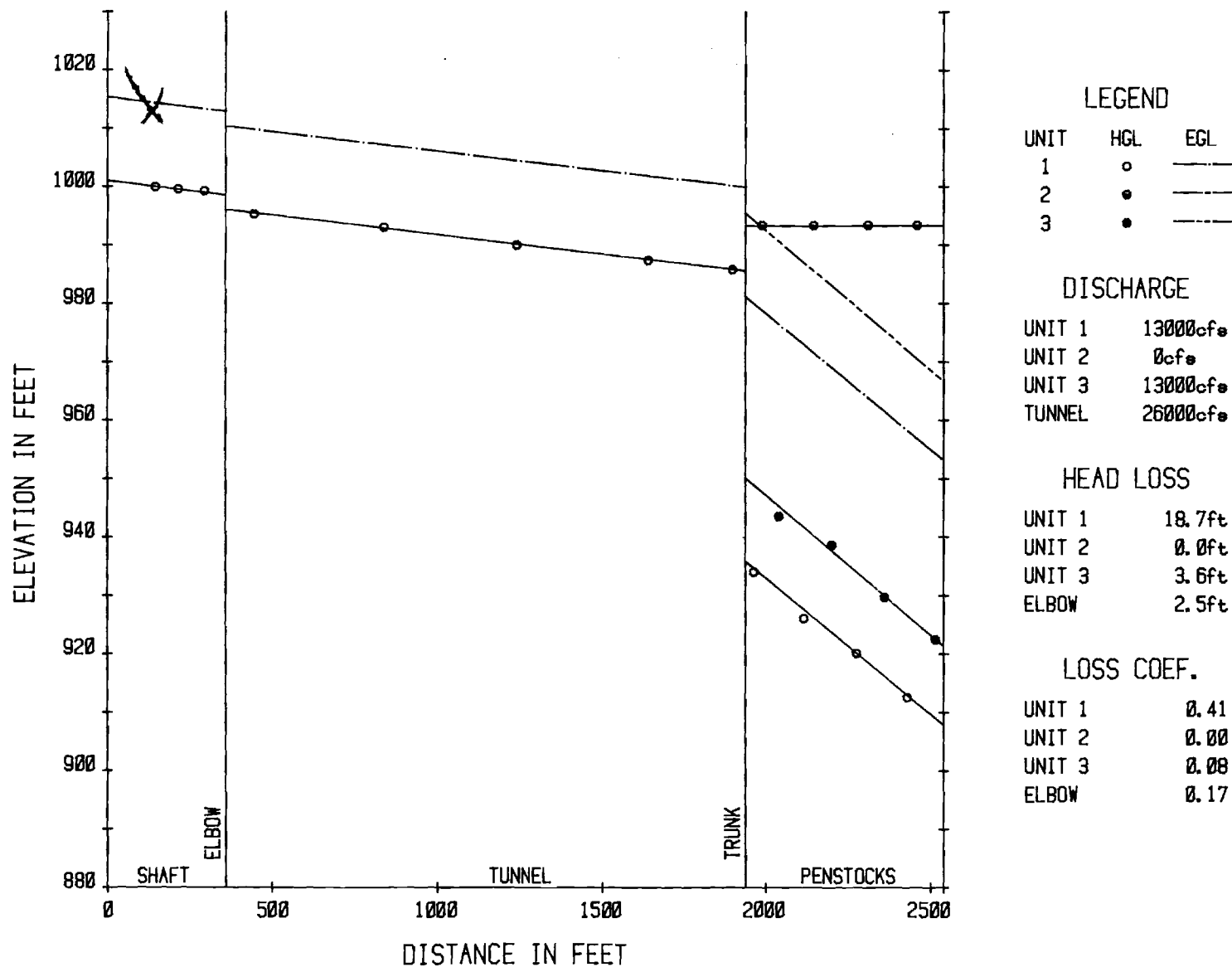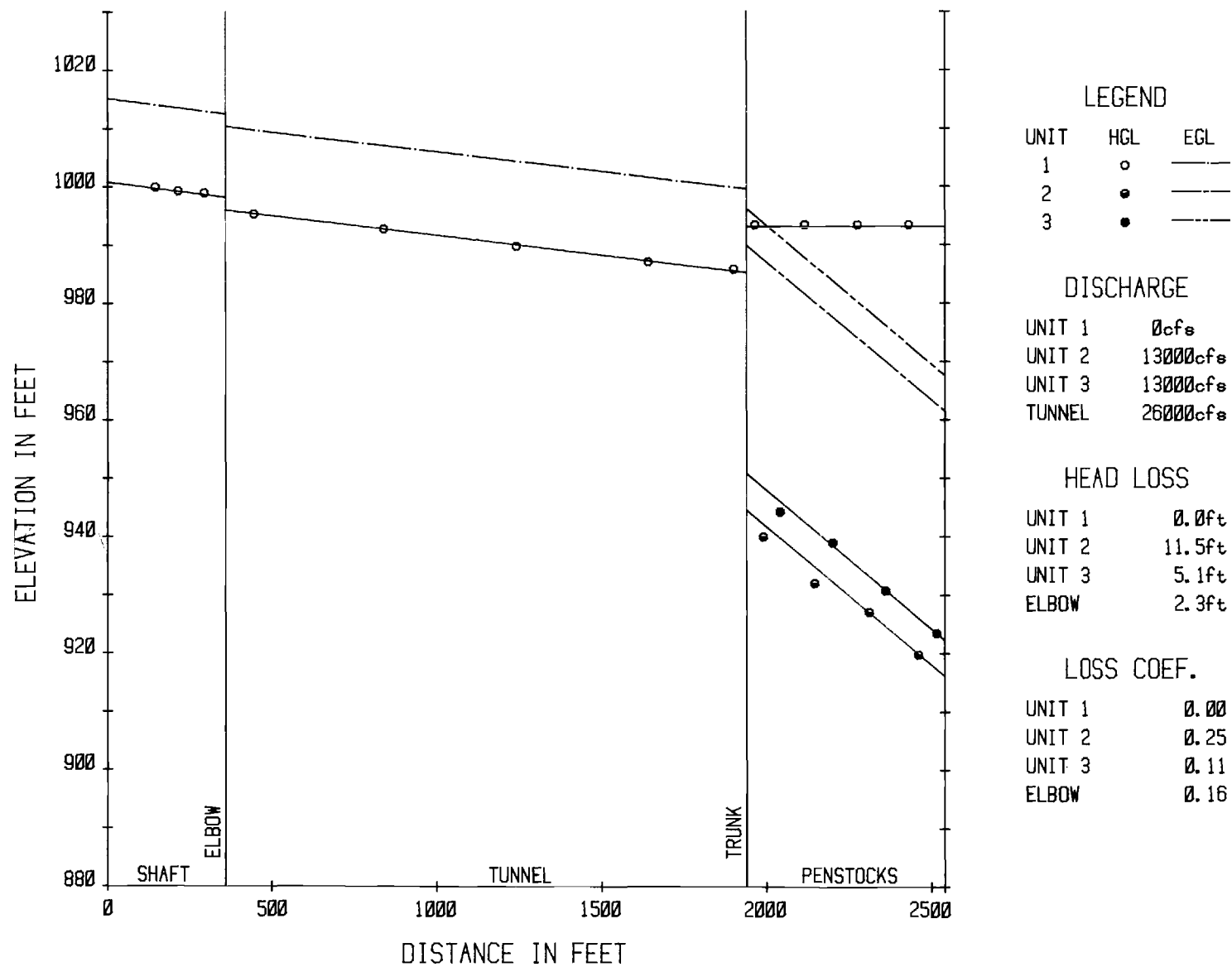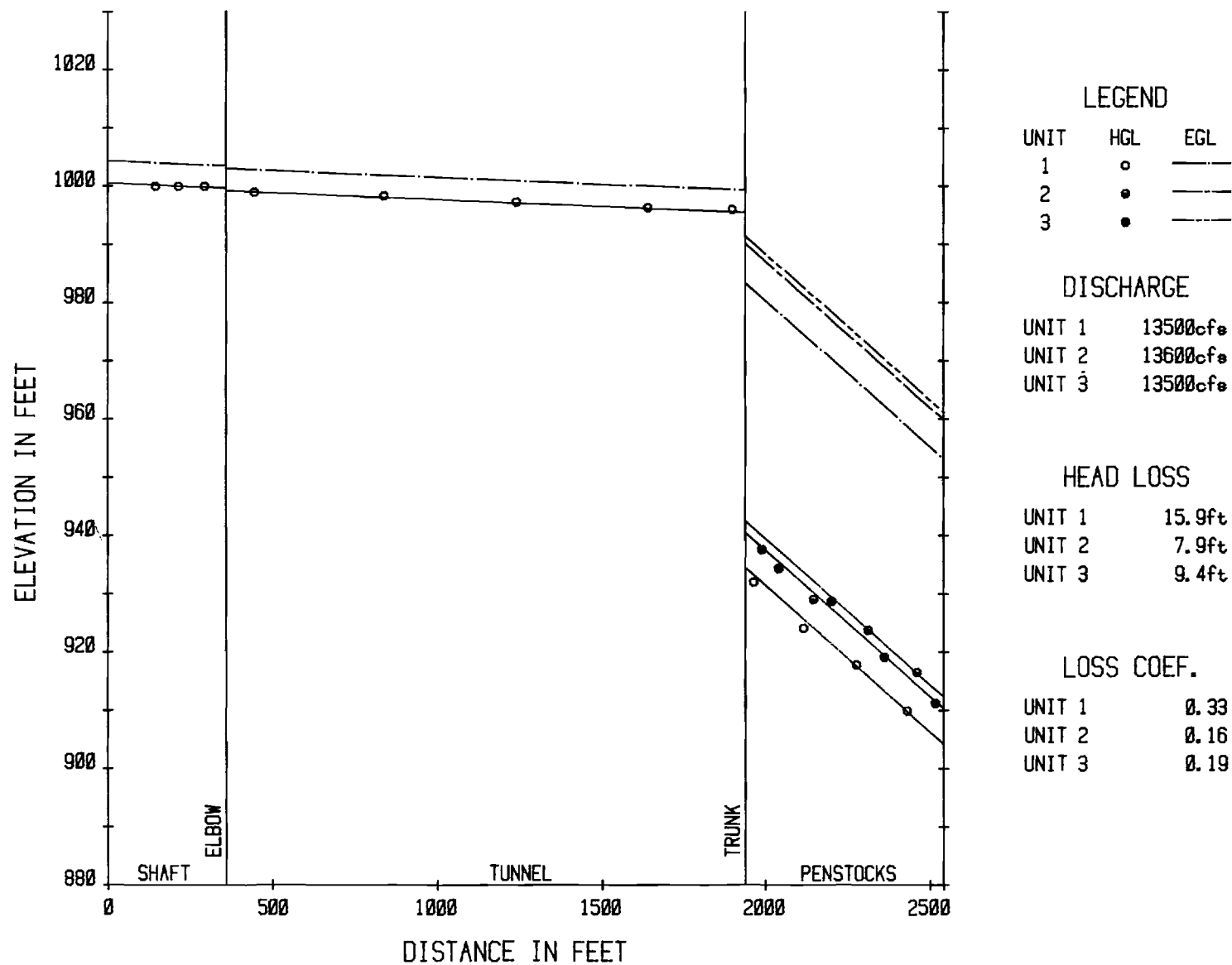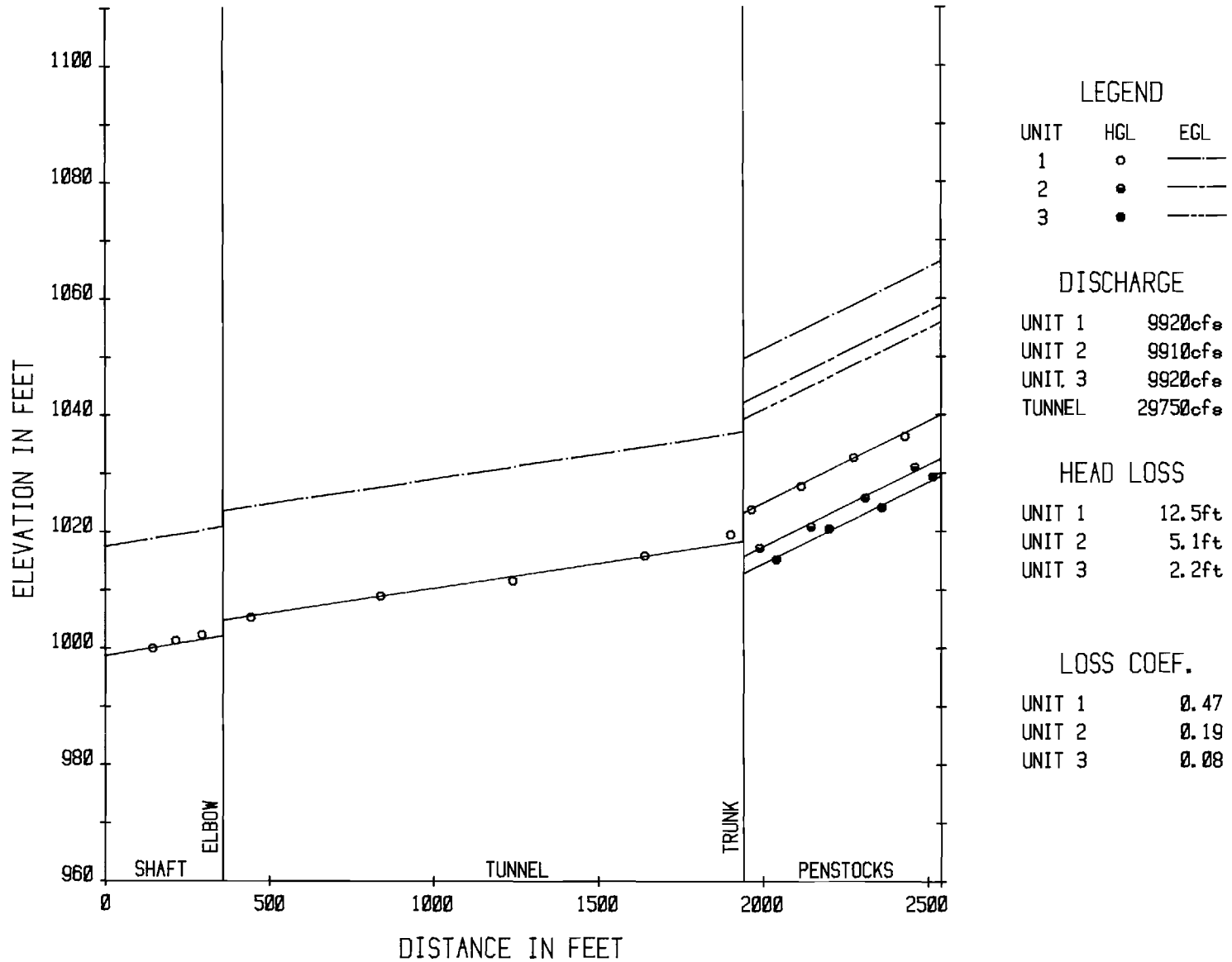
DISTANCE IN FEET
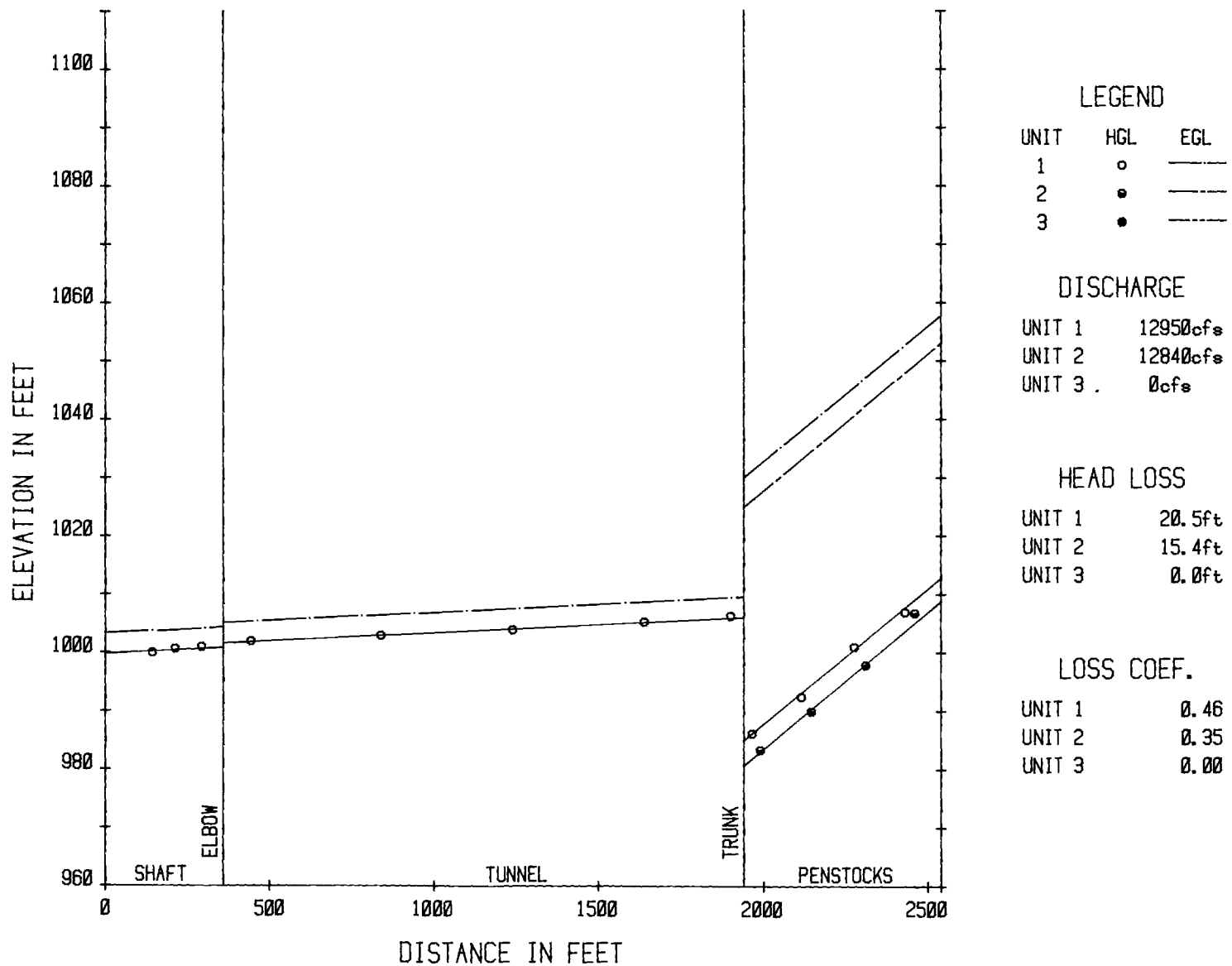
Exhibit 39a.   Hydraulic and Energy Grade Lines in Scheme B-2 for
Single Units 1 and 2 Pumping.
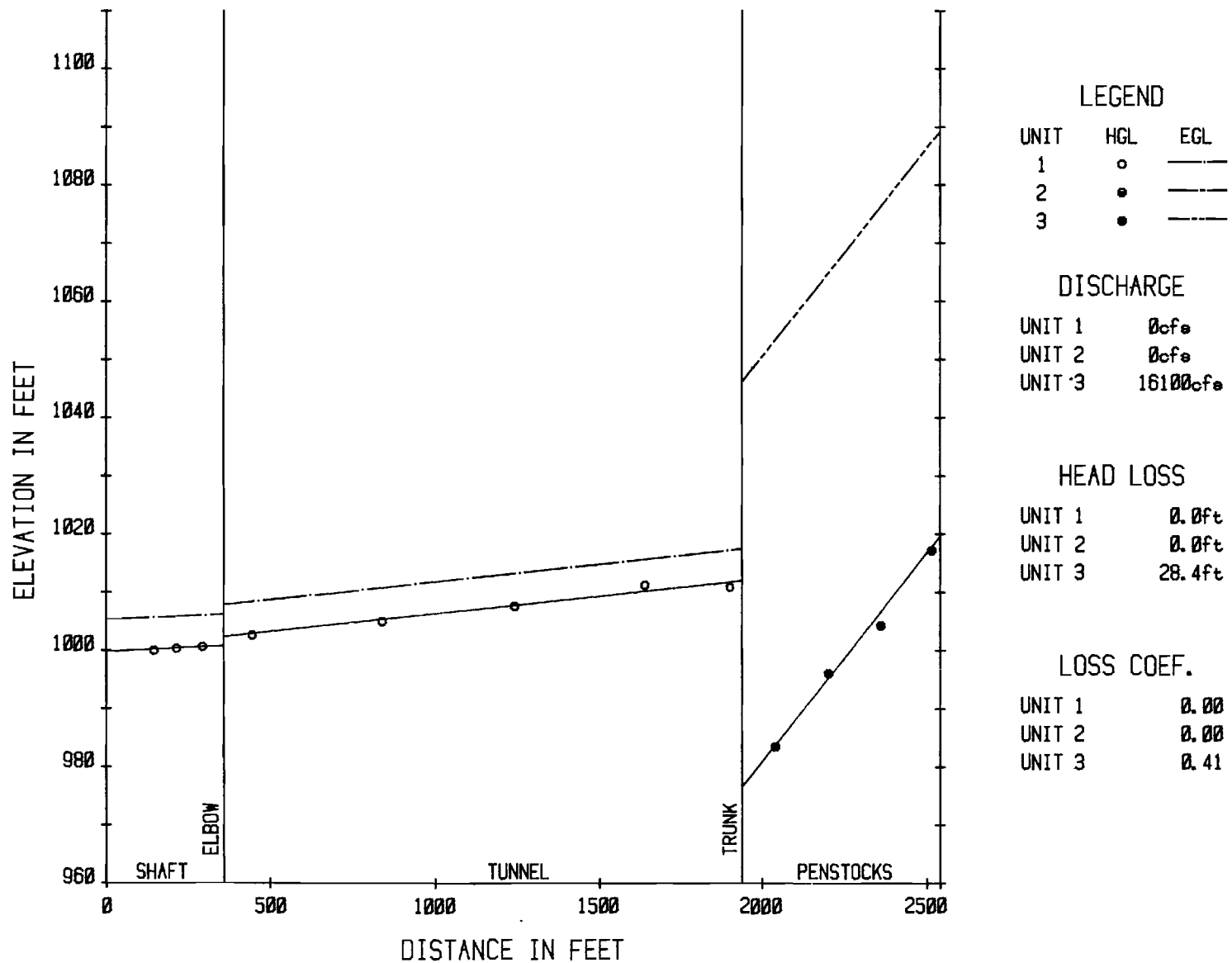
Exhibit 39b. Hydraulic and Energy Grade Lines in Scheme B-2 for Unit 3 Pumping.

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TABLE 5

SUMMARY OF ACTUAL LOSS COEFFICIENTS

FOR B-2 SCHEME

MODE	K_{L_1} (UNIT 1)	K_{L_2} (UNIT 2)	K_{L_3} (UNIT 3)
Three Units Generating	0.57	0.24	0.07
Units 1 and 2 Generating	0.38	0.18	--
Units 1 and 3 Generating	0.41	--	0.08
Units 2 and 3 Generating	--	0.25	0.11
Single Unit Generating	0.33	0.16	0.19
Three Units Pumping	0.47	0.19	0.08
Units 1 and 2 Pumping	0.45	0.15	--
Units 1 and 3 Pumping	0.30	--	0.30
Units 2 and 3 Pumping	--	0.26	0.32
Single Unit Pumping	0.46	0.35	0.41

TABLE 6

SUMMARY OF

RELATIVE LOSS COEFFICIENTS

FOR B-2 SCHEME

MODE	K_{R_1} (UNIT 1)	K_{R_2} (UNIT 2)	K_{R_3} (UNIT 3)
Three Units Generating	0.57	0.26	0.15
Units 1 and 2 Generating	0.38	0.20	--
Units 1 and 3 Generating	0.41	--	0.16
Units 2 and 3 Generating	--	0.27	0.19
Single Unit Generating	0.33	0.18	0.27
Three Units Pumping	0.47	0.21	0.16
Units 1 and 2 Pumping	0.45	0.17	--
Units 1 and 3 Pumping	0.30	--	0.38
Units 2 and 3 Pumping	--	0.28	0.40
Single Unit Pumping	0.46	0.37	0.49

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Exhibit 40. View of Tuft Pattern in Trunk of Scheme B-2 for
Three Units Generating.

Exhibit 41. View of Tuft Pattern in Trunk of Scheme B-2 for
            Unit 3 Generating.

Exhibit 42.   View of Tuft Pattern in Trunk of Scheme B-2 for
Three Units Pumping.
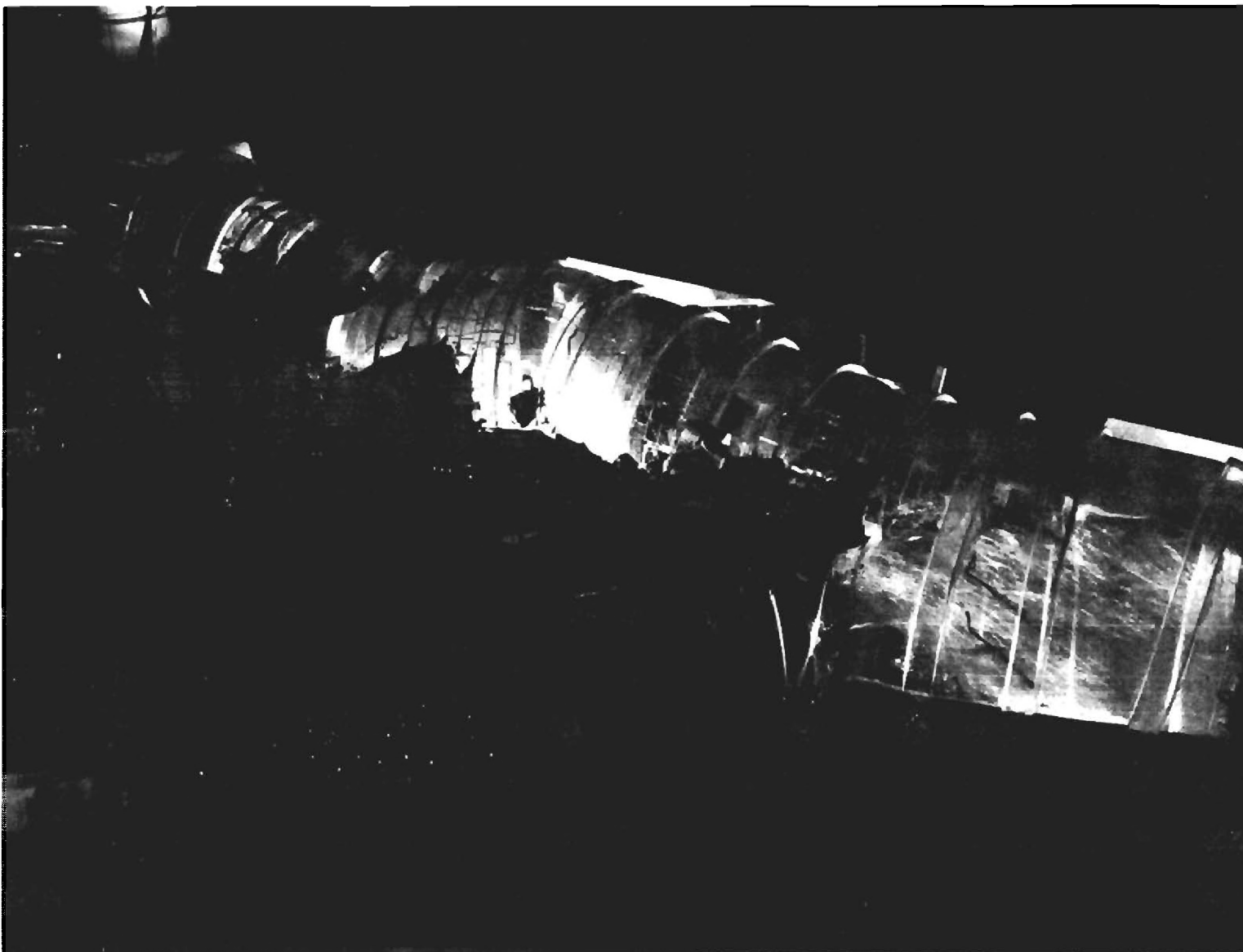
Exhibit 43.   View of Tuft Pattern in Trunk of Scheme B-2 for
Units 2 and 3 Pumping.
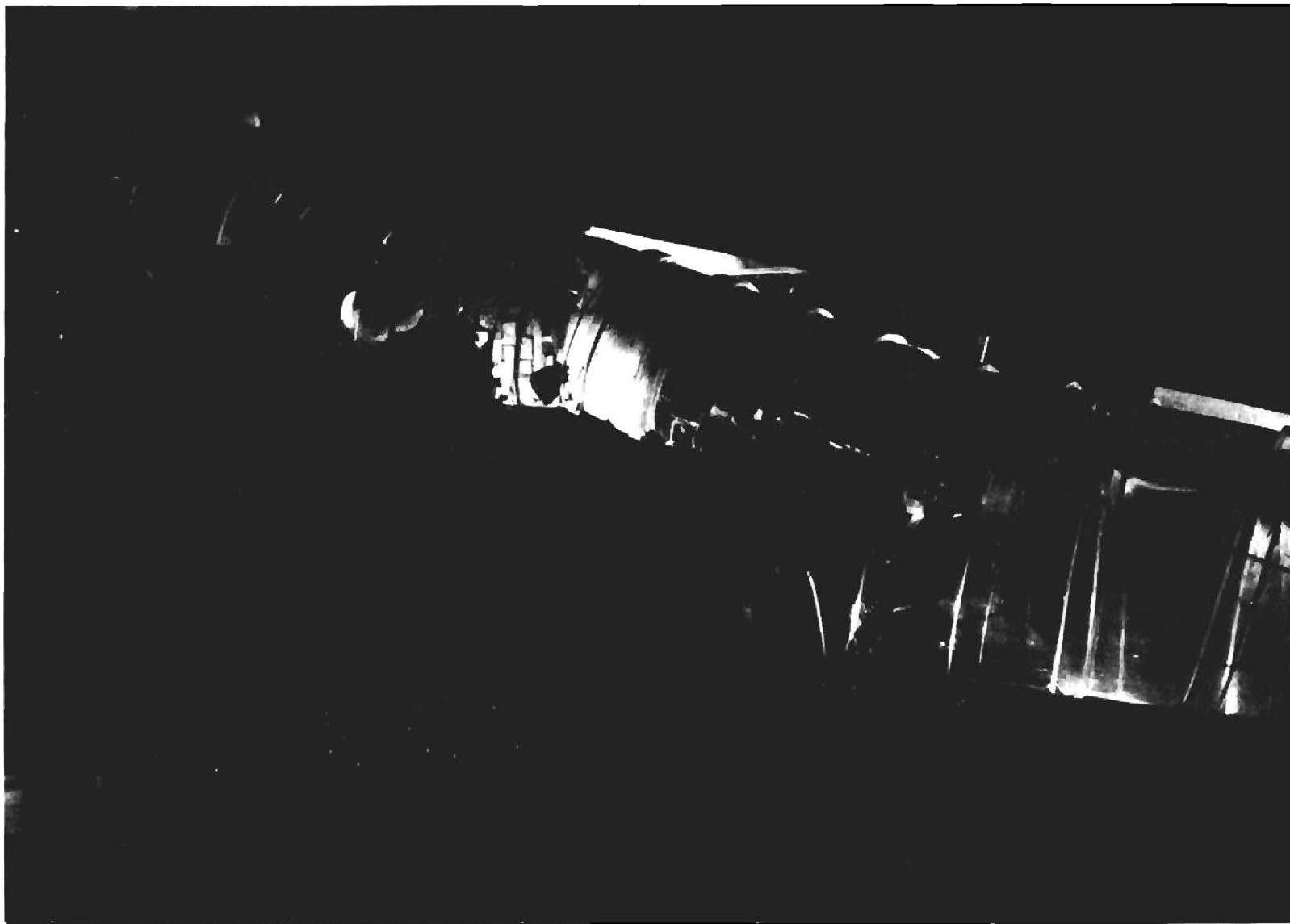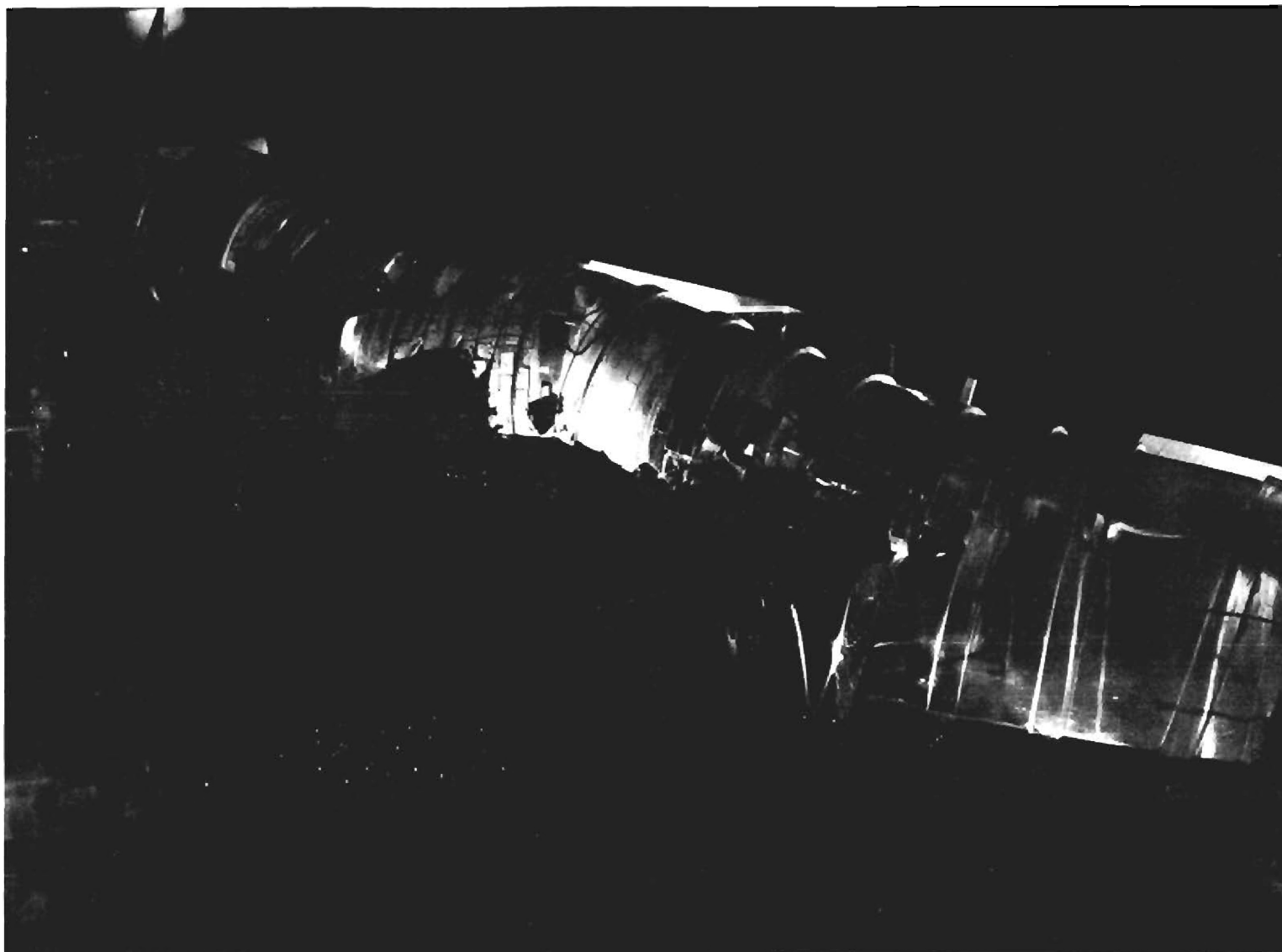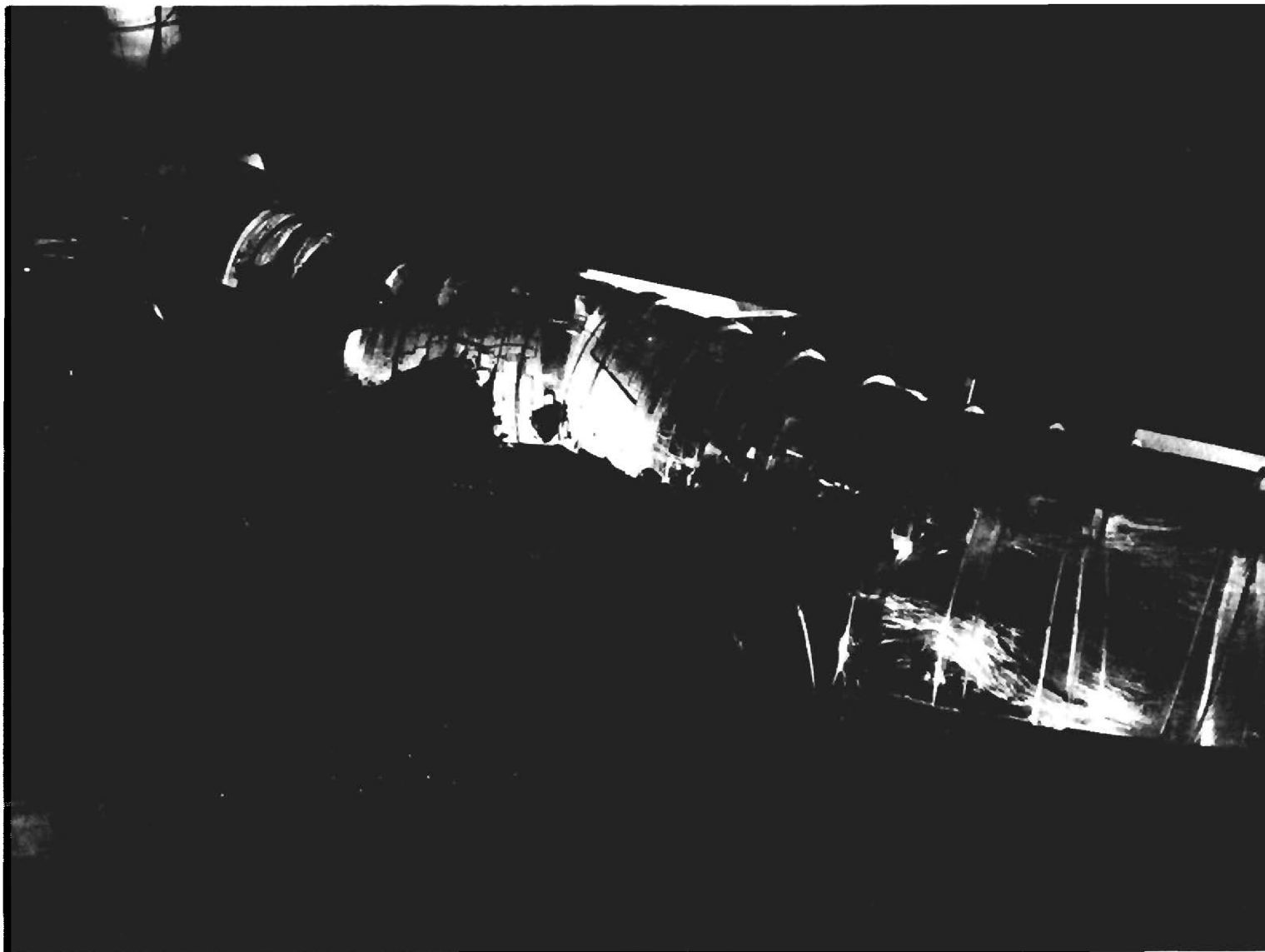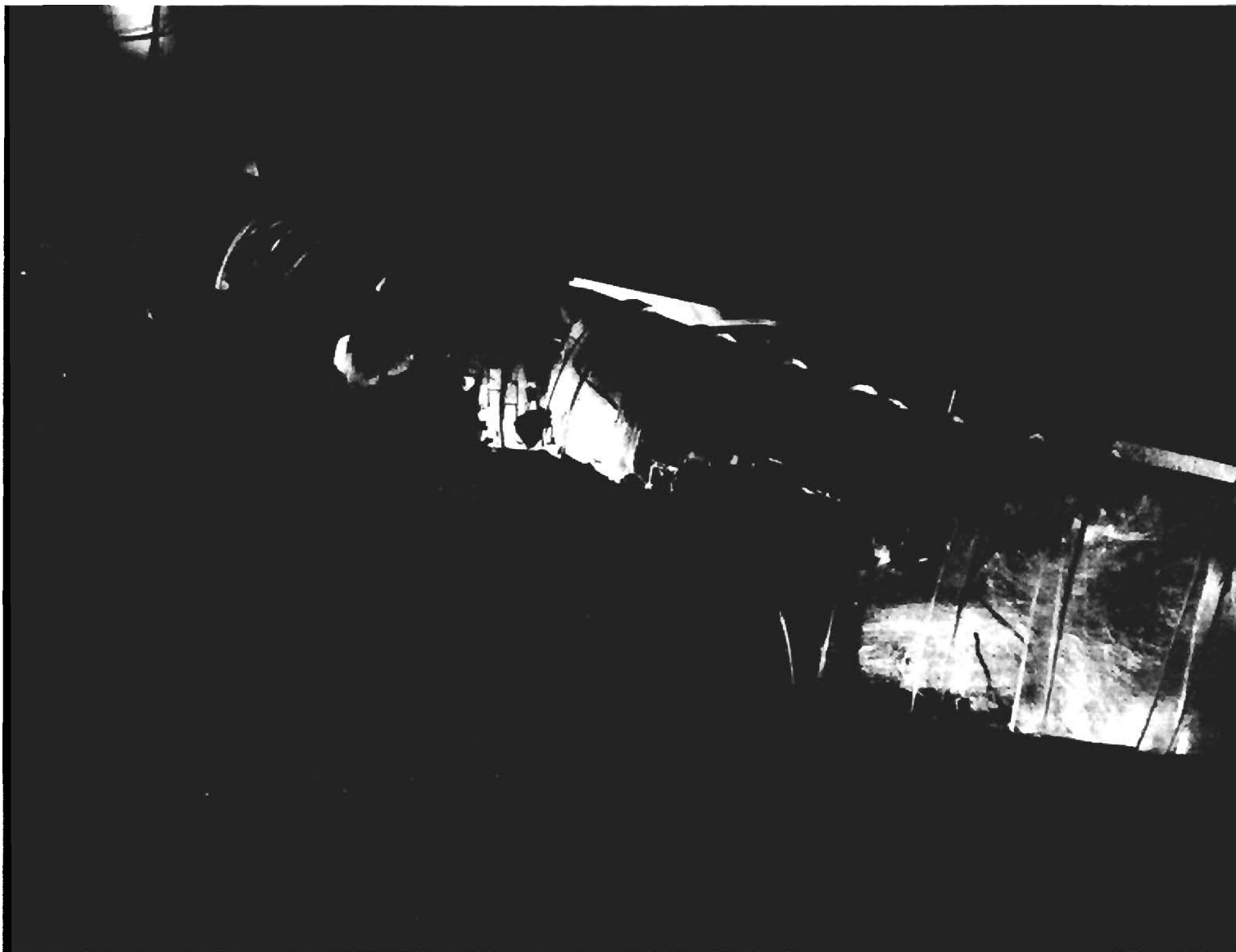
Exhibit 44. View of Tuft Pattern in Trunk of Scheme B-2 for
Unit 3 pumping.

Table 7. Values of Relative Hydraulic Grade
Line in Trunk of B-2 Scheme.

TRUNK HYDRAULIC GRADE LINE
SCHEME B-2

UNIT 1	UNIT 2	UNIT 3	PIEZOMETER NUMBER						
(cfs)	(cfs)	(cfs)	1	2	3	4	5	6	7
			PUMPING MODE						
10030	9860	9970	1020.5	1018.2	1025.1	1030.0	1021.1	1021.1	1021.8
12770	12900	0	999.3	1006.3	1007.6	1015.5	1001.0	1001.0	1012.9
12770	0	13070	1002.6	1006.3	1000.0	1012.5	1013.9	1014.9	1017.2
0	12750	13040	1006.9	1008.3	1014.9	1032.3	1015.8	1016.2	1019.1
12800	0	0	988.8	1001.3	985.8	998.0	999.0	999.7	1003.3
0	12790	0	990.8	1001.7	997.4	1018.8	999.7	1000.0	1004.0
0	0	13000	1000.7	995.7	1000.7	1001.0	1001.3	1001.0	1023.1
			GENERATING MODE						
0	0	12960	997.0	957.1	997.4	997.4	997.0	996.4	994.7
11070	11070	11070	969.0	974.3	964.4	976.2	970.6	972.3	974.3
13510	13530	0	952.2	993.4	950.2	967.0	957.1	964.4	981.5
13460	0	13440	992.4	961.1	948.5	987.2	985.5	984.8	981.9
0	13440	13440	952.8	961.7	992.7	987.8	985.5	985.2	982.2
0	0	13310	997.0	956.1	997.4	997.0	997.0	996.4	994.4
0	13490	0	954.8	997.7	994.4	991.1	988.1	989.8	994.4
13440	0	0	992.4	994.4	951.5	990.4	988.8	990.4	994.7

HYDRAULIC GRADE LINE ELEVATIONS ARE IN FEET

CHAPTER V

TEST RESULTS FOR SCHEME C-1

Principally for the purpose of providing a basis for comparison the

straight pipe Scheme C-1 shown in Exhibit 1 was tested for head loss for the

fourteen cases listed in Table 1.

Head-Loss Data

The hydraulic grade lines in the vertical shaft, tunnel, and penstocks

are plotted on Exhibits 45-54 for Scheme C-1. In contrast to the corres-

ponding plots for Schemes B-1 and B-2, the location of the piezometers in

the penstocks are referenced to the D-Line of Exhibit 1 rather than to the

junction with the trunk. Hence the head losses of Exhibits 45-54 are

relative to the U-Line and D-Line, yielding relative loss coefficients.

For purposes of comparison with the other schemes the actual loss coeffi-

cients have been computed and reported in Table 8, while Table 9 summarizes

the relative loss coefficients printed on Exhibits 45-54.

As expected the head loss coefficients for the unstreamlined bifurca-

tion model are much greater than for the two previous schemes.

Flow Patterns in Bifurcation Model

Although photographs were taken of the tuft orientation for all four-

teen test cases, only several are reported here. Only in the pumping mode

was photography of the air bubble patterns very successful.

Exhibit 55 illustrates the condition of three units generating. In

this single case Scheme C-1 performed nearly as well as Modified Scheme B-1.

In the pumping mode the turbulence created by the sudden expansion was

very severe as shown by Exhibit 56 for three units pumping and Exhibit 57

for only Unit 3 pumping. In the latter case the turbulence can be seen to

persist through the elbow in the tunnel.

No measurements were made of the pressure distribution in the trunk of Scheme C-1.
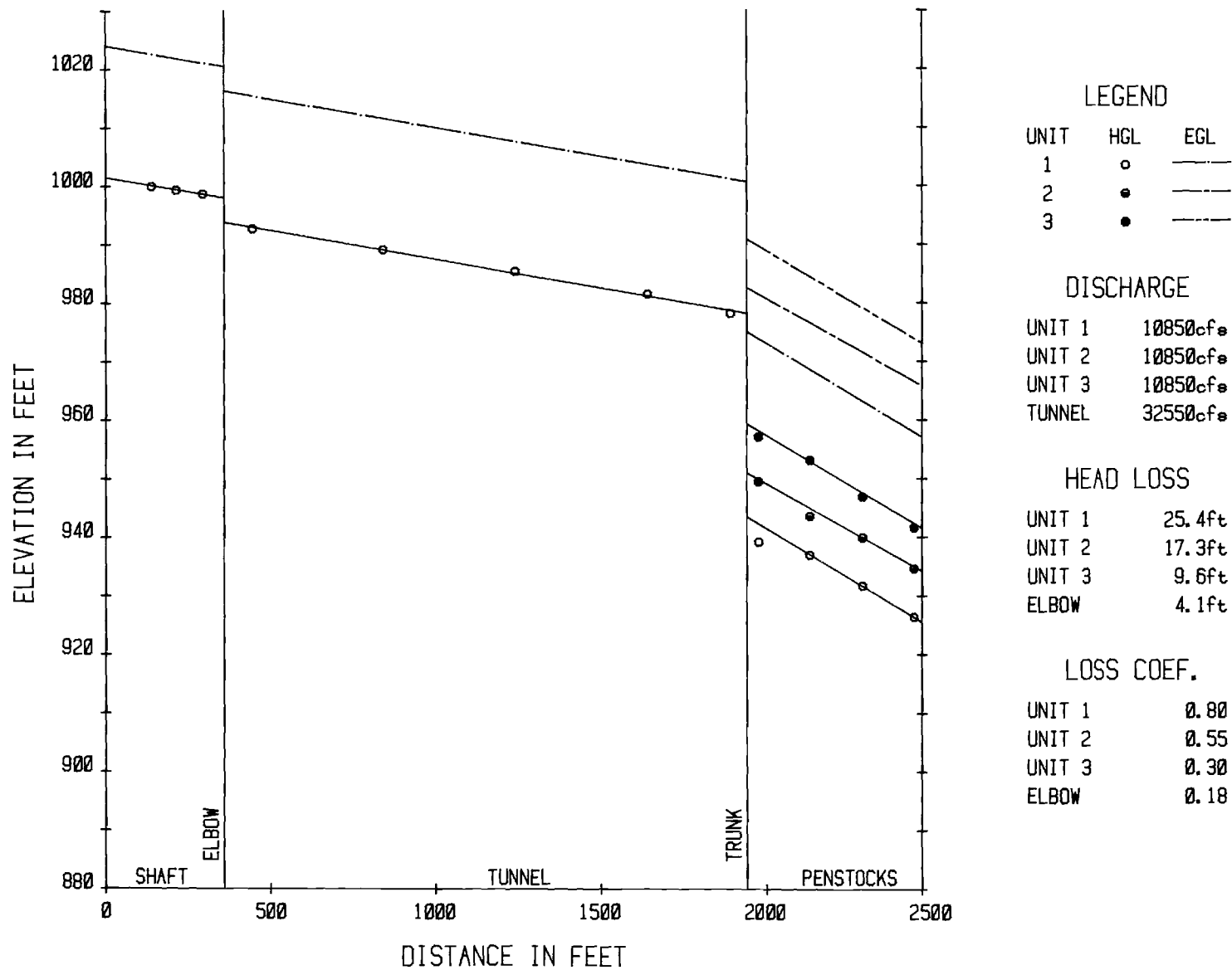
Exhibit 45. Hydraulic and Energy Grade Lines in Scheme C-1 for
Three Units Generating.

99
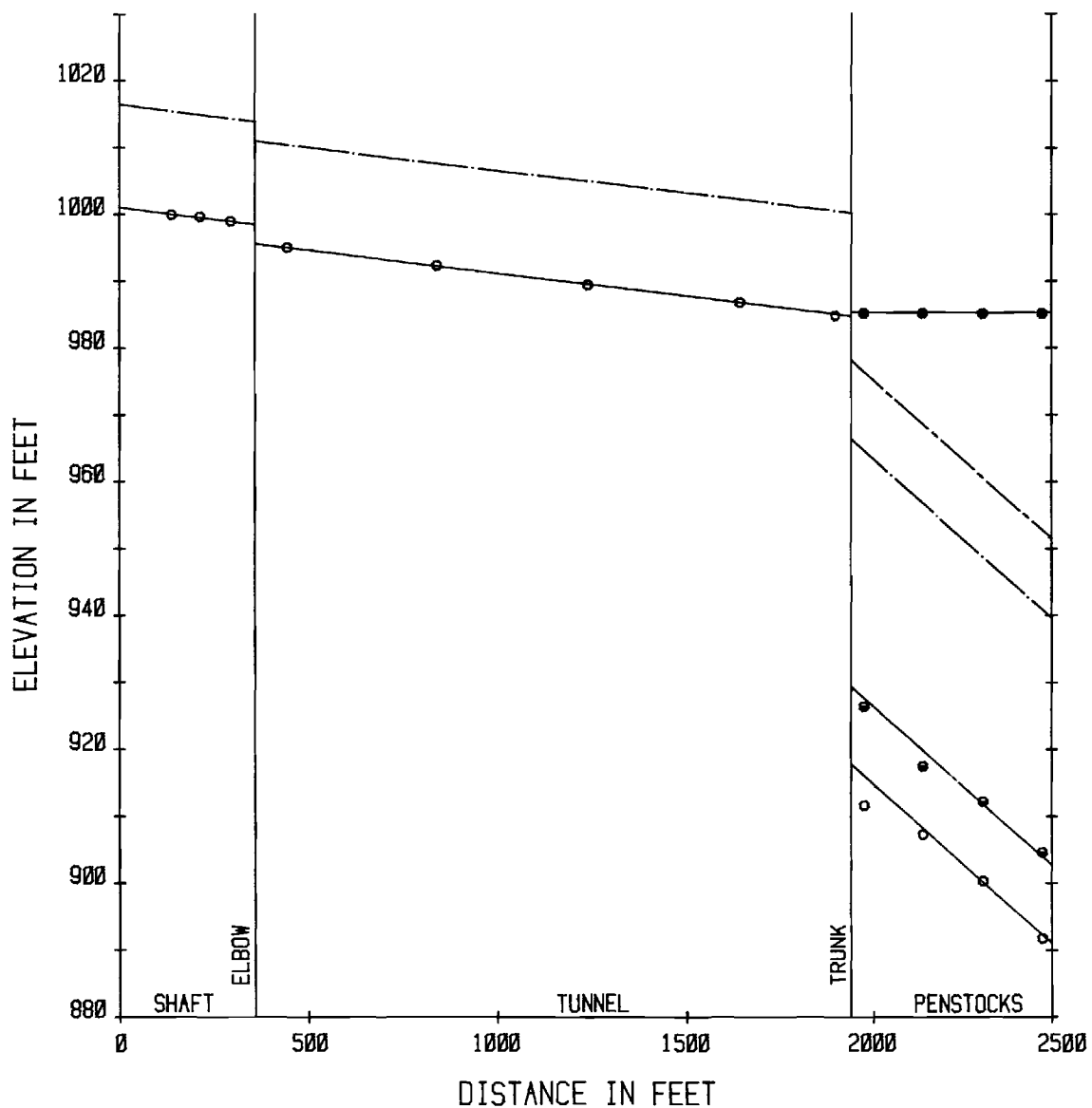
LEGEND

UNIT	HGL	EGL
1	o	——
2	◉	—·—
3	●	—··—

DISCHARGE

UNIT 1	13460cfs
UNIT 2	13490cfs
UNIT 3	0cfs
TUNNEL	26950cfs

HEAD LOSS

UNIT 1	33.6ft
UNIT 2	21.7ft
UNIT 3	0.0ft
ELBOW	2.8ft

LOSS COEF.

UNIT 1	0.69
UNIT 2	0.45
UNIT 3	0.00
ELBOW	0.18

ELEVATION IN FEET

1020
1000
980
960
940
920
900
880

SHAFT   ELBOW   TUNNEL   TRUNK   PENSTOCKS

0   500   1000   1500   2000   2500

DISTANCE IN FEET

Exhibit 46.   Hydraulic and Energy Grade Lines in Schem C-1 for
Units 1 and 2 Generating.

Exhibit 47. Hydraulic and Energy Grade Lines in Scheme C-1 for
Units 1 and 3 Generating.
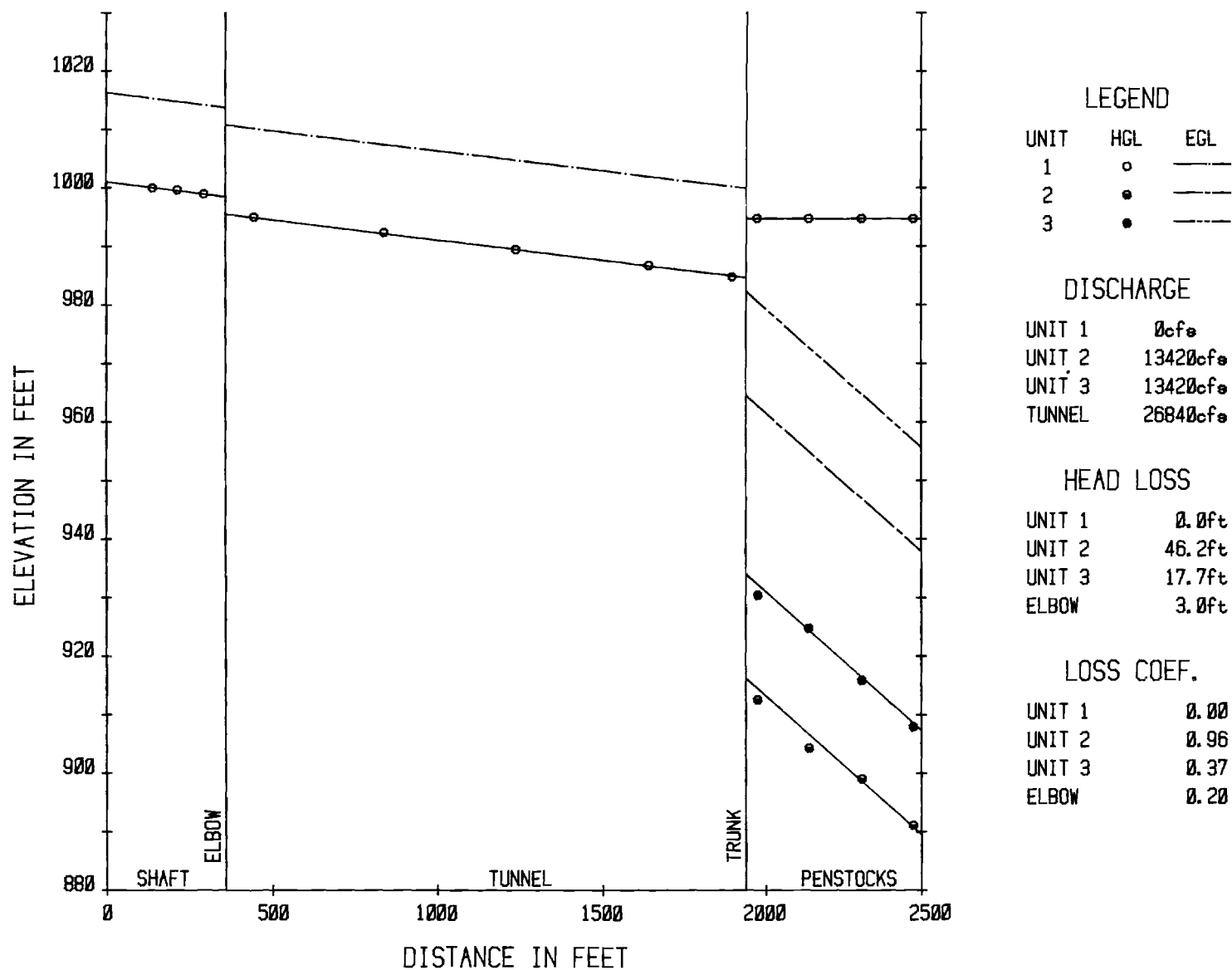
Exhibit 48. Hydraulic and Energy Grade Lines in Scheme C-1 for
Units 2 and 3 Generating.

ELEVATION IN FEET

1020

1000

980

960

940

920

900

880

SHAFT

ELBOW

TUNNEL

TRUNK

PENSTOCKS

0   500   1000   1500   2000   2500

DISTANCE IN FEET

LEGEND

UNIT	HGL	EGL
1	o	
2	◐	
3	●	

DISCHARGE

UNIT 1   13440cfs
UNIT 2   13440cfs
UNIT 3   13440cfs

HEAD LOSS

UNIT 1   30.4ft
UNIT 2   30.4ft
UNIT 3   34.4ft

LOSS COEF.

UNIT 1   0.63
UNIT 2   0.63
UNIT 3   0.71
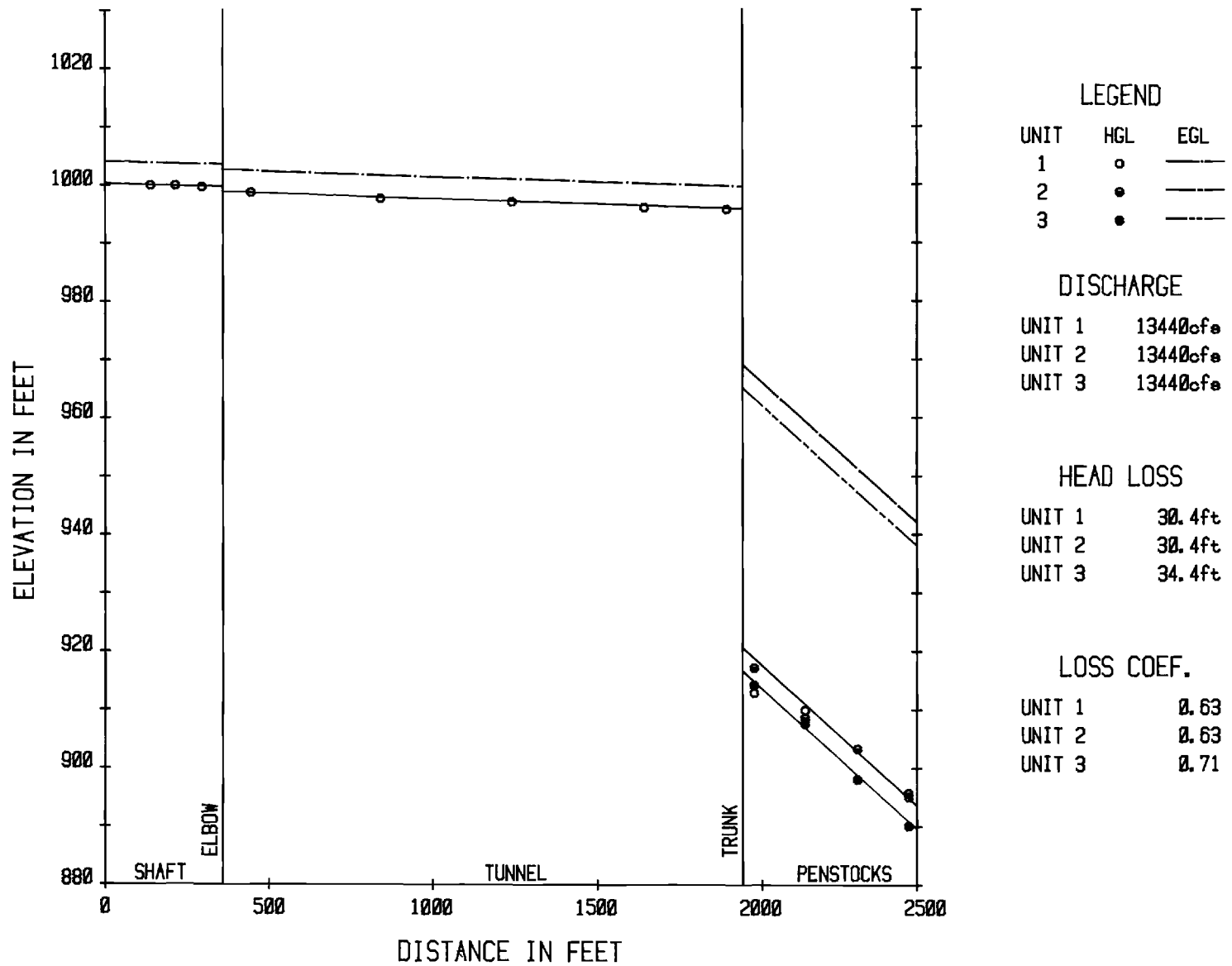
Exhibit 49.   Hydraulic and Energy Grade Lines in Scheme C-1 for
Single Unit Generating.
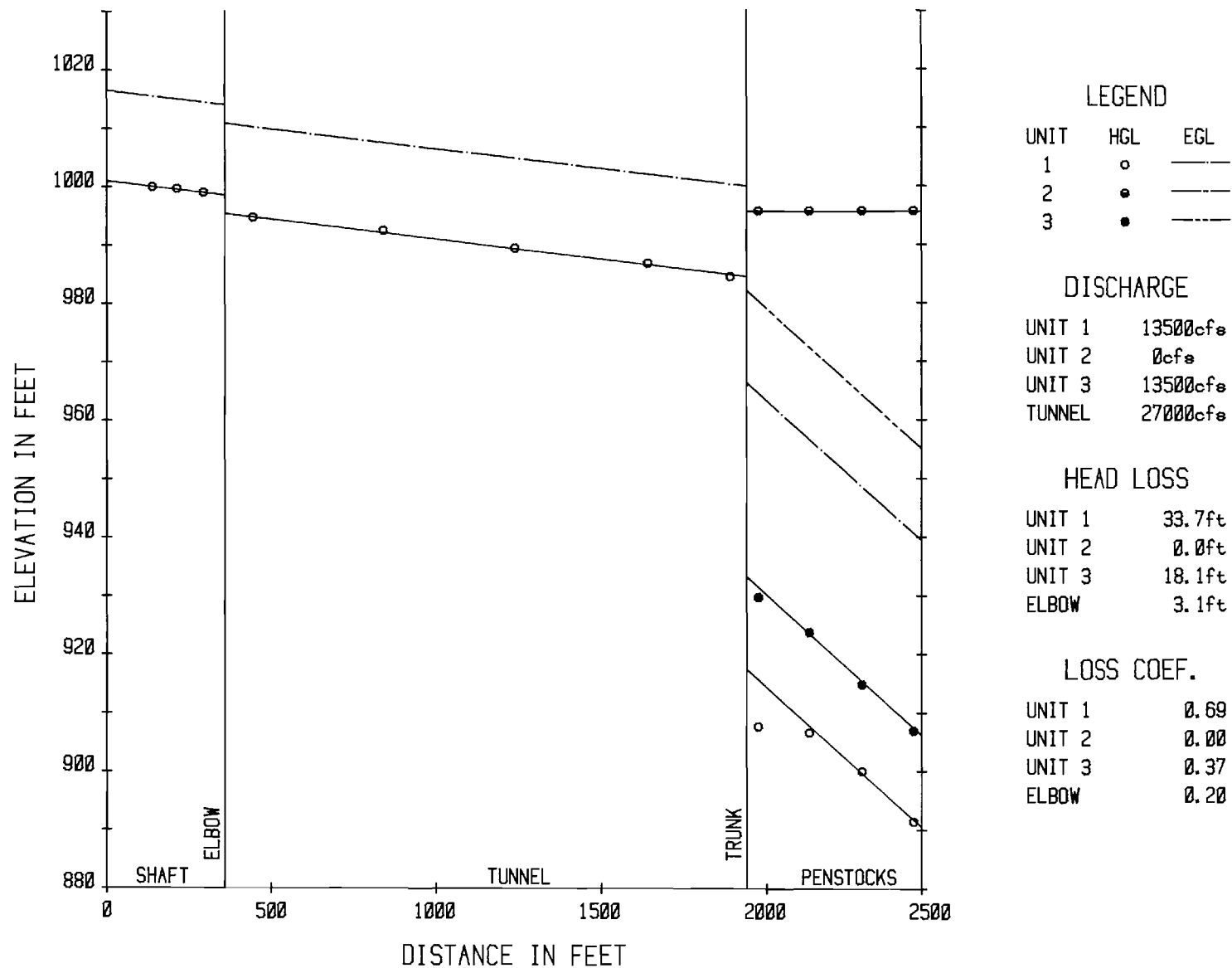
ELEVATION IN FEET

1100
1080
1060
1040
1020
1000
980
960

SHAFT
ELBOW
TUNNEL
TRUNK
PENSTOCKS

0   500   1000   1500   2000   2500

DISTANCE IN FEET

LEGEND

UNIT	HGL	EGL
1	o	——
2	◑	——-
3	●	——-

DISCHARGE

UNIT 1	10000cfs
UNIT 2	9990cfs
UNIT 3	10100cfs
TUNNEL	30090cfs

HEAD LOSS

UNIT 1	15.7ft
UNIT 2	20.2ft
UNIT 3	22.6ft
ELBOW	2.3ft

LOSS COEF.

UNIT 1	0.58
UNIT 2	0.75
UNIT 3	0.83
ELBOW	0.12

Exhibit 50.   Hydraulic and Energy Grade Lines in Scheme C-1 for
Three Units Pumping.

LEGEND

UNIT	HGL	EGL
1	o	————
2	◐	— ——
3	●	—·—·—

DISCHARGE

UNIT 1	12840cfs
UNIT 2	12800cfs
UNIT 3	0cfs
TUNNEL	25640cfs

HEAD LOSS

UNIT 1	32.2ft
UNIT 2	39.3ft
UNIT 3	0.0ft

LOSS COEF.

UNIT 1	0.73
UNIT 2	0.89
UNIT 3	0.00

ELEVATION IN FEET

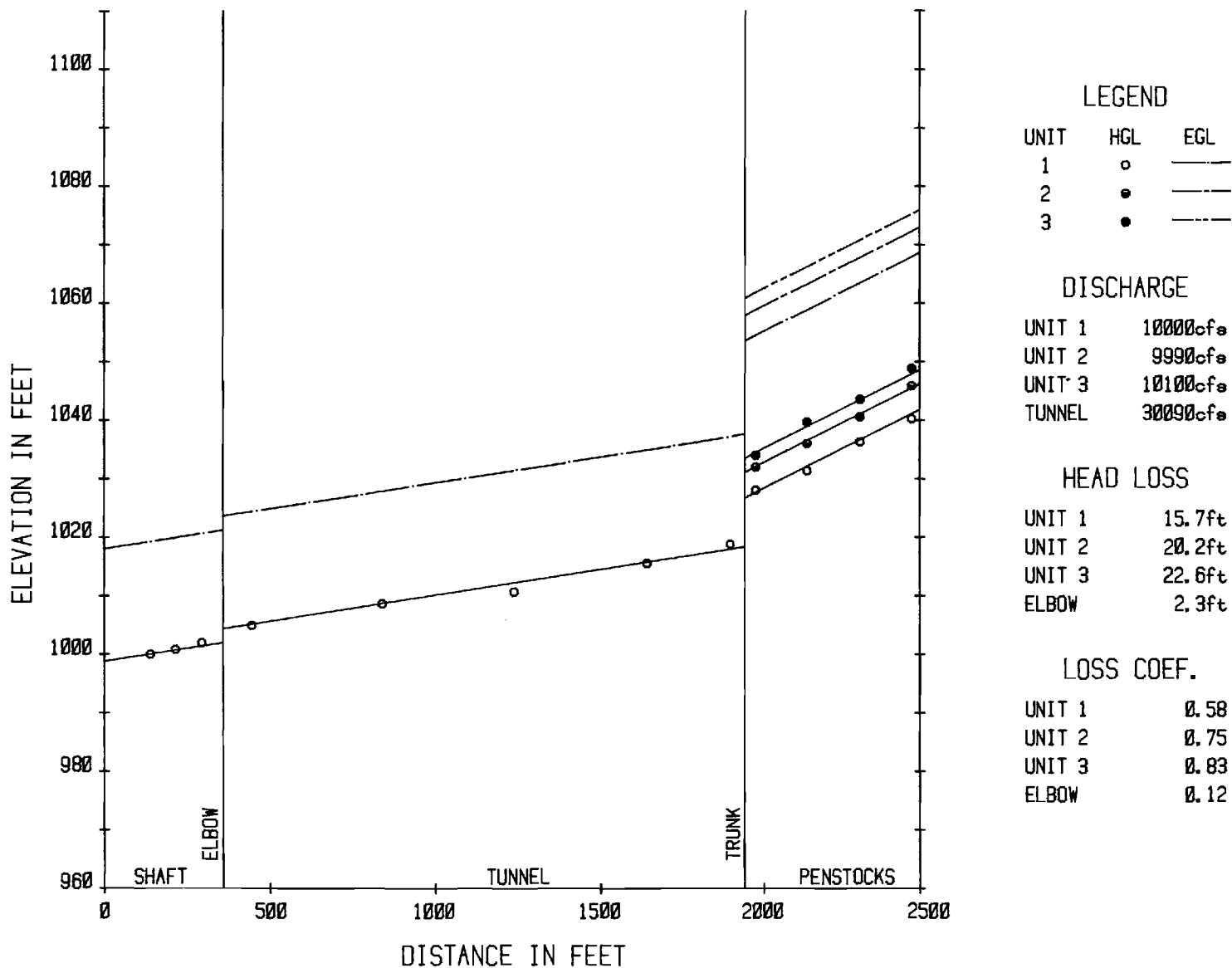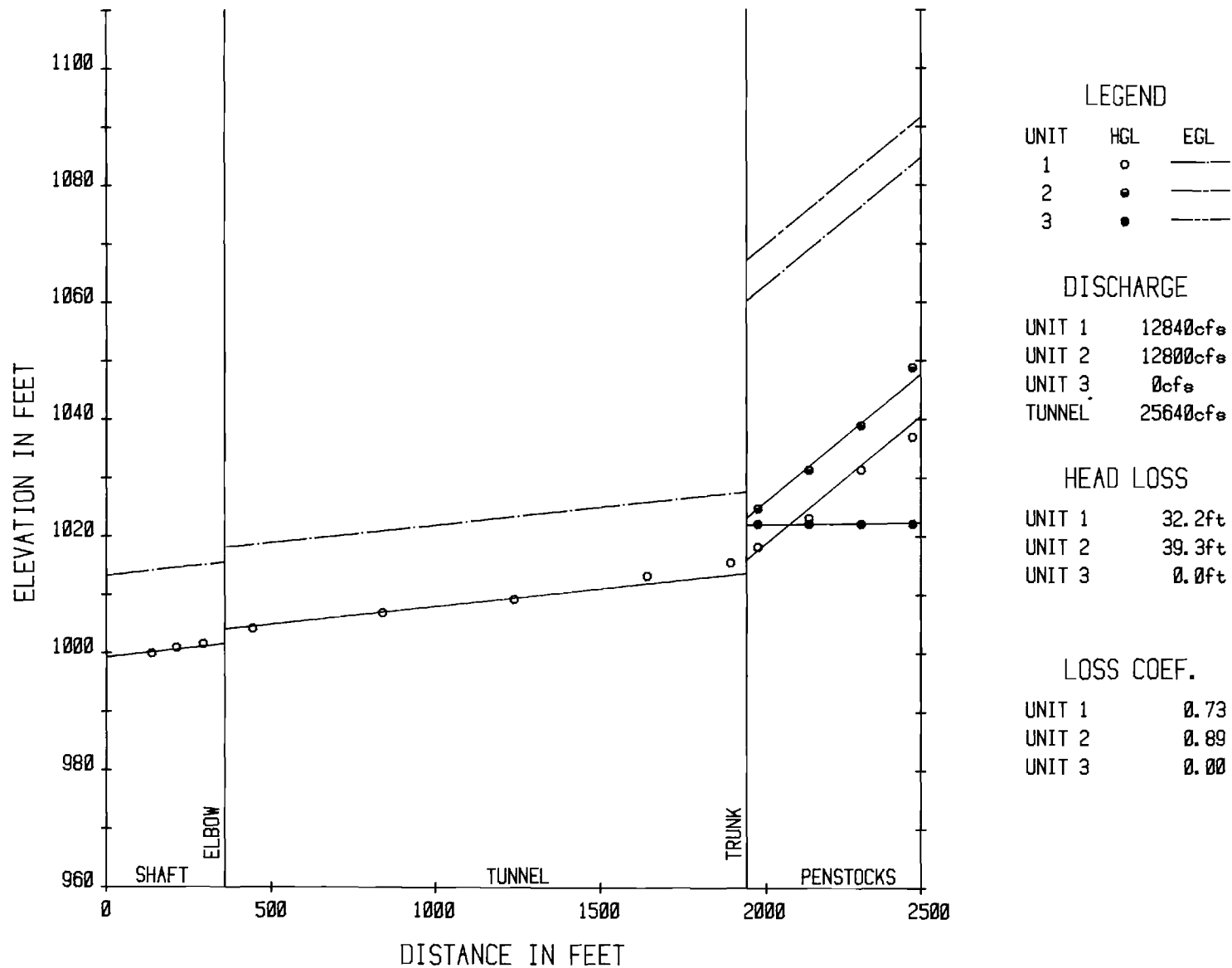SHAFT   ELBOW   TUNNEL   TRUNK   PENSTOCKS
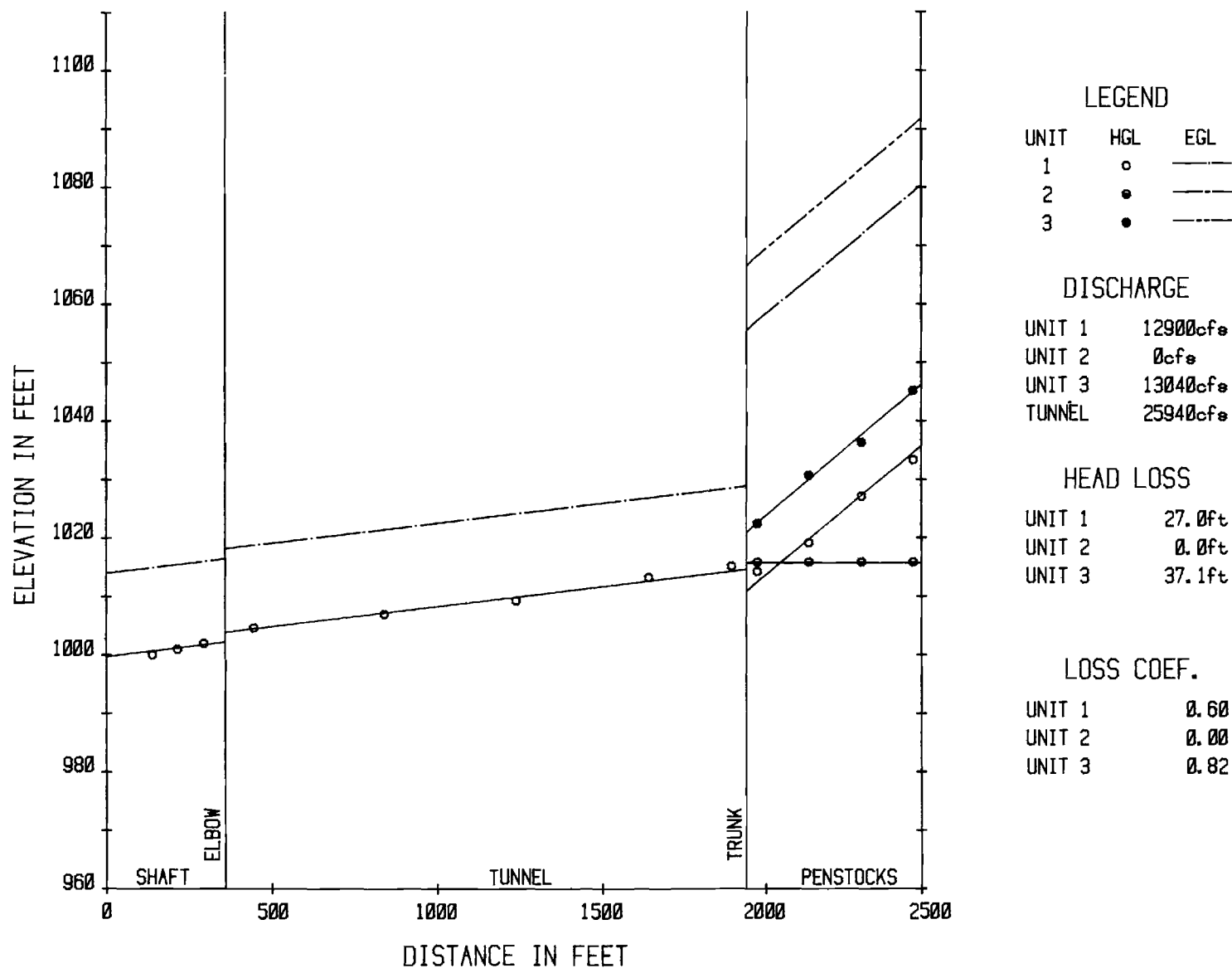
DISTANCE IN FEET

Exhibit 51.   Hydraulic and Energy Grade Lines in Scheme C-1 for
Units 1 and 2 Pumping.

Exhibit 52. Hydraulic and Energy Grade Lines in Scheme C-1 for
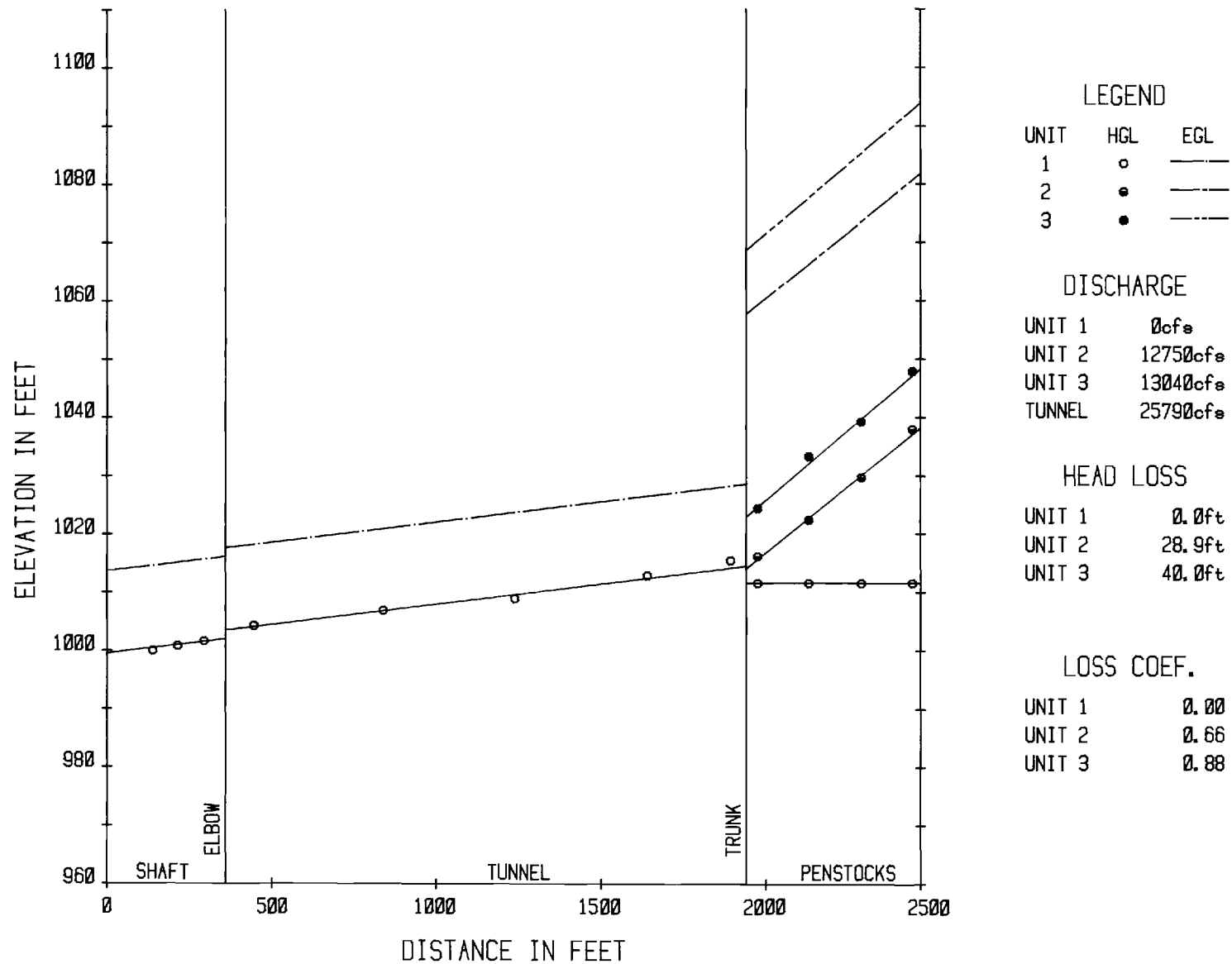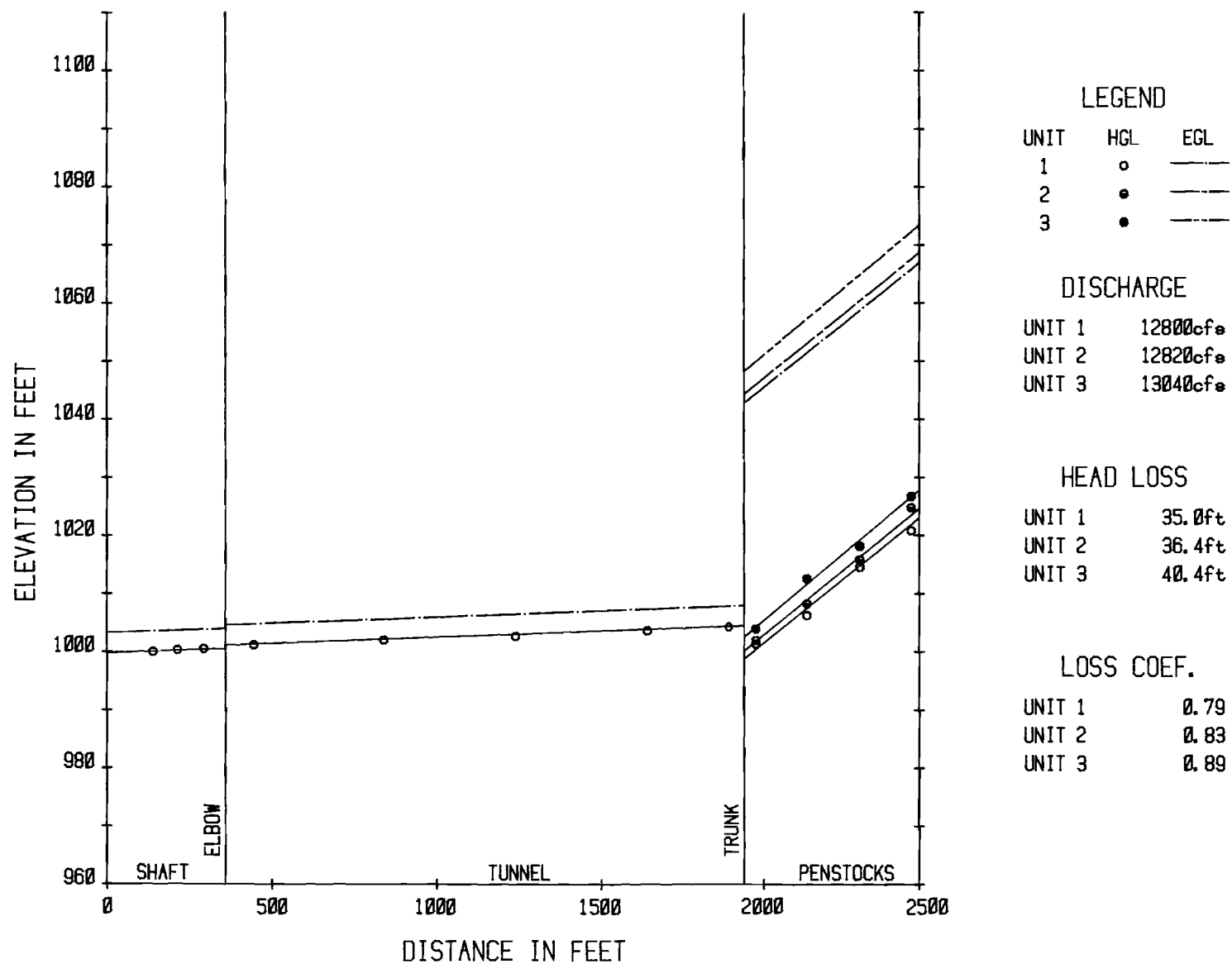Units 1 and 3 Pumping.

LEGEND

UNIT	HGL	EGL
1	o	——————
2	●	—·—·—
3	●	—··—··

DISCHARGE

UNIT 1	0cfs
UNIT 2	12750cfs
UNIT 3	13040cfs
TUNNEL	25790cfs

HEAD LOSS

UNIT 1	0.0ft
UNIT 2	28.9ft
UNIT 3	40.0ft

LOSS COEF.

UNIT 1	0.00
UNIT 2	0.66
UNIT 3	0.88

Exhibit 53.   Hydraulic and Energy Grade Lines in Scheme C-1 for
Units 2 and 3 Pumping.

ELEVATION IN FEET

1100
1080
1060
1040
1020
1000
980
960

SHAFT   ELBOW   TUNNEL   TRUNK   PENSTOCKS

0   500   1000   1500   2000   2500

DISTANCE IN FEET

LEGEND

UNIT	HGL	EGL
1	o	—··—
2	●	———
3	●	—·—

DISCHARGE

UNIT 1	12800cfs
UNIT 2	12820cfs
UNIT 3	13040cfs

HEAD LOSS

UNIT 1	35.0ft
UNIT 2	36.4ft
UNIT 3	40.4ft

LOSS COEF.

UNIT 1	0.79
UNIT 2	0.83
UNIT 3	0.89

Exhibit 54. Hydraulic and Energy Grade Lines in Scheme C-1 for
Single Unit Pumping.

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TABLE 8

SUMMARY OF

ACTUAL LOSS COEFFICIENTS

FOR C-1 SCHEME

MODE	K_{L_1} (UNIT 1)	K_{L_2} (UNIT 2)	K_{L_3} (UNIT 3)
Three Units Generating	0.80	0.49	0.18
Units 1 and 2 Generating	0.69	0.39	–
Units 1 and 3 Generating	0.69	–	0.25
Units 2 and 2 Generating	–	0.90	0.25
Single Unit Generating	0.63	0.57	0.59
Three Units Pumping	0.58	0.69	0.71
Units 1 and 2 Pumping	0.73	0.83	–
Units 1 and 3 Pumping	0.60	–	0.70
Units 2 and 3 Pumping	–	0.60	0.76
Single Unit Pumping	0.79	0.77	0.77

TABLE 9

SUMMARY OF

RELATIVE LOSS COEFFICIENTS

FOR C-1 SCHEME

MODE	K_{R_1} (UNIT 1)	K_{R_2} (UNIT 2)	K_{R_3} (UNIT 3)
Three Units Generating	0.80	0.55	0.30
Units 1 and 2 Generating	0.69	0.45	–
Units 1 and 3 Generating	0.69	–	0.37
Units 2 and 3 Generating	–	0.96	0.37
Single Unit Generating	0.63	0.63	0.71
Three Units Pumping	0.58	0.75	0.83
Units 1 and 2 Pumping	0.73	0.89	–
Units 1 and 3 Pumping	0.60	–	0.82
Units 2 and 3 Pumping	–	0.66	0.88
Single Unit Pumping	0.79	0.83	0.89

Exhibit 55.   View of Tuft Pattern in Trunk of Scheme C-1 for
Three Units Generating.

Exhibit 56. View of Tuft Pattern in Trunk of Scheme C-1 for Three Units Pumping.

Exhibit 57.   View of Tuft Pattern in Trunk of Scheme C-1 for
Unit 3 Pumping.

CHAPTER VI

TEST RESULTS FOR SCHEME A-1

As shown by Exhibit 1 the final scheme tested, Scheme A-1, differed

by the absence of the elbow at the transition from the tunnel to the

trunk, as well as the manner of bifurcating from trunk to penstocks.

This scheme was also tested for the fourteen cases listed in Table 1.

In an attempt to prevent structural failure of the model, the trunk was

reinforced by bands prior to installation. This modification has an

adverse effect on documentation of flow patterns because of the light

scattering effect of the structural bands.

Head-Loss Data

Using the piezometer locations indicated on Exhibit 6, the hydraulic

grade lines of all fourteen test cases are plotted on Exhibits 58-67. As

with Schemes B-1 and B-2 the head loss coefficients listed on the

exhibits are actual ones, not relative. Tables 10 and 11 are included

to summarize the actual and relative loss coefficients for Scheme A-1,

respectively. The results will be compared with the other three schemes

in the next chapter.

Flow Patterns in Bifurcation Model

Exhibits 68-74 show that the flow pattern in the generating mode of

operation is fairly smooth. Dead zones apparently only occur in the

penstocks of the units that are not operating.

Because of the relatively gradual transition in the deceleration

regions between penstock and trunk the flow pattern for three units

pumping shows an improvement over Schemes B-1 and B-2, especially in the

case of Scheme B-1. Exhibits 76-78 illustrate the flow patterns in the

trunk for the three respective combinations of two units pumping. For single

unit operation Exhibits 79-81 show that the flow is highly turbulent in

the trunk because of the sudden deceleration. There is no marked improve-

ment of Scheme A-1 over Schemes B-1 and B-2 for single unit pumping except

in the case of Unit 3.

Pressure Distribution in Trunk

The locations of the eight piezometer taps used to measure the pressure

distribution in the trunk of Scheme A-1 are depicted on Exhibit 9. The

results in prototype units referenced to the 1000 ft value assigned to

piezometer number 0 are listed in Table 12. Values for piezometer number 4

are not reported because it was discovered that it malfunctioned during the

testing. The differences in pressure through the trunk are generally

smaller for Scheme A-1 than for Schemes B-1 and B-2 because of better flow

patterns.
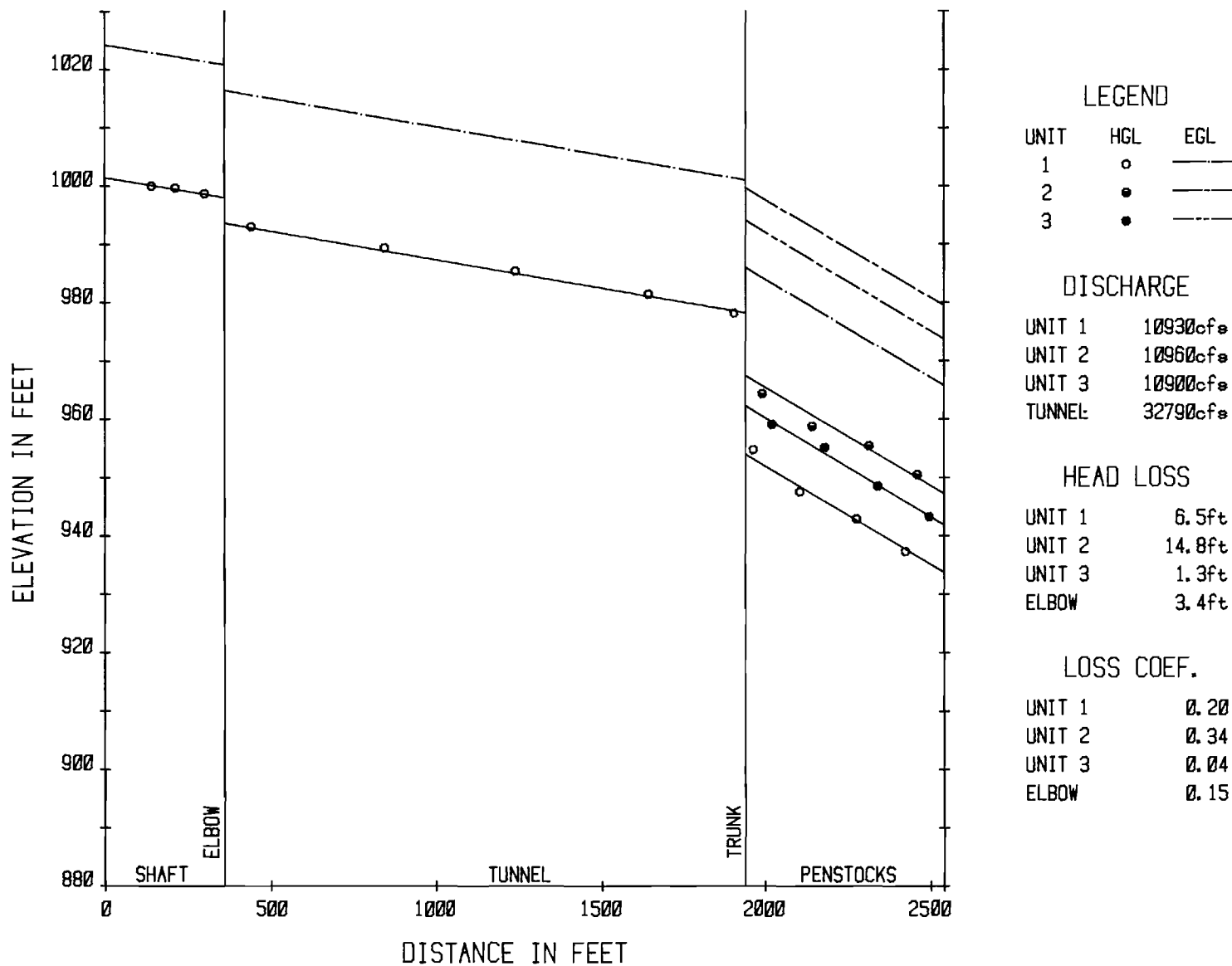
Exhibit 58.   Hydraulic and Energy Grade Lines in Scheme A-1 for
Three Units Generating.
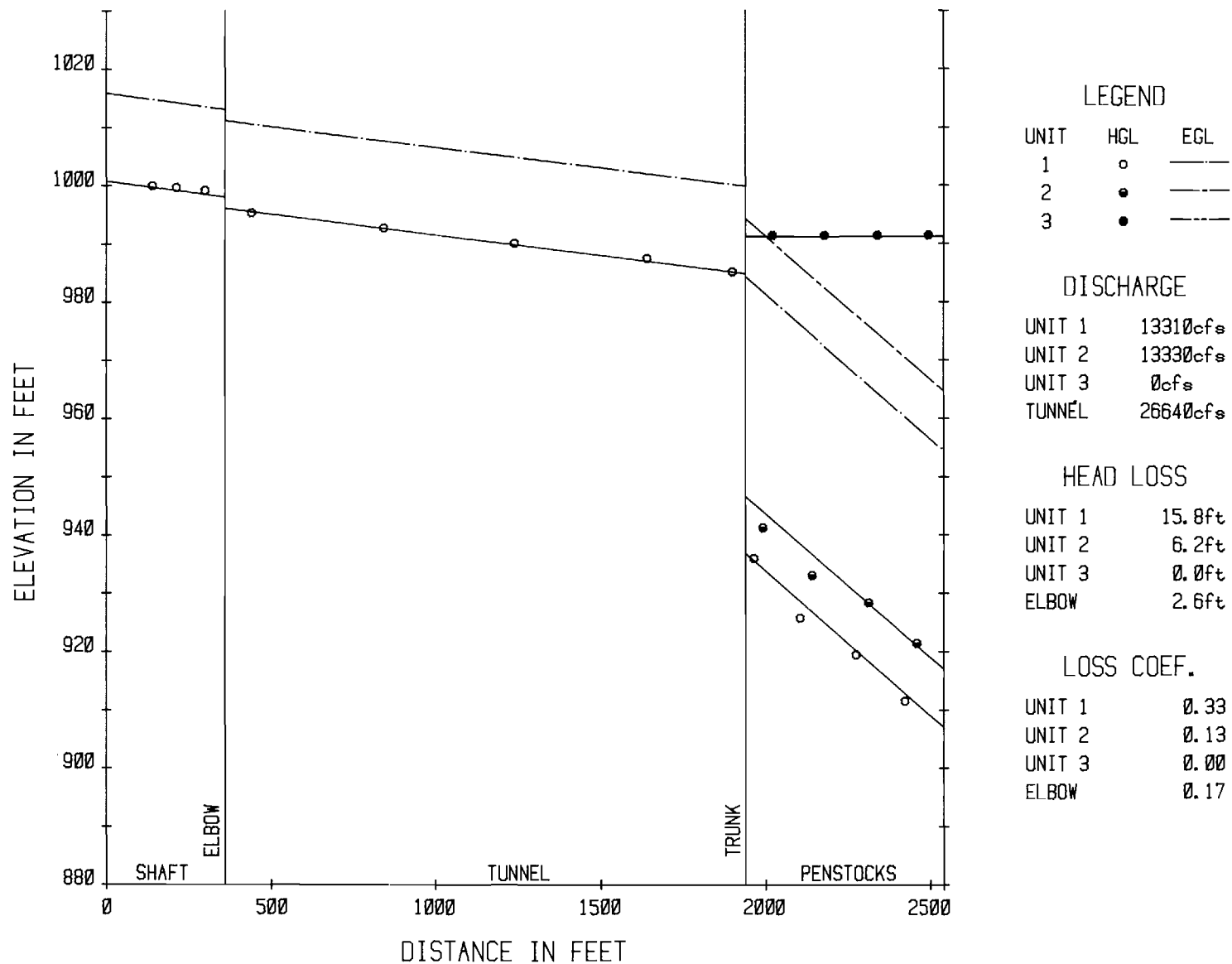
Exhibit 59.   Hydraulic and Energy Grade Lines in Scheme A-1 for
                Units 1 and 2 Generating.
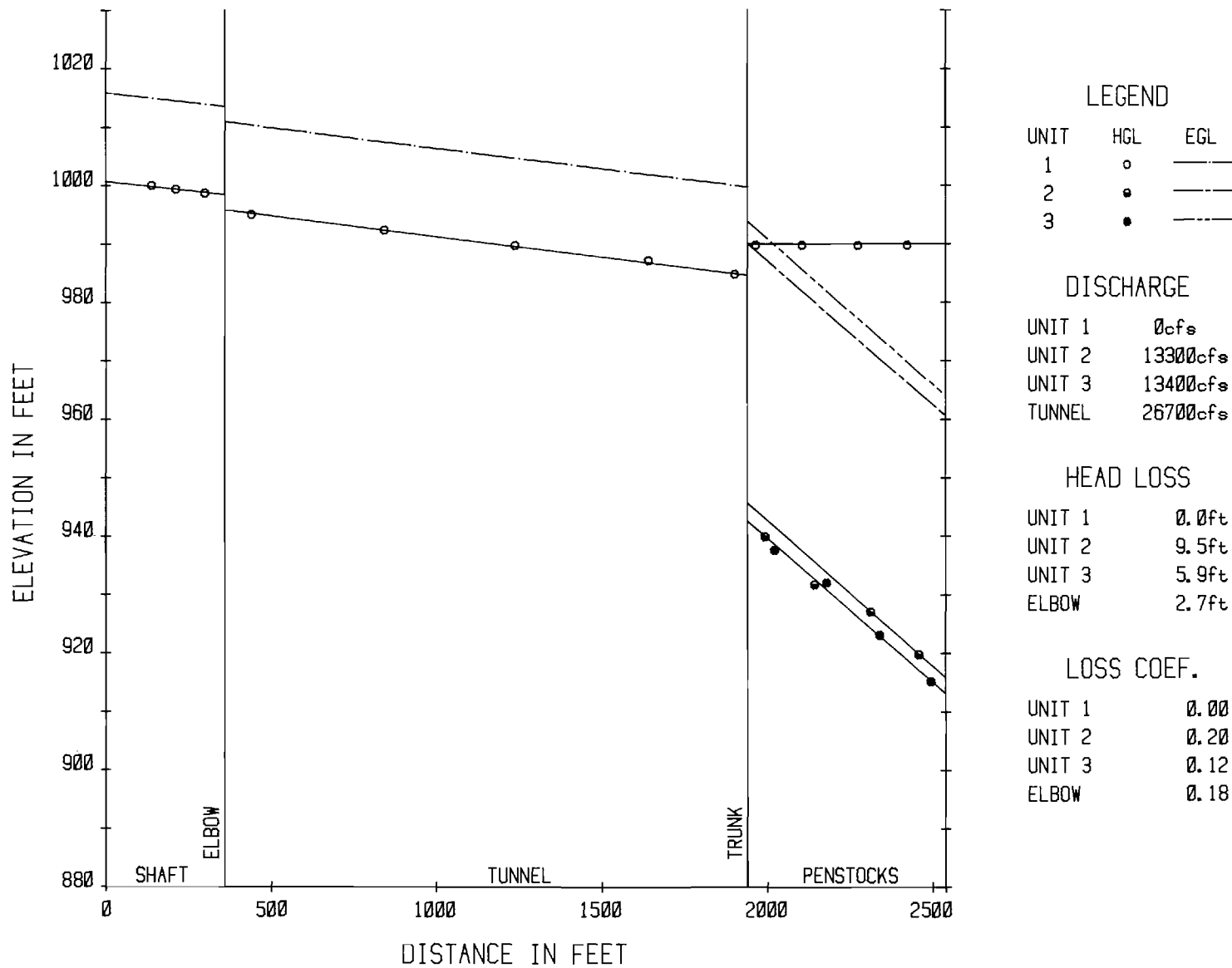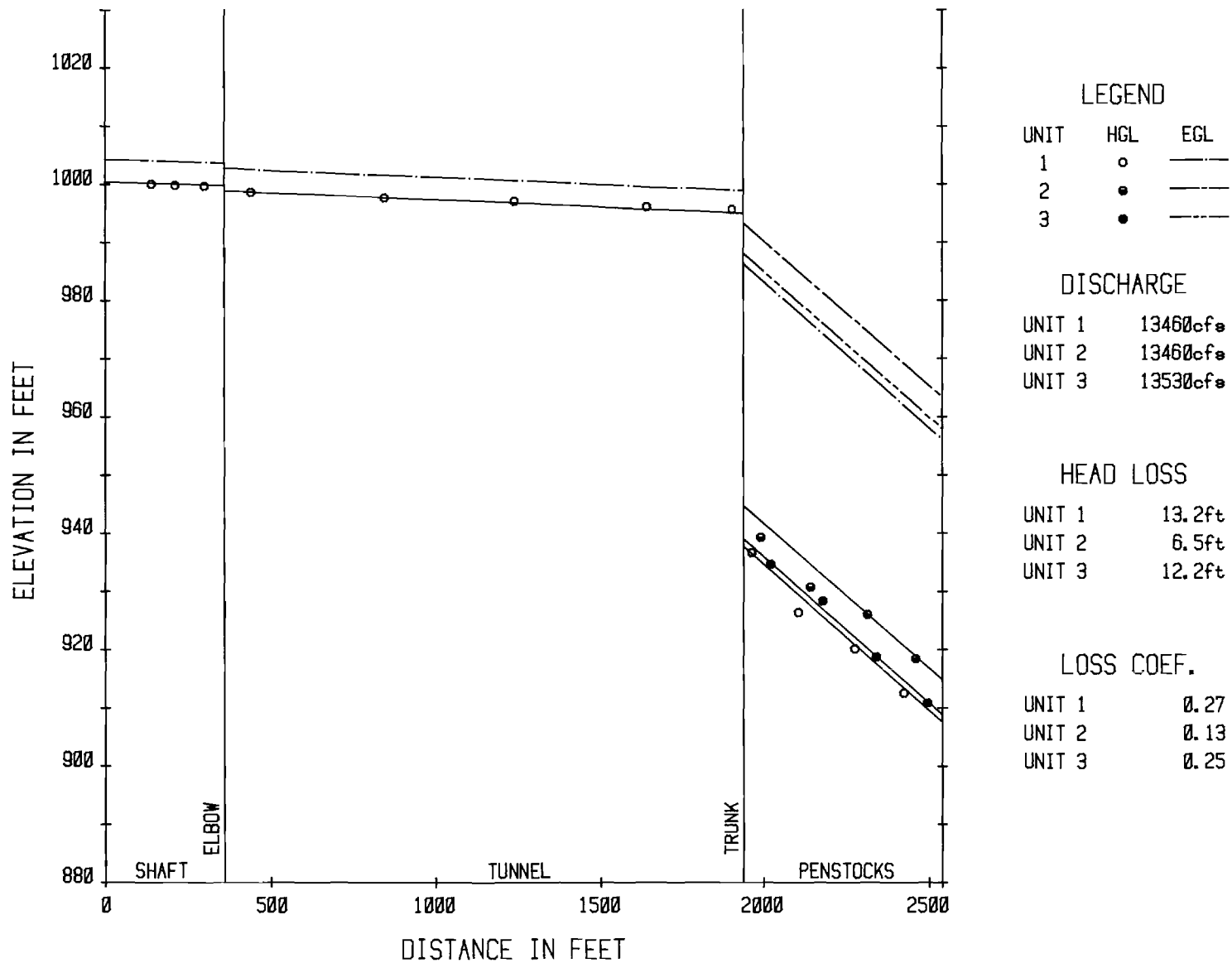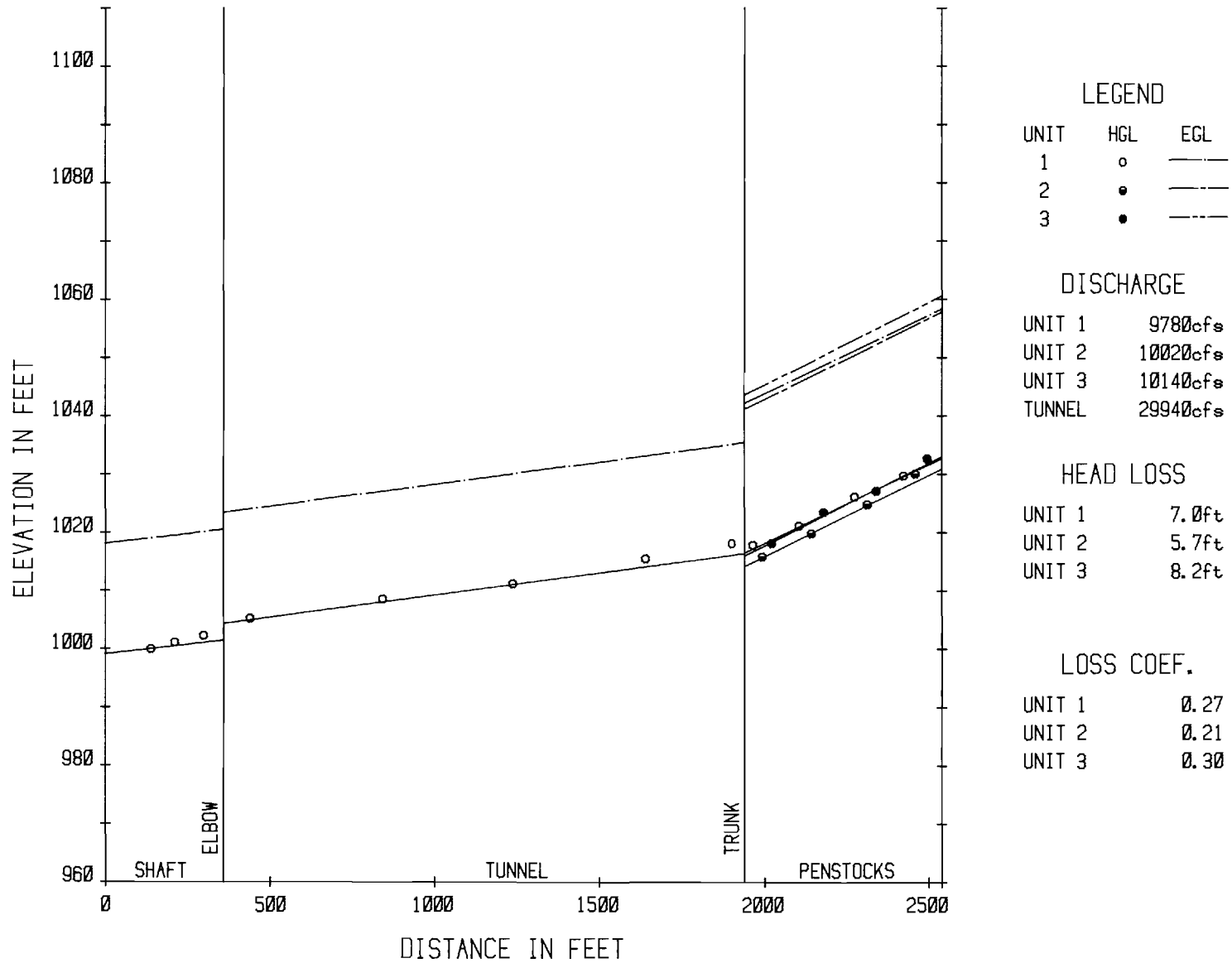
ELEVATION IN FEET

1020

1000

980

960

940

920

900

880

0   500   1000   1500   2000   2500

DISTANCE IN FEET

SHAFT   ELBOW   TUNNEL   TRUNK   PENSTOCKS

LEGEND

UNIT	HGL	EGL
1	o	—––—
2	◐	—–—
3	●	—·–—

DISCHARGE

UNIT 1	13300cfs
UNIT 2	0cfs
UNIT 3	13200cfs
TUNNEL	26500cfs

HEAD LOSS

UNIT 1	14.8ft
UNIT 2	0.0ft
UNIT 3	6.8ft
ELBOW	3.1ft

LOSS COEF.

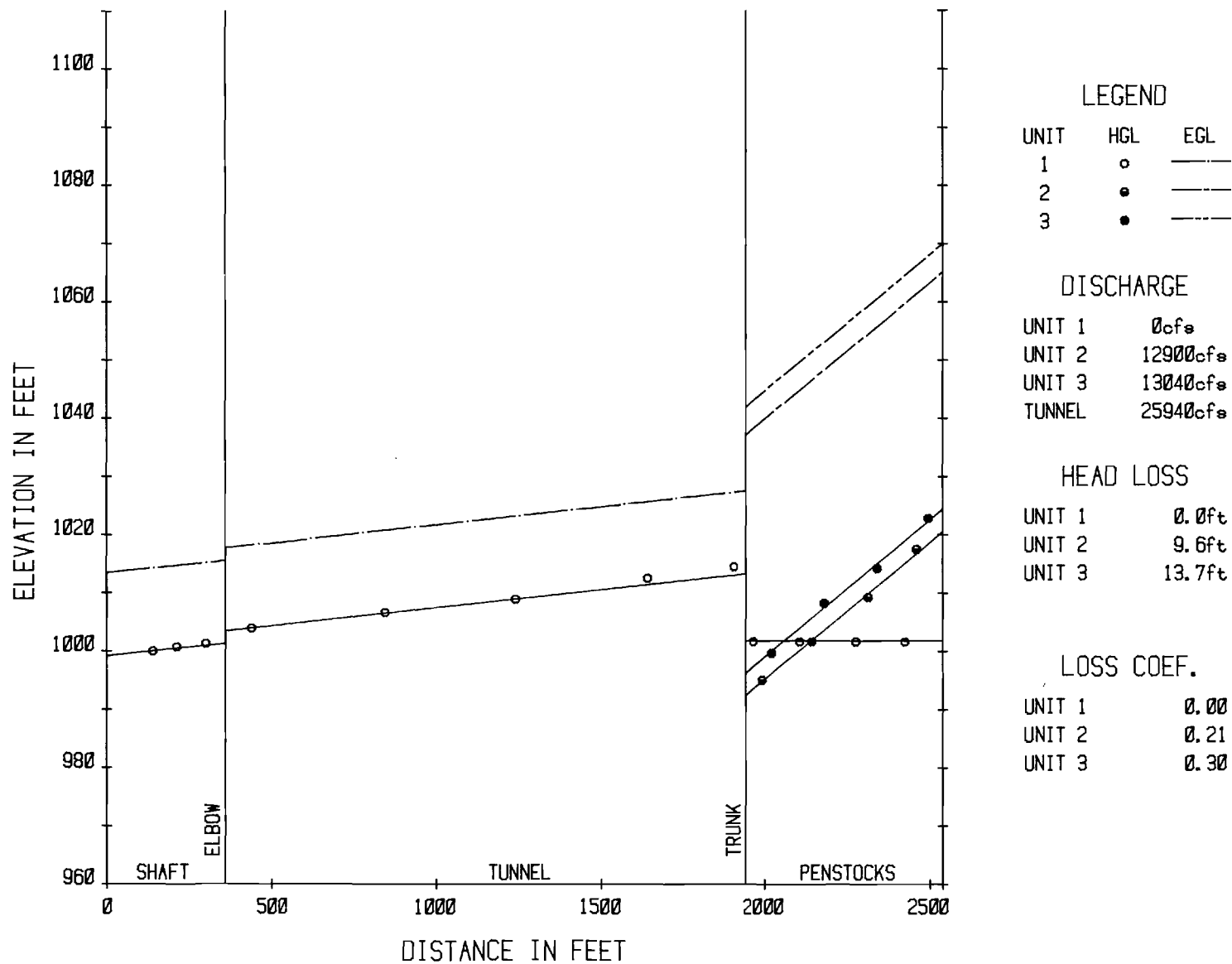|	
UNIT 1	0.31
UNIT 2	0.00
UNIT 3	0.15
ELBOW	0.21
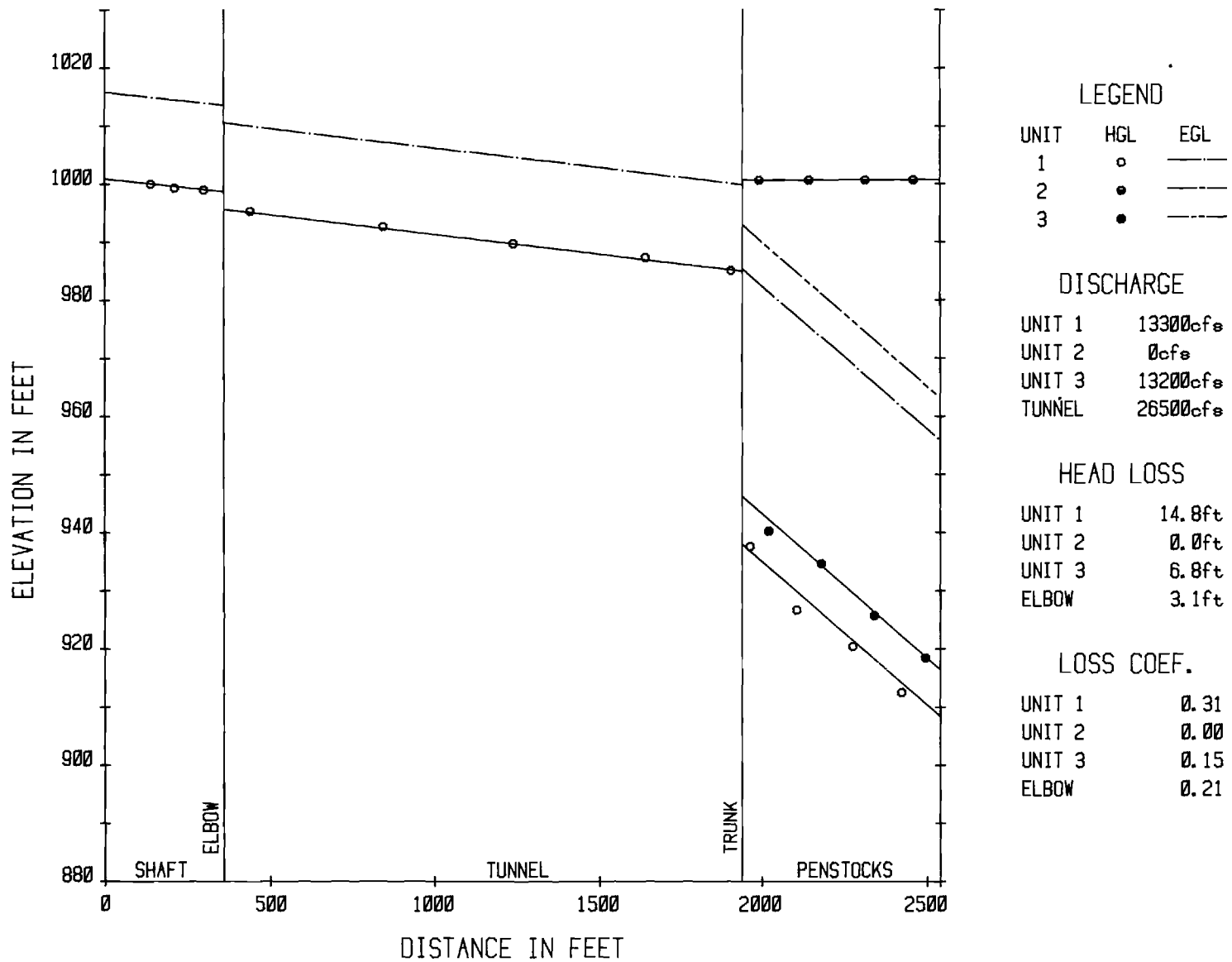
Exhibit 60.   Hydraulic and Energy Grade Lines in Scheme A-1 for
Units 1 and 3 Generating.

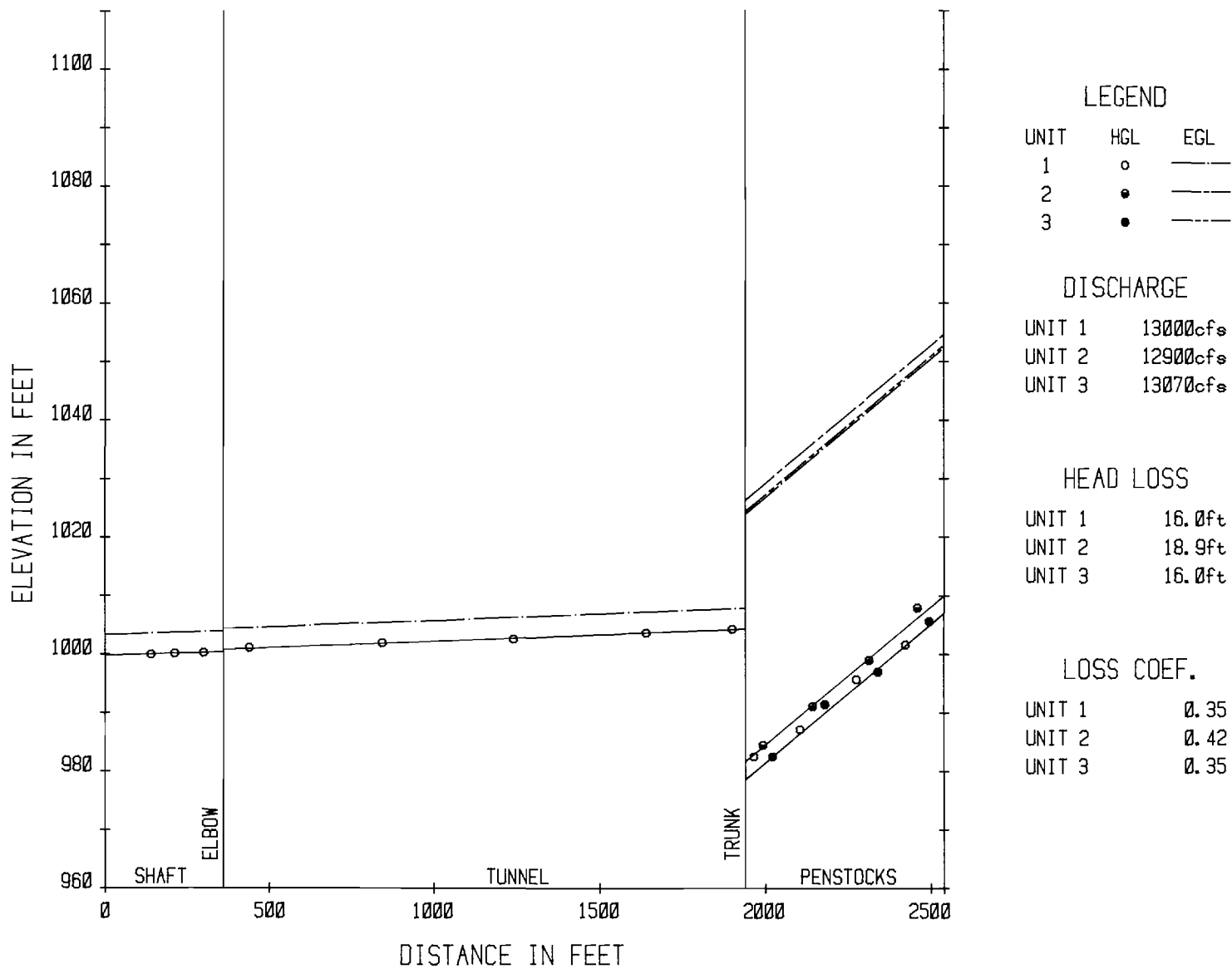Exhibit 61.   Hydraulic and Energy Grade Lines in Scheme A-1 for
Units 2 and 3 Generating.

LEGEND

UNIT	HGL	EGL
1	o	————
2	◉	————
3	●	—·——·

DISCHARGE

UNIT 1	13460cfs
UNIT 2	13460cfs
UNIT 3	13530cfs

HEAD LOSS

UNIT 1	13.2ft
UNIT 2	6.5ft
UNIT 3	12.2ft

LOSS COEF.

UNIT 1	0.27
UNIT 2	0.13
UNIT 3	0.25

ELEVATION IN FEET

1020

1000

980

960

940

920

900

880

DISTANCE IN FEET

0   500   1000   1500   2000   2500

SHAFT   ELBOW   TUNNEL   TRUNK   PENSTOCKS

Exhibit 62.   Hydraulic and Energy Grade Lines in Scheme A-1 for
Single Unit Generating.

Exhibit 63.   Hydraulic and Energy Grade Lines in Scheme A-1 for
Three Units Pumping.
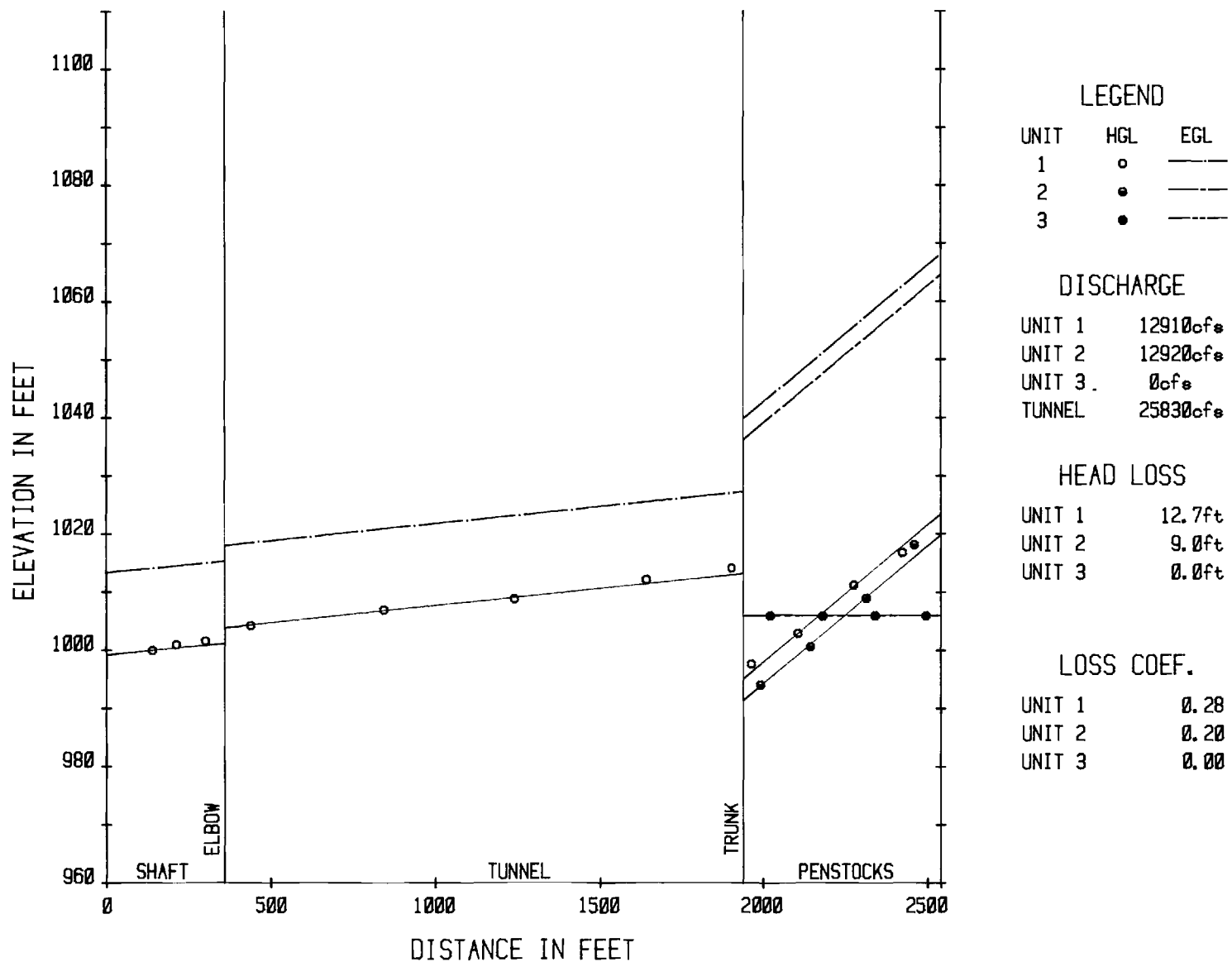
Exhibit 64. Hydraulic and Energy Grade Lines in Scheme A-1 for
Units 1 and 2 Pumping.
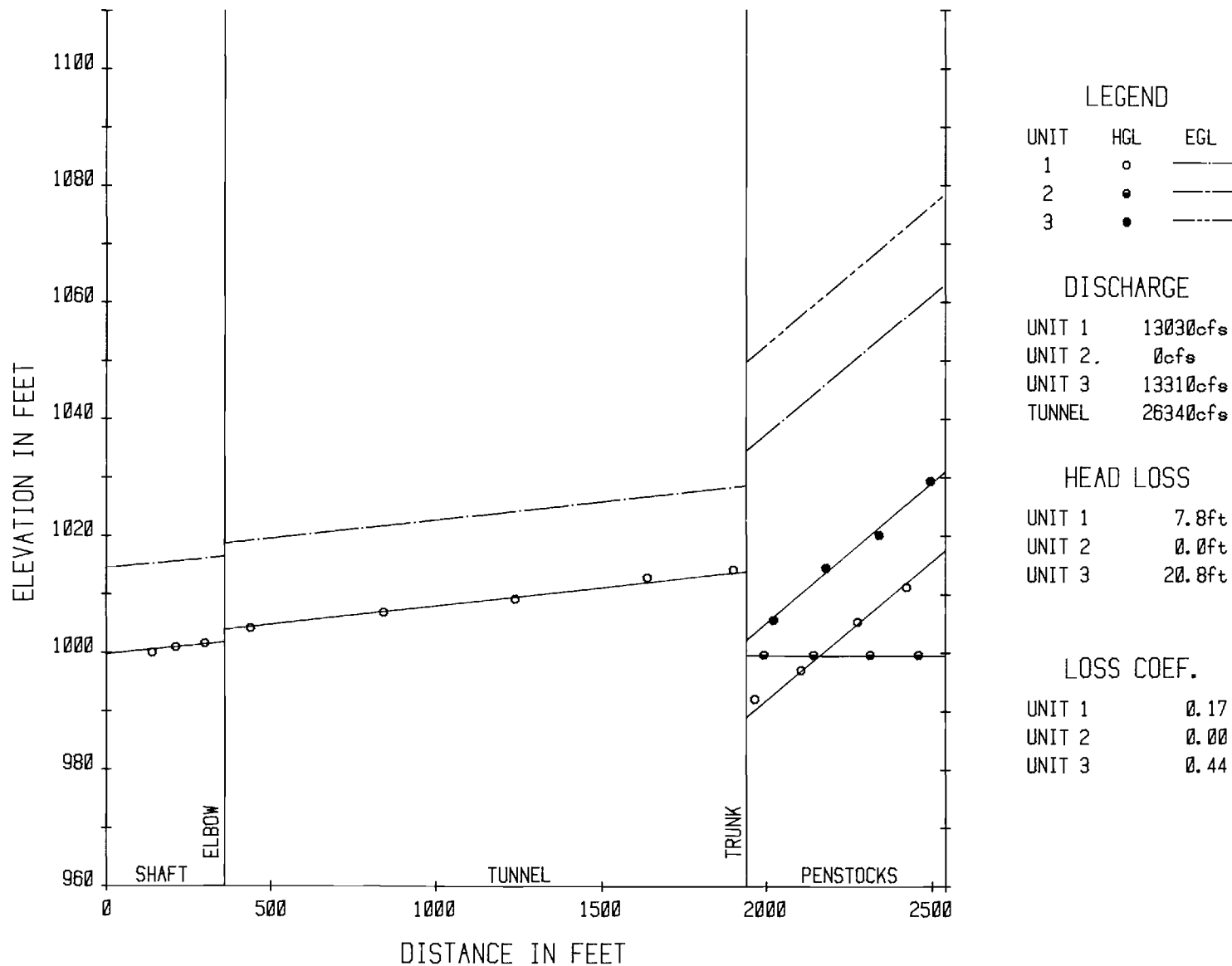
Exhibit 65.   Hydraulic and Energy Grade Lines in Scheme A-1 for
Units 1 and 3 Pumping.

Exhibit 66. Hydraulic and Energy Grade Lines in Scheme A-1 for
Units 2 and 3 Pumping.

LEGEND

UNIT	HGL	EGL
1	o	—··—
2	◉	—·—
3	●	—···—

DISCHARGE

UNIT 1	13000cfs
UNIT 2	12900cfs
UNIT 3	13070cfs

HEAD LOSS

UNIT 1	16.0ft
UNIT 2	18.9ft
UNIT 3	16.0ft

LOSS COEF.

UNIT 1	0.35
UNIT 2	0.42
UNIT 3	0.35

Exhibit 67.   Hydraulic and Energy Grade Lines in Scheme A-1 for
Single Unit Pumping.

TABLE 10

SUMMARY OF ACTUAL LOSS COEFFICIENTS

FOR A-1 SCHEME

MODE	K_{L_1} (UNIT 1)	K_{L_2} (UNIT 2)	K_{L_3} (UNIT 3)
Three Units Generating	0.20	0.34	0.04
Units 1 and 2 Generating	0.33	0.13	--
Units 1 and 3 Generating	0.31	--	0.15
Units 2 and 3 Generating	--	0.20	0.12
Single Unit Generating	0.27	0.13	0.25
Three Units Pumping	0.27	0.21	0.30
Units 1 and 2 Pumping	0.28	0.20	--
Units 1 and 3 Pumping	0.17	--	0.44
Units 2 and 3 Pumping	--	0.21	0.30
Single Unit Pumping	0.35	0.42	0.35

TABLE 11

SUMMARY OF

RELATIVE LOSS COEFFICIENTS

FOR A-1 SCHEME

MODE	K_{R_1} (UNIT 1)	K_{R_2} (UNIT 2)	K_{R_3} (UNIT 3)
Three Units Generating	0.20	0.36	0.11
Units 1 and 2 Generating	0.33	0.15	--
Units 1 and 3 Generating	0.31	--	0.22
Units 2 and 3 Generating	--	0.22	0.19
Single Unit Generating	0.27	0.15	0.32
Three Units Pumping	0.27	0.23	0.37
Units 1 and 2 Pumping	0.28	0.22	--
Units 1 and 3 Pumping	0.17	--	0.51
Units 2 and 3 Pumping	--	0.23	0.37
Single Unit Pumping	0.35	0.44	0.42
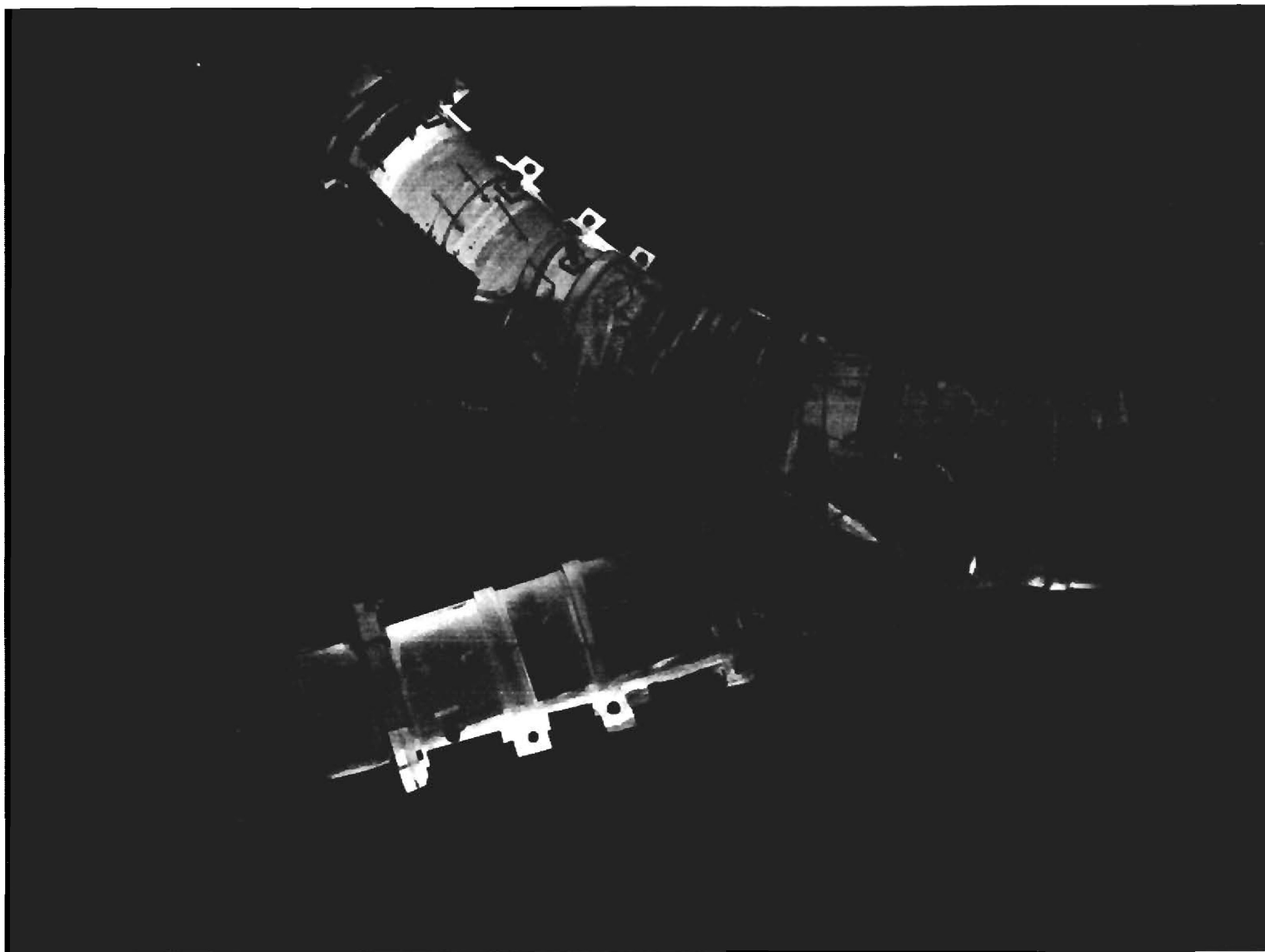
Exhibit 68. View of Tuft Pattern in Trunk of Scheme A-1 for
Three Units Generating.
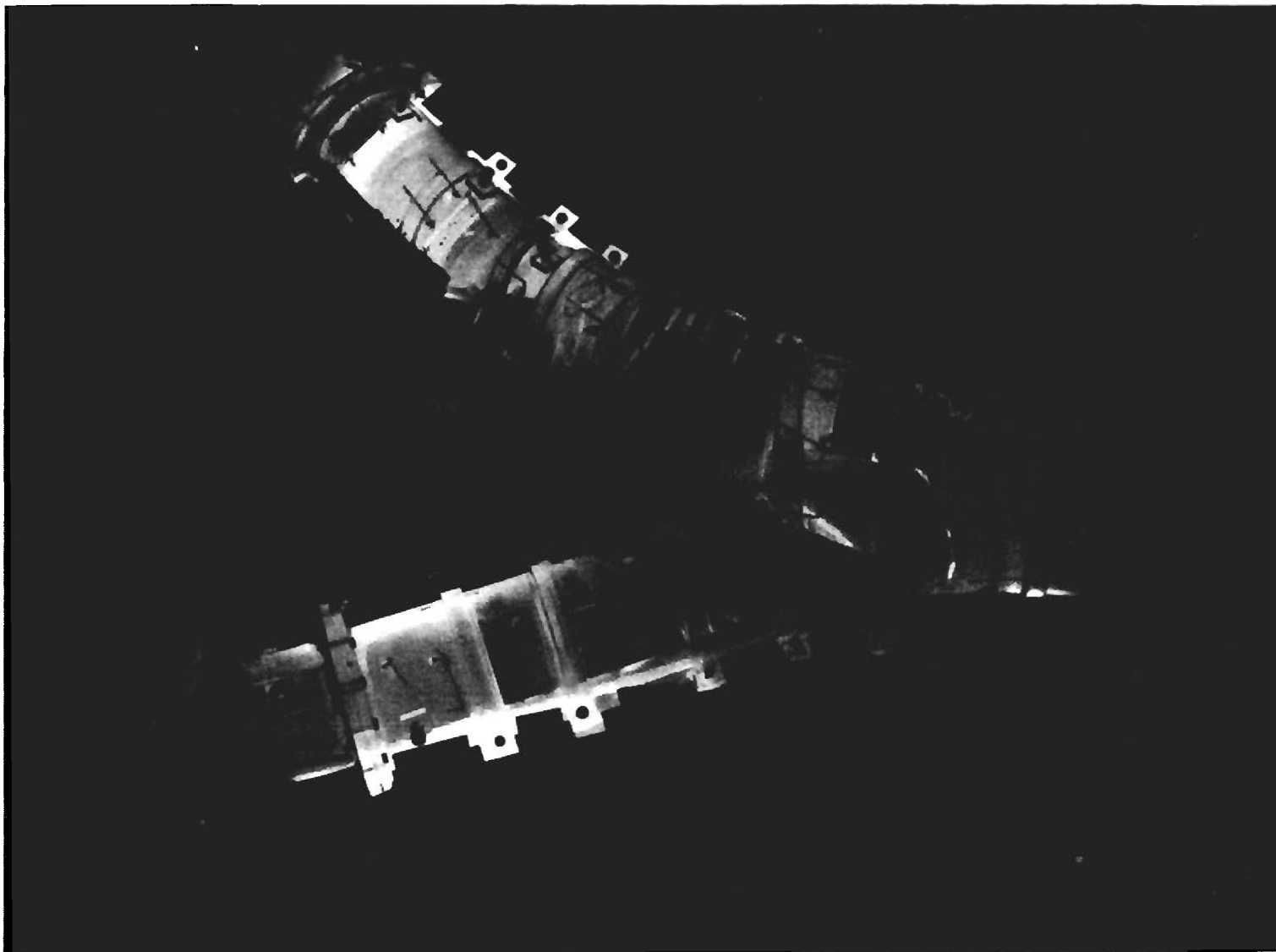
Exhibit 69. View of Tuft Pattern in Trunk of Scheme A-1 for
Units 1 and 2 Generating.
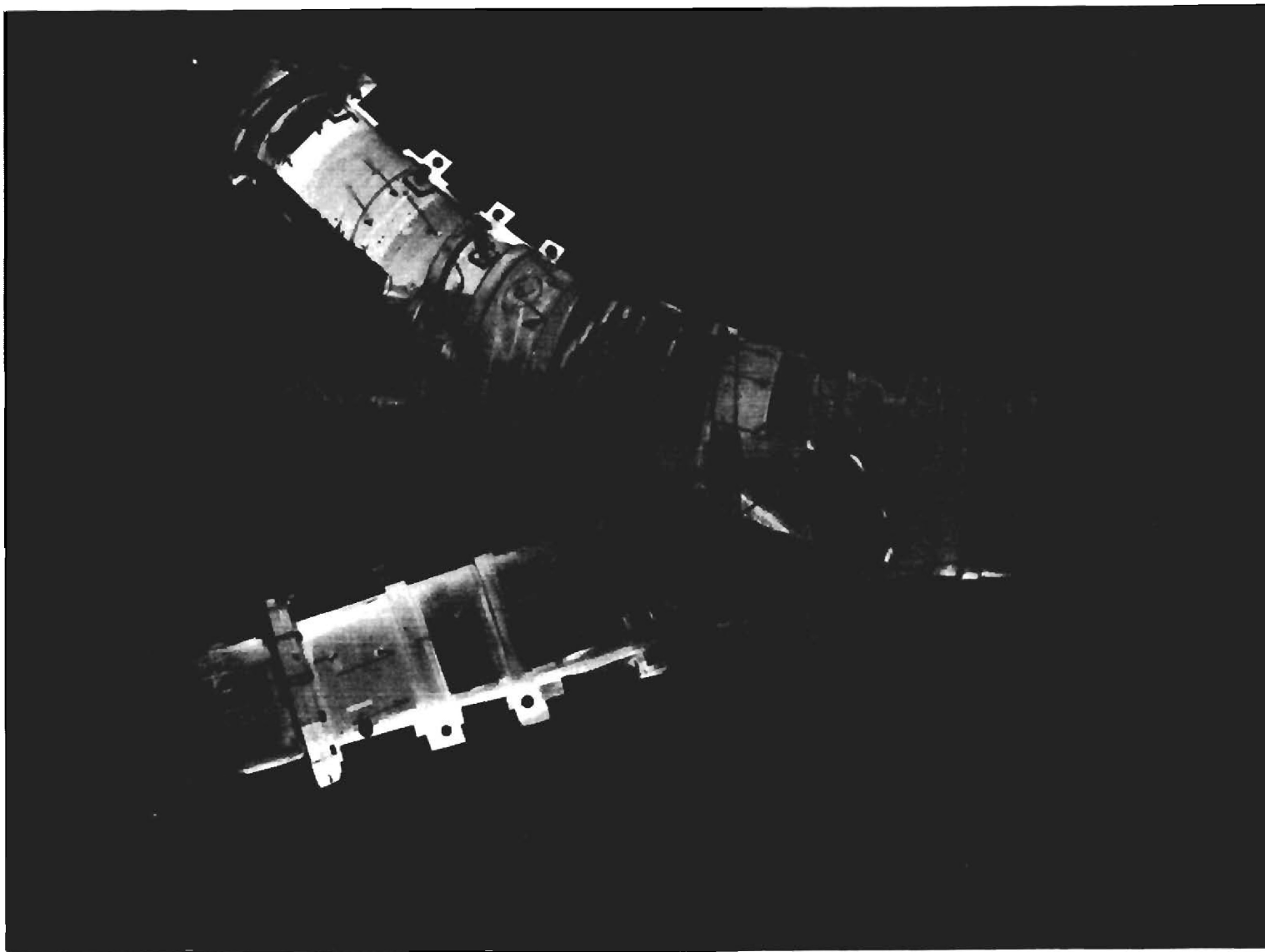
Exhibit 70. View of Tuft Pattern in Trunk of Scheme A-1 for
Units 1 and 3 Generating.
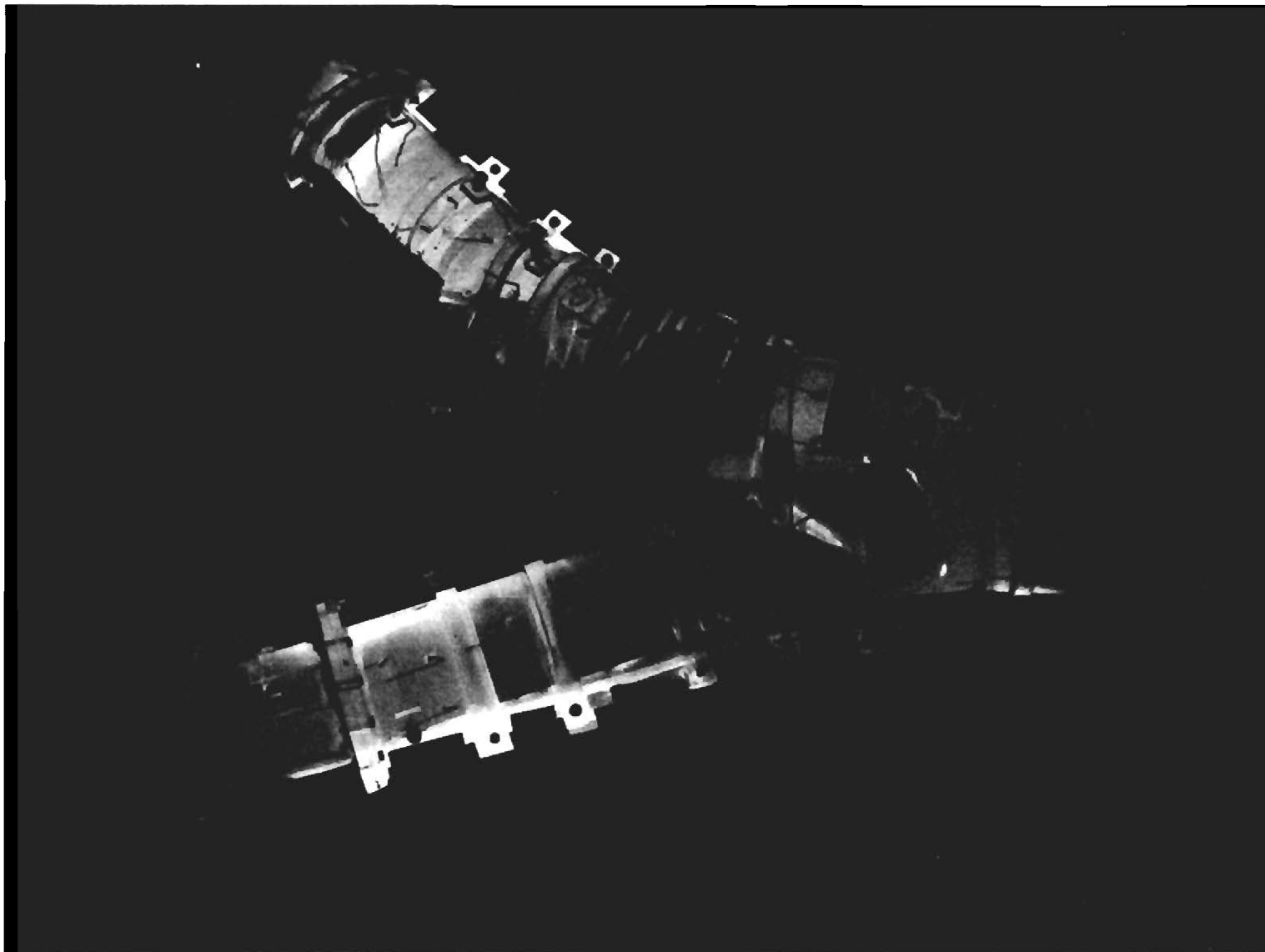
Exhibit 71. View of Tuft Pattern in Trunk of Scheme A-1 for
Units 2 and 3 Generating.
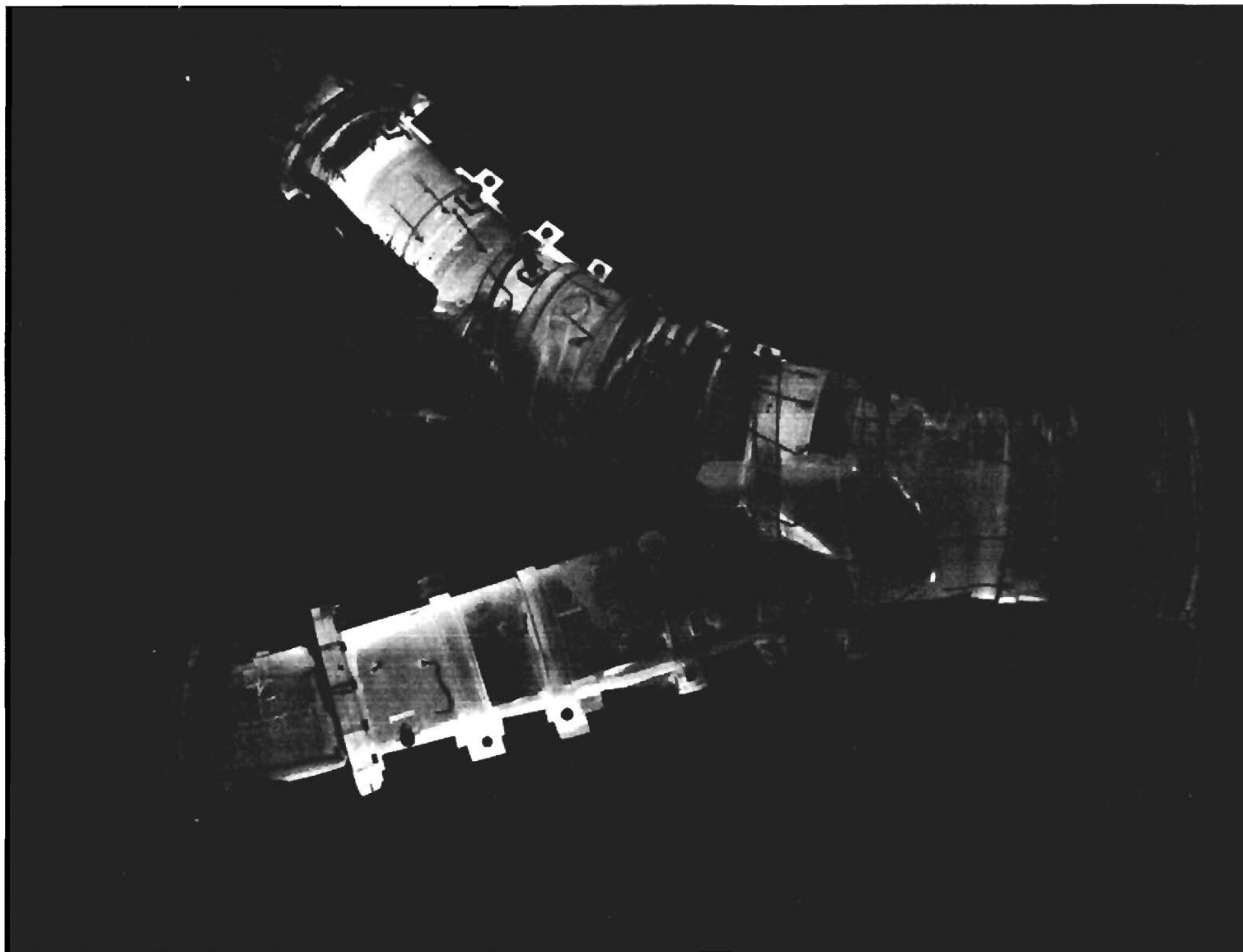
Exhibit 72. View of Tuft Pattern in Trunk of Scheme A-1 for
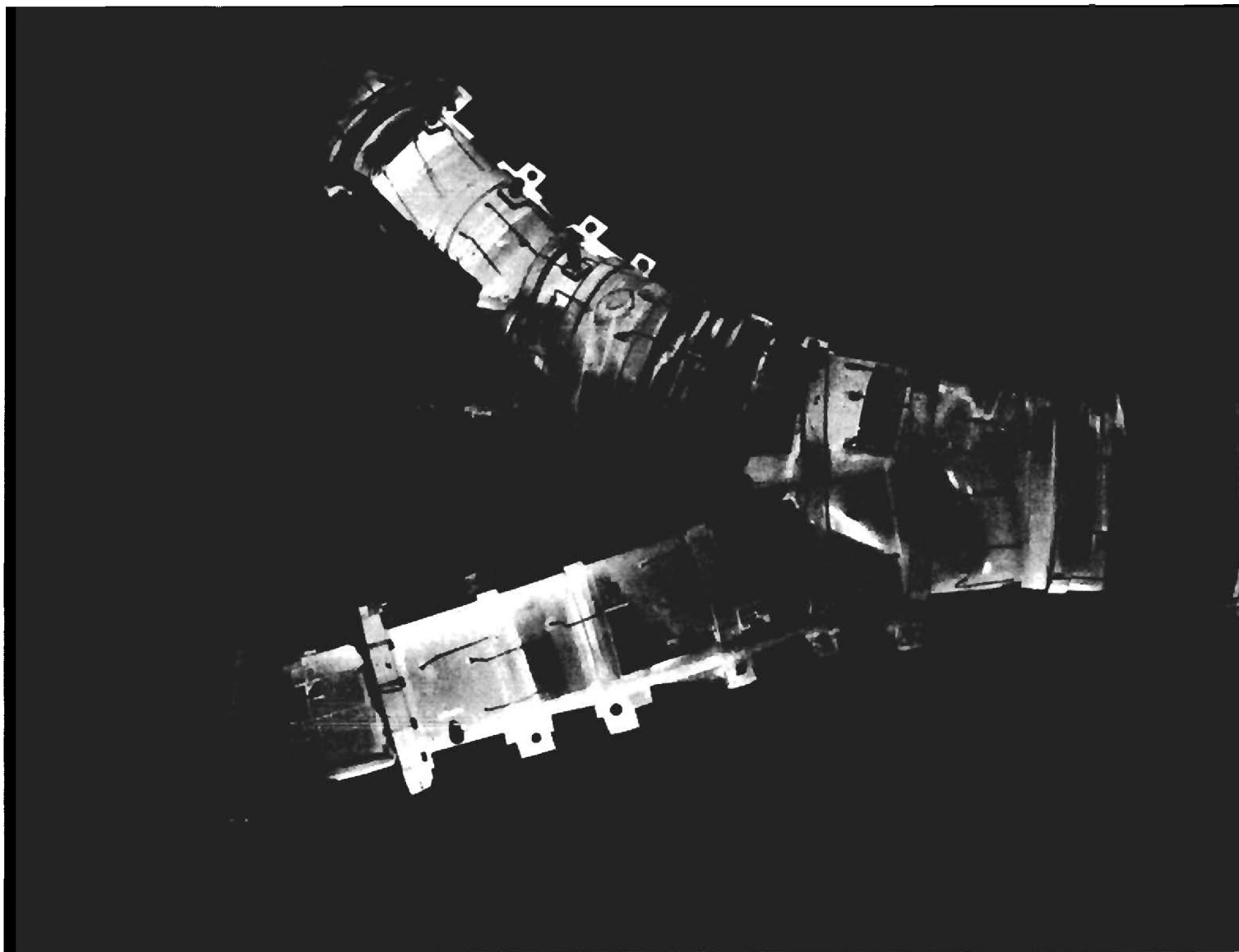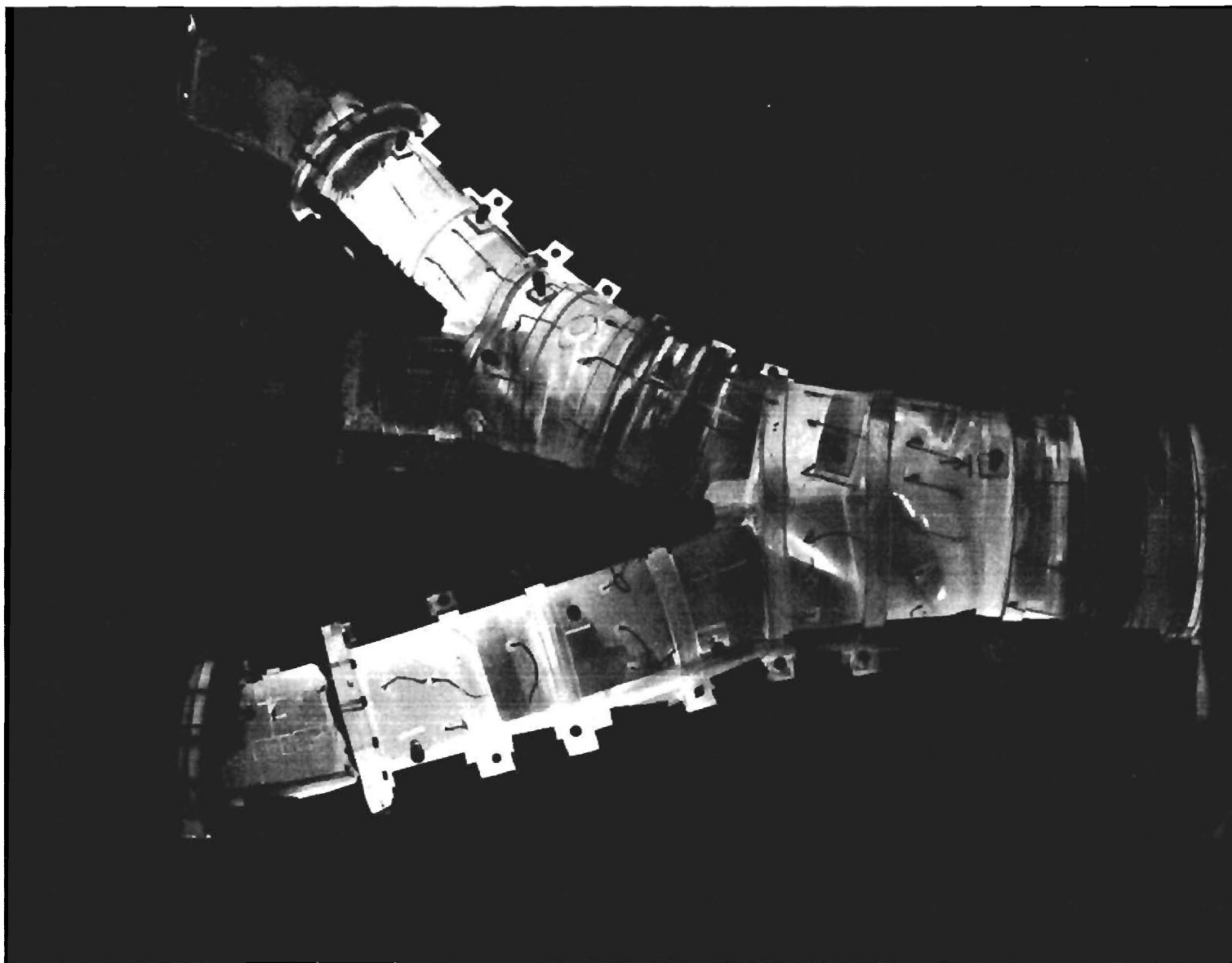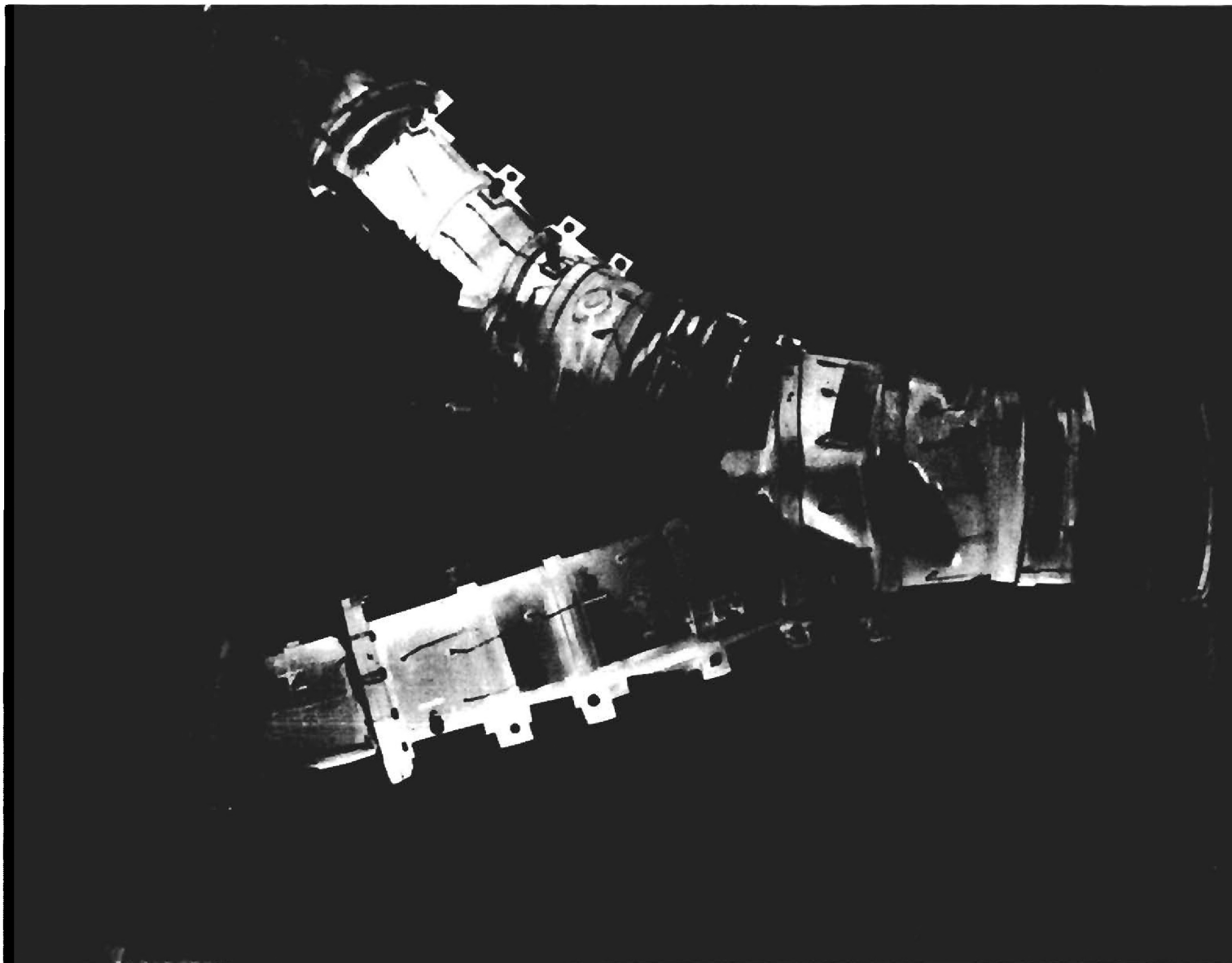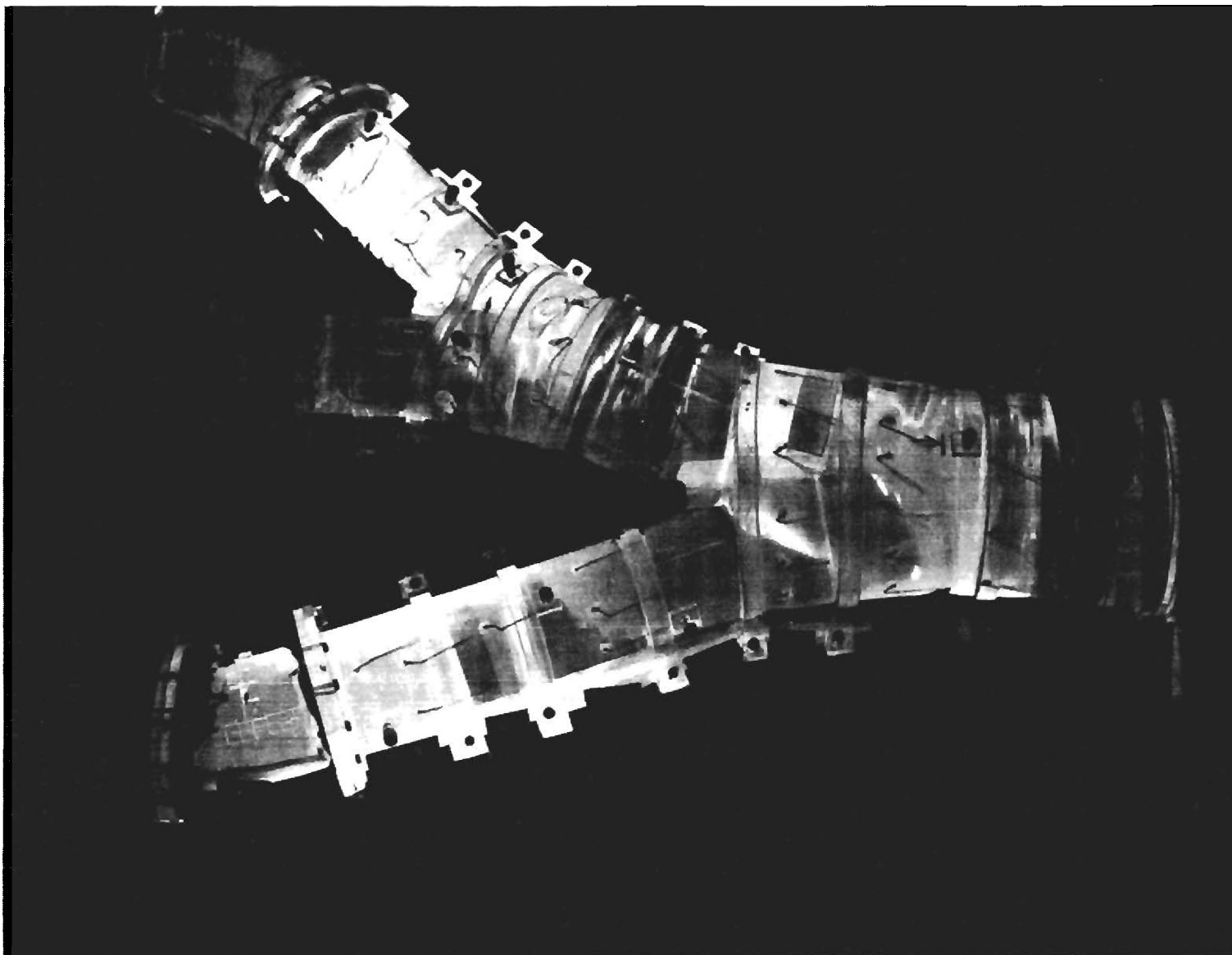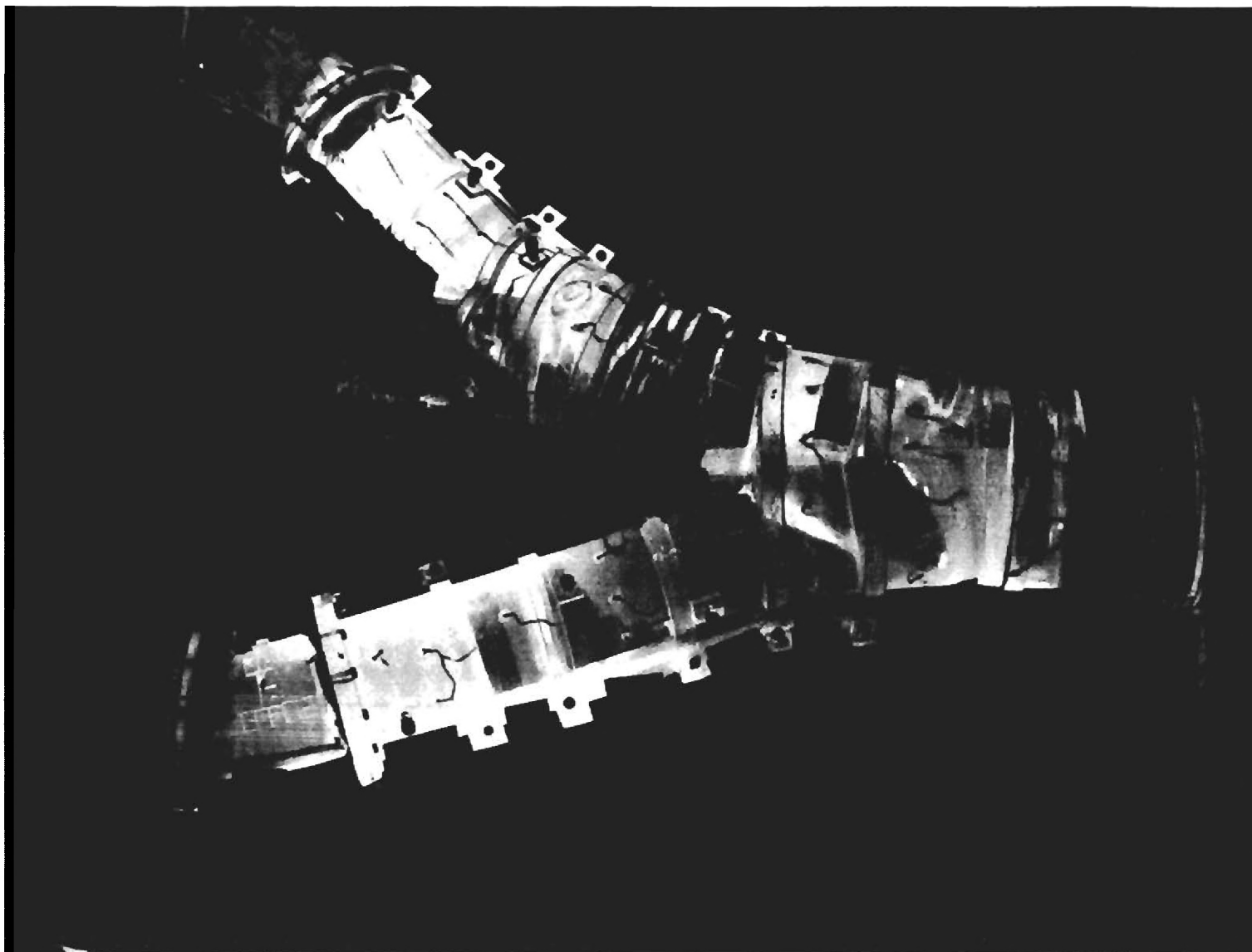Unit 1 Generating.
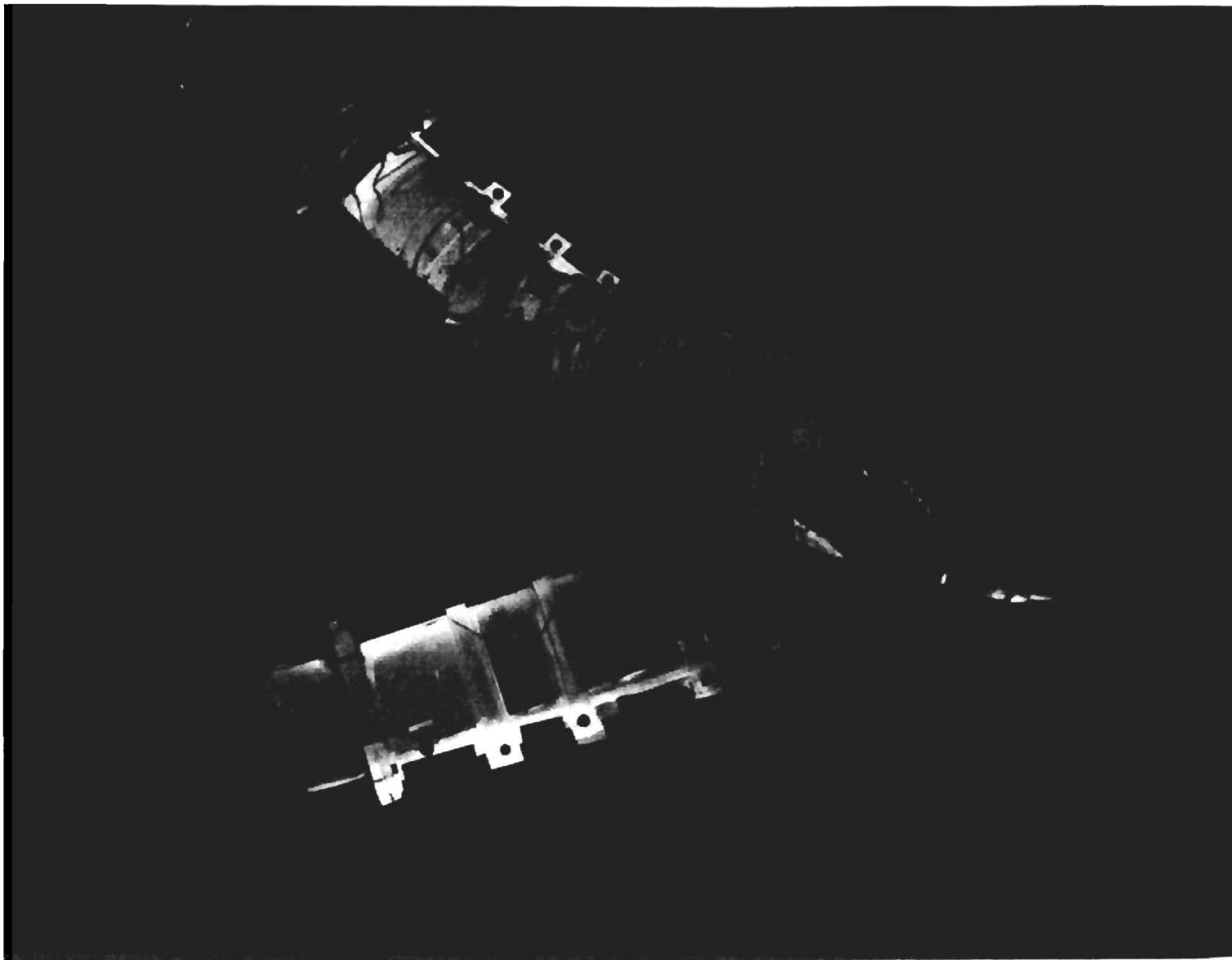
Exhibit 73. View of Tuft Pattern in Trunk of Scheme A-1 for
Unit 2 Generating.
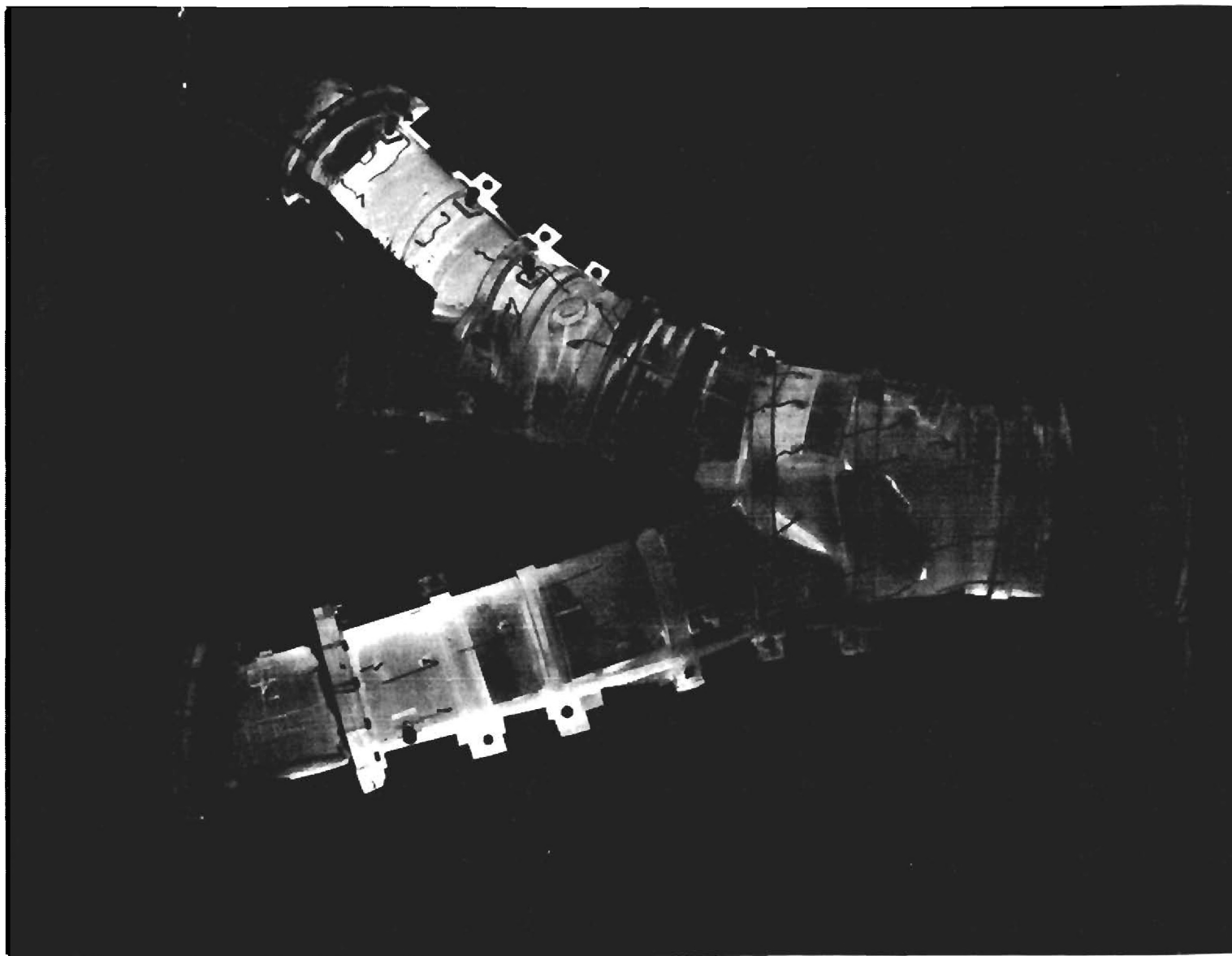
Exhibit 74.   View of Tuft Pattern in Trunk of Scheme A-1 for
Unit 3 Generating.

Exhibit 75.   View of Tuft Pattern in Trunk of Scheme A-1 for
Three Units Pumping.

Exhibit 76. View of Tuft Pattern in Trunk of Scheme A-1 for
Units 1 and 2 Pumping.

Exhibit 77.   View of Tuft Pattern in Trunk of Scheme A-1 for
Units 1 and 3 Pumping.

Exhibit 78. View of Tuft Pattern in Trunk of Scheme A-1 for
Units 2 and 3 Pumping.

Exhibit 79.   View of Tuft Pattern in Trunk of Scheme A-1 for
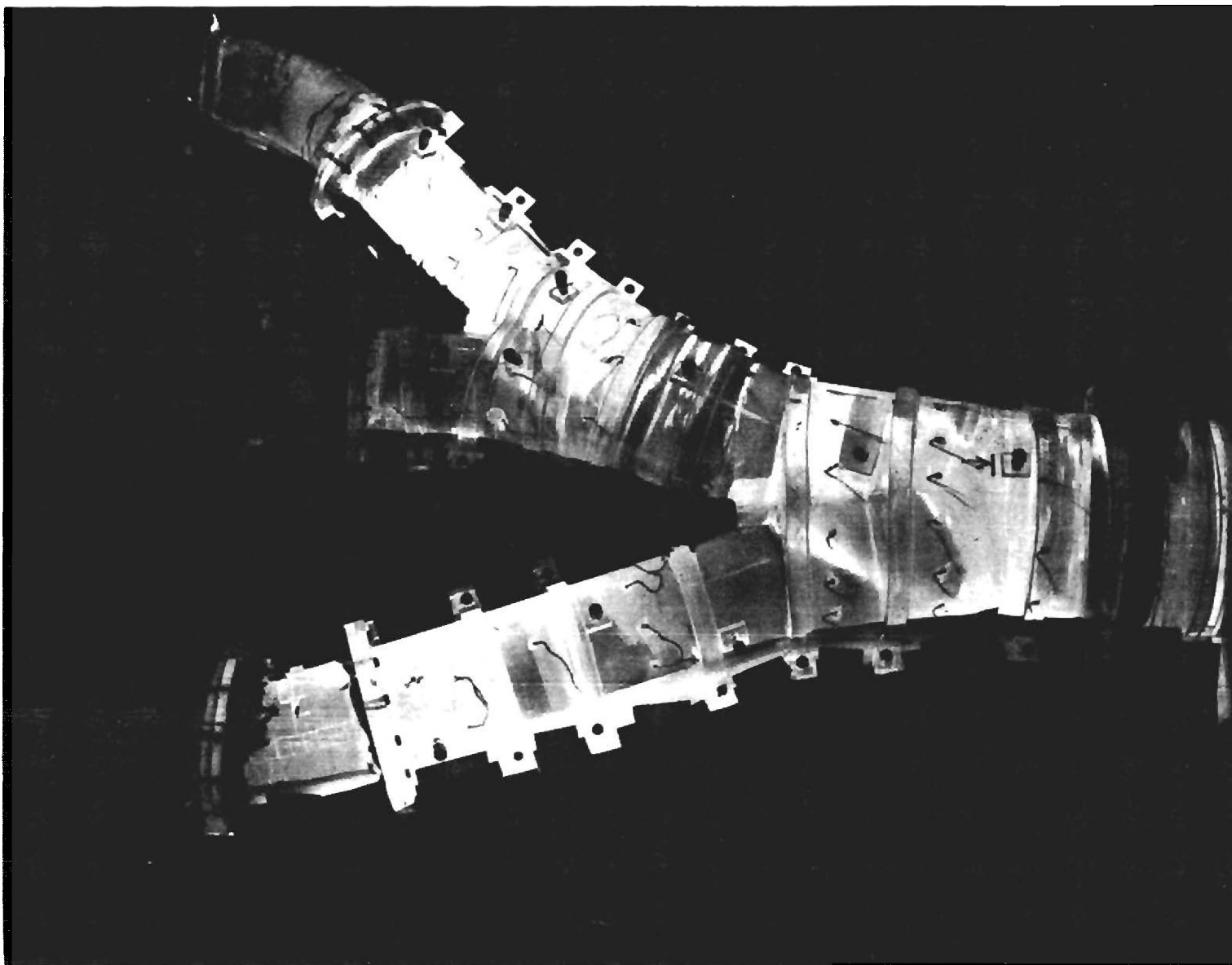   Unit 1 Pumping.

Exhibit 80.   View of Tuft Pattern in Trunk of Scheme A-1 for
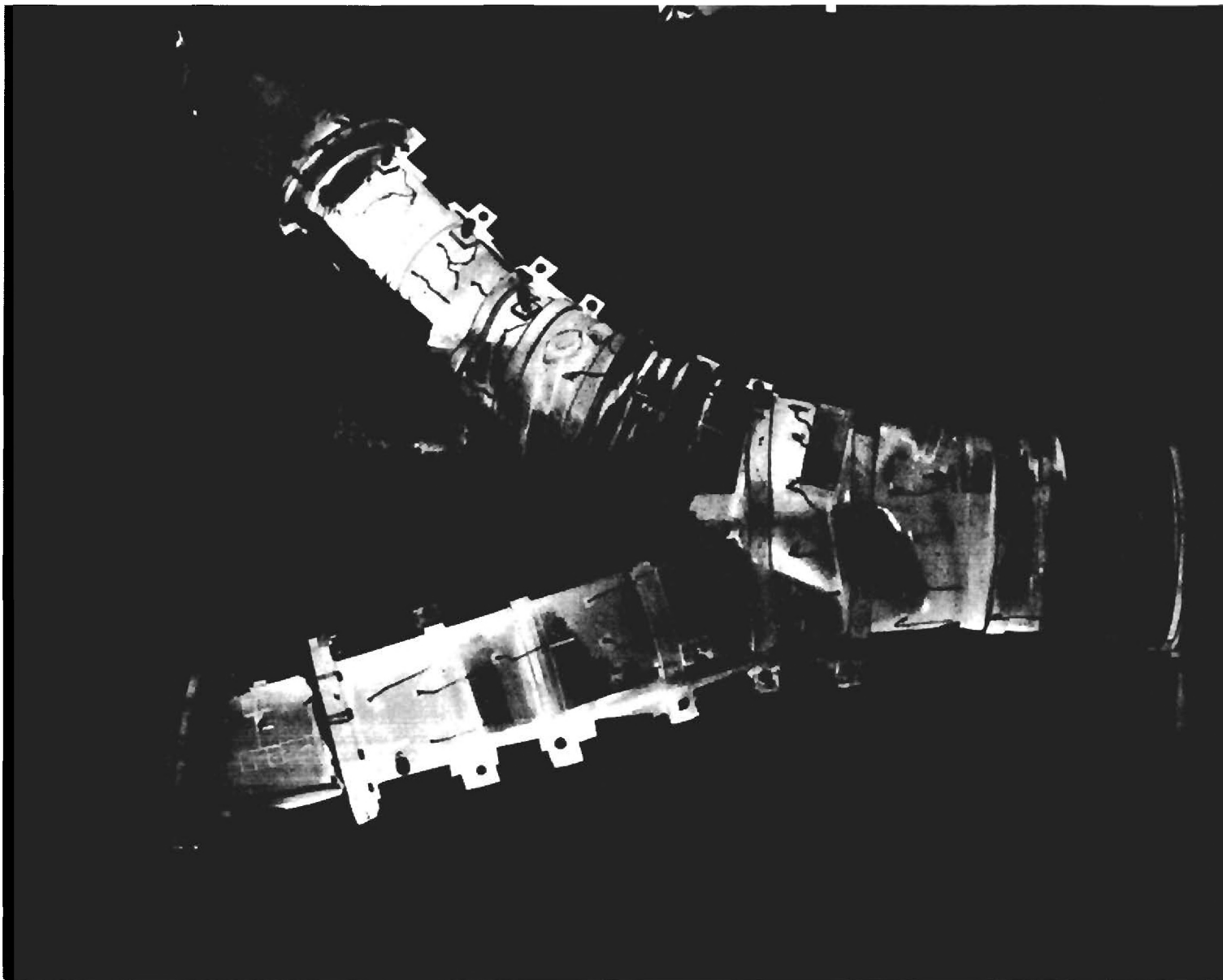Unit 2 Pumping.

Exhibit 81.   View of Tuft Pattern in Trunk Scheme A-1 for
Unit 3 Pumping.

Table 12. Values of Relative Hydraulic Grade
Line in Trunk of A-1 Scheme.

TRUNK HYDRAULIC GRADE LINE
SCHEME A-1

UNIT 1 (cfs)	UNIT 2 (cfs)	UNIT 3 (cfs)	\#1	\#2	\#3	\#5	\#6	\#7	\#8
						PIEZOMETER NUMBER			

PUMPING MODE

9750	9690	10010	1021.8	1015.5	1020.1	1022.1	1018.8	1022.4	1021.5
12710	12820	0	1004.6	993.4	1002.0	1005.9	1000.7	1006.3	1013.2
12770	0	13170	999.0	1000.3	999.7	1011.6	1008.3	1013.2	1014.5
0	12750	13240	1002.0	999.0	1004.6	1006.6	1008.6	1010.2	1014.5
0	0	13170	989.8	989.8	989.8	989.8	989.8	989.4	991.4
0	12790	0	991.4	987.1	994.1	996.4	998.0	997.0	1000.0
12880	0	0	987.8	988.8	988.1	1001.7	997.4	1001.0	1004.0

GENERATING MODE

13260	0	0	960.4	995.4	994.7	998.0	990.4	996.0	996.4
0	13330	0	993.4	955.1	985.2	997.4	989.8	995.1	995.7
0	0	13440	997.4	997.4	997.4	953.1	997.0	996.7	995.7
0	13440	13420	990.4	954.8	984.5	955.8	988.1	988.1	985.5
13420	13420	0	956.8	950.5	968.0	991.4	963.0	983.2	985.5
13490	0	13530	957.1	998.7	996.7	953.8	988.5	987.5	985.2
10930	10960	10980	969.3	971.3	981.9	969.0	975.3	981.2	979.5

HYDRAULIC GRADE LINE ELEVATIONS ARE IN FEET

CHAPTER VII

COMPARISON OF FOUR SCHEMES

Each of the four schemes was tested under the fourteen test cases

listed in Table 1. For all of the schemes head loss coefficients were

determined from the direct measurement of piezometric head in the straight

legs of the comprehensive model, and flow patterns in the trunk and penstocks

were observed. In addition, with the exception of Case C-1 the pressure

distribution in the trunks of the bifurcation models was measured. The

most useful comparison of the various schemes is that of head loss coeffi-

cients. In general the comparison of flow patterns from scheme to scheme

for the same operating condition would result in virtually the same

conclusion, that is, one scheme is deemed better than the other.

Table 13 has been prepared to allow for the comparison of the rela-

tive loss coefficients for the various schemes. For multiple unit operation

the values of the loss coefficients from Tables 3, 6, 9, and 11 are

averaged to yield a single value for the particular condition. For

Modified Scheme B-1 the values reported in Table 13 for some of the genera-

ting modes will not check with those on Table 3 because there were some

additional tests that are not listed in the latter table.

In the 14 test cases Scheme A-1 was best 9 times; Scheme B-2, 3 times,

Modified B-1 once, with Schemes A-1 and B-2 tied once. In the 3-unit genera-

ting mode Scheme B-2 head loss was 50 percent greater and Modified B-1 125

percent greater than Scheme A-1. In the 3-unit pumping mode Scheme B-2

head loss was 3 percent less than and Scheme Modified B-1 45 percent greater

than Scheme A-1. Overall Scheme A-1 was the best scheme.

The flow patterns observed in Scheme A-1 always appeared to have less

110

turbulence and be more streamlined than in Scheme B-2, which itself showed a considerable improvement over Modified Scheme B-1.

From a hydraulic flow pattern standpoint Scheme A-1 was the best of the four schemes tested. The improvement was principally a result of (1) more gradual transitions from penstocks to trunks and (2) the absence of the elbow, and (3) the manner in which the flow was divided off the trunk to the penstocks, and vice versa.

TABLE 13

COMPARISON OF PERFORMANCE OF SCHEMES

A-1, B-1, B-2, AND C-1

BASED ON RELATIVE LOSS COEFFICIENTS K_R

MODE	A-1	MODIFIED B-1	B-2	C-1	Least Head Loss Scheme
Three Units Generating	0.22	0.50	0.33	0.55	A-1
Units 1 and 2 Generating	0.24	0.38	0.29	0.57	A-1
Units 1 and 3 Generating	0.27	0.42	0.29	0.53	A-1
Units 2 and 3 Generating	0.21	0.42	0.23	0.67	A-1
Unit 1 Generating	0.27	0.34	0.33	0.63	A-1
Unit 2 Generating	0.15	0.30	0.18	0.63	A-1
Unit 3 Generating	0.32	0.50	0.27	0.71	B-2
Three Units Pumping	0.29	0.42	0.28	0.72	B-2
Units 1 and 2 Pumping	0.25	0.34	0.31	0.81	A-1
Units 1 and 3 Pumping	0.34	0.36	0.34	0.71	$\left(\begin{array}{c}A-1\\B-2\end{array}\right)$
Units 2 and 3 Pumping	0.30	0.46	0.34	0.77	A-1
Unit 1 Pumping	0.35	0.31	0.46	0.79	B-1
Unit 2 Pumping	0.44	0.48	0.37	0.83	B-2
Unit 3 Pumping	0.42	0.74	0.49	0.89	A-1

PERFORMANCE OF ELBOW BETWEEN
VERTICAL SHAFT AND TUNNEL

For each test of the four schemes investigated the complete set of
values of the HGL in the vertical shaft and the tunnel allowed for the
determination of the elbow loss coefficient K_L defined by Eq. (4). Because
of the difficulty in assessing the head loss H_L for the smaller flows only
data for two-unit and three-unit operation is considered. Furthermore,
the nonlinear variation of the HGL in the vertical shaft for data taken in
the pumping mode (see Exhibits 15-18, 35-38, 50-53, and 75-78) precluded
the determination of reliable values of K_L with flow in that direction.
The nonuniform flow downstream of the elbow did not have adequate time to
develop in the relatively short vertical shaft when flow was in the pumping
mode. In contrast the straightening varies in the upper elbow enhanced flow
development in the shaft when operation was in the generating mode.
Moreover, in the generating mode flow development in the tunnel was greatly
augmented by the much longer conduit.

Elbow loss coefficients for the pumping mode will not be considered
in the analysis or discussion because of the reasons just cited.

For flow in the generating mode the elbow loss coefficients are as
follows:

K_L

Units Operating	Modified B-1	Scheme B-2	C-1	A-1	Average
1 and 2	0.14	0.20	0.18	0.17	0.17
1 and 3	0.19	0.17	0.20	0.21	0.19
2 and 3	0.17	0.16	0.20	0.18	0.18
1, 2, and 3	0.15	0.17	0.18	0.15	0.16
Average	0.16	0.18	0.19	0.18	0.18

The overall average value of K_L is 0.18, compared with a value of 0.12 used in the actual design of the units. The standard deviation of the data listed above is 0.02. Previous laboratory investigations at the University of Munich by Hofmann and Wasielewski and in Japan by $\overline{\text{Ito}}$, who thoroughly summarized the German work, consistently yielded values of $K_L = 0.19$ for 90° elbows with a ratio of radius of curvature to pipe diameter $r/D = 3.3$. The maximum Reynolds number attained in the Japanese test program was approximately 325,000, corresponding to a range of 200,000 to 270,000 for the model study, for which the ratio of radius of curvature to tunnel diameter $r/D = 95/33 = 2.88$.

The results of the three laboratory investigations suggest that $K_L = 0.18$ to 0.19 for 90° elbows, for which $r/D \sim 3$ and the model Reynolds number is approximately 250,000. Even for the much greater prototype Reynolds number of approximately 58,000,000 the elbow loss coefficient would not be expected to be as low as 0.12.

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

Based upon the numerous tests conducted for the four schemes the average head-loss coefficient for the long-radius elbow at the base of the vertical shaft was found to be 0.18.

Based upon head-loss measurements and flow visualization in the trunk of the bifurcation portion of the model Scheme A-1 was overall the best scheme tested. The flow patterns observed in Scheme A-1 always appeared to possess less turbulence than in the other schemes, which in descending order of performance were B-1, Modified B-1, and C-1. It is believed that Scheme A-1 outperformed the others because of (1) more gradual transitions between trunk and penstocks, (2) the absence of the elbow, and (3) the manner in which the flow was divided from trunk to penstocks.

On the basis of the extensive model study results, Scheme A-1 is recommended as having the lowest overall hydraulic losses and the best hydraulic performance.

APPENDIX

The detailed design drawings of Schemes B-1 Modified, B-2, and A-1

are shown in Exhibits 82, 83, and 84, respectively. For purposes of

comparison scaled-up cross sections of the as built model are also indi-

cated on the exhibits. The greatest deviation between design and model

construction occurred for Scheme B-1 Modified, as mentioned previously in

the text.

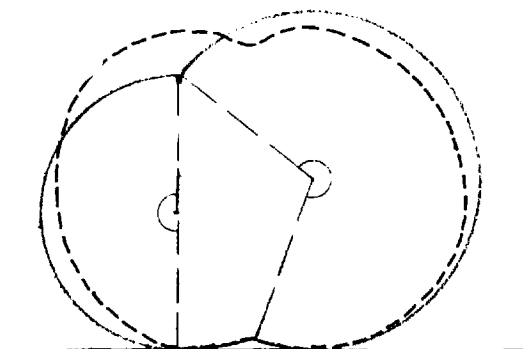Exhibit 82. Design Drawings and Model Cross Sections
for Modified Scheme B-1.
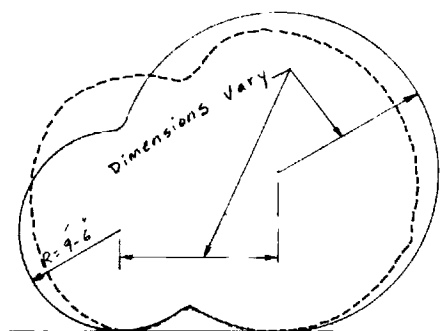
SECTION A-A
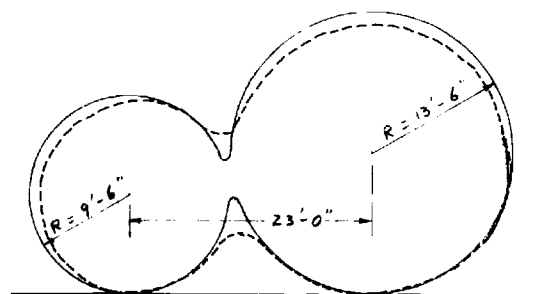
SECTION B-B
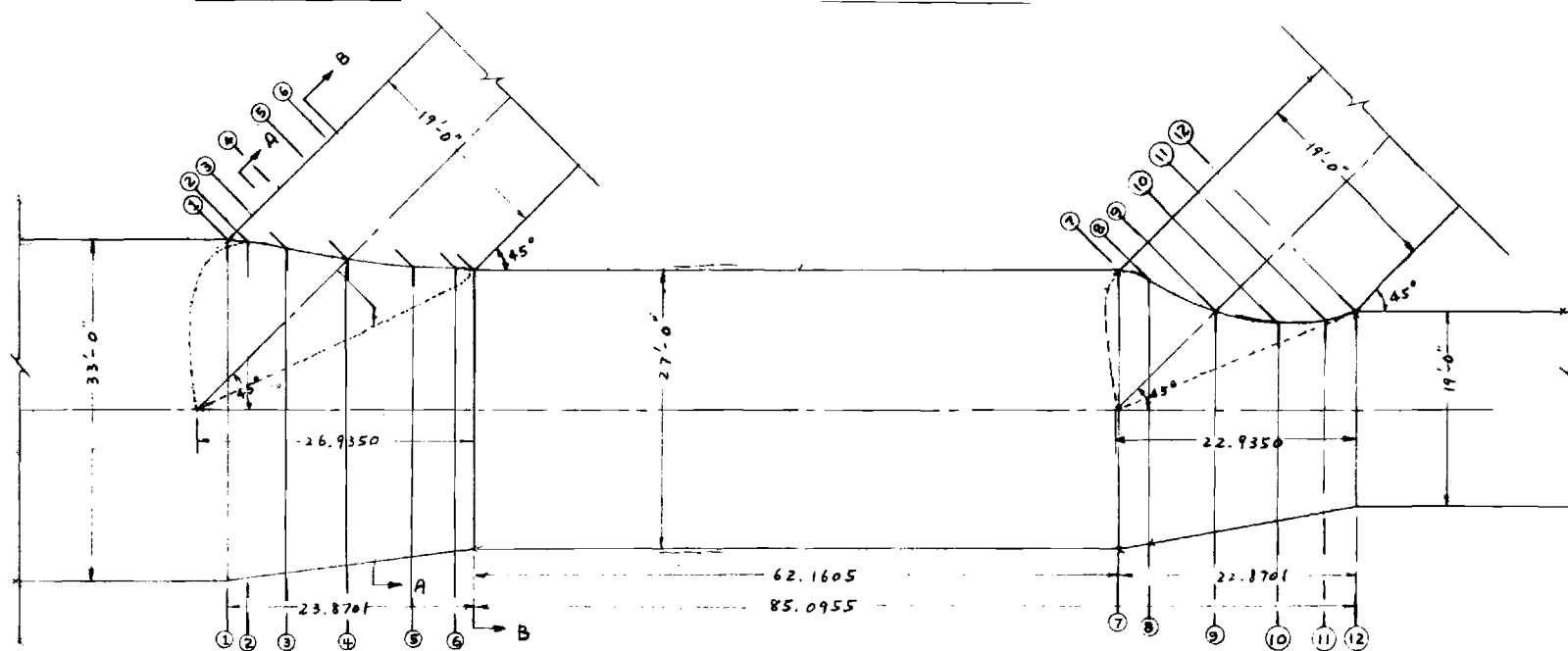
Exhibit 82.(Contd.) Design Drawings and Model Cross Sections
for Modified Scheme B-1.

——————— DESIGN
– – – – MODEL AS BUILT

See note

① — ①   ② — ②   ③ — ③

④ — ④   ⑤ — ⑤   ⑥ — ⑥

See note

Exhibit 82.(Contd.)   Design Drawings and Model Cross Sections
for Modified Scheme B-1.

———— DESIGN
— — — MODEL AS BUILT

119

7 — 7

8 — 8

9 — 9

10 — 10

11 — 11

12 — 12
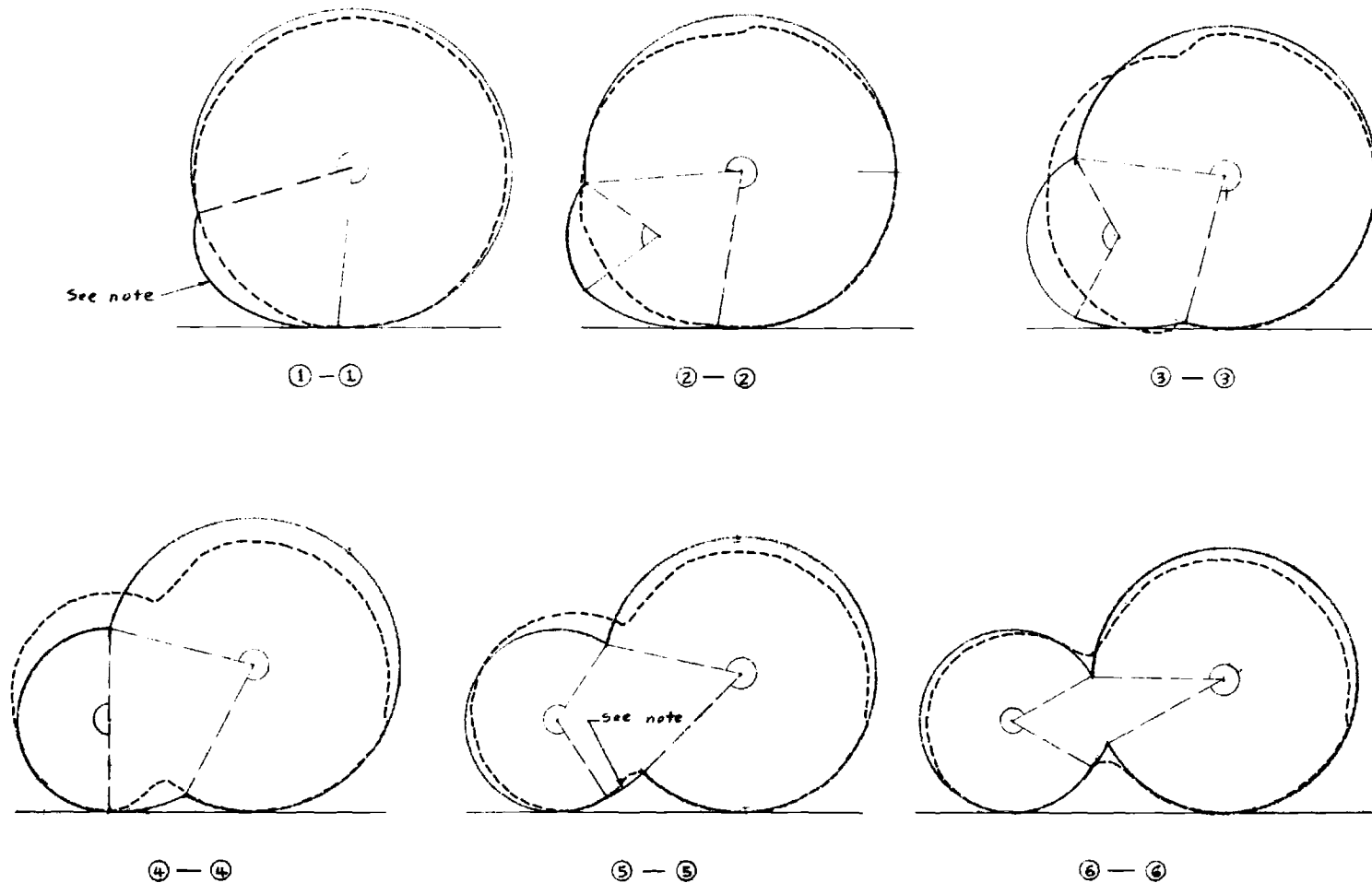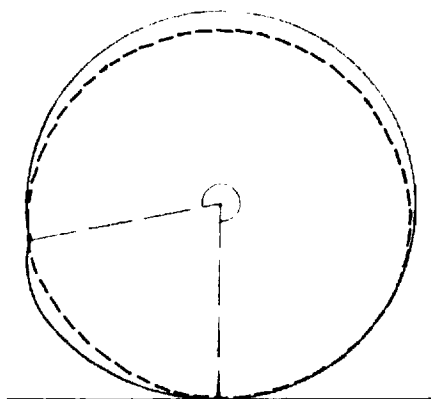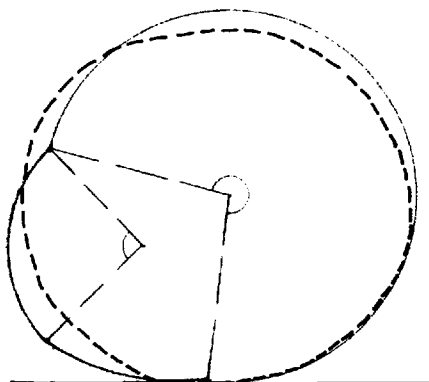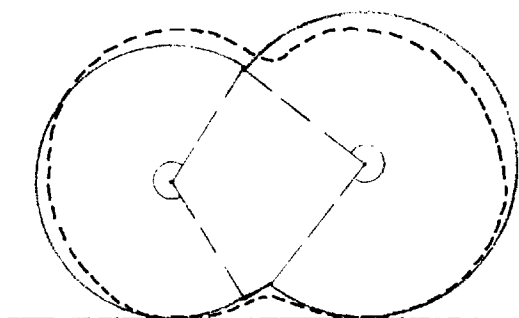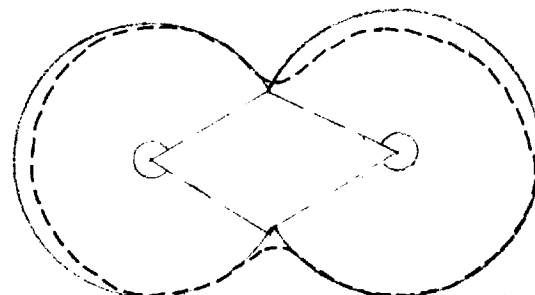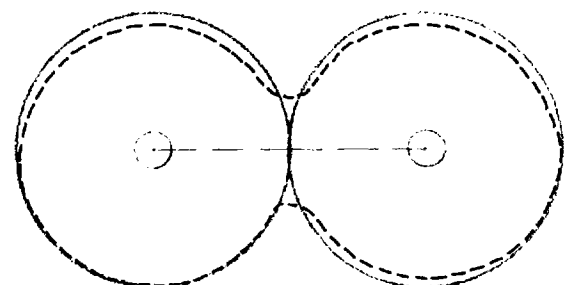
Exhibit 82.(Contd.) Design Drawings and Model Cross Sections
for Modified Scheme B-1.

DESIGN
MODEL AS BUILT

Exhibit 83. Design Drawings and Model Cross Sections
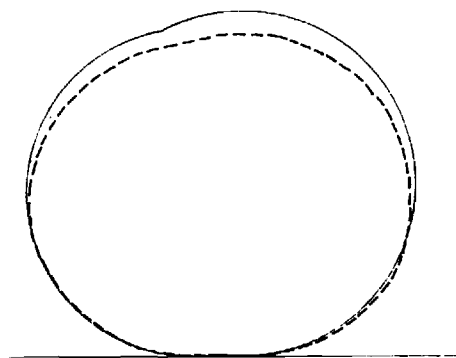for Scheme B-2.

SECTION A-A
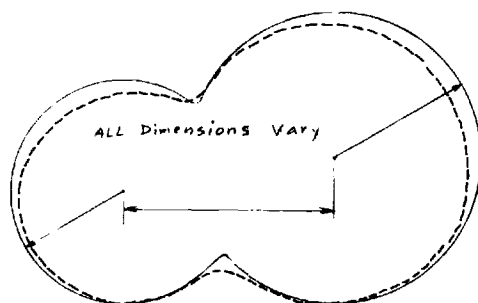
SECTION B-B
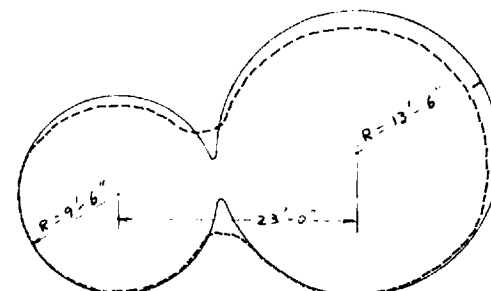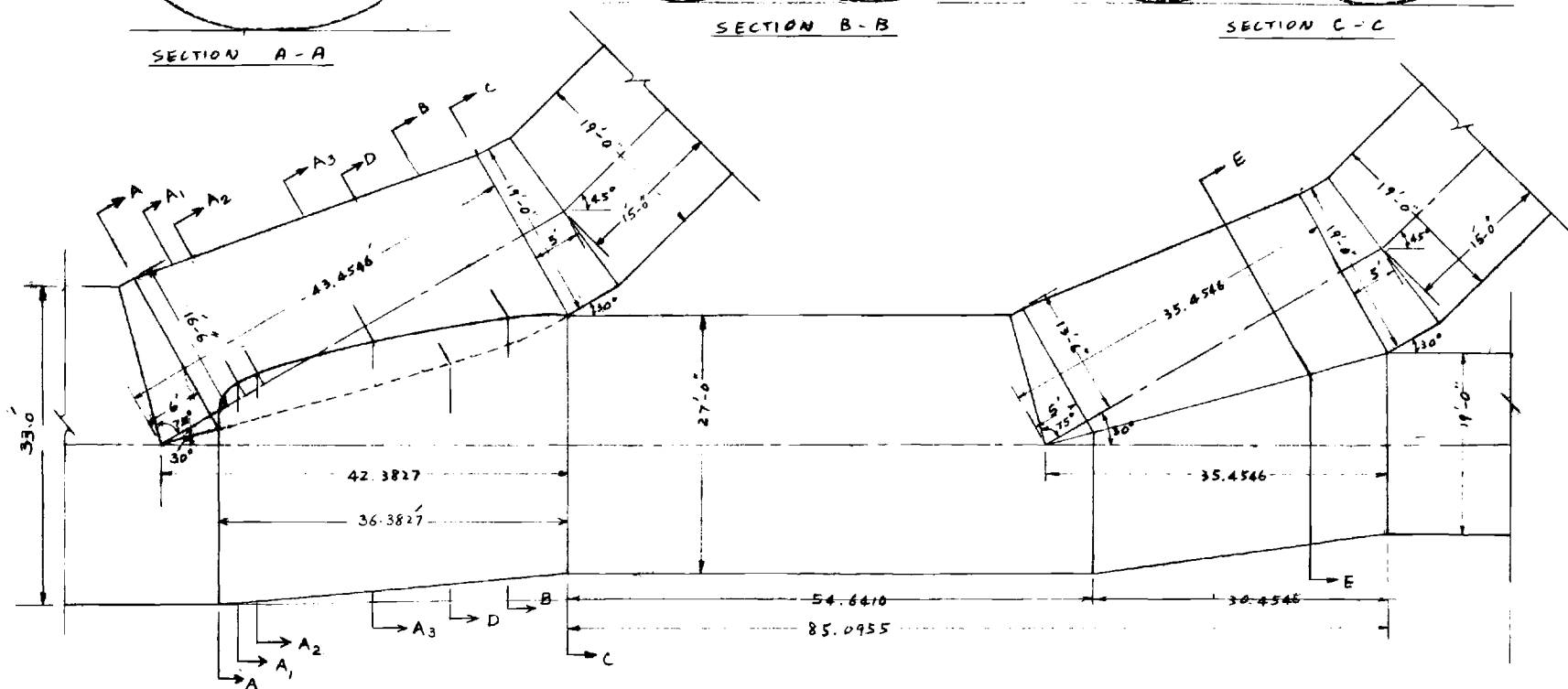
ALL Dimensions Vary

SECTION C-C
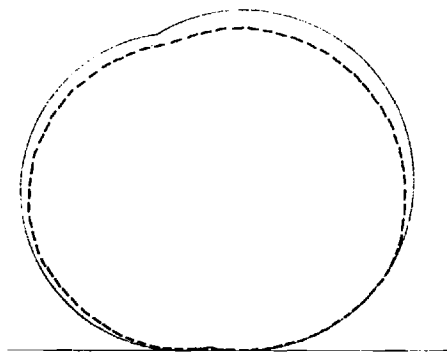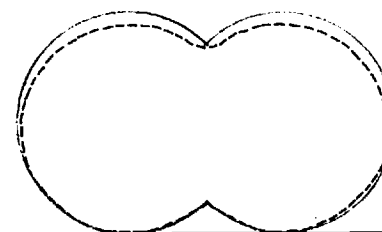
R=16'-6"

R=16'-6"

1.6077'

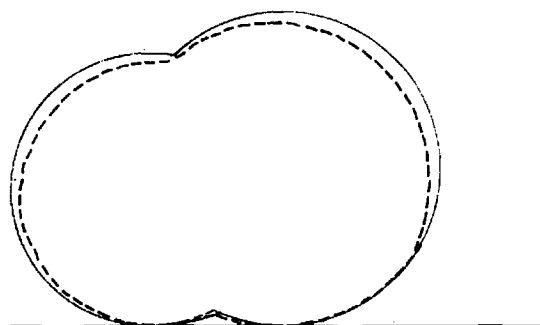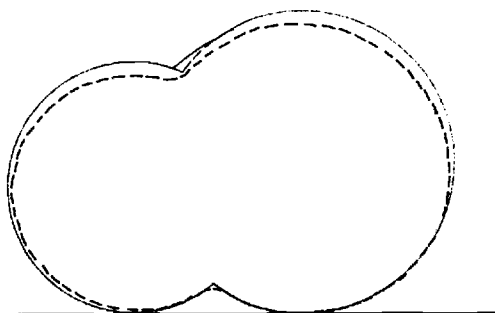R=9'-6"

R=13'-6"

23'-0"

Exhibit 83.(Contd.)   Design Drawings and Model Cross Sections
for Scheme B-2.

——— DESIGN
– – – MODEL AS BUILT

SECTION A_1-A_1

SECTION A_2-A_2

SECTION $E-E$

SECTION A_3-A_3

SECTION $D-D$

Exhibit 83.(Contd.)   Design Drawings and Model Cross Sections
for Scheme B-2.

——— DESIGN
– – – – MODEL AS BUILT

Exhibit 84. Design Drawings and Model Cross Sections for Scheme A-1.

Exhibit 84.(Contd.) Design Drawings and Model Cross
Sections for Scheme A-1.
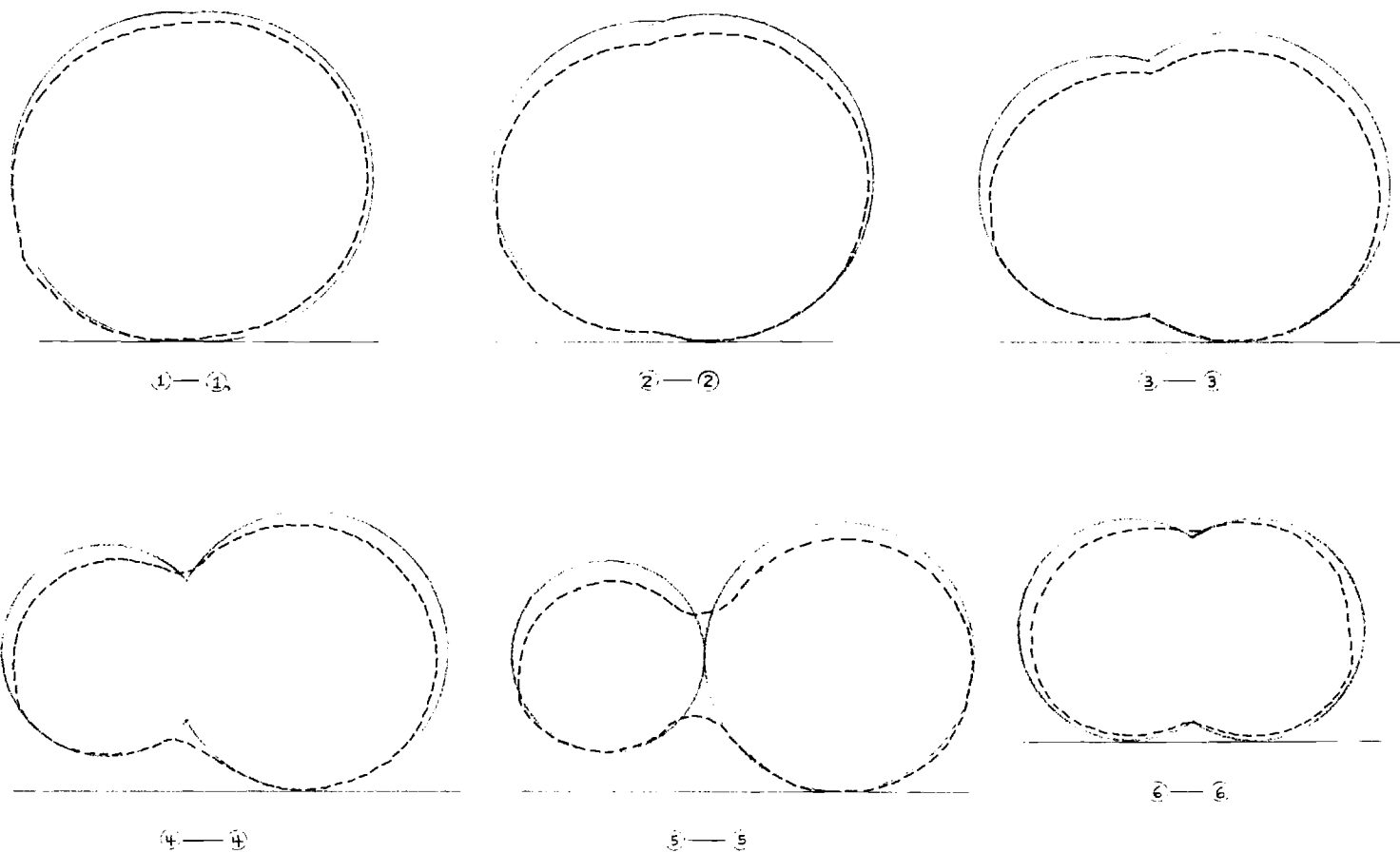
———— DESIGN
– – – – MODEL AS BUILT

Exhibit 84.(Contd.) Design Drawings and Model Cross
Sections for Scheme A-1.

——— DESIGN
– – – MODEL AS BUILT