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TECHNICAL REPORT NO. 2-739

FILLING AND EMPTYING SYSTEM CORDELL HULL NAVIGATION LOCK CUMBERLAND RIVER, TENNESSEE

Hydraulic Model Investigation

by

N. R. Oswalt

M. B. Boyd

CONFERENCE ROOM

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FOREWORD

The model investigation reported herein was authorized in a letter from the U. S. Army Engineer District, Nashville, to the Director, U. S. Army Engineer Waterways Experiment Station.

The study was conducted in the Hydraulics Division of the Waterways Experiment Station during the period February 1964 to February 1965 under the direction of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division. Tests were conducted by Messrs. B. C. Parker, H. H. Allen, J. O. Farrell, and N. R. Oswalt under the general supervision of Messrs. J. H. Ables, Jr., M. B. Boyd, Chief of the Locks Section, and T. E. Murphy, Chief of the Structures Branch. This report was prepared by Messrs. Oswalt and Boyd and reviewed by Mr. Murphy.

During the course of the study Messrs. J. P. Davis, Office, Chief of Engineers; M. E. Nelson, St. Paul District; H. P. Theus, North Pacific Division Hydraulic Laboratory; W. H. Browne, Jr., Ohio River Division; and G. O. Prados, C. H. Brown, H. T. Glenn, Jr., and John Mathewson, Nashville District, visited the Waterways Experiment Station to observe model operation and discuss test results.

Directors of the Waterways Experiment Station during the conduct of the tests and preparation and publication of this report were Col. Alex G. Sutton, Jr., CE, and Col. John R. Oswalt, Jr., CE. Technical Director was Mr. J. B. Tiffany.

CONTENTS

SUMMARY

Cordell Hull Lock, located on the Cumberland River near Carthage, Tenn., 313.5 miles above its junction with the Ohio River, will be 84 ft wide by 450 ft long and will have a normal lift of 59 ft with a maximum lift of 62 ft occurring about 5 percent of the time. The model study (scale 1:25) of the filling and emptying system proposed for this lock was confined to the portion of the hydraulic system between the filling and emptying valves.

Performance of the type 1 (original) multiport arrangement was, in general, satisfactory even though it was evident from test results that certain improvements could be made in the system. The lock chamber manifold includes three horizontal rows of seventy-two 8-in.-diam ports resulting in an overall port-to-culvert area ratio of 0.75 based on the culvert area at the valves. The manifold extends over 48 percent of the chamber length and is centered about 3.9 percent of the chamber length upstream from the midpoint of the chamber. The ports discharge into a 3-ft-wide by 6.5-ft-deep trench along the toe of the lock wall. With this system the lock can be filled in 11.0 min (4-min valve) and emptied in 11.2 min (1.5-min valve) with acceptable hawser stresses and turbulence conditions in the chamber. Consideration of the performance of the system and construction schedules at the project resulted in its adoption for use at the Cordell Hull project.

Additional tests of the multiport system were conducted since this type of system was under consideration for use at another project. These tests resulted in the following suggestions for improvements in the system.

- a. Flow distribution from the multiport manifold can be improved by separating the manifold and the filling valves by at least 60 ft.

- b. The port-to-culvert area ratio can be increased to 0.95 (based on the area of the culvert at the valve) to permit faster filling and emptying without adversely affecting operating characteristics.

- c. Pressure conditions downstream from the filling valves can be improved by using an alternate transition design.

d. Admission of small quantities of air in the low-pressure region at the filling valves should minimize possible cavitation damage.

Multiport manifolds composed of two rows of 10- or 12-in.-diam ports or one row of 14-in.-diam ports also were tested. Satisfactory arrangements were developed using 10- and 12-in.-diam ports. No satisfactory arrangement of 14-in. ports was developed because of the sensitivity of the relative position of the ports and the lock chamber floor.

Port arrangements in which conventional sidewall ports discharged into a trench at the toe of the lock wall were also investigated. The performance of these arrangements did not compare favorably with that of the better multiport arrangements.

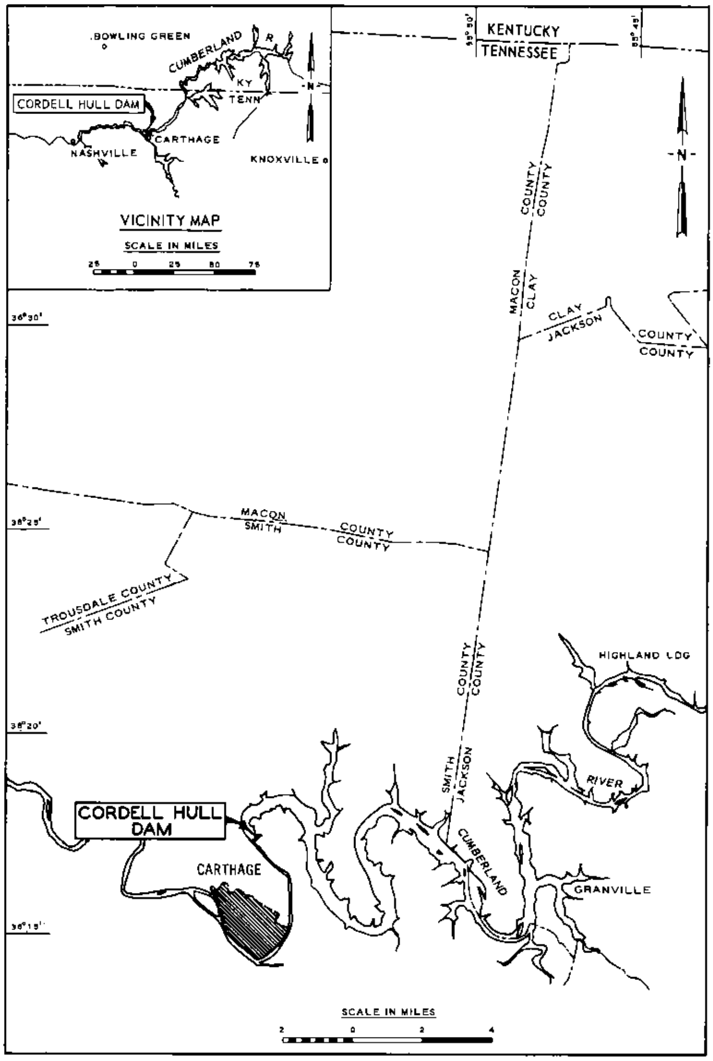

Fig. 1. Location map

FILLING AND EMPTYING SYSTEM, CORDELL HULL NAVIGATION LOCK
CUMBERLAND RIVER, TENNESSEE

Hydraulic Model Investigation

PART I: INTRODUCTION

The Prototype

Location

1. Cordell Hull Lock and Dam is one feature of the comprehensive plan for development of the Cumberland River Basin. The project is located on the Cumberland River near Carthage, Tenn., 313.5 miles above its junction with the Ohio River (fig. 1). It will extend the canalization of the Cumberland River an additional 72.2 miles to the proposed Celina Lock and Dam at mile 385.7.

Project features

2. The plan for the Cordell Hull project is shown in plate 1. The powerhouse is located in the main channel near the right bank. Adjacent to the powerhouse is a gated spillway having an overall length of 275 ft with the crest at elevation 464.5;* flow through the spillway will be regulated by five tainter gates, each 45 ft long and 41 ft high. The navigation lock is located next to the spillway in the left overbank area with an earth embankment forming the damming surface between the lock and natural ground on the north.

3. The lock will be 84 ft wide and have a usable length of 400 ft; total length, pintle to pintle, will be 450 ft. The tops of the chamber walls and upstream guide walls will be at elevation 512.0, and the tops of the downstream guide and guard walls at elevation 480.0. The upper and lower sills will be at elevations 485.0 and 429.0, respectively. Normal upper and lower pool elevations will be 504.0 and 445.0, respectively, resulting in a lift of 59 ft; minimum lower pool elevation

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* All elevations are in feet referred to mean sea level.

(occurring about 5 percent of the time) will be 442.0, resulting in a maximum lift of 62 ft.

4. A multiport filling and emptying system developed by the Tennessee Valley Authority (TVA) was proposed for use at the Cordell Hull Lock. Selection of this type of system was based on the following considerations. At the lock site, rock is encountered at a relatively high elevation. Consequently, excavation to provide the submergence needed to obtain satisfactory performance with a conventional sidewall port system would be very costly. Similarly, excavation for floor culverts in a bottom lateral system would be expensive. Also, observations of prototype lock operations at two projects, Old Hickory and Melton Hill (TVA), which have similar lift-submergence conditions, indicated that the multiport system used at Melton Hill resulted in more satisfactory performance than the conventional sidewall port system used at Old Hickory. Details of the multiport filling and emptying system proposed for Cordell Hull Lock are shown in plate 2.

Purpose of Model Study

5. The model study was authorized to verify the adequacy of the proposed multiport filling and emptying system for Cordell Hull Lock. After initiation of the study, the test program was expanded to include additional generalized testing of the multiport system. The test program was designed primarily to provide information on:

a. The optimum number, size, and arrangement of ports.

b. Pressure conditions downstream from the filling valves (including evaluation of structural and operational modifications designed to improve undesirable conditions).

PART II: THE MODEL

Description

6. Established construction schedules on the Cordell Hull project allowed only a limited time for testing the lock filling and emptying system. Consequently, an existing 1:25-scale model of the Jonesville Lock* was modified to permit simulation of the portion of the proposed Cordell Hull Lock between the filling and emptying valves. The model of the 84-ft-wide by 600-ft-long Jonesville Lock included wall manifold intakes and outlets and 10- by 10-ft wall culverts which could be readily connected to the reproduced portion of the Cordell Hull Lock. The resulting model (plate 3) was considered satisfactory since the information desired from the study concerned only those elements of the system between the filling and emptying valves.

7. The lock chamber was constructed of plywood. Intake manifolds, culverts, and outlet manifolds were constructed of plexiglass, sheet metal, and wood. The multiport lock chamber manifolds were drilled in plexiglass blocks (fig. 2). Four sheet metal barges, each simulating a length of 195 ft, a width of 35 ft, and a depth of 16 ft, were used in the model tests. The barges were grouped into full (four barges) or half (two barges) tows and loaded with lead weights to produce the desired draft of 9 ft (plate 4).

Appurtenances and Instrumentation

8. Water was supplied to the model through a circulating system. Skimming weirs were used to maintain constant upper and lower pools. Vertical adjustment of the skimming weirs permitted simulation of the desired range of pool elevations. Water-surface elevations were recorded

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* U. S. Army Engineer Waterways Experiment Station, CE, Filling and Emptying System, Jonesville Lock, Ouachita-Black Rivers, Louisiana; Hydraulic Model Investigation, by N. R. Oswalt and others, Technical Report No. 2-678 (Vicksburg, Miss., June 1965).

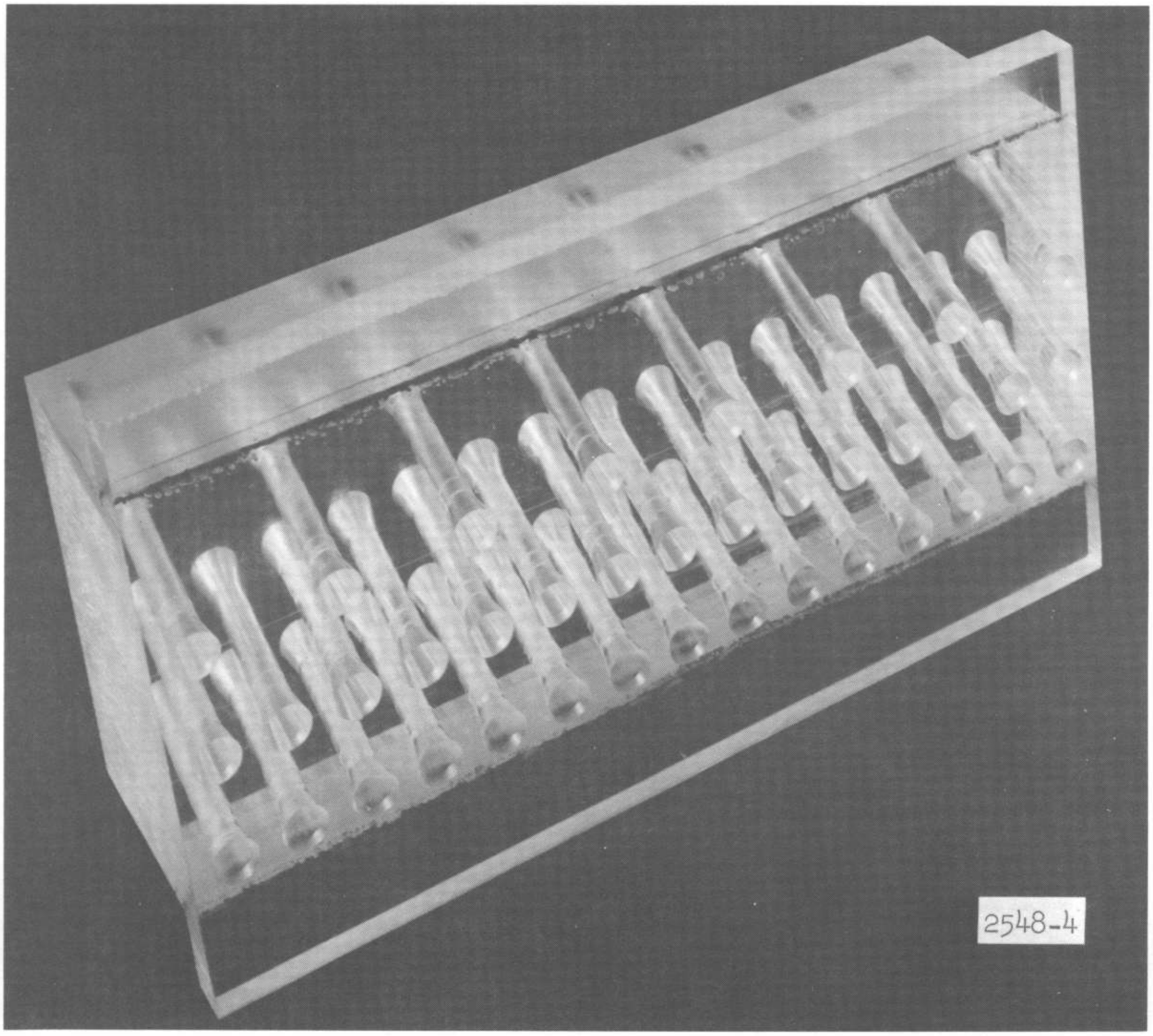


Fig. 2. Section of multiport manifold

by means of pressure cells. A differential cell was used to measure water-surface differentials between selected locations in the lock chamber. Dye and confetti were used to study subsurface and surface currents. Piezometers were installed at the filling and emptying valves and along the wall culvert to permit evaluation of pressure conditions during filling and emptying operations (plate 5).

9. By means of the linear motion of a gear-rack-driven cam plate, the culvert-valve drive mechanism (fig. 3) accurately controlled the rate

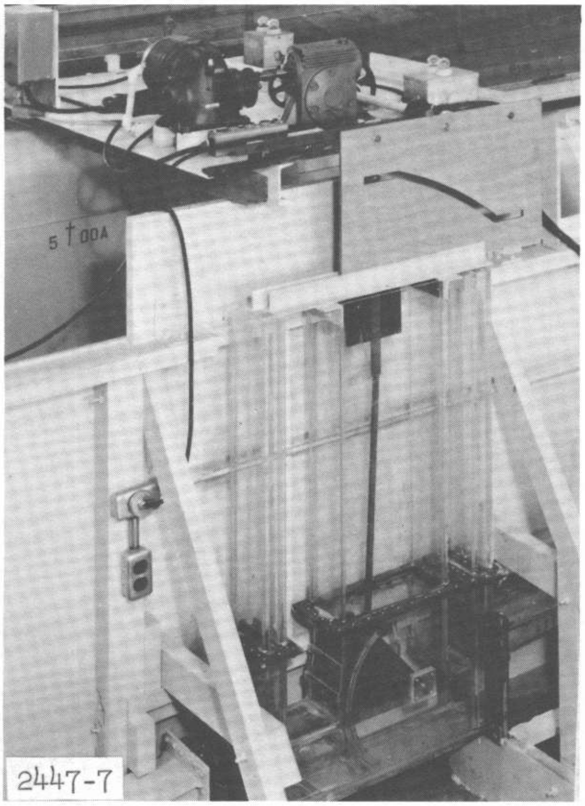


Fig. 3. Culvert-valve drive mechanism

at which the tainter valves were operated. The gear drive was powered by a three-phase, 1/4-hp reversible motor. Limit switches mounted on the gear-rack guide automatically shut off the valve drivers when either the fully open or closed position was reached.

10. The hawser-pull (force links) device for determining the transverse and longitudinal forces acting on tows in the lock chamber during filling and emptying operations is shown in fig. 4. These links were machined from aluminum and had SR-4 strain gages cemented to the inner and outer edges. When the device was mounted on the model barges, one end of the link was pin-connected to the barge while the other end engaged a fixed vertical rod and was free to move up and down with changes in water-surface elevation in the lock. Any horizontal motion of the barge caused the links to deform and vary the signal to a recorder. The links were calibrated by inducing deflection with known weights.

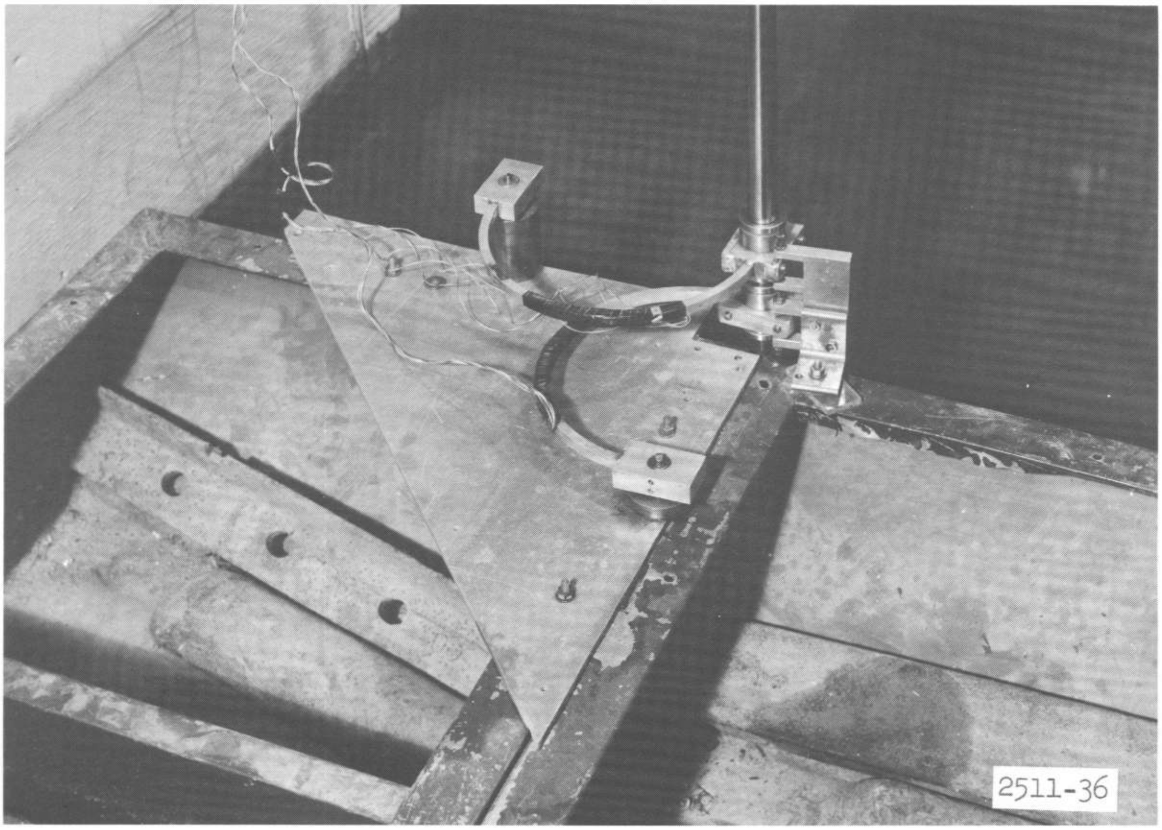


Fig. 4. Hawser-pull measuring device (force links) on bow of tow

11. Data were recorded graphically on a commercial direct-writing recorder. The sensing elements (mechanical-to-electrical conversion devices) located at various points on the model were connected by shielded cables to amplifiers where the outputs were stepped up to the level required for graphical recording.

Scale Relations

12. The accepted equations of hydraulic similitude, based upon the Froudian relations, were used to express the mathematical relations between the dimensions and hydraulic quantities of the model and the prototype. General relations for transference of model data to prototype equivalents are presented in the following tabulation:

Dimension	Ratio	Scale Relations
Length	$L_r = L$	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Time	$T_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3125
Force	$F_r = L_r^3$	1:15,625

PART III: TESTS AND RESULTS

Test Procedure

13. General operating data measured during normal filling and emptying tests provided the primary means of evaluating the various multiport arrangements. Hawser stresses on the barge tows, water-surface turbulence in the lock chamber, and pressure conditions downstream from the filling valves were the principal characteristics considered in the evaluation. Filling tests were made with valve opening times of 2, 4, and 8 min. Valve opening times of 1.5, 3, and 6 min were used during emptying tests. The valve opening schedule shown in plate 6 was used in all tests.

Test Program

14. Model tests were scheduled to evaluate the performance of the multiport arrangement proposed for use at the Cordell Hull Lock and to determine whether certain modifications would result in improvements in the system. Data collected during tests of the type 1 (original) multiport arrangement indicated that although performance of the system was, in general, satisfactory some improvement in filling characteristics might be realized by shifting the position of the multiport manifold within the lock chamber or with respect to the filling valves. Nine additional multiport arrangements were tested to determine the optimum position for the multiport manifold used in the original design. Results of these tests showed that the most satisfactory performance was obtained with an arrangement that differed from the original design only in the position of the filling valves with respect to the port manifold. However, in a conference at the U. S. Army Engineer Waterways Experiment Station on 26 August 1964, attended by representatives of the Office, Chief of Engineers, Ohio River Division, Nashville District, St. Paul District, and Waterways Experiment Station, it was decided that the original design multiport arrangement would be used at the Cordell Hull Lock. Two principal factors contributed

to this decision. First, performance of the original design system was considered satisfactory. Second, since construction was in progress at the time, shifting the location of the filling valves would have required modification of existing contracts, and the prospective performance improvements were not considered sufficient justification for making the change at this project.

15. It was also agreed at this conference that further testing of the multiport system was desirable since a system of this type was being considered for the proposed Celina Lock. The additional tests were designed to provide data on operating characteristics over a range of hydraulic conditions and to investigate the effect of various possible system modifications. Major system modifications to be studied included multiport arrangements with larger port-to-culvert area ratios, multiport arrangements using larger diameter ports, and port arrangements in which conventional ports (2 ft by 3 ft at the throat) discharged into the trench at the foot of the lock wall. Detailed discussions of all tests and results are presented in subsequent paragraphs.

Multiport Arrangements Using 8-in.-diam Ports

Type 1 (original)

16. Details of the type 1 (original) multiport arrangement are given in table 1, and the arrangement of the lock chamber manifold is shown in plate 7. The design specifies 216 8-in.-diam ports in each wall culvert. The ports are located in three horizontal rows with the ports in each row directly above those in the row beneath it. They are inclined downward away from the culvert at an angle of 15 deg and are spaced 2.5 ft on centers vertically and 3 ft on centers horizontally. The manifold extends over 48 percent of the lock chamber length (pintle to pintle) and is centered about 3.9 percent of the chamber length upstream from the midpoint of the chamber. The ports discharge into a 3-ft-wide by 6.5-ft-deep trench along the toe of the lock wall. The overall port-to-culvert area ratio for this multiport manifold is 0.75 based

on the culvert section at the valves and 0.58 based on the culvert section at the port manifold.

17. Initial tests quickly verified that a physical adjustment in the model would be required to compensate for the difference in resistance losses in model and prototype. Experience with models of conventional side port and bottom lateral systems has indicated that models constructed geometrically similar to the prototype using the Froudian relations result in filling times approximately 5 percent longer than prototype filling times. This difference, caused by the lack of model-to-prototype conformance in Reynolds number, has not been considered sufficient to necessitate physical adjustment in the model. However, with the multiport system, the extremely low Reynolds number of the flow in the small diameter ports makes the difference in resistance losses too large to be ignored. Consequently, an adjustment for the higher model losses was made utilizing additional 8-in.-diam ports distributed evenly along the manifold to obtain the computed filling time. The computed time was based on loss coefficients obtained from data collected during prototype tests of the Melton Hill multiport filling and emptying system. Thirty-three additional ports were required in the original manifold, representing approximately a 15 percent increase in port area. This percentage was maintained in the adjustment of all multiport arrangements.

18. Data obtained during filling and emptying operations with the type 1 multiport arrangement installed in the model are given in table 2. Plates 8 and 9 show typical data obtained during filling and emptying tests, respectively. The filling data were recorded during operation tests with a lift of 62 ft and a valve opening time of 4 min (plate 8); a filling time of 11.0 min resulted. The maximum longitudinal hawser stresses measured on the 4-barge tow were 4.0 tons upstream and 2.7 tons downstream. Transverse hawser stresses did not exceed 2.4 tons. Hawser stresses during emptying using a 1.5-min valve time (emptying time of 11.2 min) did not exceed 1.5 tons (plate 9). Plates 10 and 11 show the influence of filling and emptying times on maximum hawser stresses measured during tests with both 2- and 4-barge tows.

19. Observations were made of lock chamber turbulence during

filling tests. Turbulence along the lock walls, typical of this type of system, was noted but the degree of turbulence was not considered excessive. Sequence photographs of the water surface in the lock chamber during a filling operation with a 4-min valve time are shown in photograph 1.

20. Observations also were made of the movement of unmoored tows in the lock chamber during a filling operation. A 4-barge tow centered in the chamber prior to initiation of valve opening moved slowly upstream during the filling operation; a 2-barge tow located in either end of the chamber moved slowly toward that end.

21. Average piezometric pressures were measured throughout the portion of the hydraulic system reproduced in the model during normal filling and emptying tests with a 4-min valve. Piezometer locations are shown in plate 5, and measured pressures are given in tables 3 and 4. During the filling operation, culvert pressures downstream from the filling valves were undesirable in two respects. First, pressures immediately downstream of the valve dropped low enough to introduce the possibility of cavitation. Pressures in this immediate area were investigated more thoroughly using a pressure cell and are discussed in detail later in this report. Second, the culvert pressure profile at the upstream end of the multiport manifold fell below the water-surface elevation in the lock chamber, resulting in reverse flow through the upstream ports during the early portion of the filling operation.

22. Overall lock coefficients (C_L) were computed for the original (type 1) design using the equation:

$$C_L = \frac{2A_L(\sqrt{H + d} - \sqrt{d})}{A_c(T - kt_v)\sqrt{2g}}$$

where

A_L = area of lock chamber, sq ft

H = initial head, ft

d = measured overtravel or undertravel of the lock water surface, ft

A_c = area of culverts at valves, sq ft

T = filling or emptying time, sec

k = constant determined from tests

t_v = valve opening time, sec

g = acceleration of gravity, ft per sec^2

The term $T - kt_v$ is the lock filling or emptying time for the hypothetical case of instantaneous valve operation and can be obtained from model test data. Overall lock coefficients of 0.65 and 0.55 were obtained for filling and emptying operations, respectively.

Types 2-10

23. Analysis of the data collected on the type 1 multiport arrangement indicated that some improvement in filling characteristics might be realized by shifting the position of the multiport manifold within the lock chamber or with respect to the filling valves. In multiport arrangement types 2-5 the multiport manifold was shifted downstream in successive steps. Details of these arrangements are listed in table 1. Filling data obtained with these arrangements are given in table 5. No measurable variation in filling time resulted from shifting the position of the manifold within the lock chamber. Maximum hawser stresses recorded during filling tests using multiport arrangement types 1-5 are plotted in plate 12. The data indicated that the type 3 multiport arrangement with the manifold approximately centered with regard to lock chamber length results in the lowest maximum hawser stresses.

24. Additional observations using dye indicated that reverse flow through the upstream ports occurred during the valve opening period unless the upstream ports were separated from the filling valves by at least 60 ft. The reverse flow was not of sufficient magnitude to cause a measurable change in lock filling time; however, its influence on other filling characteristics was not readily determinable. Consequently, the miter gates were shifted in the model flume to permit testing with the manifold at other positions in the lock chamber with a minimum distance of 60 ft between the filling valves and the upstream ports. Details of multiport arrangements tested under these conditions (types 6-10) are given in table 1. Test results are given in table 5, and maximum hawser stresses are plotted in plate 13. Consideration of these data indicated the type 8 arrangement to be the most satisfactory.

Type 8

25. The type 8 multiport arrangement differed from the original design only in the distance between the filling valves and the upstream ports. The distance was increased by 21 ft in type 8, thereby separating the manifold and filling valves to avoid reverse flow at the upstream ports during the early stage of filling. Additional tests were conducted at the design lift (62 ft) with this arrangement to provide more information on operating characteristics of the system. Filling and emptying data obtained during tests with both 4- and 2-barge tows are given in table 6. Maximum hawser stresses measured during filling and emptying are plotted in plates 14 and 15, respectively. Typical data traces recorded during filling and emptying tests are presented in plates 16 and 17. Maximum hawser stresses were lower and better balanced (upstream and downstream) than those obtained in tests of the type 1 arrangement.

26. Observations of lock chamber turbulence during filling tests indicated that the distribution over the chamber was satisfactory and that the intensity of turbulence was not excessive. Photograph 2 shows sequence photographs of the water surface in the lock chamber during a filling test with an initial head of 62 ft and a 4-min valve time. The effect of varying the location of the lock chamber floor with respect to the port outlets also was investigated. Turbulence observations and measurements of filling characteristics were made with the floor at positions 0.5 and 1.0 ft below and 0.25 ft above the original design elevation of 428.0. Hawser stresses did not change materially, but water-surface turbulence was sensitive to floor position. Lowering the floor resulted in strong boiling action in the center of the lock chamber. Increased turbulence along the walls was observed with the floor at the higher elevation. Consequently, it was concluded that original floor elevation was the optimum.

27. Average piezometric pressures were again measured throughout the system during normal filling and emptying operations with a 4-min valve. These data are presented in tables 7 and 8. The increased distance between the filling valves and the upstream end of the multiport manifold resulted in improved pressure conditions at the upstream ports.

28. One test simulating single-culvert operation also was conducted

with the type 8 arrangement. In this test the lock chamber was filled and emptied using only the culvert in the landward wall. Pertinent data are given in table 9. Filling and emptying times were almost double those obtained during normal two-culvert operation. Hawser stresses during filling were reduced to about half those obtained with normal operation but showed little change during emptying.

29. Tests also were conducted with the type 8 arrangement at a range of operating conditions to obtain general design data. Filling data obtained during the tests at lifts from 40 to 72 ft are presented in table 10. Emptying data were not recorded since earlier tests had shown conditions during emptying to be very satisfactory. The hawser stress plots in plate 18 show the relatively small influence which head exerted on maximum hawser stresses. Tests with a 72-ft lift resulted in a maximum hawser stress of only 3.1 tons. The following tabulation gives measured filling times and computed lock coefficients (equation given in paragraph 22) for the different conditions tested.

Initial Head ft	Valve Opening Time min	Filling Time min	Overall Lock Coefficient
40	2	8.0	0.66
	4	9.2	
	8	11.4	
50	2	8.8	0.66
	4	10.0	
	8	12.2	
60	2	9.6	0.66
	4	10.8	
	8	13.0	
66	2	10.1	0.65
	4	11.3	
	8	13.5	
72	2	10.6	0.64
	4	11.8	
	8	14.0	

Type 11

30. The type 11 multiport arrangement (table 1) was tested to

evaluate the effect of increasing the port-to-culvert area ratio. The port manifold in this arrangement consisted of 273 ports (exclusive of ports added to compensate for higher resistance losses in the model), resulting in a port-to-culvert area ratio of 0.95 based on the culvert area at the filling valve and a ratio of 0.74 based on the culvert area at the port manifold. The manifold extended over 61 percent of the lock chamber length and was centered about 2.5 percent of the chamber length upstream from the center point between the miter gate pintles. Filling data obtained during tests at lifts of 40, 62, and 72 ft are given in table 11. Filling times and computed lock coefficients (equation given in paragraph 22) are given in the following tabulation.

Initial Head ft	Valve Opening Time min	Filling Time min	Overall Lock Coefficient
40	2	7.4	0.72
	4	8.6	
	8	10.9	
62	2	8.9	0.73
	4	10.1	
	8	12.4	
72	2	9.6	0.72
	4	10.8	
	8	13.1	

For equal valve times the reduction in filling times with the higher area ratio varied from about 0.6 min at a 40-ft lift to 1.0 min at a 72-ft lift (compare arrangement types 8 and 11). Emptying times were decreased approximately 0.6 min.

31. Maximum hawser stresses obtained during filling tests with this arrangement are plotted in plate 19. Comparison of these data with the data for the type 8 arrangement indicates that maximum hawser stresses for comparable filling times are in reasonably close agreement.

32. Photograph 3 shows lock chamber water-surface turbulence during a filling operation (62-ft lift) with the type 11 multiport arrangement. Turbulence conditions appeared to be comparable to conditions observed during tests of the type 8 arrangement (photograph 2).

Pressures downstream
from filling valves

33. Pressures in the culvert just downstream from the filling valves were investigated in the model with a pressure cell since pressures conducive to cavitation were considered likely at the lift-submergence conditions expected at the Cordell Hull Lock. The pressure cell was mounted in the roof of the culvert just downstream from the valve well as shown in plate 5. Pressure traces were recorded during tests of all multiport arrangements. The average pressure lines shown in plate 20 are typical of the data obtained. These pressures were measured during tests of the type 1 (original) multiport arrangement using 2-, 4-, and 8-min valve times. Minimum average pressures on the culvert roof during these tests were -9.8, -5.3, and 1.2 ft, respectively. Minimum instantaneous pressures were approximately 5 ft lower than the average pressures. For these tests the roof of the culvert was horizontal at elevation 434.0 to the downstream edge of the bulkhead slot where a transition to elevation 437.0 began. An alternate roof arrangement in which the transition began at the downstream edge of the valve well also was used in some of the later tests. Both arrangements are shown in plate 5.

34. Pressures downstream of the valves also were investigated during tests at a range of heads with both types 8 and 11 multiport arrangements. Tests were made using both culvert roof arrangements with each multiport arrangement. Minimum average pressures recorded in tests of the type 8 arrangement (port area/culvert area ratio of 0.75 based on culvert at valves) are plotted in plate 21, and similar data for the type 11 arrangement (area ratio of 0.95) are plotted in plate 22. These data show that the transition which began the sloping roof at the downstream edge of the valve well resulted in significant improvement in minimum gradient elevations. A comparison of the plots for the types 8 and 11 multiport arrangements indicates that for a specific lift comparable filling times result in approximately the same minimum pressure.

Air-venting

35. Tests were conducted to determine the effect of air-venting on minimum pressures downstream from the filling valves and on filling

characteristics. Tests were made with vent sizes ranging up to 12 in. in diameter. The effect on minimum pressures recorded with the type 8 multiport arrangement is shown in plate 23. Minimum pressures obtained during single-culvert operation also are shown in this plot. Use of the 12-in.-diam vent raised the minimum pressure only about 5 and 3 ft during filling operations with 2- and 4-min valve times, respectively. However, even though air-venting may not raise the minimum pressure out of the cavitation range, admission of small quantities of air should cushion the collapse of vapor pockets and minimize the possibility of structural damage. Since laws for scaling air entrainment from model to prototype have not been established, the optimum amount of air-venting should be determined in the prototype.

36. Maximum hawser stresses measured during the filling tests with air-venting are plotted in plate 24. These model data indicate that air-venting had no detrimental effect on filling characteristics. In fact, they show that maximum hawser stresses decreased slightly as the air-vent area was increased. Typical data traces with and without air-venting (plate 25) also suggest that the admission of small air bubbles into the lock chamber increases the rate of dissipation of surging in the chamber. Model tests of other types of filling systems (sidewall port and floor lateral systems) have indicated that if too much air is allowed to enter the culvert, air pockets will form and when discharged into the chamber will increase surging and hawser stresses. Air pockets were observed along the roof of the culverts during tests of the multiport system, but they were not discharged into the chamber, presumably because of the size and arrangement of ports in the multiport manifold.

Multiport Arrangements Using 10-in.-diam Ports

37. Multiport arrangements utilizing 10-in.-diam ports were tested at the Cordell Hull base test conditions (62-ft lift and 14-ft submergence). Visual observations were made during filling operations with several port arrangements. However, measurements were made only on the three arrangements (multiport arrangement types 12-14) described in table 1 and in

plate 26. Pertinent data obtained during these tests are given in table 12, and maximum hawser stresses are plotted in plate 27. The types 12 and 13 arrangements used ports in the top two rows only to obtain a port-to-culvert area ratio of 0.95 (based on culvert area at the valve) and retained the lock chamber floor elevation (428.0) used in earlier multiport arrangements. They differed only in the depth of the trench, with the type 12 arrangement including a 6.5-ft-deep trench and the type 13 arrangement a 4-ft-deep trench. Filling characteristics for the two arrangements showed only minor differences, indicating that the depth of the trench below the bottom row of ports is not a critical consideration. Sequence photographs of the lock chamber water surface during a filling operation with the type 13 arrangement are presented in photograph 4. Average pressures recorded throughout the system during filling and emptying operations with this arrangement are given in tables 13 and 14.

38. Observations showed that an arrangement which utilized ports in the bottom two rows to provide the same area ratio resulted in strong boiling along the lock walls.

39. Turbulence observations were made during filling operations with the top of the trench wall beveled on a 45-deg angle. In these tests the breakpoint of the bevel was located at the point where the projected center line of the upper row of ports intersected the trench wall. Turbulence conditions in the lock chamber did not appear as favorable with the beveled trench wall as they were with either the type 12 or type 13 arrangement. The limited observations made with the beveled trench wall certainly do not eliminate the possibility that trench modifications of this type could be used to improve turbulence conditions in the chamber. However, this method of improvement was not pursued because of the desire to test larger diameter ports and the belief that the sensitivity of the desirable division of flow into and over the top of the trench would not be materially reduced by the beveled lip.

40. The type 14 multiport arrangement which used ports from all three rows to obtain an area ratio of 1.23 (based on culvert area at the valve) resulted in boiling along the walls and frequent swirls in the center of the chamber. For a 2-min valve time, this arrangement decreased

the filling time by 0.6 min but increased maximum hawser stresses by approximately 2 tons (table 12).

41. Performance of the types 12 and 13 multiport arrangements composed of 10-in.-diam ports is considered comparable to the optimum arrangement using 8-in.-diam ports.

Multiport Arrangements Using 12-in.-diam Ports

42. Multiport arrangements composed of 12-in.-diam ports were tested at the same conditions used during tests of 8- and 10-in.-diam ports. After preliminary tests of several port arrangements, filling characteristics were measured on the three arrangements described in table 1 and plate 28 (types 15-17). These arrangements utilized ports from the top two rows to again provide a total port-to-culvert area ratio of 0.95. Pertinent data recorded in the tests are given in table 12, and maximum hawser stresses are plotted in plate 29. Sequence photographs of the lock chamber water surface during a typical filling operation with the type 17 arrangement are presented in photograph 5.

43. Turbulence conditions with the type 16 arrangement, in which three-fourths of the open ports were in the top row, were considered more favorable than conditions observed during tests of the type 15 arrangement which had the open ports equally divided between the two rows. Both arrangements had the lock floor at elevation 428.0 and used a 4-ft-deep trench. The type 17 arrangement differed from type 16 only in that the depth of the trench was increased to 6.5 ft. The additional trench depth resulted in a small reduction in hawser stresses and a slight improvement in turbulence conditions.

44. The type 17 arrangement yielded results which are considered comparable to those obtained in arrangements using 8- and 10-in.-diam ports. However, the relative positions of the top row of ports and the lock floor becomes more critical as the port diameter increases. Tests with the lock floor raised and lowered 0.25 ft from the original position (elevation 428.0) showed strong boiling along the lock walls and in the center of the lock chamber, respectively.

Multiport Arrangements Using 14-in.-diam Ports

45. A multiport arrangement utilizing 14-in.-diam ports also was tested. The manifold in this arrangement was composed of one row of 89 ports covering approximately 60 percent of the lock chamber length. Satisfactory performance was not obtained with this arrangement because of the sensitivity of the relative positions of the ports and the lock floor. Tests with numerous trench modifications involving width, depth, and top elevation of the trench wall (i.e. lock chamber floor elevation) did not reveal a modification which would appreciably decrease the influence of this factor.

Port Arrangements Using Conventional Sidewall Ports

46. Additional tests were performed to investigate the performance of port arrangements (types 18-23) in which conventional sidewall ports discharged into a trench at the toe of the lock walls. For all of these arrangements, the upstream miter gate pintle was located at sta 0+30; the farthest upstream and downstream ports were located at sta 1+31 and 3+71, respectively; and the percentage of lock chamber upstream of the ports, occupied by the ports, and downstream of the ports was 22.5, 53.3, and 24.2, respectively. Sixteen ports, each 2 ft wide by 3 ft high at the throat, were spaced on 16-ft centers in each wall. This arrangement resulted in a port-to-culvert area ratio of 0.96 based on the culvert area at the valve. The culvert was 10 ft by 10 ft at the valve and 10 ft wide by 13 ft high at the ports. A 6.5-ft-deep trench with the lock chamber floor at elevation 428.0 was used in all tests. Observations were made during filling operations using the base test conditions (62-ft lift and 14-ft submergence) with trench widths of 4 and 8 ft. Sequence photographs of the lock water surface (photograph 6) taken during tests with a 4-ft-wide trench (port arrangement type 18) show severe boiling along the lock walls and strong longitudinal currents in the chamber. These characteristics were evident in varying degrees with both trench widths.

47. An 8-ft-wide trench was selected for exploratory measurements

of filling characteristics (port arrangement types 19-23). The conventional open trench used in previous tests and in port arrangement type 19 resulted in very high upstream longitudinal hawser stresses; therefore, deflectors and dividers were tested in the trench in an effort to reduce the magnitude of these stresses and improve the balance between upstream and downstream stresses (port arrangement types 20-23). Arrangements 19-22 utilized deflectors on 0, 6, 8, and 7 of the upstream ports, respectively. The deflectors were located in the trench at the downstream face of the ports and were angled 15 deg upstream. Arrangement 23 did not used deflectors, but instead used dividers in the trench to form 14-ft-long recess basins in front of all 16 ports. Data obtained during tests of arrangement types 19-23 are given in table 15. The reduction of the high upstream hawser stresses by use of the deflectors is evident in the hawser stress plot in plate 30. Installation of dividers in the trench between each port (type 23) also improved hawser stresses, but resulted in increased turbulence in the downstream end of the lock chamber.

48. Typical traces of longitudinal hawser stresses and lock chamber water-surface differentials (end to end) obtained during operation with multiport arrangement type 11 and conventional port arrangement types 19 and 22 are shown in plate 31. The record from tests of the open trench (type 19) shows an extended period of high unbalanced upstream hawser stresses. The use of deflectors angled 15 deg upstream at seven upstream ports (type 22) resulted in well-balanced stresses of reasonable magnitude. However, turbulence in the lock chamber was still considered excessive (photograph 7).

49. These test results indicate that the performance of conventional sidewall ports discharging into a trench does not compare favorably with that of a multiport system at lifts in the 60-ft range.

PART IV: DISCUSSION OF RESULTS

50. Performance of the original design lock filling and emptying system for Cordell Hull Lock was, in general, satisfactory even though it was evident from model test results that certain improvements could be made in the system. At the design conditions, 62-ft lift and 14-ft submergence, the type 1 (original) multiport arrangement permitted the lock to be filled in 11.0 min (4-min valve) with hawser stresses no higher than 4.0 tons. Turbulence conditions in the lock chamber during the filling operation were satisfactory. The culvert pressure gradient downstream from the filling valves dropped about 5.3 ft below the culvert roof during the valve opening period. The low-pressure area extended along the culvert to the upstream end of the multiport manifold, resulting in some reverse flow through the upstream ports during the early portion of the filling operation. Emptying required 11.2 min (1.5-min valve) and resulted in maximum stresses of only about 1.5 tons.

51. Consideration of results of model tests of the original design and the construction schedule at the project resulted in the decision to adopt the original design system for use at the Cordell Hull project (see paragraph 14). However, additional tests were conducted to investigate refinements to the system and to explore the feasibility of several major system modifications since the multiport system was being considered for use at a similar project.

52. Subsequent tests resulted in the following conclusions and/or recommendations for improvements in the multiport system utilizing three rows of 8-in.-diam ports:

- a. The filling valves should be separated from the multiport manifold by at least 60 ft to avoid reverse flow through the upstream ports during the early portion of the filling operation. The improved flow distribution from the multiport manifold reduces maximum hawser stresses, as shown by a comparison of data recorded with multiport arrangement types 1 and 8.

- b. The overall port-to-culvert area ratio can be increased from 0.75 (based on culvert area at the valves) as used in the original design to 0.95 with no appreciable detrimental effect on the performance of the system (compare data obtained for multiport arrangement types 8 and 11). The larger area ratio permits faster filling of the lock provided acceptable pressure conditions can be maintained downstream of the filling valves.

c. Pressure conditions downstream of the filling valves were significantly improved by using an alternate culvert transition section. In this transition, the culvert height was increased from 10 ft at the valves to 13 ft by a roof flare beginning at the downstream end of the valve well rather than at the downstream edge of the bulkhead slot as in the original culvert transition.

d. Controlled air-venting in the low-pressure area downstream from the filling valves is recommended. Model tests did not indicate that air-venting necessarily would raise minimum pressures sufficiently to preclude cavitation; however, admission of a small quantity of air should cushion the collapse of vapor pockets and minimize possible structural damage without adversely affecting the performance of the system. Since laws for scaling air entrainment have not been defined, the desired amount of air should be determined during prototype operation. A valve on the prototype vent should allow observers to determine the opening required to admit only enough air to quiet the crackling noise associated with cavitation.

53. Additional tests were conducted to investigate the feasibility of multiport manifolds composed of two rows of 10- or 12-in.-diam ports or one row of 14-in.-diam ports. All arrangements tested in this series had multiport manifolds resulting in a port-to-culvert area ratio of 0.95 (see subparagraph 52b). Satisfactory arrangements were developed using 10- and 12-in.-diam ports. Operating characteristics of these arrangements (type 13 for 10-in. ports and type 17 for 12-in. ports) were considered comparable to those of the type 11 multiport arrangement. However, it was evident that as the port diameter increased the relative position of the top row of ports and the lock chamber floor (lip of trench) became progressively more sensitive. Tests with the lock floor slightly higher and lower than the optimum elevation showed strong boiling along the lock walls and in the center of the lock chamber, respectively. For this reason, no satisfactory arrangement using one row of 14-in. ports was developed. Recommendations presented in subparagraphs 52a, 52c, and 52d also are

applicable to multiport arrangements utilizing the larger diameter ports.

54. Results of tests of port arrangements utilizing conventional sidewall ports discharging into a trench at the toe of the lock wall did not compare favorably with results of tests of the better multiport systems. Satisfactory hawser stresses could be obtained through the use of deflectors in the trench, but attempts to reduce the intensity of turbulence in the lock chamber to an acceptable level were unsuccessful.

Table 1

Details of Types 1-17 Multiport Arrangements

Type	No. of Horizontal Rows	Total No. of Ports	Port Area/ Culvert Area at Valve	Depth of 3-ft-wide Trench ft	Station Location, ft: Upstream Miter Gate Pintle	Station Location, ft: Upstream Port	Station Location, ft: Downstream Port	Percent of Lock Chamber: Upstream of Ports	Percent of Lock Chamber: Occupied by Ports	Percent of Lock Chamber: Downstream of Ports
						Arrangements with 8-in.-diam Ports				
1	3	216	0.75	6.5	0+09	1+08.5	3+24.5	22.1	48.0	29.9
2	3	216	0.75	6.5	0+09	1+17.5	3+33.5	24.1	48.0	27.9
3	3	216	0.75	6.5	0+09	1+26.5	3+42.0	26.1	48.0	25.9
4	3	216	0.75	6.5	0+09	1+35.5	3+51.5	28.1	48.0	23.9
5	3	216	0.75	6.5	0+09	1+47.5	3+63.5	30.8	48.0	21.2
6	3	216	0.75	6.5	0+30	1+08.5	3+24.5	17.4	48.0	34.6
7	3	216	0.75	6.5	0+30	1+20.5	3+36.5	20.1	48.0	31.9
8	3	216	0.75	6.5	0+30	1+29.5	3+45.5	22.1	48.0	29.9
9	3	216	0.75	6.5	0+30	1+35.5	3+51.5	23.4	48.0	28.6
10	3	216	0.75	6.5	0+30	1+47.5	3+63.5	26.1	48.0	25.9
11	3	273	0.95	6.5	0+30	1+08.5	3+81.5	17.4	60.7	21.9
						Arrangements with 10-in.-diam Ports				
12	2	174	0.95	6.5	0+30	1+14.5	3+75.5	18.8	58.0	23.2
13	2	174	0.95	4.0	0+30	1+14.5	3+75.5	18.8	58.0	23.2
14	3	226	1.23	6.5	0+30	1+08.5	3+81.5	17.4	60.7	21.9
						Arrangements with 12-in.-diam Ports				
15	2	121	0.95	4.0	0+30	[illegible]	3+81.5	18.1	60.0	21.9
16	2	121	0.95	4.0	0+30	1+11.5	3+81.5	18.1	60.0	21.9
17	2	121	0.95	6.5	0+30	1+1[illegible].5	3+81.5	18.1	60.0	21.9

Note: A port spacing of 2 ft 6 in. vertically and 3 ft horizontally was maintained with the ports inclined downward away from the culvert at an angle of 15 deg.
Culvert is 10 ft by 10 ft at valve and 10 ft wide by 13 ft high at port manifold.
Trench depth is measured from lock floor el 428.0

Table 2

Effect of Tow Size and Position on Filling and Emptying Characteristics

Type 1 (Original) Multiport Arrangement, 8-in.-diam Ports

Number of Barges	Distance Between Tow and Upstream Miter Gate Pintles ft	Valve Time min	Filling or Emptying Time min	Maximum Hawser Stresses															
				Longitudinal				Upstream Transverse				Downstream Transverse							
				Upstream		Downstream		Left		Right		Left		Right					
				Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min				
				Filling Operations															
4*	30	2	9.8	5.2	1.6	3.5	2.1	3.5	2.3	1.8	1.1	3.3	2.5	1.7	2.4				
		4	11.0	4.0	3.4	2.7	4.0	2.2	4.4	1.7	1.8	2.4	4.3	1.8	4.6				
		8	13.3	3.5	5.1	2.2	5.0	1.7	6.1	1.1	4.8	2.1	4.9	1.4	4.8				
2	30	2	9.8	3.5	0.6	2.3	2.7	2.5	2.0	1.5	1.7	3.1	2.4	1.2	2.6				
		4	11.0	2.8	2.2	2.0	3.6	2.0	2.6	1.6	2.4	2.0	3.2	2.0	2.4				
		8	13.3	2.7	5.9	2.1	6.1	1.4	5.0	1.4	4.5	1.6	4.7	1.4	3.9				
2	225	2	9.8	2.9	1.6	4.7	1.2	2.0	2.8	2.1	3.8	1.6	3.7	2.1	1.8				
		4	11.0	2.7	3.8	3.1	6.2	1.2	3.5	1.2	3.8	1.2	1.9	1.6	3.4				
		8	13.3	2.5	3.7	2.1	6.1	0.8	5.8	0.8	5.7	1.0	5.6	1.2	5.7				
				Emptying Operations															
4	30	1.5	11.2	1.5	1.6	1.4	1.1	0.8	2.1	0.6	2.8	0.8	2.2	0.8	2.5				
		3	12.0	1.2	6.6	1.2	6.5	0.8	2.4	0.4	2.5	1.1	3.8	0.8	4.6				
		6	13.6	1.1	8.2	1.1	8.1	0.9	7.1	0.4	8.8	1.0	4.7	0.8	5.5				
2	30	1.5	11.2	2.9	5.0	2.7	4.9	1.2	8.3	1.2	8.2	1.2	8.3	1.4	8.2				
		3	12.0	2.3	3.5	2.3	3.4	1.2	3.4	0.8	4.6	1.2	2.5	1.2	2.3				
		6	13.6	1.6	3.5	2.0	4.9	0.8	4.4	0.8	4.9	1.4	7.1	1.4	4.3				
2	225	1.5	11.2	2.3	3.4	2.1	4.3	0.8	4.1	0.8	5.3	0.8	4.0	0.8	5.1				
		3	12.0	2.0	5.3	2.1	5.2	0.8	7.3	0.6	7.4	1.0	6.2	0.8	6.1				
		6	13.6	2.0	7.2	1.8	7.0	0.8	7.6	0.8	7.7	0.7	10.6	0.8	10.7				

Note: Time listed under hawser stresses is time of occurrence after beginning of movement of valves.
Upper pool el 504.0 and lower pool el 442.0.
* 4-barge tow, 7280 tons displacement; 2-barge tow, 3640 tons displacement.

Table 3

Average Piezometer Readings During Filling Operation - Type 1 (Original) Multiport Arrangement

Piezometer Locations			Average Piezometer Reading in Prototype Feet of Water																				
Piez No.	Station	El	T* = 0 LC** = 442.0	T = 30 LC = 412.5	T = 60 LC = 443.5	T = 90 LC = 444.7	T = 120 LC = 446.5	T = 150 LC = 449.4	T = 180 LC = 453.6	T = 210 LC = 459.0	T = 240 LC = 464.7	T = 270 LC = 470.4	T = 300 LC = 475.1	T = 330 LC = 479.9	T = 360 LC = 484.1	T = 390 LC = 488.0	T = 420 LC = 491.4	T = 450 LC = 493.1	T = 480 LC = 496.8	T = 540 LC = 500.8	T = 600 LC = 503.2	T = 660 LC = 504.0	T = 720
Filling Valve Piezometer Group A																							
1	0+21	424.0	504.0	504.0	503.0	501.2	498.7	492.4	482.0	472.0	474.1	478.0	481.9	485.7	488.6	491.7	494.3	496.9	498.8	501.8	503.5	504.2	504.3
2	0+24	424.0	504.0	504.0	503.0	501.1	498.5	492.3	481.9	472.0	474.1	477.9	481.8	485.5	488.5	491.6	494.2	496.8	498.7	501.9	503.7	504.2	504.3
3	0+30	434.0	504.0	503.8	502.9	501.0	498.3	491.9	481.4	471.2	473.5	477.3	481.1	484.9	488.0	491.0	493.9	496.3	498.3	501.6	503.4	504.0	504.0
4	0+33	434.0	504.0	504.0	503.0	501.0	498.4	492.0	481.4	471.2	473.6	477.4	481.3	485.0	488.1	491.3	494.0	496.5	498.5	501.8	503.7	504.3	504.4
5	0+40	434.0	504.0	504.0	503.0	501.0	498.4	491.9	481.1	471.2	474.0	477.7	481.7	485.2	488.2	491.4	494.1	496.6	498.6	501.9	503.7	504.1	504.3
6	0+59	424.0	442.0	442.0	449.3	466.3	473.5	472.0	465.9	465.0	472.1	476.2	480.2	482.0	487.2	490.4	493.4	496.0	498.0	501.1	503.0	503.8	503.9
8	0+67	424.0	442.0	439.6	435.9	435.0	434.0	434.1	439.4	458.5	471.4	475.8	479.9	483.8	487.0	490.4	493.4	495.9	498.0	501.4	503.2	504.0	504.2
9	0+70	424.0	442.0	439.0	435.0	434.6	433.5	432.8	437.1	458.9	471.1	475.5	479.6	483.5	486.8	490.0	493.1	495.7	497.9	501.1	503.0	503.9	504.0
10	0+73	424.0	442.0	438.9	435.0	435.0	433.8	433.0	438.0	460.3	471.2	475.7	479.8	483.6	486.9	490.3	493.2	495.8	498.0	501.3	503.2	504.0	504.0
11	0+76	424.0	442.0	438.8	435.8	435.5	434.3	433.9	440.0	461.6	471.4	475.9	479.9	483.8	487.0	490.4	494.4	495.9	498.0	501.4	503.2	504.0	504.1
12	0+79	424.0	442.0	439.1	436.9	436.0	435.0	434.9	442.3	463.2	471.7	476.0	480.1	483.9	487.1	490.5	493.4	495.9	498.0	501.4	503.3	504.1	504.3
13	0+82	424.0	442.0	439.3	438.2	436.7	435.7	435.7	444.7	464.0	471.7	476.0	480.1	483.9	487.1	490.5	493.4	495.9	498.0	501.3	503.2	504.1	504.2
14	0+85	424.0	442.0	439.4	439.2	437.0	436.0	436.2	446.5	465.0	472.0	476.6	480.7	484.3	487.6	490.8	493.6	496.0	498.1	501.6	503.5	504.1	504.4
15	0+88	424.0	442.0	439.8	439.3	437.6	436.1	437.0	449.0	465.9	472.5	477.0	481.0	484.6	487.8	491.0	493.9	496.0	498.2	501.9	503.4	504.0	504.2
16	0+91	424.0	442.0	440.2	439.5	438.1	436.7	438.7	451.1	466.8	473.2	477.7	481.5	484.9	488.0	491.1	494.0	496.3	498.3	501.6	503.4	504.0	504.2
17	0+94	424.0	442.0	441.0	439.9	438.4	437.2	440.6	453.2	467.6	473.9	478.1	481.9	485.4	488.3	491.5	494.1	496.3	498.4	501.7	503.4	504.1	504.3
18	0+97	424.0	442.0	441.5	440.1	438.8	438.0	442.0	454.9	467.9	474.1	478.3	482.1	485.5	488.4	491.5	494.1	496.3	498.3	501.5	503.3	503.9	504.0
19	1+00	424.0	442.0	441.9	440.7	439.6	439.0	443.6	455.8	468.4	474.9	478.9	482.5	485.9	488.8	491.9	494.5	496.5	498.6	501.8	503.4	504.0	504.1
Culvert Piezometer Group B																							
1	1+21	430.0	442.0	442.1	443.3	444.4	446.3	451.3	460.2	472.0	478.0	481.6	484.8	487.9	490.4	493.0	495.6	497.6	499.2	502.0	503.4	503.9	504.0
3	1+61	430.0	442.0	442.3	443.8	446.0	449.6	455.4	465.0	477.2	482.8	485.7	487.9	490.6	492.9	495.0	497.0	498.7	500.2	502.3	503.7	504.1	504.1
5	2+01	430.0	442.0	442.2	443.9	446.5	450.4	456.8	467.1	480.8	486.1	488.7	490.6	492.7	494.8	496.4	498.2	499.5	500.9	502.8	504.0	504.3	504.3
7	2+41	430.0	442.0	442.0	443.6	446.2	450.3	457.1	468.1	482.8	488.0	490.1	492.0	493.9	495.8	497.4	499.0	500.0	501.4	503.0	504.0	504.3	504.4
9	2+81	430.0	442.0	442.1	443.9	446.5	450.5	457.8	469.2	484.0	489.1	491.1	493.0	494.5	496.2	498.0	499.6	500.5	501.6	503.1	504.1	504.3	504.4
11	3+21	430.0	442.0	442.0	443.8	446.5	450.6	457.7	469.2	484.6	489.7	491.7	493.1	494 9	496.7	498.2	499.6	500.5	501.8	503.3	504.0	504.5	504.5
13	3+61	430.0	442.0	442.0	443.8	446.4	450.5	457.6	469.1	484.5	489.9	491.9	493.3	495.1	496.9	498.3	499.8	500.6	501.9	503.4	504.2	504.6	504.6

Note: Upper pool el 504.0 and lower pool el 442.0.
Lock filled in 11.0 min with 4-min valve.
Bulkhead slots below filling valve closed.
* T denotes time (in prototype seconds) after beginning of movement of valves.
** LC denotes elevation of water surface in lock chamber.

Table 4

Average Piezometer Readings During Emptying Operation - Type 1 (Original) Multiport Arrangement

Piezometer Locations			Average Piezometer Reading in Prototype Feet of Water																				
Piez No.	Station	El	T* = 0 LC** = 504.0	T = 30 LC = 503.1	T = 60 LC = 501.0	T = 90 LC = 496.4	T = 120 LC = 491.3	T = 150 LC = 486.3	T = 180 LC = 481.8	T = 210 LC = 477.2	T = 240 LC = 472.9	T = 270 LC = 468.8	T = 300 LC = 465.3	T = 330 LC = 461.8	T = 360 LC = 458.8	T = 390 LC = 456.0	T = 420 LC = 453.5	T = 450 LC = 451.2	T = 480 LC = 449.2	T = 540 LC = 446.1	T = 600 LC = 443.5	T = 660 LC = 442.3	T = 720 LC = 441.7
Culvert Piezometer Group B																							
2	1+41	430.0	504.0	502.5	497.9	486.9	480.4	475.2	471.7	468.4	465.0	462.0	459.3	456.7	454.0	451.8	450.0	448.0	446.7	444.1	442.8	441.8	441.3
4	1+81	430.0	504.0	502.1	497.4	485.6	479.0	473.8	470.3	467.2	464.1	461.2	458.7	456.0	453.6	451.4	449.7	447.9	446.4	444.0	442.7	441.7	441.3
6	2+21	430.0	504.0	502.0	496.6	482.8	476.7	476.3	468.1	465.1	462.3	459.9	457.3	454.9	452.7	450.7	449.0	447.4	446.0	443.9	442.7	441.7	441.3
8	2+61	430.0	504.0	501.6	495.1	478.7	472.4	467.1	464.2	461.9	459.4	457.2	455.1	453.0	451.0	449.4	447.9	446.5	445.4	443.5	442.3	441.6	441.3
10	3+01	430.0	504.0	501.1	492.9	471.0	466.1	460.7	458.4	456.6	454.7	453.0	451.7	450.0	448.5	447.2	446.1	445.1	444.3	443.0	442.1	441.6	441.3
12	3+41	430.0	504.0	500.7	491.0	466.0	461.4	455.8	454.1	452.7	451.2	450.0	448.9	447.6	446.5	445.8	444.9	444.1	443.7	442.7	442.0	441.6	441.3
14	3+81	430.0	504.0	500.2	490.0	463.6	460.2	454.9	453.3	452.0	450.7	449.4	448.1	447.0	446.0	445.3	444.7	444.0	443.5	442.6	442.0	441.6	441.4
Emptying Valve Piezometer Group C																							
1	4+13	427.0	504.0	499.6	486.2	451.8	449.0	443.8	443.3	443.3	443.0	442.8	442.5	442.1	441.9	442.0	441.9	444.0	441.9	441.8	441.7	441.5	441.4
2	4+29	427.0	442.0	454.5	470.7	447.2	447.9	442.9	442.4	442.6	442.6	442.4	442.2	442.0	441.9	441.9	441.9	441.8	441.8	441.7	441.6	441.5	441.4
3	4+33	427.0	442.0	437.1	442.0	443.0	446.8	442.3	441.9	442.1	442.1	442.0	441.9	441.6	441.5	441.7	441.6	441.5	441.5	441.4	441.3	441.3	441.2
4	4+33	437.0	442.0	436.9	437.3	439.1	439.6	439.0	439.0	439.4	439.1	439.7	439.9	439.8	439.9	440.1	440.0	440.1	440.0	440.1	440.3	440.3	440.4
5	4+37	427.0	442.0	435.1	431.7	440.1	446.5	442.2	441.8	442.0	442.0	441.9	441.8	441.6	441.4	441.7	441.6	441.6	441.5	441.4	441.4	441.3	441.3
6	4+37	437.0	442.0	437.6	438.6	440.0	442.6	441.0	440.8	441.0	441.0	441.0	440.9	440.8	440.8	440.8	440.8	440.8	440.7	440.8	440.8	440.7	440.7
7	4+41	427.0	442.0	433.8	429.9	437.7	446.1	442.0	441.7	441.9	441.9	441.8	441.7	441.5	441.3	441.5	441.5	441.5	441.4	441.4	441.4	441.4	441.3
8	4+41	437.0	442.0	438.8	439.8	441.7	444.0	442.7	442.6	442.6	442.6	442.4	442.5	442.4	442.4	442.3	442.4	442.3	442.4	442.3	442.3	442.3	442.3
9	4+45	427.0	442.0	434.6	430.7	437.0	446.2	442.1	441.9	442.0	442.0	441.9	441.8	441.6	441.4	441.6	441.6	441.7	441.5	441.6	441.6	441.5	441.5
10	4+45	437.0	442.0	439.0	438.9	440.7	443.8	442.2	442.1	442.1	442.1	442.0	442.0	442.0	442.0	442.0	442.0	442.0	441.9	441.9	442.0	441.9	441.9
11	4+49	427.0	442.0	435.6	431.3	437.1	446.1	442.0	441.8	441.9	442.0	441.8	441.8	441.4	441.3	441.5	441.5	441.5	441.4	441.5	441.4	441.5	441.4
12	4+49	437.0	442.0	439.8	439.4	441.5	443.9	442.6	442.5	441.6	442.4	442.4	442.4	442.3	442.3	442.3	442.3	442.3	442.2	442.2	442.2	442.2	442.1
13	4+53	427.0	442.0	436.7	432.2	437.4	446.1	442.0	441.8	441.9	441.9	441.8	441.8	441.4	441.4	441.6	441.6	441.6	441.5	441.5	441.5	441.5	441.5
14	4+53	437.0	442.0	440.9	439.7	440.8	444.8	443.2	443.1	443.2	443.1	443.1	443.1	443.0	443.0	443.0	443.0	443.0	443.0	443.0	443.0	443.0	443.0
15	4+57	427.0	442.0	437.8	433.5	438.8	446.0	442.0	441.8	442.0	442.0	441.9	441.8	441.5	441.5	441.7	441.7	441.7	441.5	441.6	441.6	441.6	441.6
16	4+57	437.0	442.0	440.9	439.4	441.5	445.1	443.5	443.2	443.2	443.2	443.2	443.1	443.0	443.0	443.0	443.0	443.0	443.0	443.0	443.0	443.0	443.0

Note: Upper pool el 504.0 and lower pool el 442.0.
Lock emptied in 11.2 min with 1.5-min valve.
Bulkhead slots below filling valve closed.
* T denotes time (in prototype seconds) after beginning of movement of valves.
** LC denotes elevation of water surface in lock chamber.

Table 5

Effect of Manifold Location on Filling Characteristics

Types 1-10 Multiport Arrangement, 8-in.-diam Ports

				Maximum Hawser Stresses											
				Longitudinal				Upstream Transverse				Downstream Transverse			
	Percent of Lock Chamber Upstream of	Valve Time	Filling Time	Upstream		Downstream		Left		Right		Left		Right	
Type	Port Manifold	min	min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min
1	22.1	2	9.8	5.2	1.6	3.5	2.1	3.5	2.3	1.8	1.1	3.3	2.5	1.7	2.4
		4	11.0	4.0	3.4	2.7	4.0	2.2	4.4	1.7	1.8	2.4	4.3	1.8	4.6
		8	13.3	3.5	5.1	2.2	5.0	1.7	6.1	1.1	4.8	2.1	4.9	1.4	4.8
2	24.1	2	9.8	4.6	1.7	2.5	2.5	2.6	2.0	2.0	3.3	2.7	2.0	2.2	1.9
		4	11.0	3.4	3.2	2.0	2.3	1.7	2.9	1.1	2.4	1.6	2.2	2.1	3.8
		8	13.3	2.4	6.0	1.8	4.6	1.2	4.4	1.4	4.3	1.3	4.2	2.0	4.3
3	26.1	2	9.8	4.5	1.6	2.0	2.5	2.0	2.0	1.6	2.3	2.1	2.0	2.5	1.8
		4	11.0	3.3	3.2	1.6	3.8	1.6	3.8	1.4	3.7	1.2	4.4	2.3	3.8
		8	13.3	2.3	5.2	1.6	4.3	1.1	7.1	1.0	6.2	1.0	7.4	2.0	6.5
4	28.1	2	9.8	5.2	1.6	1.8	2.7	2.2	2.6	1.3	3.4	1.9	2.1	2.3	2.7
		4	11.0	3.0	3.1	1.6	3.9	1.6	3.7	1.2	3.3	1.2	3.2	2.0	4.0
		8	13.3	2.3	4.9	1.4	5.0	1.1	4.5	1.0	5.1	1.1	4.2	1.6	5.1
5	30.8	2	9.8	6.5	1.5	1.7	2.3	2.2	2.9	1.5	2.3	2.2	1.9	2.2	2.2
		4	11.0	3.1	3.1	1.6	3.8	2.0	3.8	1.8	3.9	1.6	4.4	2.1	3.7
		8	13.3	1.6	4.9	1.5	10.8	0.7	6.3	1.2	6.4	1.2	10.2	1.4	5.7
6	17.4	2	9.8	4.3	2.3	4.5	1.3	2.7	2.0	1.6	1.7	2.3	2.5	2.7	1.7
		4	11.0	3.5	3.4	3.2	2.3	2.1	3.9	1.2	3.5	2.4	2.5	2.5	3.1
		8	13.3	2.8	5.9	2.7	4.6	1.5	6.5	1.2	5.6	1.8	3.9	1.2	4.1
7	20.1	2	9.8	3.2	1.6	3.1	0.4	2.4	1.8	1.2	1.7	1.6	2.6	1.5	1.0
		4	11.0	2.6	3.5	2.4	0.3	1.5	3.7	1.8	3.4	1.4	3.7	1.7	3.4
		8	13.3	2.3	5.5	2.0	5.2	1.0	6.9	1.6	6.0	1.2	5.9	1.6	6.2
8	22.1	2	9.8	2.8	1.7	2.7	0.3	2.3	2.4	1.6	2.2	2.3	2.3	2.4	2.0
		4	11.0	2.5	3.2	2.0	0.4	1.7	4.1	1.6	4.0	1.5	2.4	2.1	3.7
		8	13.3	2.0	6.2	1.6	3.8	1.2	6.9	1.0	7.1	1.2	5.8	1.4	5.7
9	23.4	2	9.8	3.2	1.5	2.3	0.3	2.1	2.4	2.0	2.1	1.6	2.5	2.2	2.1
		4	11.0	2.5	2.5	1.6	1.3	1.6	4.2	0.9	3.3	1.2	4.1	1.7	4.0
		8	13.3	2.0	5.9	1.2	7.6	0.7	5.2	1.1	7.1	0.9	8.1	1.3	6.9
10	26.1	2	9.8	4.0	1.5	2.0	0.3	1.9	2.4	1.3	1.6	1.6	2.4	2.0	3.4
		4	11.0	2.7	3.4	1.4	3.9	1.2	4.5	1.2	3.4	0.9	3.3	1.8	3.4
		8	13.3	2.0	5.5	1.0	5.4	0.6	5.5	0.8	6.2	0.8	6.1	1.2	7.7

Note: Time listed under hawser stresses is time of occurrence after beginning of movement of valves.
Upper pool el 504.0 and lower pool el 442.0.
4-barge tow (7280 tons displacement) positioned 30 ft below upstream miter gate pintles.
(In arrangements 6-10 the miter gates were shifted 21 ft downstream to increase distance between filling valves and port manifold.)

Table 6

Effect of Tow Size and Position on Filling and Emptying Characteristics

Type 8 Multiport Arrangement, 8-in.-diam Ports

Number of Barges	Distance Between Tow and Upstream Miter Gate Pintles, ft	Valve Time min	Filling or Emptying Time, min	Maximum Hawser Stresses: Longitudinal, Upstream, Pull tons	Longitudinal, Upstream, Time min	Longitudinal, Downstream, Pull tons	Longitudinal, Downstream, Time min	Upstream Transverse, Left, Pull tons	Upstream Transverse, Left, Time min	Upstream Transverse, Right, Pull tons	Upstream Transverse, Right, Time min	Downstream Transverse, Left, Pull tons	Downstream Transverse, Left, Time min	Downstream Transverse, Right, Pull tons	Downstream Transverse, Right, Time min
Filling Operations															
4*	30	2	9.8	2.8	1.7	2.7	0.3	2.3	2.4	1.6	2.2	2.3	2.3	2.4	2.0
		4	11.0	2.5	3.2	2.0	0.4	1.7	4.1	1.6	4.0	1.5	2.4	2.1	3.7
		8	13.3	2.0	6.2	1.6	3.8	1.2	6.9	1.0	7.1	1.2	5.8	1.4	5.7
2	30	2	9.8	3.0	1.4	2.9	2.2	1.9	1.7	0.9	0.5	2.3	2.1	0.9	0.5
		4	11.0	2.0	2.4	1.7	4.1	1.4	3.0	0.8	3.1	1.8	2.9	0.7	1.4
		8	13.3	1.8	5.7	1.6	6.5	1.0	4.9	0.6	5.0	1.2	4.7	0.5	3.3
2	225	2	9.8	2.3	2.1	3.1	1.1	0.9	1.9	1.1	1.6	0.7	1.8	1.1	1.6
		4	11.0	1.8	3.8	1.7	0.3	0.8	2.4	0.5	3.4	0.8	2.2	0.9	3.0
		8	13.3	1.3	7.8	1.3	4.0	0.6	3.7	0.6	6.0	0.5	3.1	0.7	3.2
Emptying Operations															
4	30	1.5	11.2	1.9	2.2	1.9	2.4	0.7	1.1	0.7	0.8	1.2	0.6	1.5	0.8
		3.0	12.0	1.8	4.3	1.4	4.6	0.7	4.0	0.5	3.7	1.2	4.4	1.2	3.5
		6.0	13.6	1.6	5.7	1.2	4.8	0.6	3.2	0.5	3.5	1.1	5.1	1.0	5.7
2	30	1.5	11.2	2.0	2.8	2.0	2.4	1.3	2.9	1.2	2.3	1.4	1.3	1.6	6.6
		3.0	12.0	1.8	2.8	1.7	2.7	1.2	4.5	1.2	7.1	1.3	6.7	1.4	4.7
		6.0	13.6	1.7	4.5	1.6	4.3	1.1	5.8	0.8	3.5	1.2	10.9	1.3	10.8
2	225	1.5	11.2	2.0	3.3	2.0	3.4	1.1	2.9	1.0	3.2	1.2	3.3	1.2	3.6
		3.0	12.0	1.6	3.6	1.5	4.4	1.1	6.5	1.2	6.5	1.1	3.2	1.1	3.5
		6.0	13.6	1.4	2.7	1.6	2.2	0.8	4.8	0.8	8.0	1.0	4.4	0.9	5.9

Note: Time listed under hawser stresses is time of occurrence after beginning of movement of valves.
Upper pool el 504.0 and lower pool el 442.0.

* 4-barge tow, 7280 tons displacement; 2-barge tow, 3640 tons displacement.

Table 7

Average Piezometer Readings During Filling Operation - Type 8 Multiport Arrangement

Piezometer Locations: Piez No.	Station	El	Average Piezometer Reading in Prototype Feet of Water: T* = 0, LC** = 442.0	T = 30, LC = 442.6	T = 60, LC = 443.6	T = 90, LC = 445.1	T = 120, LC = 447.0	T = 150, LC = 449.8	T = 180, LC = 453.9	T = 210, LC = 459.1	T = 240, LC = 464.9	T = 270, LC = 470.3	T = 300, LC = 475.4	T = 330, LC = 479.8	T = 360, LC = 484.1	T = 390, LC = 488.0	T = 420, LC = 491.1	T = 450, LC = 494.1	T = 480, LC = 496.3	T = 540, LC = 500.7	T = 600, LC = 503.1	T = 660, LC = 504.0
Filling Valve Piezometer Group A																							
1	0+21	424.0	504.0	504.0	502.6	501.0	498.1	492.0	481.5	472.9	474.5	478.0	482.0	485.8	488.7	491.2	493.0	495.9	498.1	501.4	503.2	504.0
2	0+24	424.0	504.0	504.0	502.6	501.0	498.0	492.0	481.5	472.9	474.5	478.0	482.0	485.3	488.7	491.2	493.5	495.9	498.1	501.4	503.2	504.0
3	0+30	434.0	504.0	504.0	502.6	501.0	498.7	491.8	481.0	472.2	474.0	477.6	481.7	485.4	488.3	491.0	493.2	495.8	497.9	501.3	503.1	504.0
4	0+33	434.0	504.0	504.0	502.6	501.0	497.9	491.7	480.9	472.2	474.0	477.7	481.7	485.8	488.3	491.0	493.2	495.8	497.9	501.3	503.1	504.0
5	0+40	434.0	504.0	504.0	502.6	500.9	497.9	491.6	480.8	472.2	474.6	477.9	481.9	484.8	488.6	491.2	493.5	495.9	498.0	501.4	503.2	504.0
6	0+59	424.0	442.0	442.0	450.6	466.2	473.2	470.0	466.3	466.1	472.9	476.6	480.8	484.7	487.6	490.2	492.8	495.1	497.9	501.2	503.1	504.0
8	0+67	424.0	442.0	439.7	435.2	434.6	433.6	434.0	442.0	460.3	472.3	476.2	480.3	484.6	487.6	490.3	492.9	495.3	497.8	501.0	503.1	504.0
9	0+70	424.0	442.0	439.6	434.5	434.1	432.9	432.8	440.2	461.0	472.3	476.1	480.3	484.6	487.5	490.2	492.9	495.3	497.8	501.0	503.1	504.0
10	0+73	424.0	442.0	439.8	434.8	434.7	433.1	433.0	441.0	461.9	472.4	476.1	480.3	484.7	487.5	490.2	492.9	495.3	497.8	501.0	503.1	504.0
11	0+76	424.0	442.0	439.8	435.2	435.2	433.5	434.0	442.8	462.8	472.4	476.1	480.3	484.5	487.5	490.2	492.9	495.3	497.8	501.0	503.1	504.0
12	0+79	424.0	442.0	440.0	435.9	438.1	434.4	435.0	445.3	464.3	472.7	476.2	480.5	484.7	487.7	490.3	492.9	495.4	497.9	501.2	503.2	504.0
13	0+82	424.0	442.0	440.0	437.0	436.3	435.3	436.3	447.8	465.2	472.9	476.5	480.7	484.8	487.7	490.4	493.0	495.5	497.9	501.2	503.2	504.0
14	0+85	424.0	442.0	439.6	438.0	436.5	435.7	437.1	449.7	465.9	473.2	476.9	480.9	484.9	487.9	490.7	493.1	495.6	498.0	501.3	503.3	504.0
15	0+88	424.0	442.0	439.7	438.7	437.0	436.0	437.9	451.9	466.9	473.8	477.5	481.4	485.3	488.1	490.9	493.2	495.8	498.1	501.4	503.3	504.0
16	0+91	424.0	442.0	440.3	439.2	437.7	436.9	438.8	453.8	467.7	474.5	478.0	481.9	485.7	488.6	491.2	493.5	496.0	498.2	501.5	503.3	504.1
17	0+94	424.0	442.0	441.4	439.8	438.3	437.8	440.0	455.3	468.2	475.0	478.6	482.2	486.0	488.9	491.4	493.7	496.1	498.3	501.5	503.3	504.0
18	0+97	424.0	442.0	441.8	440.1	439.0	439.0	441.7	456.8	468.8	475.6	479.0	482.8	486.3	489.0	491.7	493.9	496.3	498.5	501.7	503.4	504.2
19	1+00	424.0	442.0	442.0	440.7	439.9	440.5	442.0	457.7	469.1	476.0	479.4	483.0	486.7	489.3	491.9	494.0	496.5	498.7	501.8	503.5	504.2
Culvert Piezometer Group B																							
1	1+21	430.0	442.0	442.6	443.5	444.6	446.8	451.3	461.6	471.1	477.8	480.8	484.2	487.8	490.2	492.5	494.7	496.8	498.9	501.9	503.6	504.2
3	1+61	430.0	442.0	442.6	444.0	446.4	449.4	455.0	465.2	475.1	481.3	483.9	486.8	489.9	492.0	494.0	495.8	497.8	499.7	502.1	503.7	504.3
5	2+01	430.0	442.0	442.4	444.0	446.6	450.0	456.3	467.2	479.0	485.0	487.1	489.8	492.3	494.1	495.8	497.3	498.9	500.5	502.7	503.9	504.4
7	2+41	430.0	442.0	442.3	444.0	446.6	450.4	456.7	468.3	481.0	487.5	489.2	490.3	493.8	495.2	496.8	498.2	499.7	500.9	502.9	503.9	504.4
9	2+81	430.0	442.0	442.2	444.0	446.5	450.7	457.2	469.6	482.9	489.0	490.5	492.6	494.7	496.0	497.4	498.8	500.0	501.2	503.0	504.0	504.6
11	3+21	430.0	442.0	442.2	444.0	446.5	450.8	457.5	470.0	483.7	489.7	491.2	493.2	495.1	496.5	497.9	498.9	500.2	501.5	503.1	504.0	504.6
13	3+61	430.0	442.0	442.2	444.0	446.5	450.6	457.3	469.8	483.6	490.0	491.6	493.1	495.3	496.6	498.0	499.0	500.3	501.6	503.2	504.0	504.6

Note: Lock filled in 11.0 min with 4-min valve.
Bulkhead slots below filling valve closed.
Upper pool el 504.0 and lower pool el 442.0.
* T denotes time (in prototype seconds) after beginning of movement of valves.
** LC denotes elevation of water surface in lock chamber.

Table 8

Average Piezometer Readings During Emptying Operation - Type 8 Multiport Arrangement

Piezometer Locations			Average Piezometer Reading in Prototype Feet of Water																				
Piez No.	Station	El	T* = 0 LC** = 504.0	T = 30 LC = 503.2	T = 60 LC = 501.0	T = 90 LC = 496.4	T = 120 LC = 491.3	T = 150 LC = 486.5	T = 180 LC = 481.6	T = 210 LC = 477.1	T = 240 LC = 472.9	T = 270 LC = 469.0	T = 300 LC = 465.2	T = 330 LC = 461.9	T = 360 LC = 458.7	T = 390 LC = 455.8	T = 420 LC = 453.4	T = 450 LC = 451.2	T = 480 LC = 449.2	T = 540 LC = 446.0	T = 600 LC = 443.7	T = 660 LC = 442.2	T = 720 LC = 441.5
Culvert Piezometer Group B																							
2	1+41	430.0	504.0	503.0	498.5	488.0	481.4	476.4	472.5	468.9	465.7	462.8	459.7	457.0	454.8	452.7	450.7	448.9	447.3	444.9	443.2	442.3	
4	1+81	430.0	504.0	502.9	498.5	487.9	480.7	475.9	472.0	468.3	465.2	462.4	459.3	456.8	454.7	452.3	450.5	448.8	447.1	444.8	443.1	442.2	
6	2+21	430.0	504.0	502.8	497.9	486.1	478.9	473.9	470.3	466.9	463.9	461.3	458.5	456.0	453.9	451.9	450.0	448.2	447.0	444.7	443.0	442.1	
8	2+61	430.0	504.0	502.6	497.0	483.2	475.8	470.8	467.6	464.5	461.8	459.4	456.8	454.6	452.6	450.8	449.1	447.6	446.5	444.3	442.9	442.0	
10	3+01	430.0	504.0	502.2	495.3	478.0	471.0	465.8	463.0	460.3	458.3	456.2	454.0	452.1	450.7	449.1	447.9	446.5	445.6	443.9	442.7	442.0	
12	3+41	430.0	504.0	501.8	493.2	470.9	463.3	458.0	455.9	454.1	452.8	450.1	449.7	448.3	447.5	446.3	445.8	444.9	444.2	443.1	442.3	442.0	
14	3+81	430.0	504.0	501.3	491.9	467.3	461.3	455.9	453.9	452.7	451.3	449.9	448.7	447.6	446.7	445.9	445.2	444.3	443.9	443.0	442.2	442.0	
Emptying Valve Piezometer Group C																							
1	4+13	427.0	504.0	500.9	488.6	455.5	450.0	444.2	443.7	443.5	443.4	442.9	442.7	442.3	442.2	442.1	442.3	442.0	442.0	442.0	442.0	442.0	
2	4+29	427.0	442.0	448.0	472.7	450.0	448.8	443.0	442.8	442.8	443.0	442.6	442.2	442.1	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	
3	4+33	427.0	442.0	438.8	440.2	444.3	448.0	442.8	442.2	442.5	442.7	442.3	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	
5	4+37	427.0	442.0	436.8	430.0	439.8	447.6	442.6	441.9	442.3	442.4	442.1	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	
7	4+41	427.0	442.0	435.7	429.1	436.4	447.3	442.5	441.9	442.2	442.3	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	
9	4+45	427.0	442.0	435.9	430.0	435.0	447.4	442.5	441.9	442.2	442.3	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	
11	4+49	427.0	442.0	436.5	431.1	434.9	447.4	442.7	442.1	442.4	442.5	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	
13	4+53	427.0	442.0	438.4	433.1	435.4	447.6	442.9	422.2	442.6	442.6	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	
15	4+57	427.0	442.0	440.0	434.1	436.2	447.3	442.8	442.0	442.3	442.4	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	

Note: Lock emptied in 11.2 min with 1.5-min valve.
Upper pool el 504.0 and lower pool el 442.0.
* T denotes time (in prototype seconds) after beginning of movement of valves.
** LC denotes elevation of water surface in lock chamber.

Table 9

Effect of Single Valve Operation on Filling and Emptying Characteristics

Type 8 Multiport Arrangement

			Maximum Hawser Stresses											
			Longitudinal				Upstream Transverse				Downstream Transverse			
		Filling	Upstream		Downstream		Left		Right		Left		Right	
Number of Barges	Valve Time min	or Emptying Time, min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min
						Filling Operations								
4*	2	19.5	1.6	1.6	1.2	0.4	1.2	2.1	1.6	1.2	1.4	2.1	1.7	1.0
	4	21.5	1.6	3.1	1.2	16.7	0.5	4.1	1.4	4.0	0.9	5.1	1.3	4.0
	8	25.5	1.6	5.5	1.2	9.7	0.6	19.6	1.2	5.9	0.8	17.5	1.3	5.0
						Emptying Operations								
4	1.5	22.9	1.9	7.9	1.9	7.8	0.8	6.1	0.5	7.0	1.1	1.7	0.9	11.4
	3	24.1	1.7	6.3	1.5	15.1	0.8	2.2	0.7	16.8	1.1	6.6	0.9	2.1
	6	26.3	1.4	3.9	1.2	5.5	0.5	3.2	0.5	8.5	0.9	1.2	0.7	6.3

Note: Time listed under hawser stresses is time of occurrence after beginning of movement of valves. River-wall filling and emptying valves were closed during operation.
Upper pool el 504.0 and lower pool el 442.0.

* 4-barge tow (7280 tons displacement) positioned 30 ft below upstream miter gate pintles.

Table 10

Filling Characteristics for Range of Lifts

Type 8 Multiport Arrangement

					Maximum Hawser Stresses															
					Longitudinal				Upstream Transverse				Downstream Transverse							
					Upstream		Downstream		Left		Right		Left		Right					
Lift ft	Lower Pool El	Upper Pool El	Valve Time min	Filling Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min				
40	442	482	2	8.0	2.2	1.8	2.3	1.2	1.1	2.9	0.7	1.4	0.8	3.1	1.6	2.4				
			4	9.2	2.0	3.5	1.6	2.4	0.8	2.7	0.9	3.0	1.1	3.8	1.4	3.9				
			8	11.4	1.3	5.4	1.3	9.0	0.8	6.1	0.7	5.6	0.9	2.6	1.1	5.6				
50	442	492	2	8.8	2.5	1.6	2.3	0.2	1.7	2.0	1.0	2.1	1.6	2.2	1.8	2.0				
			4	10.0	2.3	3.4	1.5	7.4	1.2	3.2	1.1	2.9	0.9	3.2	1.2	2.9				
			8	12.2	1.5	6.4	1.1	7.2	1.0	3.8	0.9	3.7	1.2	5.2	1.2	6.2				
60	442	502	2	9.6	2.3	1.6	2.5	0.3	1.6	2.6	1.3	1.8	1.3	2.5	2.3	1.8				
			4	10.8	1.9	3.2	1.2	3.0	1.3	4.4	1.1	3.0	1.5	4.2	2.1	2.9				
			8	13.0	1.5	6.0	1.4	5.2	0.7	8.0	0.7	6.2	0.9	8.8	1.2	6.5				
66	442	508	2	10.1	2.5	2.6	2.9	0.3	1.8	2.5	0.8	1.7	1.6	1.3	2.1	1.9				
			4	11.3	2.3	3.5	1.6	3.7	1.2	4.9	1.2	3.5	1.8	4.1	2.0	3.5				
			8	13.5	1.6	6.2	1.4	1.3	0.8	6.3	1.0	7.0	1.2	6.2	1.4	6.6				
72	442	514	2	10.6	2.3	1.5	3.1	0.3	2.0	2.3	1.6	1.6	1.9	2.1	2.5	1.4				
			4	11.8	2.0	3.4	2.0	2.2	1.8	3.5	1.0	3.6	1.2	3.5	2.0	3.4				
			8	14.0	1.9	6.0	1.6	4.2	0.8	5.7	0.8	5.5	1.4	4.6	1.1	5.6				

Note: Time listed under hawser stresses is time of occurrence after beginning of movement of valves. Submergence was 14 ft.

Table 11

Filling Characteristics for Range of Lifts

Type 11 Multiport Arrangement

					Maximum Hawser Stresses															
					Longitudinal				Upstream Transverse				Downstream Transverse			
					Upstream		Downstream		Left		Right		Left		Right	
Lift ft	Number of Barges*	Distance Between Tow and Upstream Miter Gate Pintles, ft	Valve Time min	Filling Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min
40	4*	30	2	7.4	2.8	0.8	2.7	0.4	2.3	2.3	0.8	0.2	2.0	2.1	0.9	0.2
			4	8.6	1.6	3.2	1.6	4.0	1.5	4.1	0.5	2.7	1.4	3.9	1.1	2.9
			8	10.9	1.4	5.9	1.5	6.2	0.7	5.9	0.7	5.2	0.8	7.0	0.9	4.1
62	4	30	2	8.9	3.5	0.7	3.1	0.4	3.1	2.1	0.7	0.2	2.7	1.7	1.2	1.5
			4	10.1	2.9	3.2	2.8	3.8	2.2	4.0	0.7	1.8	2.0	2.7	1.2	3.0
			8	12.4	1.8	6.7	1.6	6.8	1.2	5.8	0.6	2.6	1.0	5.9	1.2	5.7
62	2	30	2	8.9	3.5	0.6	2.4	2.8	1.8	2.6	1.8	1.0	2.5	2.7	1.9	1.0
			4	10.1	2.7	2.7	2.1	4.9	1.6	2.2	1.5	3.0	2.3	3.4	1.7	2.3
			8	12.4	2.1	5.8	2.0	5.2	1.3	4.4	1.3	4.6	1.7	4.7	1.4	5.0
62	2	225	2	8.9	2.7	2.5	3.7	1.2	1.2	1.7	0.9	1.8	1.6	1.7	1.5	1.6
			4	10.1	2.3	4.0	2.7	2.8	1.1	3.8	0.6	2.1	1.1	3.7	1.0	3.4
			8	12.4	1.6	6.5	2.3	4.0	1.1	5.8	0.4	6.2	1.1	4.6	0.7	3.4
72	4	30	2	9.6	3.5	0.7	3.2	0.4	3.2	2.0	1.1	1.3	3.0	1.5	1.8	1.4
			4	10.8	2.8	3.2	2.1	3.0	2.4	4.2	0.5	2.5	2.5	3.0	1.6	2.2
			8	13.1	2.0	5.9	2.3	5.8	1.6	7.9	0.7	3.7	1.5	4.7	1.1	4.5

Note: Time listed under hawser stresses is time of occurrence after beginning of movement of valves. Submergence is 14 ft.
* 4-barge tow, 7280 tons displacement; 2-barge tow, 3640 tons displacement.

Table 12

Effect of Port Diameter and Positioning on Filling Characteristics

Types 12-17 Multiport Arrangements

			Maximum Hawser Stresses											
			Longitudinal				Upstream Transverse				Downstream Transverse			
			Upstream		Downstream		Left		Right		Left		Right	
Type	Valve Time min	Filling Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min	Pull tons	Time min
			Arrangements with 10-in.-diam Ports											
12	2	8.9	3.1	0.7	2.9	0.3	1.9	2.0	1.2	1.6	1.6	1.5	2.0	2.1
	4	10.1	2.7	3.6	2.4	3.5	1.6	3.9	1.5	2.7	1.6	3.7	2.0	3.6
	8	12.4	2.1	6.1	2.1	5.9	1.3	3.9	1.3	4.7	1.8	4.3	1.8	4.7
13	2	8.9	3.3	1.7	3.1	0.4	1.8	2.1	1.0	1.3	2.2	1.7	1.6	1.2
	4	10.1	2.5	3.2	2.0	2.9	1.6	3.2	1.1	3.3	1.7	3.8	1.6	3.5
	8	12.4	2.3	7.5	1.9	7.4	1.2	4.6	0.9	4.5	1.6	6.0	1.6	5.7
14	2	8.3	5.1	0.8	4.7	1.9	2.3	2.6	2.3	1.9	2.0	2.5	3.3	1.9
	4	9.5	3.5	3.8	4.5	4.0	1.7	3.5	1.9	3.3	1.9	3.2	2.2	3.3
	8	11.8	3.2	6.8	3.2	6.2	1.7	7.5	1.8	7.6	1.8	6.0	2.1	5.9
			Arrangements with 12-in.-diam Ports											
15	2	8.9	4.5	1.8	3.0	0.4	2.6	2.1	1.2	2.4	1.6	1.5	2.2	2.1
	4	10.1	2.7	3.5	2.0	2.7	1.9	2.3	1.1	2.4	1.6	4.5	2.0	4.1
	8	12.4	2.1	6.1	1.6	4.5	1.6	5.5	1.1	5.6	2.0	5.6	1.9	5.5
16	2	8.9	4.0	0.8	3.1	1.3	1.2	2.3	1.4	1.7	1.8	1.6	2.1	1.2
	4	10.1	2.0	3.3	1.6	3.0	1.9	3.1	1.4	2.7	1.9	2.0	2.0	2.1
	8	12.4	1.6	5.1	1.3	4.4	1.6	6.2	1.4	6.3	1.7	5.4	1.7	5.5
17	2	8.9	3.4	0.8	2.7	0.4	2.0	2.1	2.4	1.8	1.6	1.2	2.6	2.2
	4	10.1	2.0	0.9	1.5	0.4	0.9	2.9	1.6	4.0	1.6	2.9	2.1	3.9
	8	12.4	1.8	7.9	1.7	6.0	1.0	4.9	1.2	5.3	1.0	5.1	1.9	7.4

Note: Time listed under hawser stresses is time of occurrence after beginning of movement of valves.
Upper pool el 504.0 and lower pool el 442.0.
4-barge tow (7280 tons displacement) positioned 30 ft below upstream miter gate pintles.
Lock emptied in 10.3 min with 1.5-min valve; 2.5-ton maximum hawser stresses.

Table 13

Average Piezometer Readings During Filling Operation - Type 13 Multiport Arrangement

Piezometer Locations			Average Piezometer Reading in Prototype Feet of Water																			
Piez No.	Station	El	T* = 0 LC** = 442.0	T = 30 LC = 442.6	T = 60 LC = 443.3	T = 90 LC = 444.6	T = 120 LC = 446.5	T = 150 LC = 449.4	T = 180 LC = 453.5	T = 210 LC = 458.6	T = 240 LC = 465.0	T = 270 LC = 471.1	T = 300 LC = 476.5	T = 330 LC = 481.3	T = 360 LC = 486.0	T = 390 LC = 489.9	T = 420 LC = 493.3	T = 450 LC = 496.2	T = 480 LC = 498.7	T = 540 LC = 502.2	T = 600 LC = 503.8	T = 660 LC = 504.5
Filling Valve Piezometer Group A																						
1	0+21	424.0	504.0	503.8	502.8	501.2	498.3	492.1	482.6	469.6	466.7	471.8	477.0	481.8	486.5	490.3	493.6	496.7	499.0	502.1	503.9	504.1
2	0+24	424.0	504.0	503.8	502.8	501.1	498.2	492.0	482.3	469.4	466.5	471.7	476.9	481.7	486.3	490.2	493.6	496.8	499.0	502.1	503.8	504.1
3	0+30	434.0	504.0	503.8	502.8	501.1	498.2	491.9	482.0	469.0	465.8	471.2	476.6	481.4	486.0	490.0	493.5	496.7	499.0	502.1	503.9	504.1
4	0+33	434.0	504.0	503.7	502.7	501.1	498.1	491.9	482.0	468.8	465.8	471.2	476.5	481.4	486.0	490.0	493.5	496.7	498.9	502.2	503.9	504.1
5	0+40	434.0	504.0	503.7	502.7	501.1	498.1	491.8	481.8	468.3	466.4	471.7	476.8	481.6	486.3	490.1	493.8	497.6	499.0	502.2	503.9	504.1
6	0+59	424.0	442.0	441.9	451.0	465.7	473.0	472.0	466.7	461.5	465.0	470.3	475.6	480.7	485.4	489.5	493.0	496.2	498.8	501.9	503.8	504.0
8	0+67	424.0	442.0	440.4	437.7	436.1	434.9	434.6	440.6	453.2	465.0	470.7	475.9	481.0	485.6	489.6	493.0	496.1	498.7	501.9	503.6	504.0
9	0+70	424.0	442.0	440.0	436.7	435.3	434.0	432.7	437.6	453.0	466.1	471.6	476.8	481.7	486.1	490.1	493.5	496.7	498.9	502.0	503.8	504.2
10	0+73	424.0	442.0	439.6	435.9	434.8	433.3	432.0	436.7	453.1	466.8	472.1	477.2	482.1	486.4	490.3	493.6	496.7	499.0	502.0	503.7	504.0
11	0+76	424.0	442.0	439.8	436.7	436.0	434.2	433.2	437.4	545.1	468.0	473.0	477.8	482.6	486.9	490.6	493.7	496.7	498.9	502.0	503.5	504.0
12	0+79	424.0	442.0	439.6	436.6	435.8	434.0	433.1	438.0	456.0	468.8	473.8	478.7	483.3	487.4	491.0	494.3	497.0	499.2	502.2	503.9	504.1
13	0+82	424.0	442.0	439.8	436.9	436.2	434.9	434.0	440.0	458.0	469.8	474.7	479.3	483.9	487.8	491.1	494.2	497.0	499.2	502.1	503.7	504.0
14	0+85	424.0	442.0	439.8	436.8	435.9	434.9	434.0	441.5	459.0	470.3	475.1	479.6	484.2	488.1	491.7	494.7	497.4	499.7	502.5	503.8	504.1
15	0+88	424.0	442.0	439.8	437.1	436.0	435.2	435.2	444.0	460.8	471.0	475.8	480.1	484.6	488.5	492.0	494.8	497.7	499.8	502.5	503.9	504.1
16	0+91	424.0	442.0	440.0	438.3	437.0	436.2	437.1	446.1	461.3	470.7	475.3	479.0	484.4	488.3	491.9	494.7	497.6	499.7	502.4	503.9	504.2
17	0+94	424.0	442.0	440.5	439.1	437.4	436.9	438.9	447.8	461.4	470.5	475.2	479.9	484.3	488.2	491.6	494.8	497.5	499.6	502.4	504.0	504.3
18	0+97	424.0	442.0	441.1	439.9	437.6	437.7	440.0	448.9	461.4	470.3	475.1	479.8	484.2	488.1	491.7	494.6	497.4	499.5	502.4	503.9	504.2
19	1+00	424.0	442.0	441.7	440.6	438.1	438.9	441.3	450.0	461.5	470.2	475.0	479.7	484.0	488.0	491.6	494.5	497.3	499.5	502.4	503.9	504.3
Culvert Piezometer Group B																						
1	1+21	430.0	442.0	442.0	442.9	443.2	445.0	448.9	454.9	464.0	472.0	476.7	481.9	485.2	489.0	492.3	495.3	498.0	500.0	502.8	504.0	504.5
3	1+61	430.0	442.0	442.2	443.3	445.1	448.0	452.6	458.7	468.3	476.1	480.1	484.0	487.7	491.0	493.8	496.4	498.9	500.6	503.0	504.0	504.4
5	2+01	430.0	442.0	442.0	443.0	445.1	448.4	453.6	460.9	471.6	480.3	483.8	487.0	490.0	493.0	495.4	497.7	499.7	501.1	503.0	504.0	504.4
7	2+41	430.0	442.0	442.0	443.0	445.1	448.7	453.9	461.8	473.2	483.4	486.5	489.3	492.0	494.5	496.7	498.6	500.4	501.8	503.6	504.3	504.6
9	2+81	430.0	442.0	442.0	443.0	445.1	448.9	454.3	462.7	474.8	485.5	488.2	490.7	493.1	495.3	497.5	499.3	500.8	502.0	503.6	504.2	504.5
11	3+21	430.0	442.0	442.0	443.0	445.1	448.9	454.7	463.1	476.0	486.7	489.1	491.6	493.8	495.8	498.0	499.6	501.0	502.0	503.5	504.1	504.4
13	3+61	430.0	442.0	442.0	443.0	445.0	448.7	454.3	462.9	475.9	486.8	489.4	491.6	493.7	495.7	497.7	499.4	500.8	501.9	503.4	504.0	504.2

Note: Lock filled in 10.1 min with 4-min valve.
Bulkhead slots below filling valve closed.
Upper pool el 504.0 and lower pool el 442.0.
* T denotes time (in prototype seconds) after beginning of movement of valves.
** LC denotes elevation of water surface in lock chamber.

Table 14

Average Piezometer Readings During Emptying Operation - Type 14 Multiport Arrangement

Piezometer Locations			Average Piezometer Reading in Prototype Feet of Water																			
Piez No.	Station	El	T* = 0 LC** = 504.0	T = 30 LC = 503.2	T = 60 LC = 501.0	T = 90 LC = 496.5	T = 120 LC = 491.3	T = 150 LC = 485.7	T = 180 LC = 480.6	T = 210 LC = 475.5	T = 240 LC = 471.3	T = 270 LC = 467.2	T = 300 LC = 463.4	T = 330 LC = 459.7	T = 360 LC = 456.5	T = 390 LC = 453.8	T = 420 LC = 451.3	T = 450 LC = 449.2	T = 480 LC = 447.1	T = 540 LC = 444.0	T = 600 LC = 442.3	T = 660 LC = 441.6
Culvert Piezometer Group B																						
2	1+41	430.0	504.0	502.0	498.1	489.8	484.0	478.6	474.0	469.7	466.0	462.7	459.6	456.9	454.2	451.8	449.7	447.8	446.3	443.8	442.3	441.6
4	1+81	430.0	504.0	502.0	498.1	489.7	483.7	478.0	473.8	468.4	465.9	462.4	459.4	456.7	454.0	451.6	449.6	447.7	446.2	443.8	442.3	441.6
6	2+21	430.0	504.0	501.9	497.5	487.8	482.0	476.7	472.2	466.8	464.9	461.6	458.6	456.0	453.5	451.0	449.3	447.4	446.0	443.7	442.2	441.6
8	2+61	430.0	504.0	501.7	496.8	485.9	479.8	474.1	470.2	463.9	463.1	460.2	457.4	454.9	452.7	450.4	448.7	447.0	445.7	443.6	442.0	441.6
10	3+01	430.0	504.0	501.3	495.2	481.8	476.0	470.6	467.0	459.6	460.9	458.0	455.6	453.4	451.4	449.4	447.8	446.3	445.3	443.3	442.0	441.6
12	3+41	430.0	504.0	500.7	493.0	476.3	470.6	465.0	462.0	453.1	457.0	455.0	452.9	451.3	449.5	447.8	446.7	445.4	444.5	443.0	442.0	441.7
14	3+81	430.0	504.0	499.9	490.0	467.7	462.5	456.9	454.9	442.0	451.8	450.3	449.0	448.0	446.9	445.8	445.0	444.3	443.6	442.6	442.0	441.7
Emptying Valve Piezometer Group C																						
1	4+13	427.0	504.0	498.8	484.7	452.9	447.8	442.3	442.0	442.0	442.1	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0
2	4+29	427.0	442.0	462.5	469.9	449.8	447.3	442.1	441.9	442.0	442.1	442.1	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0
3	4+33	427.0	442.0	435.7	445.0	446.9	447.0	442.0	441.8	441.9	442.2	442.2	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0
5	4+37	427.0	442.0	434.0	432.9	444.0	446.8	441.9	441.7	441.8	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0
7	4+41	427.0	442.0	433.0	430.0	442.3	446.7	441.7	441.6	441.9	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0
9	4+45	427.0	442.0	433.6	430.3	442.6	446.7	441.9	441.8	441.8	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0
11	4+49	427.0	442.0	434.0	430.8	442.9	446.3	441.8	441.7	441.8	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0
13	4+53	427.0	442.0	435.2	431.8	443.0	446.6	441.9	441.8	441.8	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0
15	4+57	427.0	442.0	435.7	432.7	444.9	446.0	441.7	441.6	441.8	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0	442.0

Note: Lock emptied in 10.3 min with 1.5-min valve.
Upper pool el 504.0 and lower pool el 442.0.
* T denotes time (in prototype seconds) after beginning of movement of valves.
** LC denotes elevation of water surface in lock chamber.

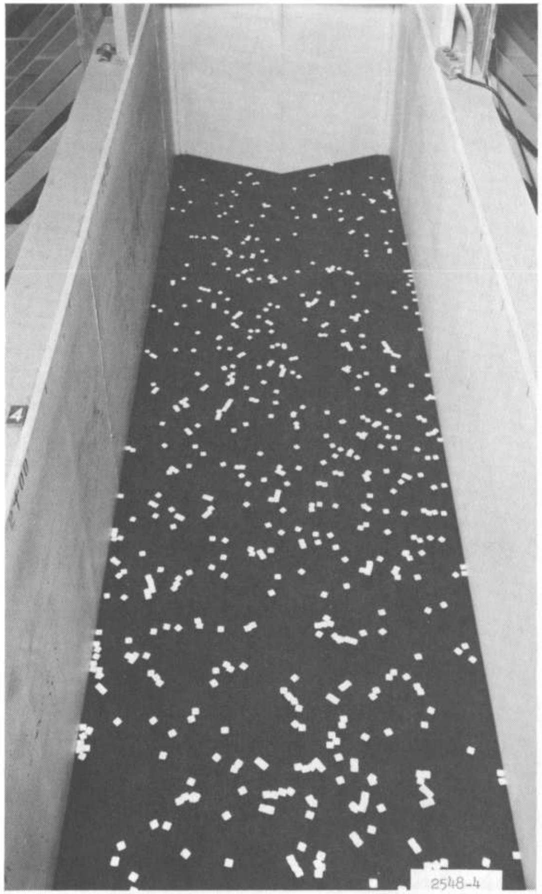
Table 15

Filling Characteristics, Types 19-23 Sidewall Port Arrangements

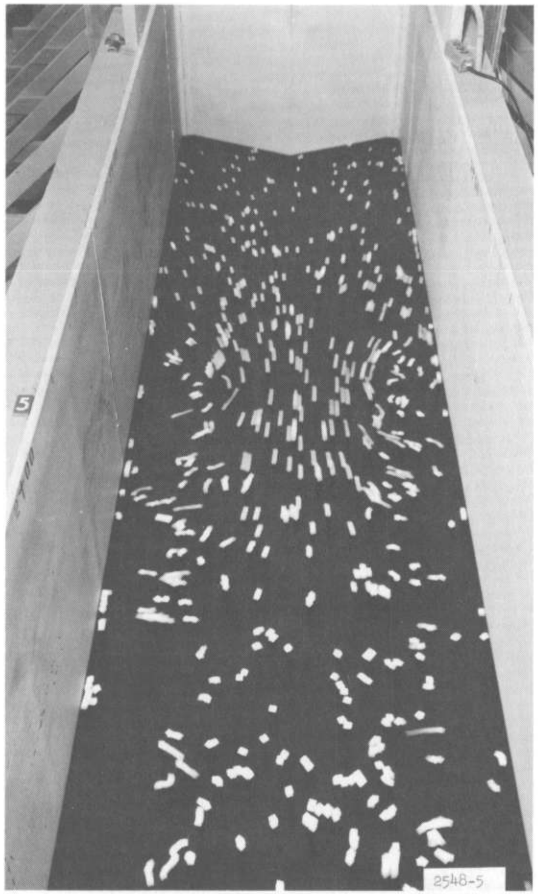
			Maximum Hawser Stresses											
			Longitudinal				Upstream Transverse				Downstream Transverse			
	Valve	Filling	Upstream		Downstream		Left		Right		Left		Right	
	Time	Time	Pull	Time	Pull	Time	Pull	Time	Pull	Time	Pull	Time	Pull	Time
Type	min	min	tons	min	tons	min	tons	min	tons	min	tons	min	tons	min
19	2	8.1	14.0	1.8	3.1	0.4	4.8	2.1	2.7	1.7	3.1	2.3	3.8	2.2
	4	9.3	10.5	3.7	2.3	3.9	2.3	5.5	2.3	3.2	3.1	3.1	3.1	2.9
	8	11.7	8.2	6.6	2.2	6.4	2.0	6.9	1.6	6.6	2.3	4.7	2.0	5.5
20	2	8.1	5.6	3.2	3.1	0.4	2.7	2.1	3.5	1.8	3.5	2.1	3.1	2.9
	4	9.3	4.5	4.2	3.0	2.5	2.3	4.5	2.1	3.1	2.8	4.4	2.8	4.5
	8	11.7	3.9	4.8	3.3	5.0	1.8	6.5	1.2	6.8	2.7	5.0	2.3	6.4
21	2	8.1	5.3	2.7	4.7	2.1	3.2	1.6	2.4	2.6	3.3	1.5	2.7	3.2
	4	9.3	3.1	3.1	4.3	2.8	2.3	3.3	2.0	3.2	2.9	2.5	2.6	2.4
	8	11.7	2.8	4.2	3.7	4.4	1.3	7.7	1.6	7.6	1.6	4.6	1.4	7.4
22	2	8.1	4.7	2.7	4.7	1.2	3.1	1.7	2.5	2.2	3.4	1.7	2.7	2.1
	4	9.3	4.3	3.1	4.1	3.4	2.3	2.4	2.0	4.0	3.1	3.9	2.5	4.1
	8	11.7	3.5	4.6	3.9	3.7	1.6	5.8	1.6	5.9	1.7	5.6	2.2	5.9
23	2	8.1	3.7	0.8	5.6	2.5	3.3	1.8	2.5	1.9	4.6	2.1	3.5	2.2
	4	9.3	2.7	4.1	4.7	4.3	2.5	4.1	1.5	4.7	3.2	4.1	2.3	3.2
	8	11.7	2.5	5.8	3.1	6.5	1.5	6.0	1.1	6.2	2.0	5.2	1.6	5.4

Note: Time listed under hawser stresses is time of occurrence after beginning of movement of valves.
Upper pool el 504.0 and lower pool el 442.0.
Lock emptied in 10.1 min with 1.5-min valve; 2.5 tons maximum hawser stresses.
4-barge tow (7280 tons displacement) positioned 30 ft below upstream miter gate pintles.

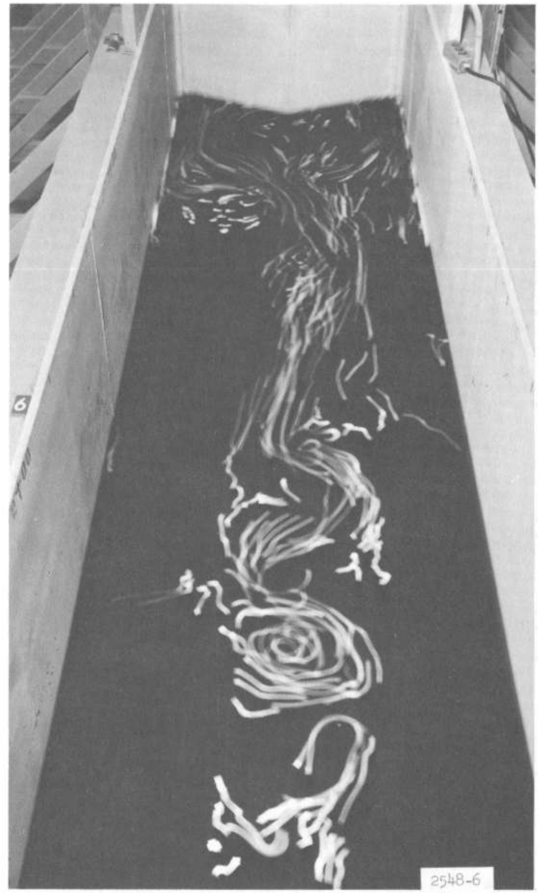
PHOTOGRAPHS



a. Before filling started

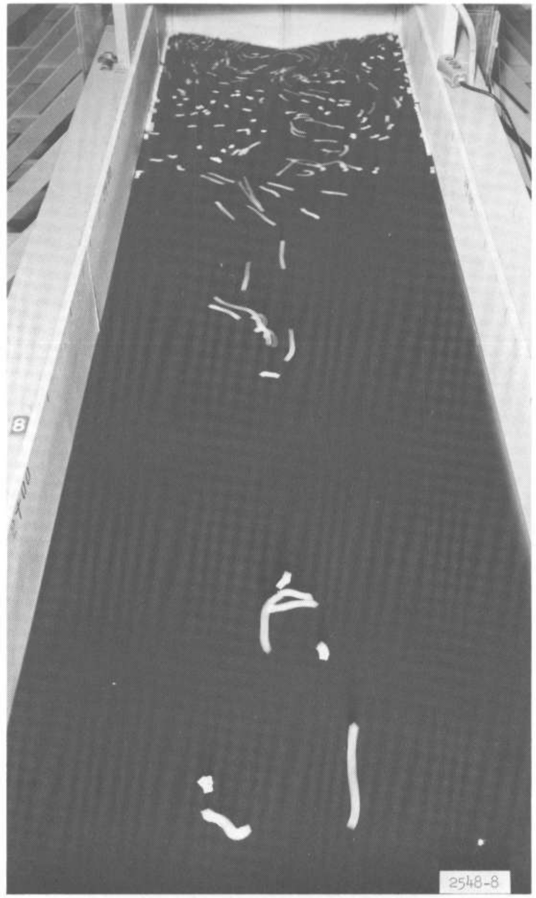


b. 2 min after filling started

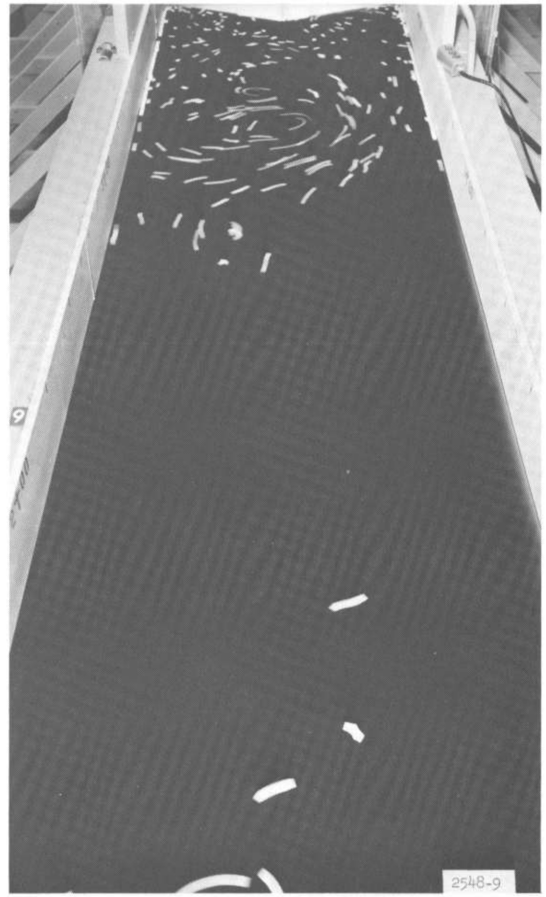


c. 4 min after filling started

d. 6 min after filling started

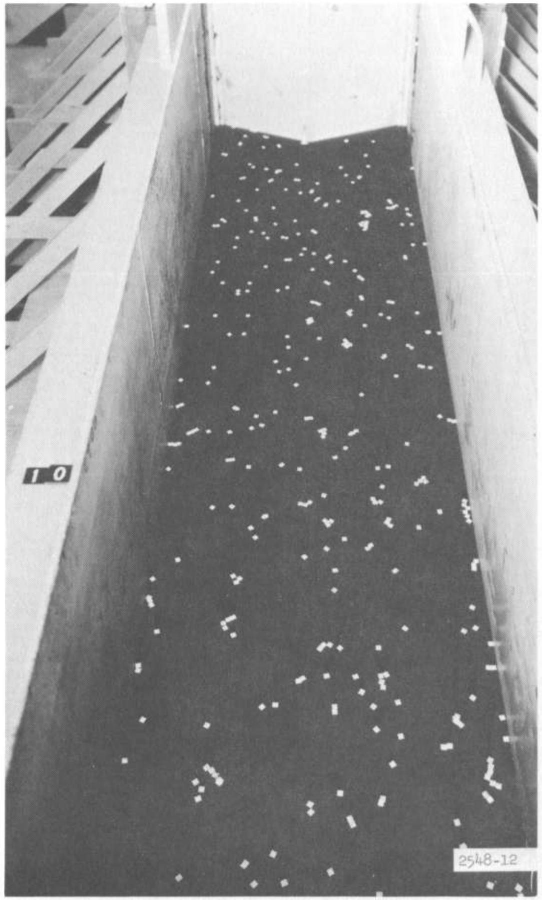


e. 8 min after filling started

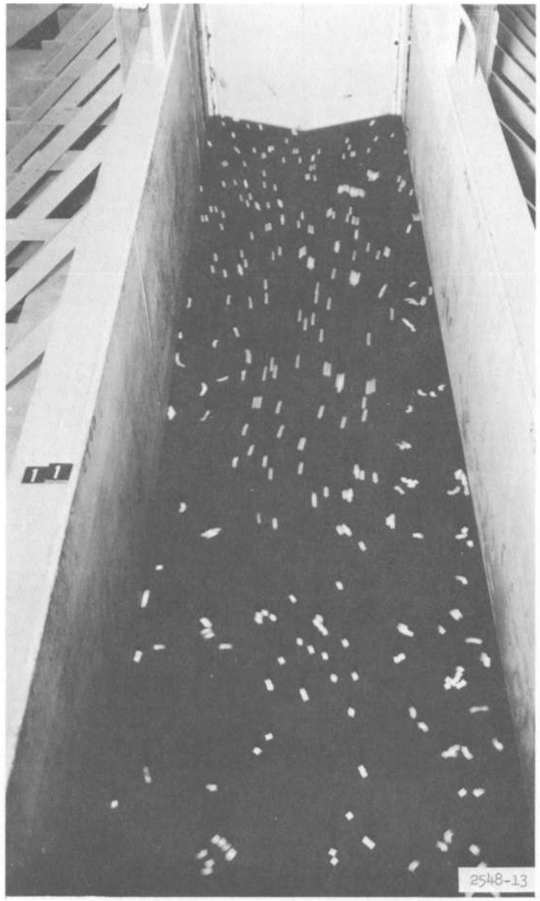


f. 10 min after filling started

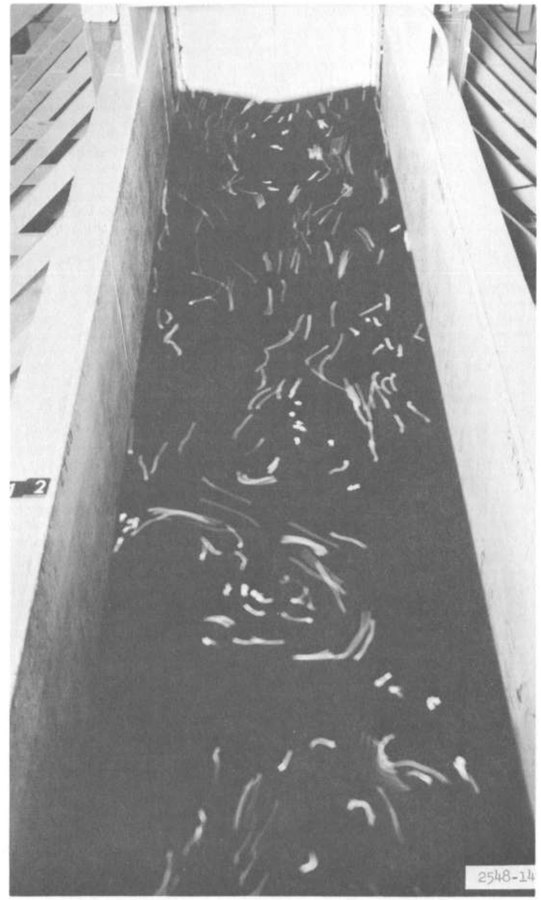
Photograph 1. Surface currents during filling operation with type 1 (original) multiport arrangement (15-sec exposure)



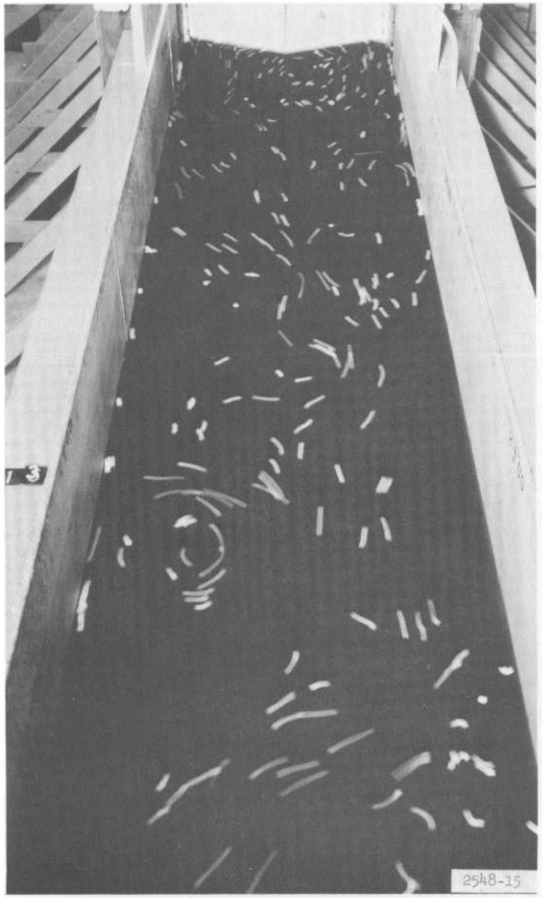
a. Before filling started



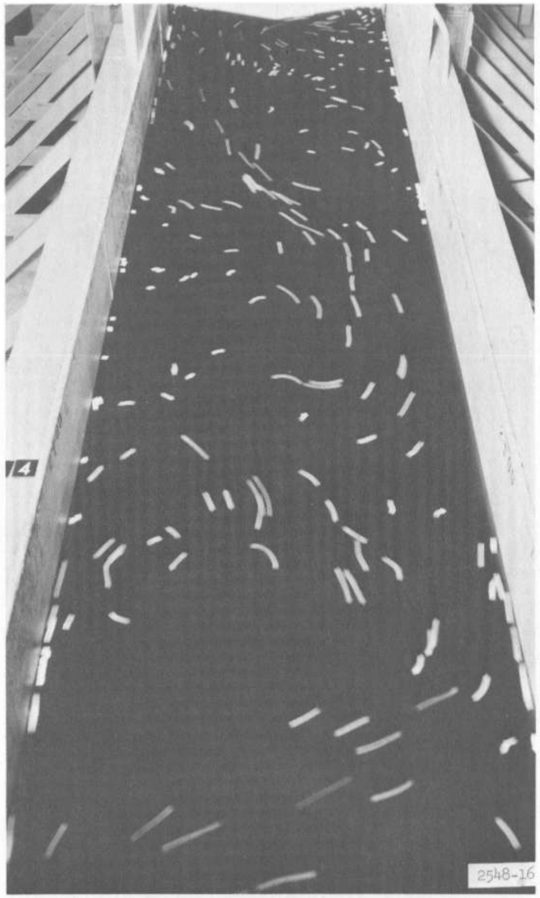
b. 2 min after filling started



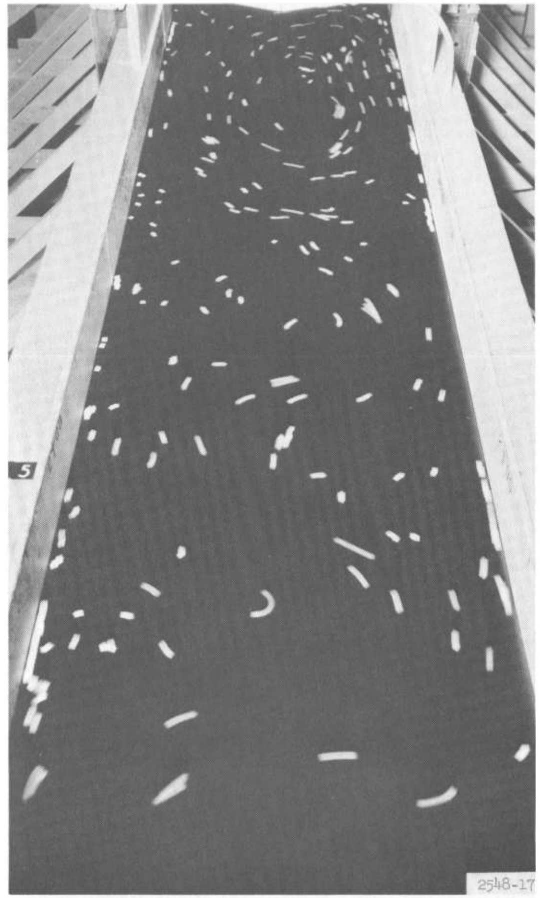
c. 4 min after filling started



d. 6 min after filling started

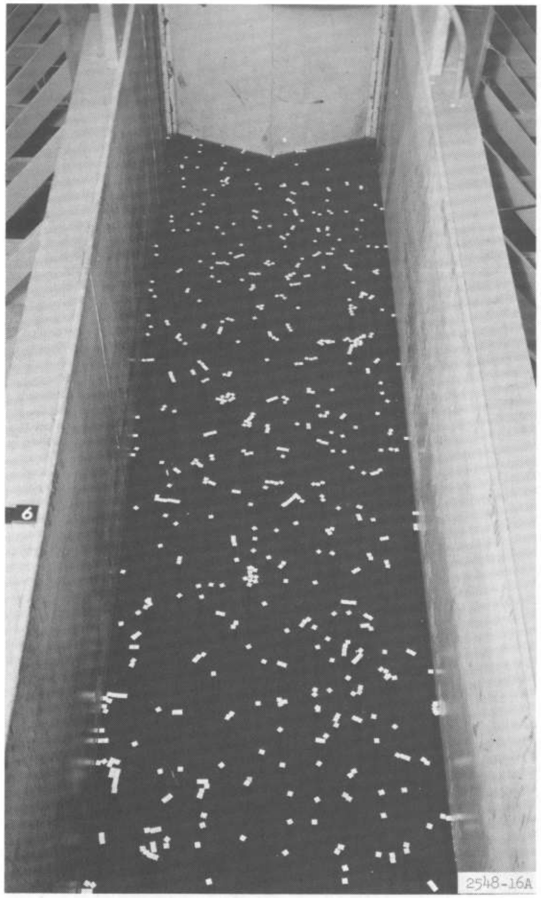


e. 8 min after filling started

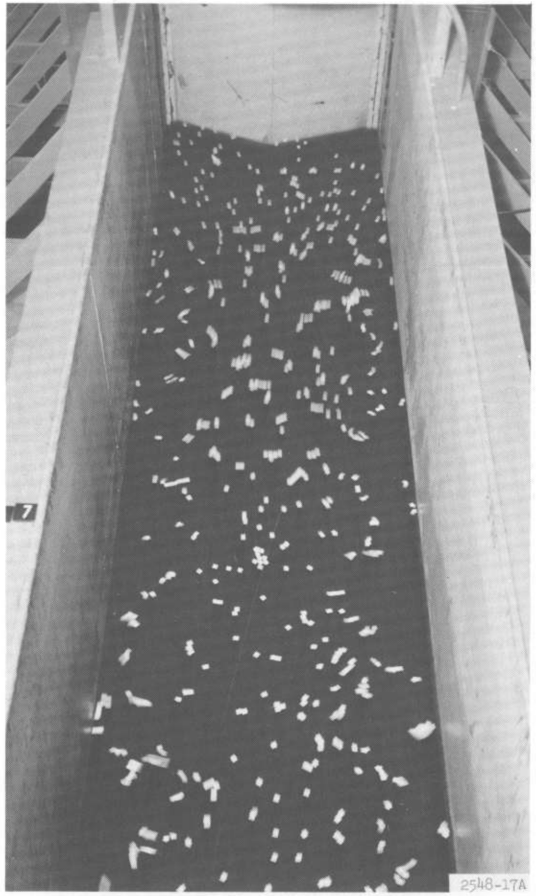


f. 10 min after filling started

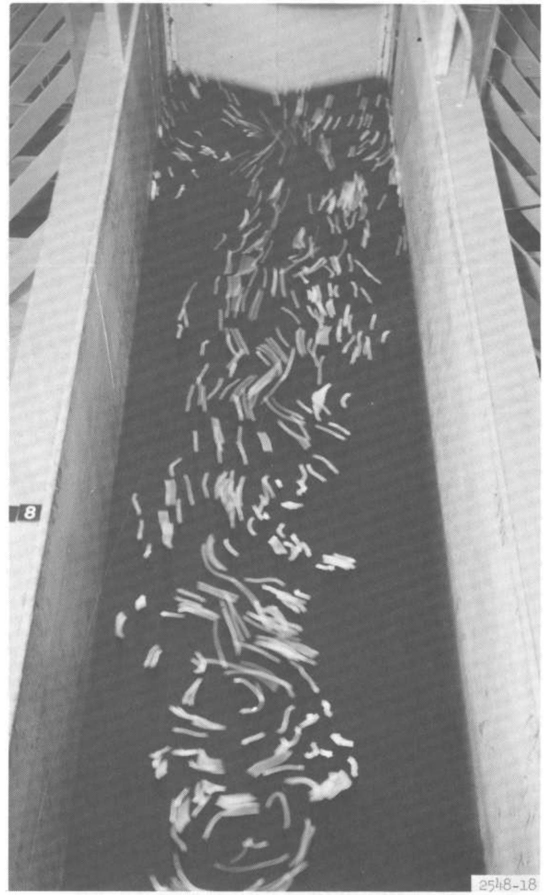
Photograph 2. Surface currents during filling operation with type 8 multiport arrangement (15-sec exposure)



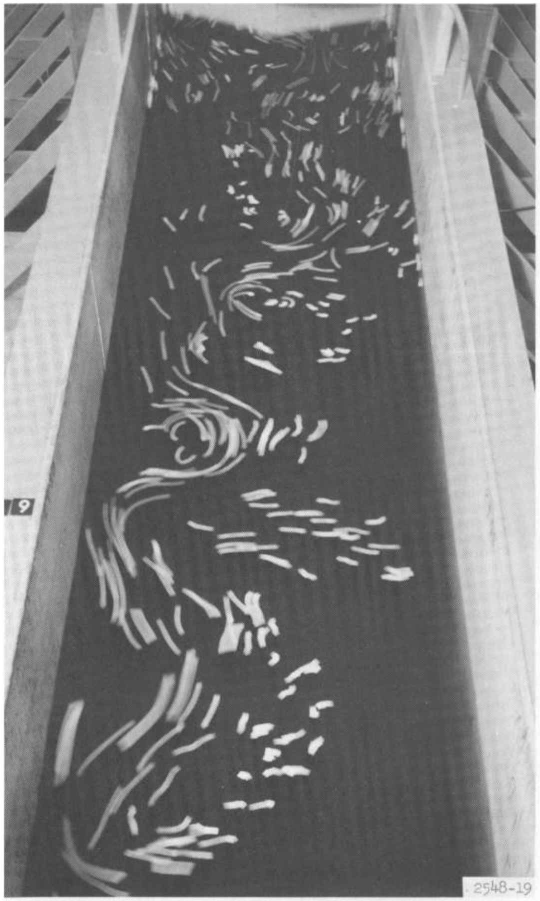
a. Before filling started



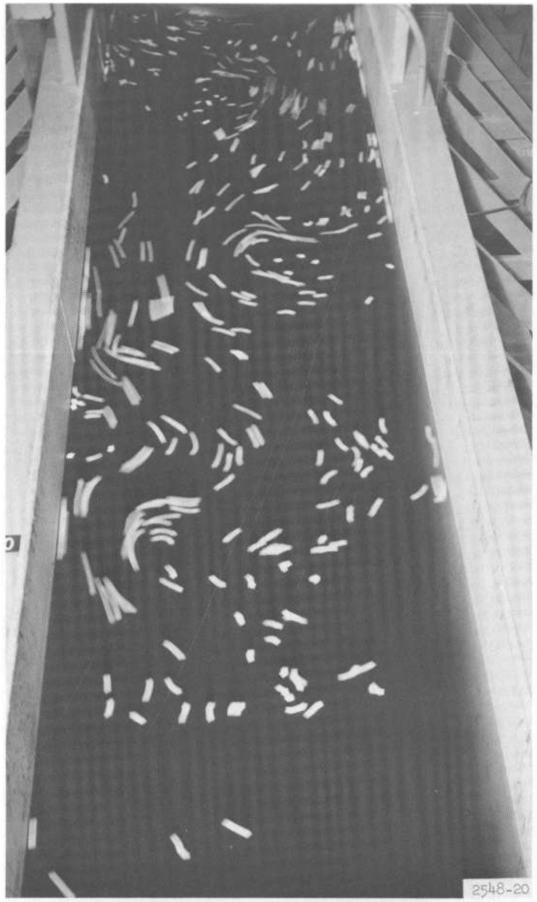
b. 2 min after filling started



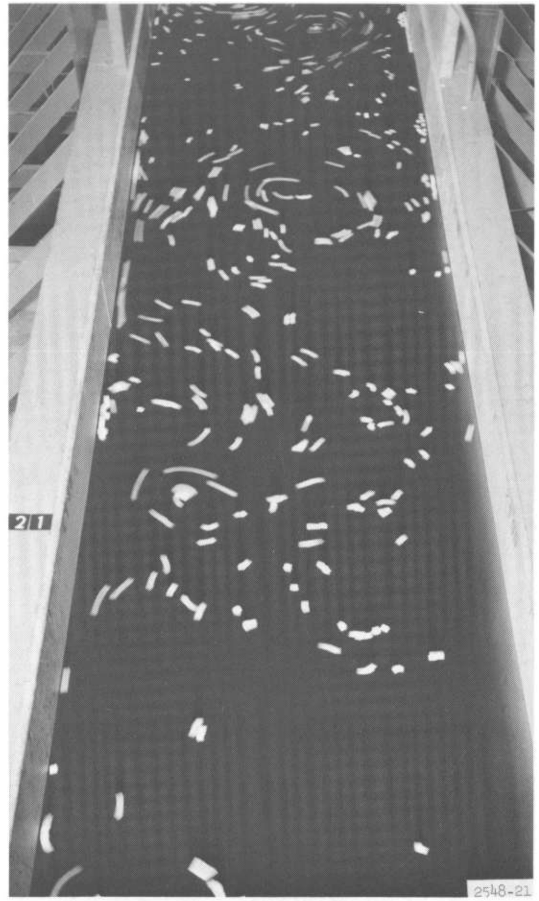
c. 4 min after filling started



d. 6 min after filling started

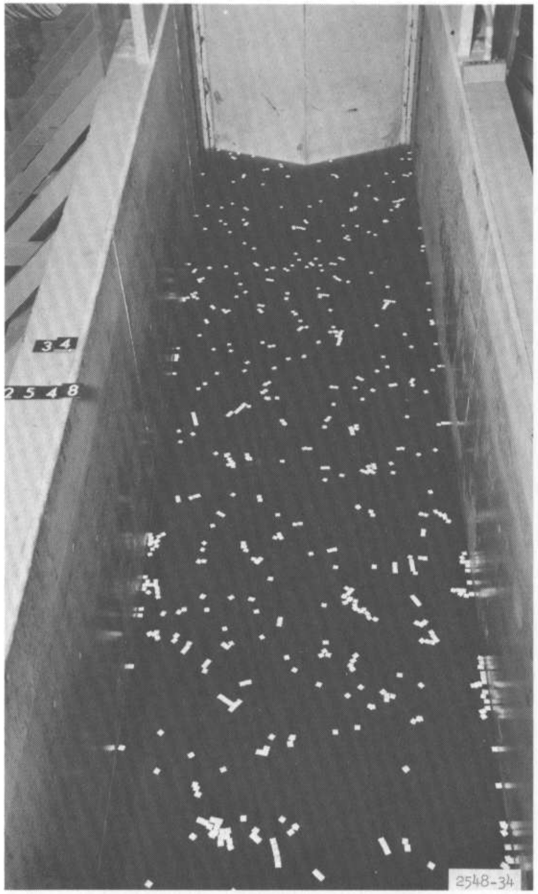


e. 8 min after filling started

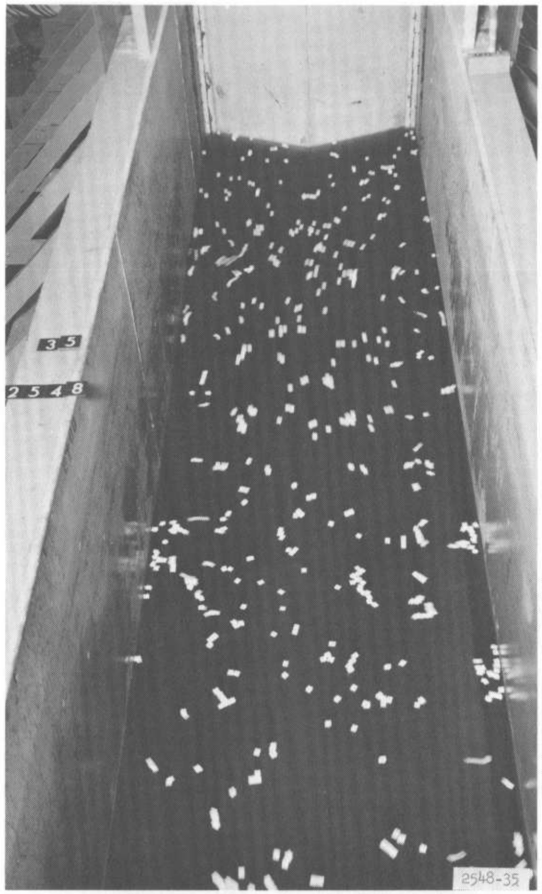


f. 10 min after filling started

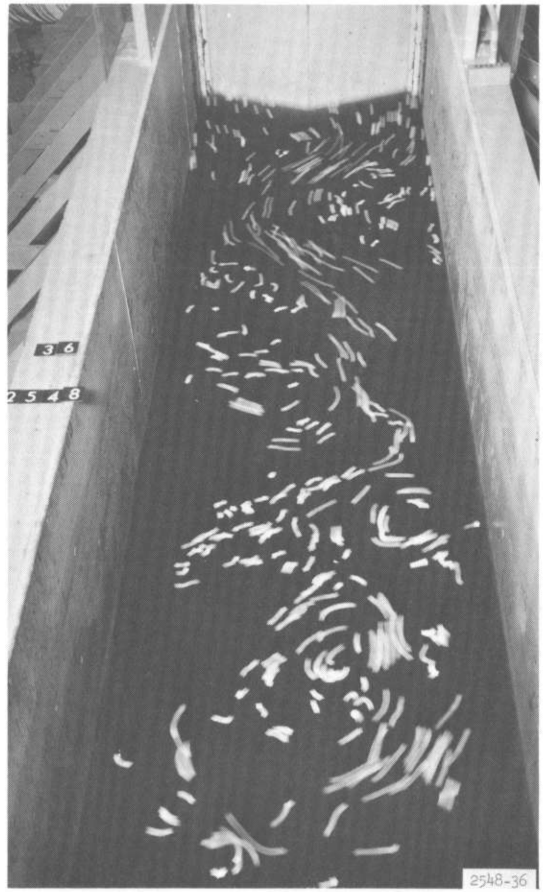
Photograph 3. Surface currents during filling operation with type 11 multiport arrangement (15-sec exposure)



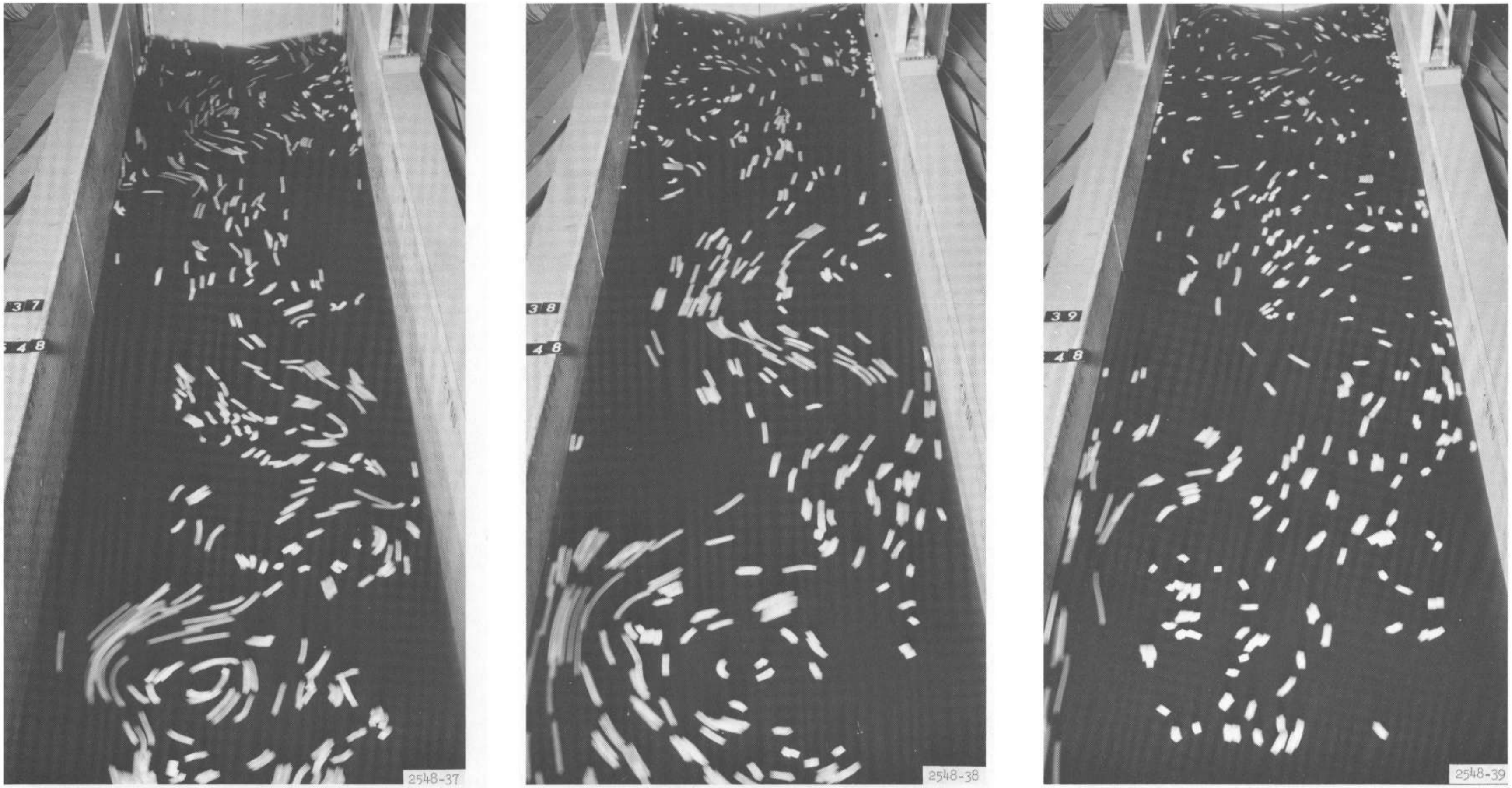
a. Before filling started



b. 2 min after filling started



c. 4 min after filling started

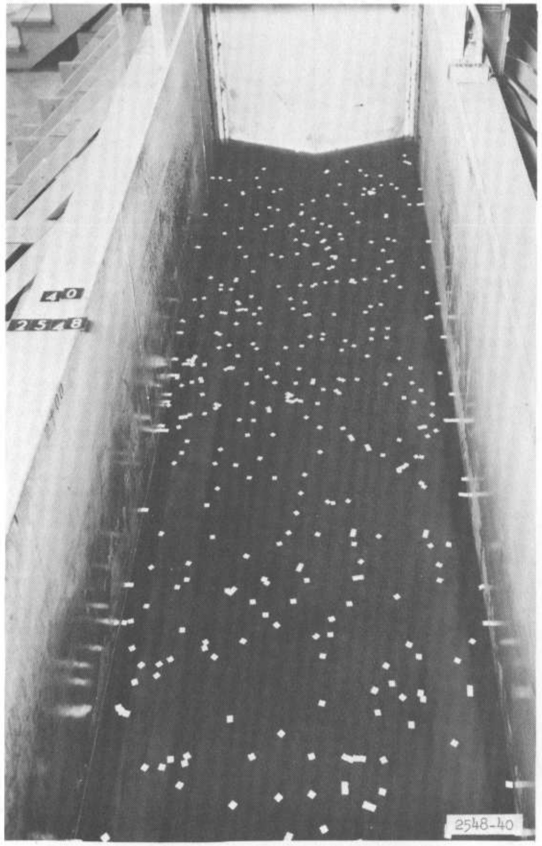


d. 6 min after filling started

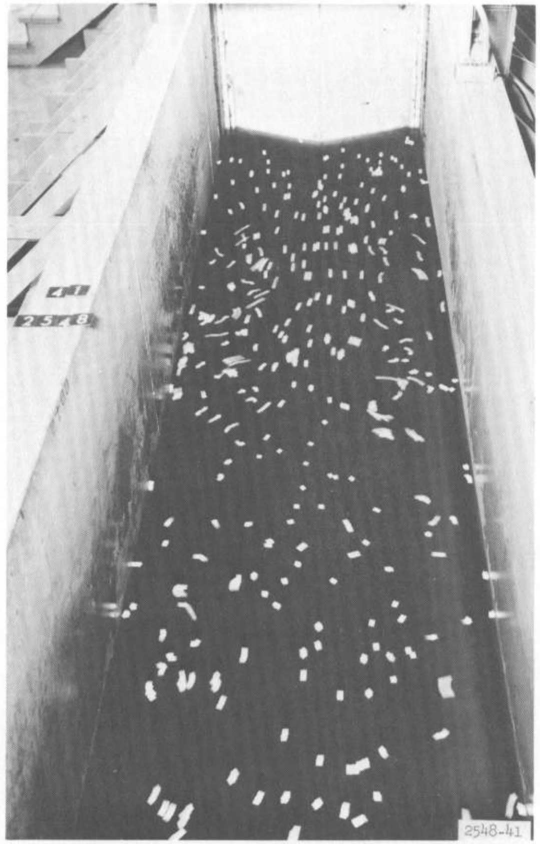
e. 8 min after filling started

f. 10 min after filling started

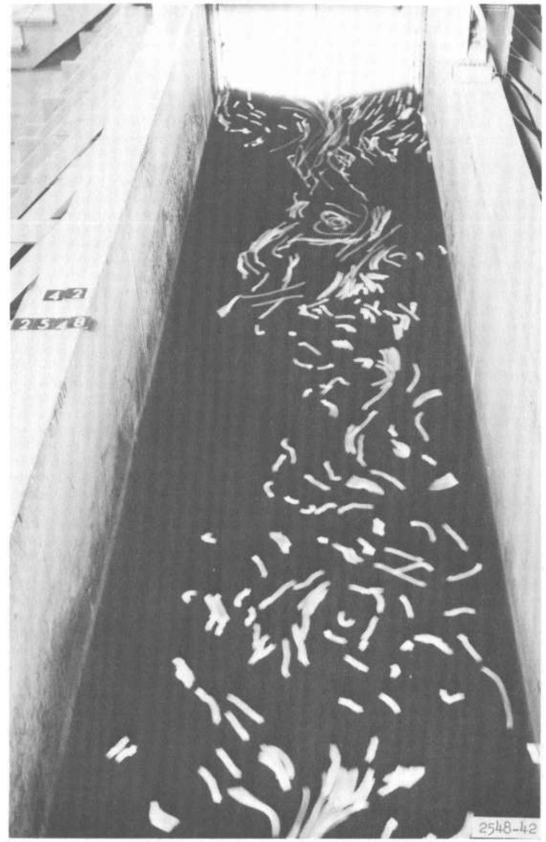
Photograph 4. Surface currents during filling operation with type 13 multiport arrangement (15-sec exposure)



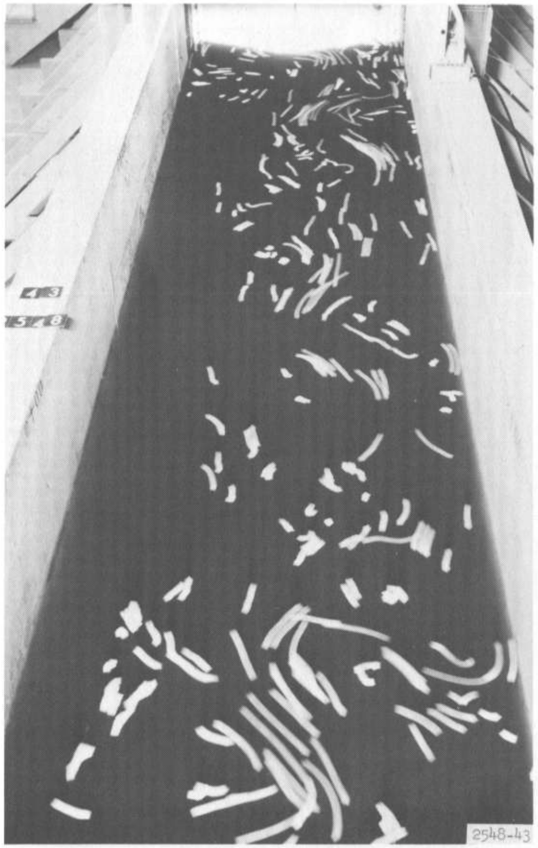
a. Before filling started



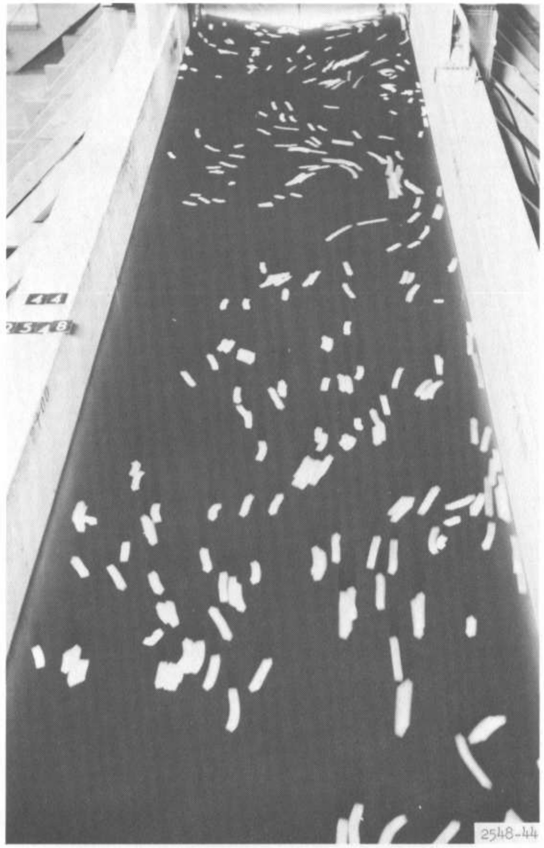
b. 2 min after filling started



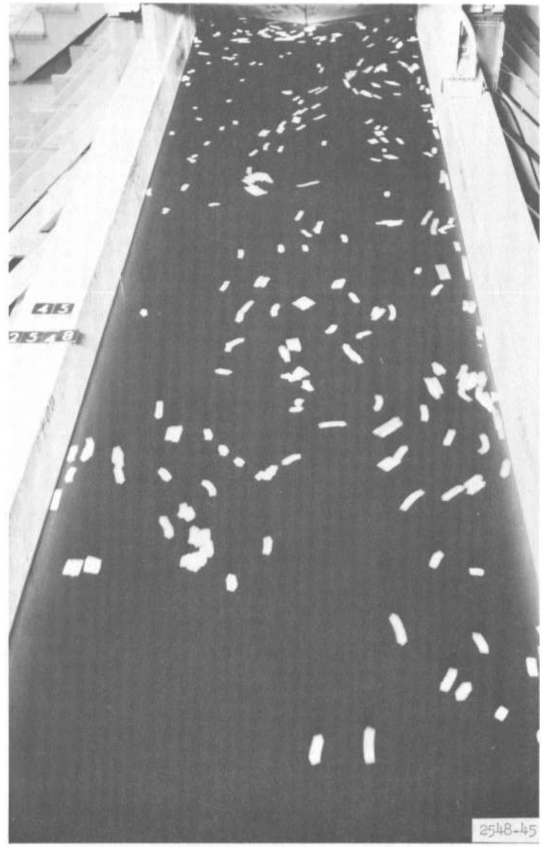
c. 4 min after filling started



d. 6 min after filling started

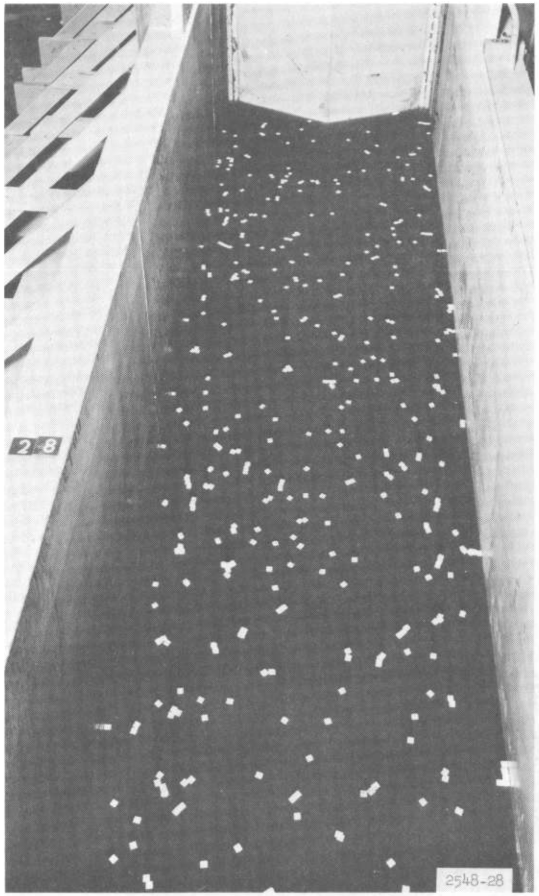


e. 8 min after filling started

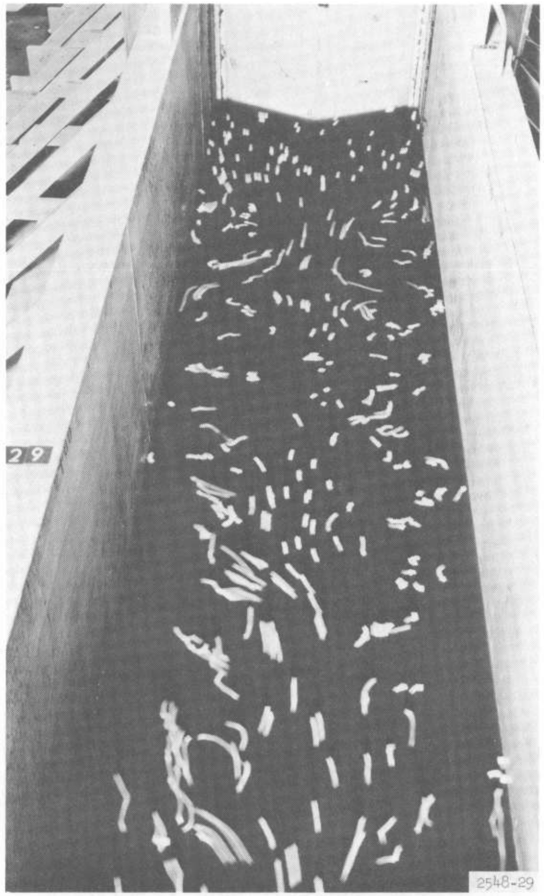


f. 10 min after filling started

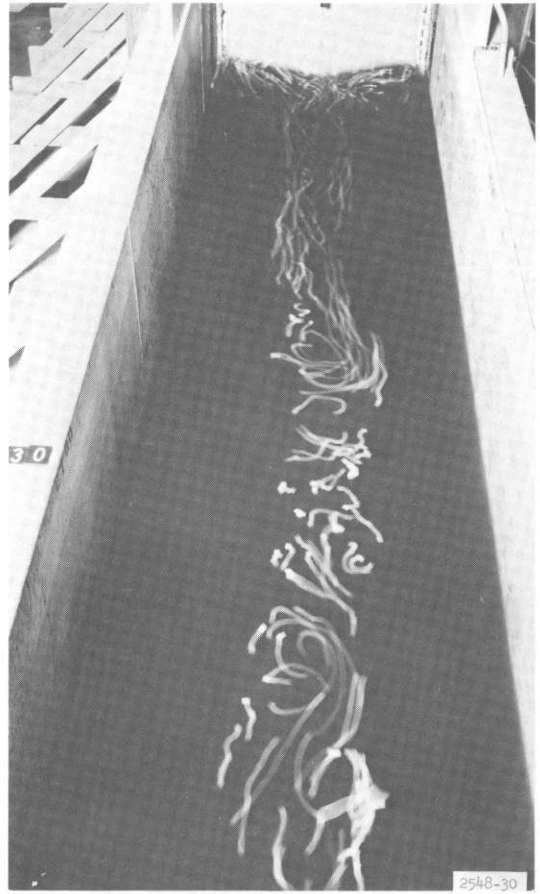
Photograph 5. Surface currents during filling operation with type 17 multiport arrangement (15-sec exposure)



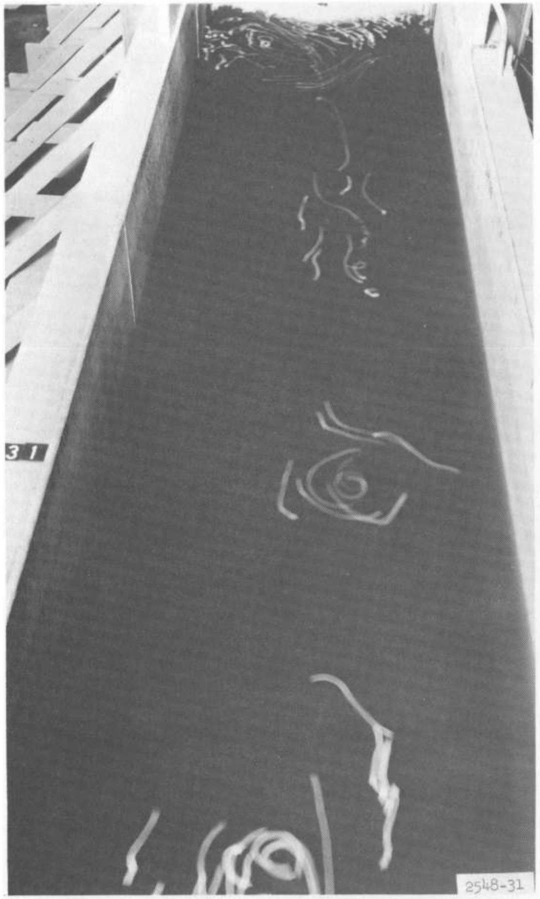
a. Before filling started



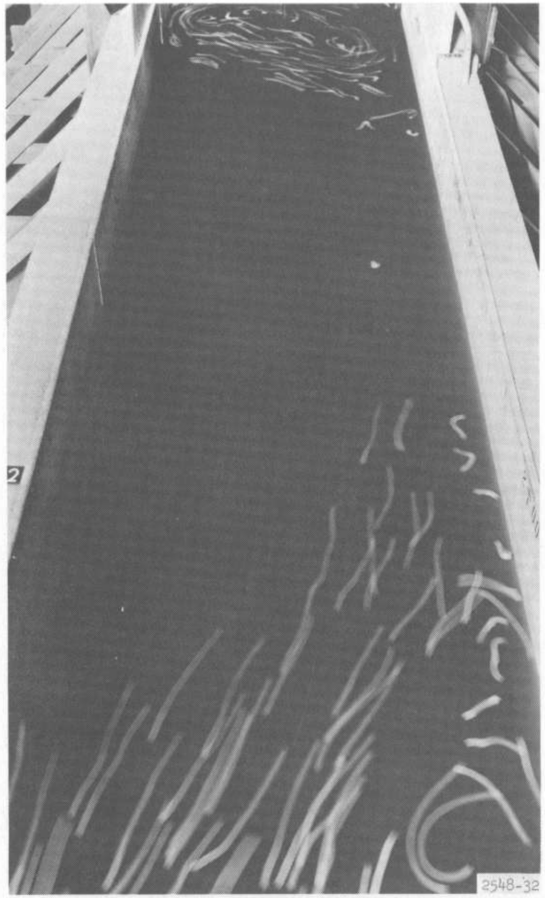
b. 2 min after filling started



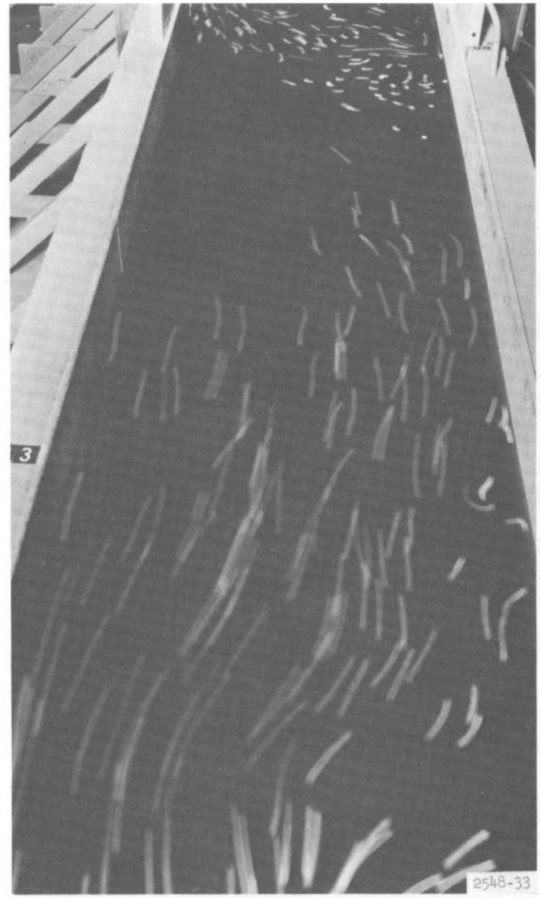
c. 4 min after filling started



d. 6 min after filling started

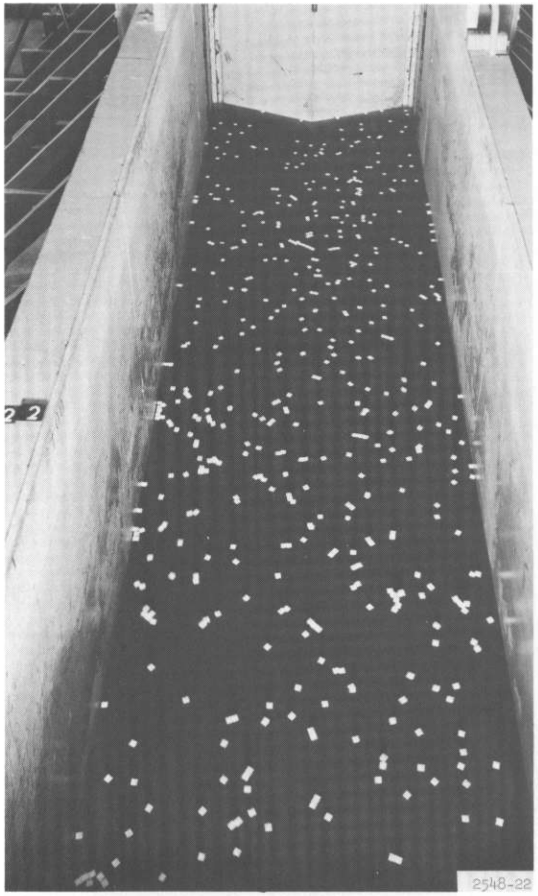


e. 8 min after filling started

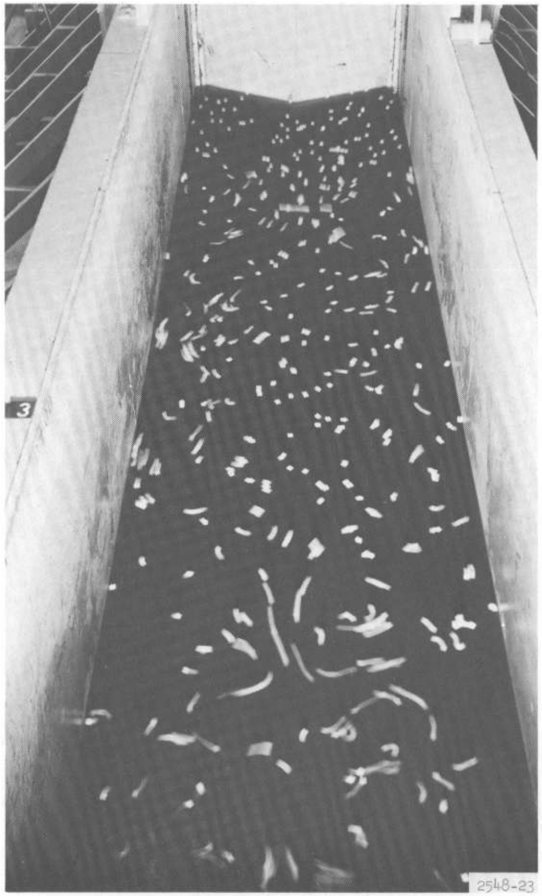


f. 10 min after filling started

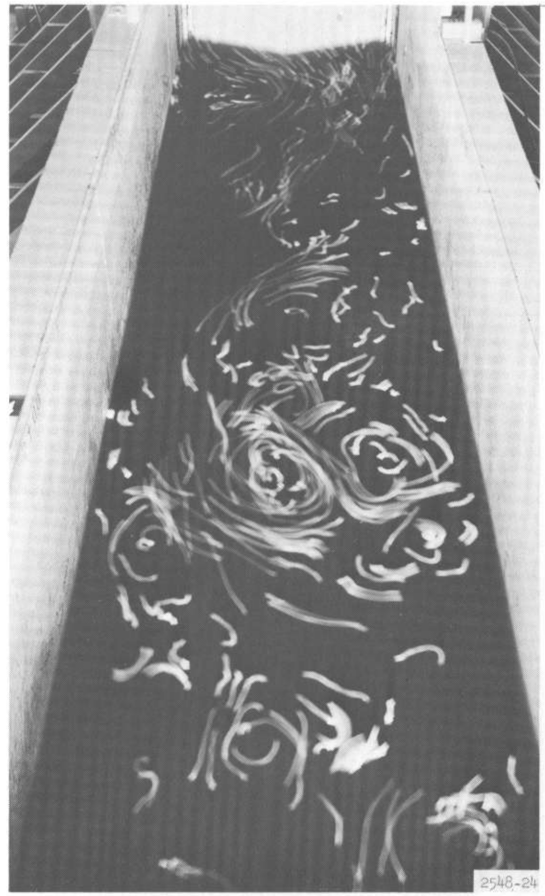
Photograph 6. Surface currents during filling operation with type 18 multiport arrangement (15-sec exposure)



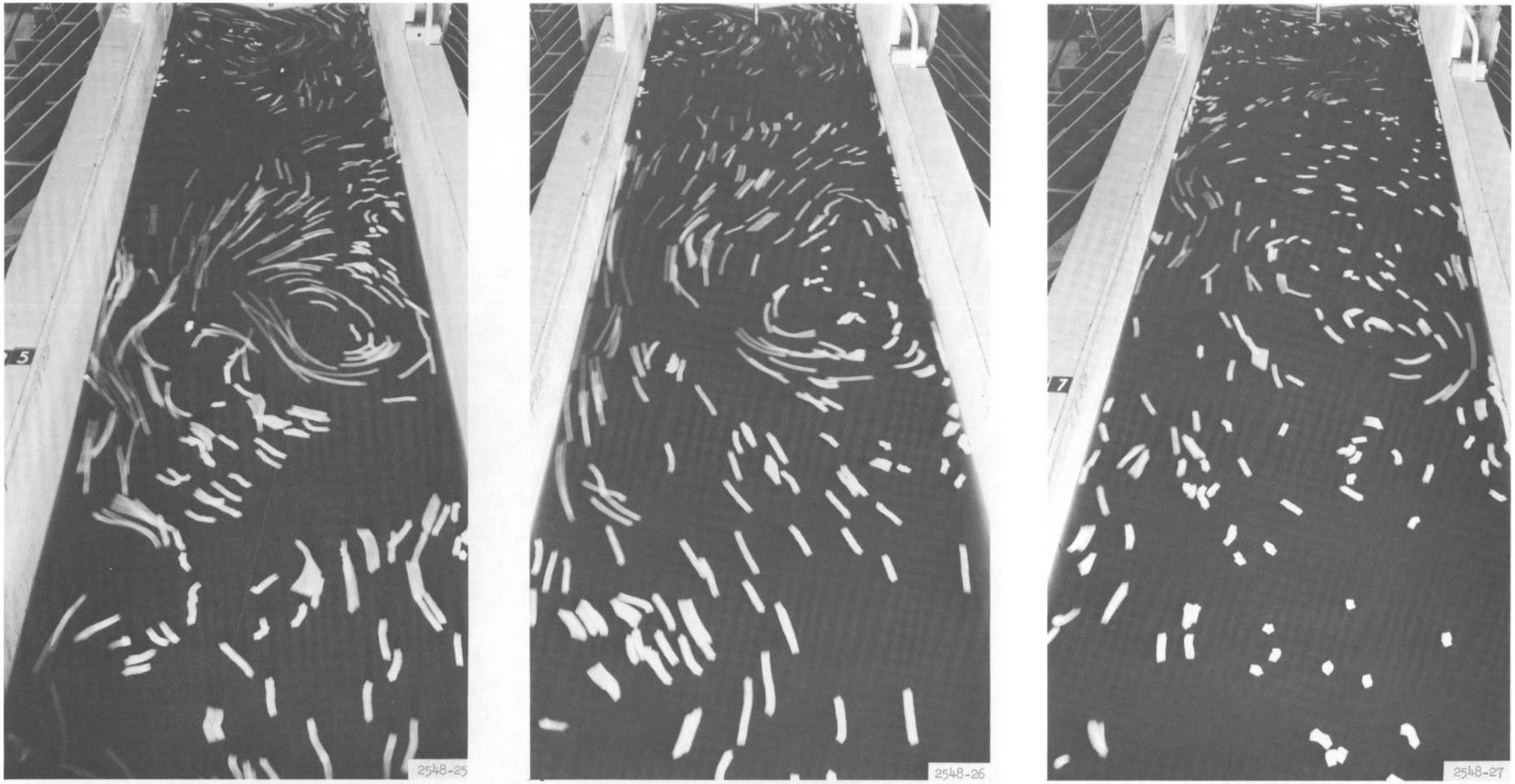
a. Before filling started



b. 2 min after filling started



c. 4 min after filling started



d. 6 min after filling started

e. 8 min after filling started

f. 10 min after filling started

Photograph 7. Surface currents during filling operation with type 22 multiport arrangement (15-sec exposure)

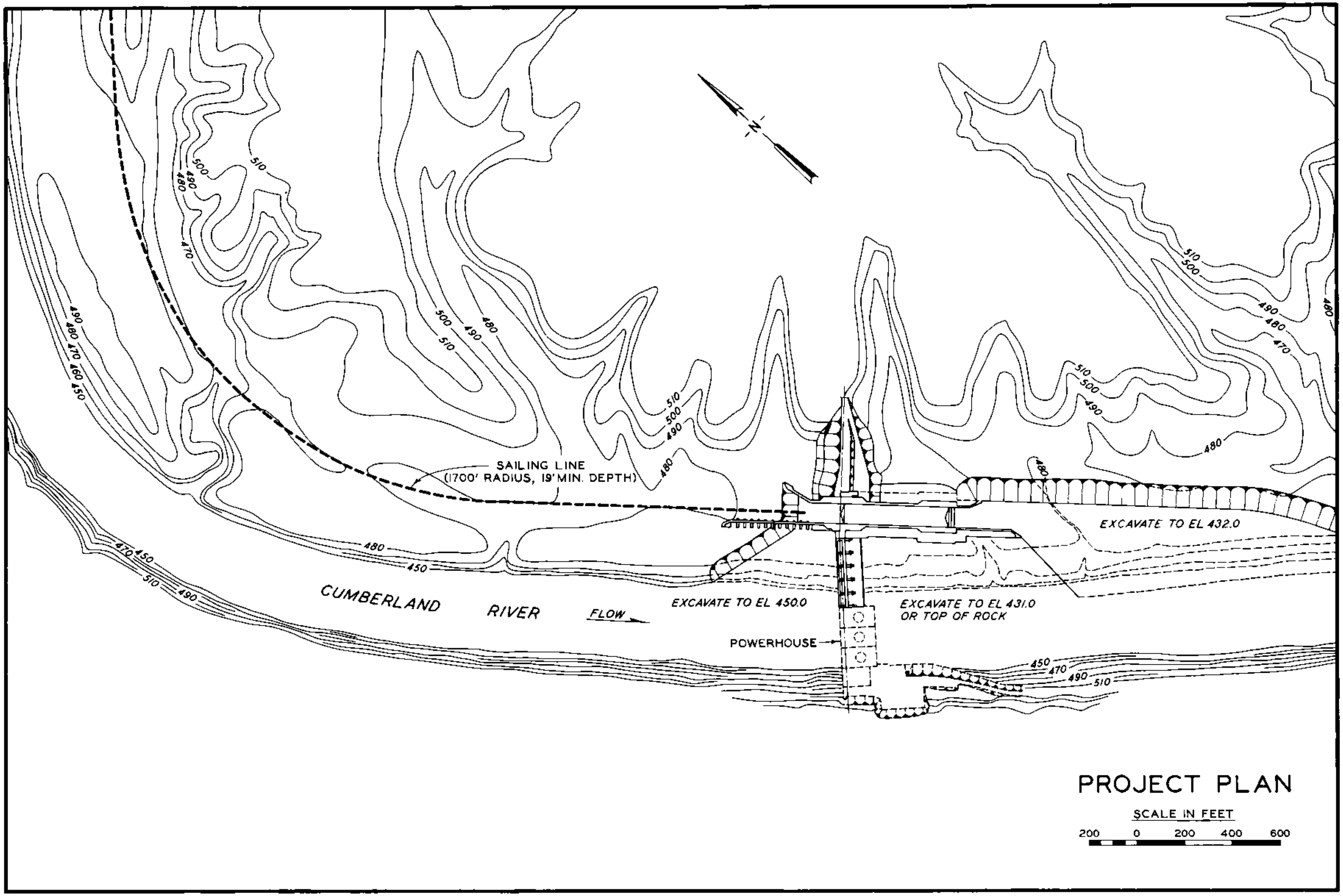
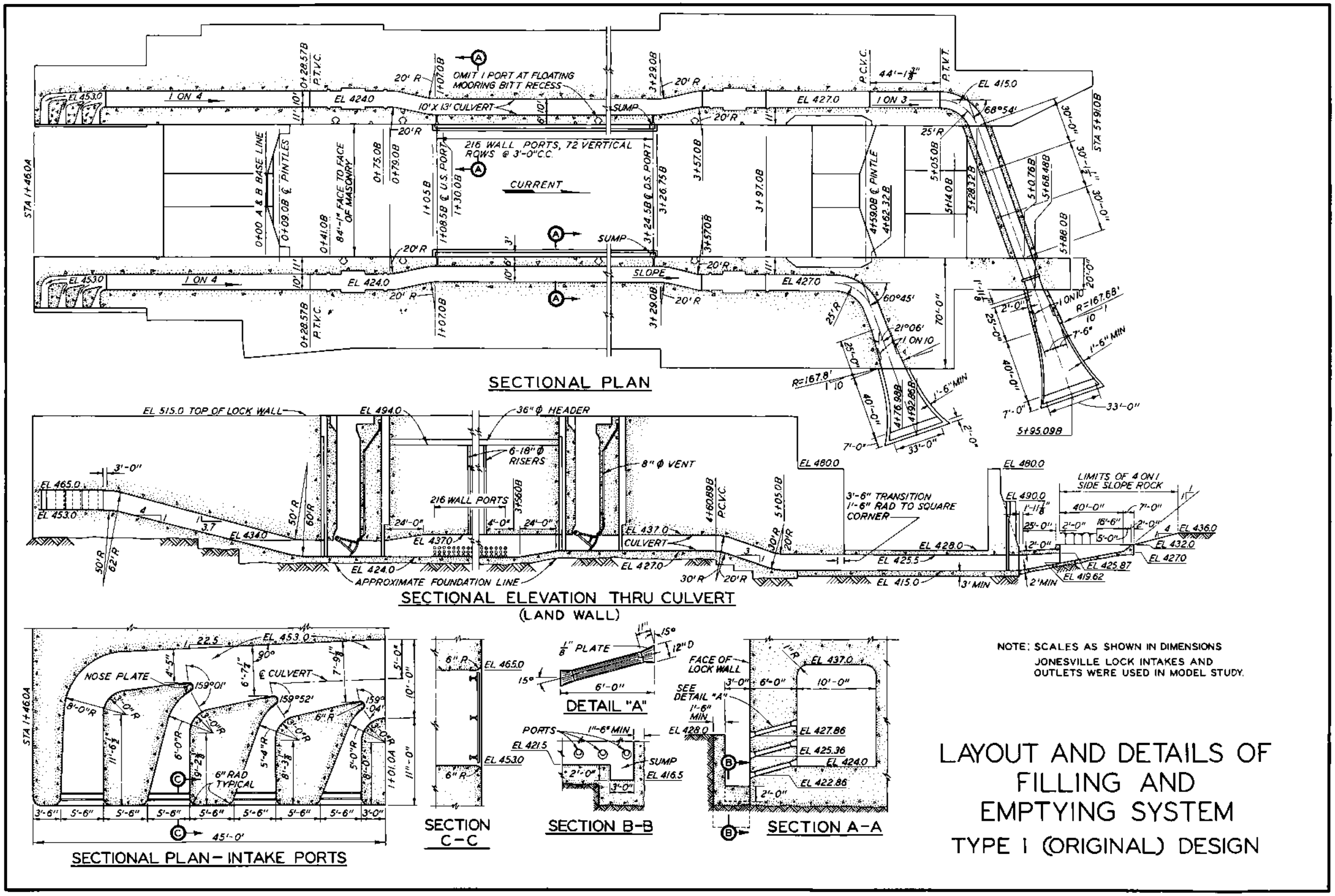

SAILING LINE
(1700' RADIUS, 19' MIN. DEPTH)
CUMBERLAND RIVER
FLOW
EXCAVATE TO EL 450.0
EXCAVATE TO EL 431.0
OR TOP OF ROCK
EXCAVATE TO EL 432.0
POWERHOUSE
N
PROJECT PLAN
SCALE IN FEET
200 0 200 400 600

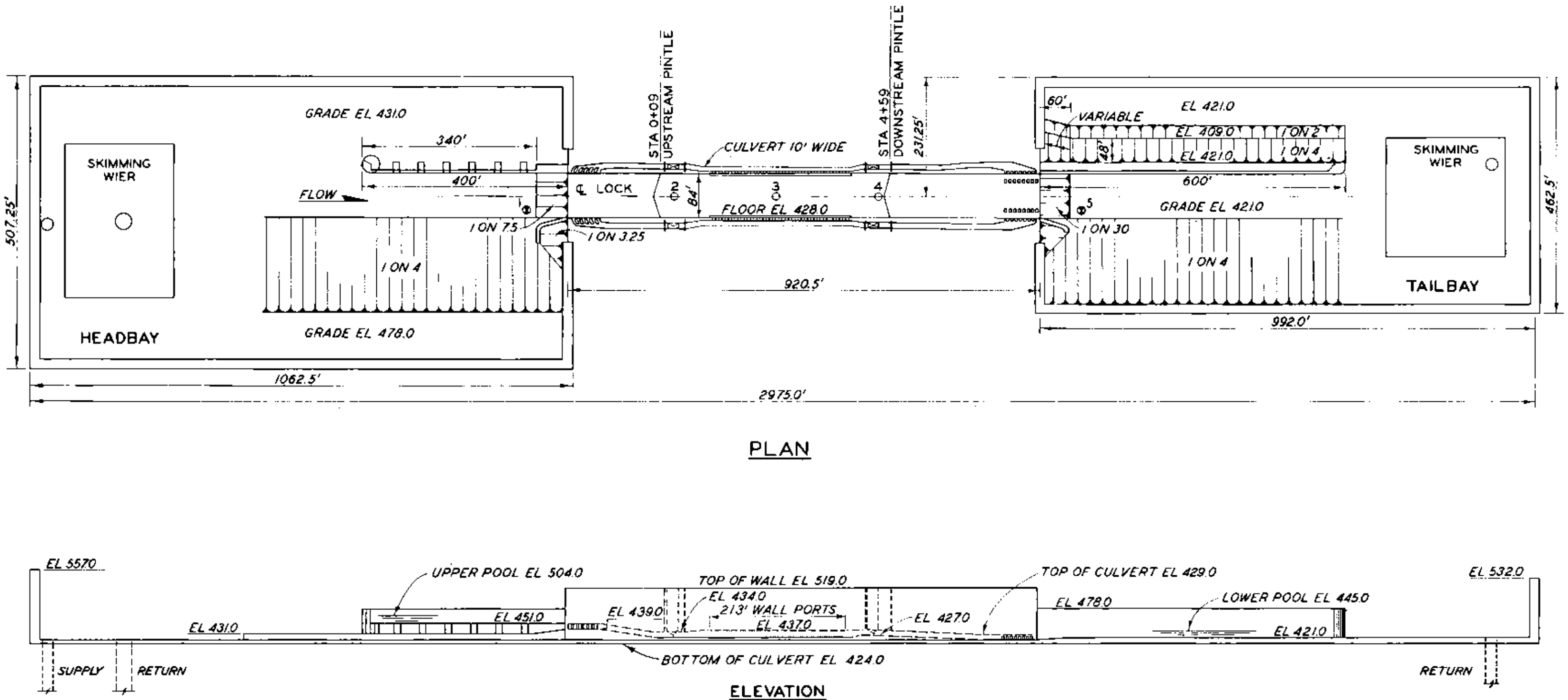
PLATE I

PLATE 2.



NOTE: SCALES AS SHOWN IN DIMENSIONS
JONESVILLE LOCK INTAKES AND OUTLETS WERE USED IN MODEL STUDY.

LAYOUT AND DETAILS OF FILLING AND EMPTYING SYSTEM
TYPE 1 (ORIGINAL) DESIGN



GAGE INDENTIFICATION

GAGE NO.	UNIT MEASURED
1	WATER SURFACE, UPPER POOL
2-4	WATER SURFACE SLOPE, LOCK CHAMBER
3	WATER SURFACE, LOCK CHAMBER (FILLING OR EMPTYING CURVE)
5	WATER SURFACE, LOWER POOL

NOTE: ELEVATIONS IN FEET ARE REFERRED TO MEAN SEA LEVEL.

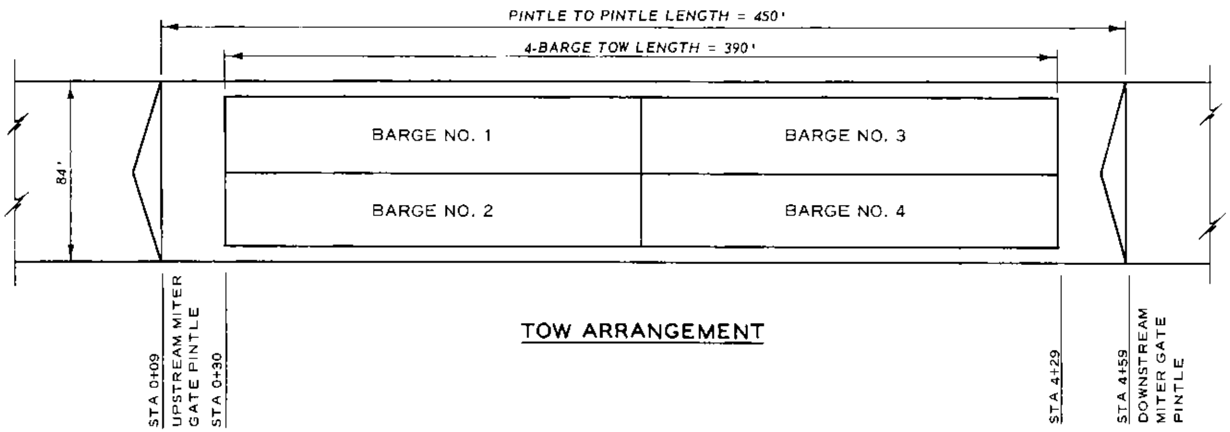
MODEL LAYOUT

SCALES IN FEET

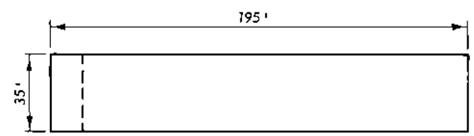
PROTOTYPE 100 0 100 200 300 400

MODEL 4 0 4 8 12 16

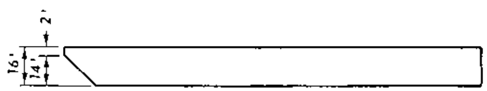
PLATE 4



TOW ARRANGEMENT



PLAN



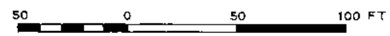
ELEVATION

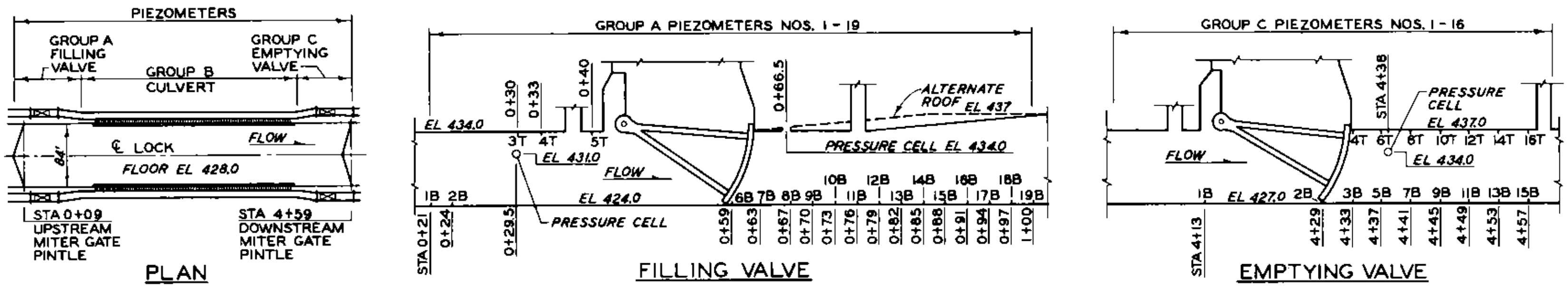
BARGE DETAIL

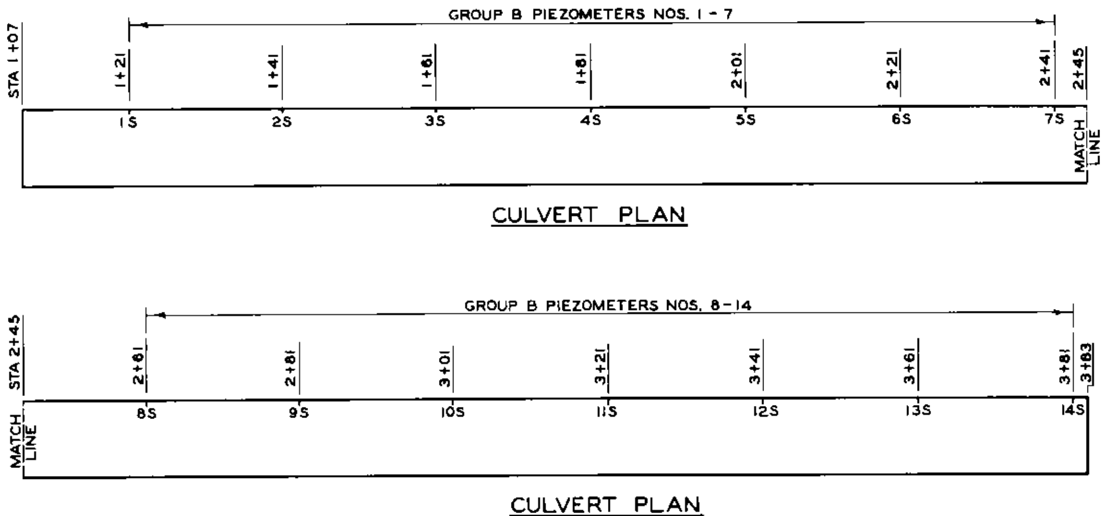
NUMBER OF BARGES IN TOW	DISPLACEMENT, TONS, AT 9-FT DRAFT
2	3640
4	7280

TOW ARRANGEMENT AND BARGE DETAILS

SCALE







NOTE: ALL VALUES ARE IN PROTOTYPE UNITS.
ELEVATIONS ARE IN FEET REFERRED TO MEAN SEA LEVEL.
TOP, SIDE, AND BOTTOM PIEZOMETERS ARE DESIGNATED RESPECTIVELY T, S, AND B.

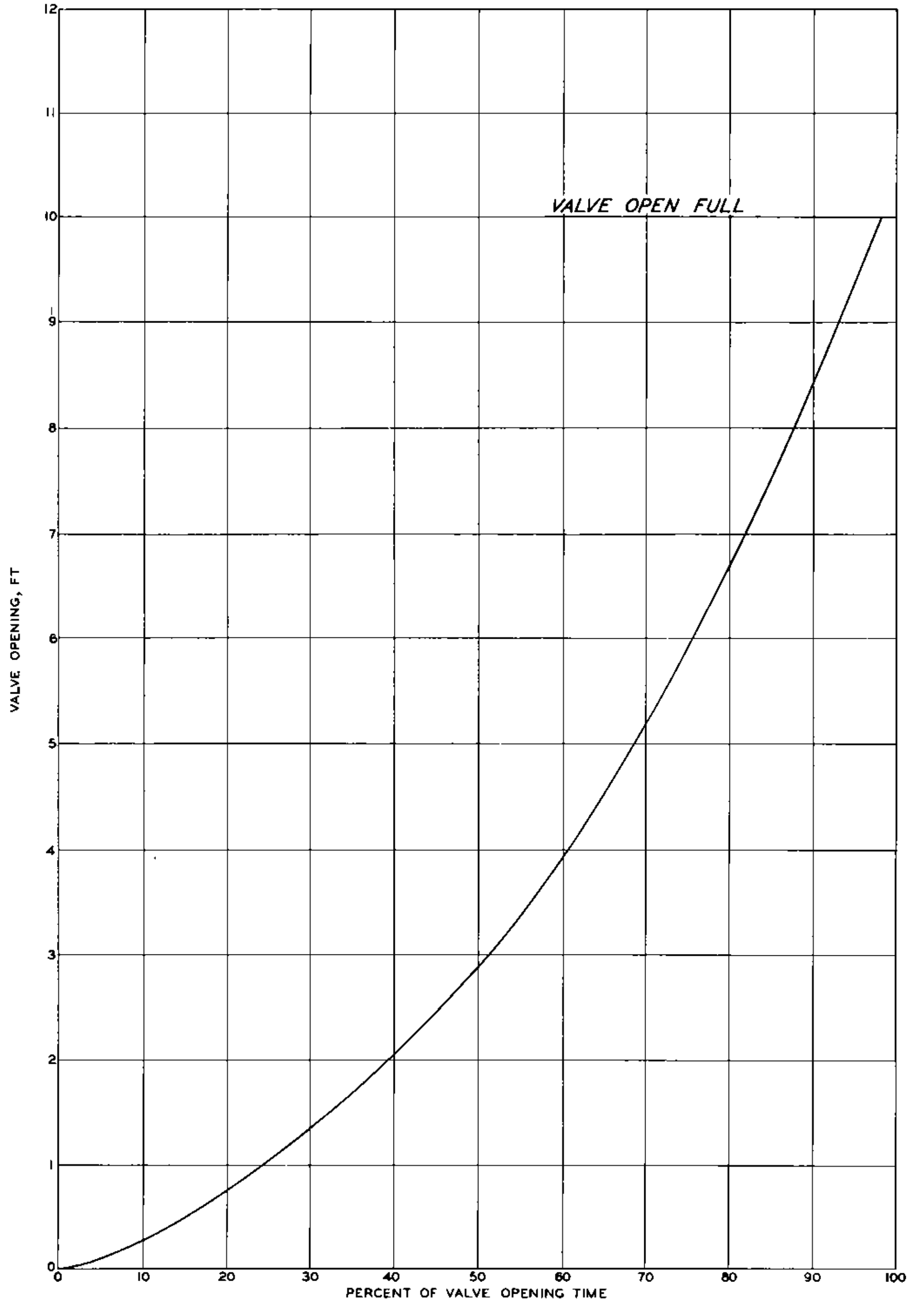
PIEZOMETER LOCATIONS

LEFT HALF OF FILLING AND EMPTYING SYSTEM

TYPE I (ORIGINAL) DESIGN

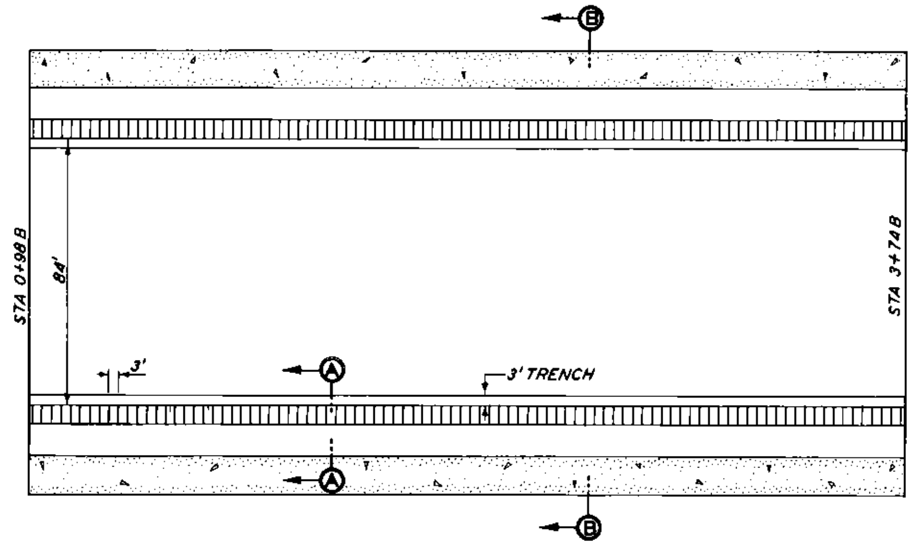
SCALE IN FEET
10 0 10 20 30 40

PLATE 5

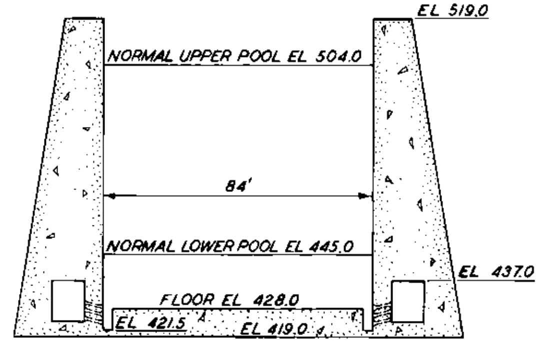


NOTE: SCHEDULE FURNISHED BY NASHVILLE DISTRICT

VALVE OPENING SCHEDULE

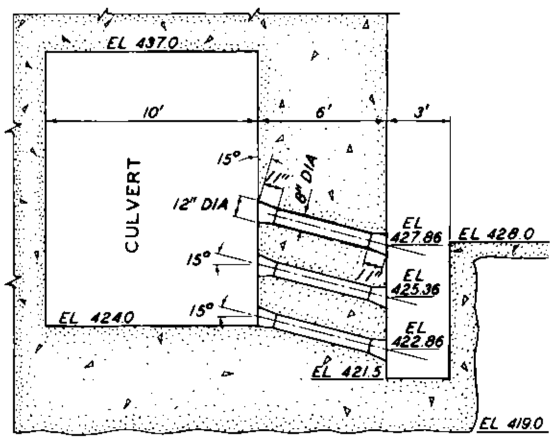


PLAN AT EL 428.0



SECTION B-B

SCALE IN FEET
25 0 25 50 75 100

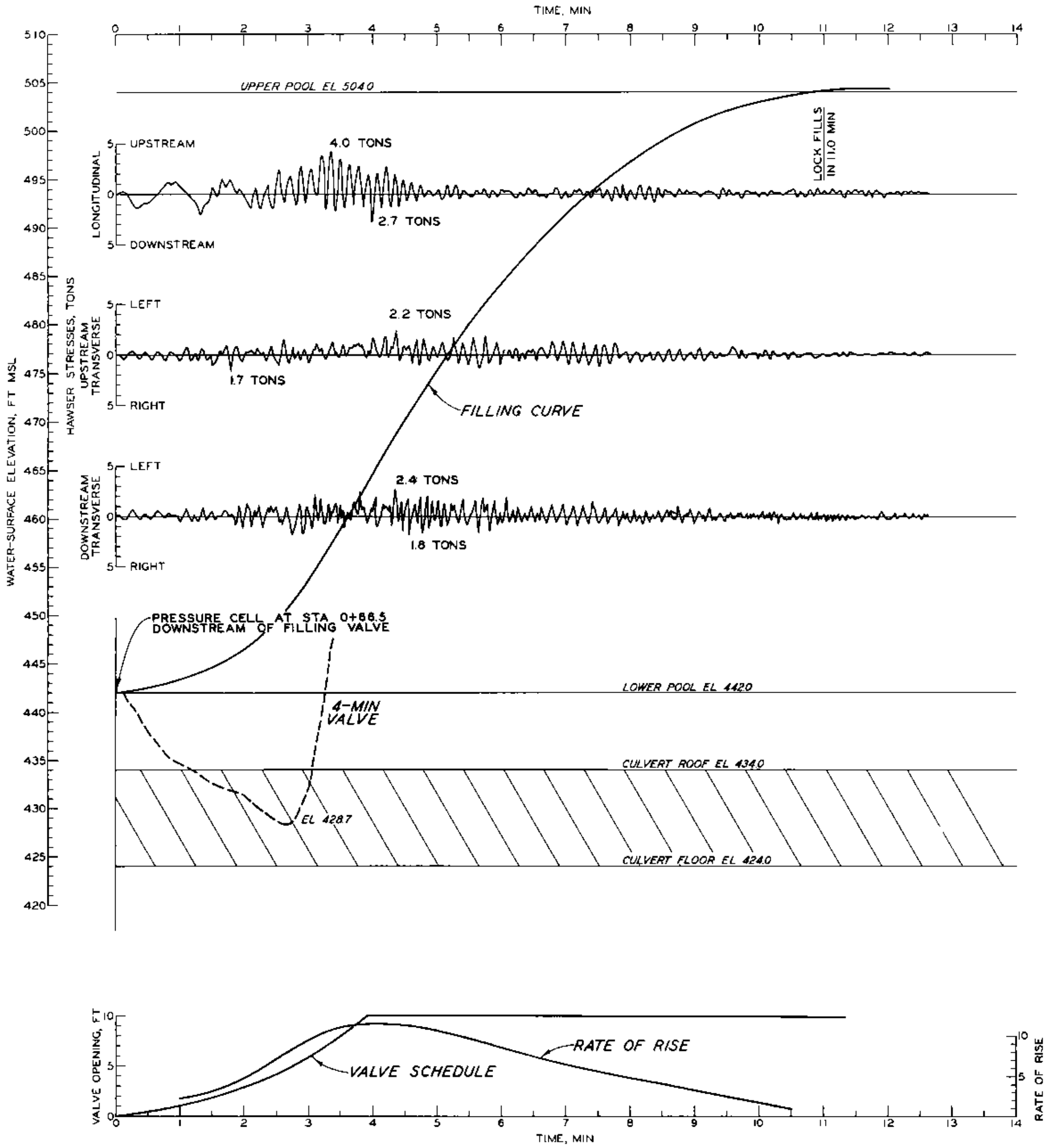


SECTION A-A

SCALE IN FEET
2 0 2 4 6

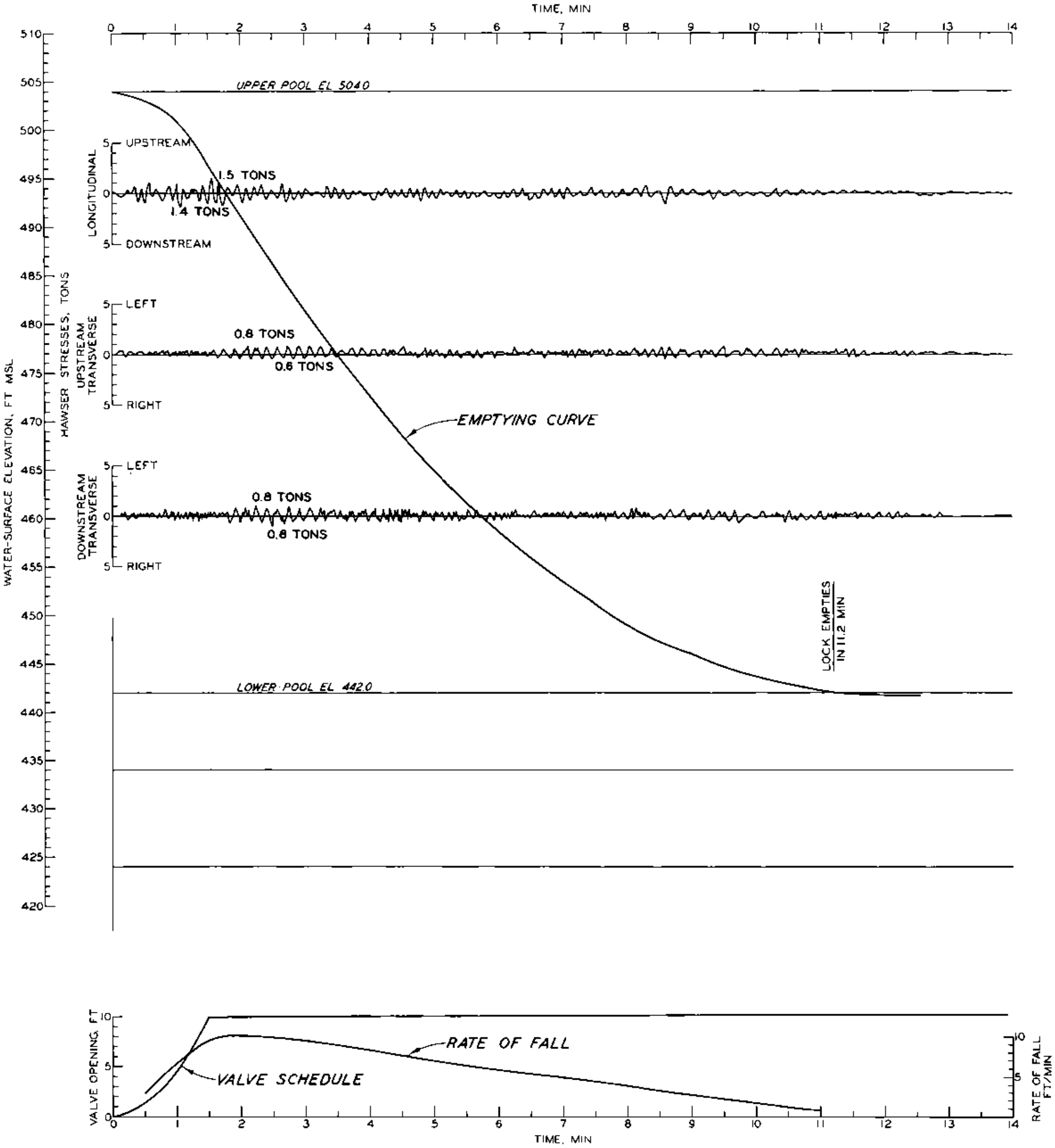
NOTE: ELEVATIONS ARE IN FEET REFERRED TO MEAN SEA LEVEL.
UPSTREAM MITER GATE AT STA 0+09.
DOWNSTREAM MITER GATE AT STA 4+59.

LOCK CHAMBER MANIFOLD



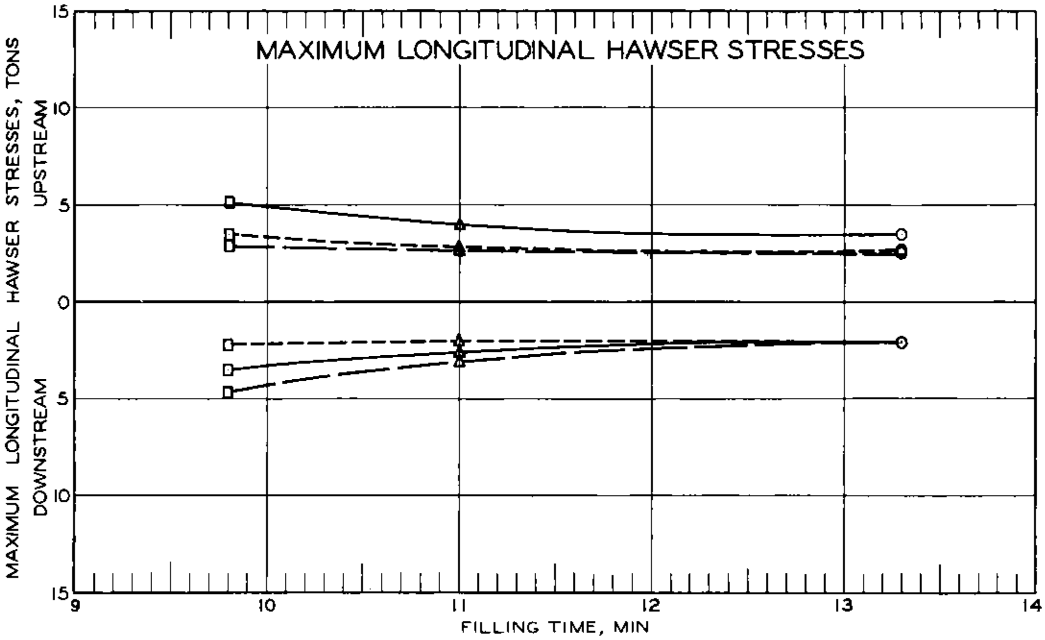
NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0)
4-BARGE TOW POSITIONED 30 FT BELOW UPSTREAM MITER GATE PINTLES
CULVERT AT VALVES, 10 FT X 10 FT.
SUBMERGENCE IS THE DIFFERENCE IN ELEVATION BETWEEN LOWER POOL AND THE LOCK CHAMBER FLOOR (EL 428.0).

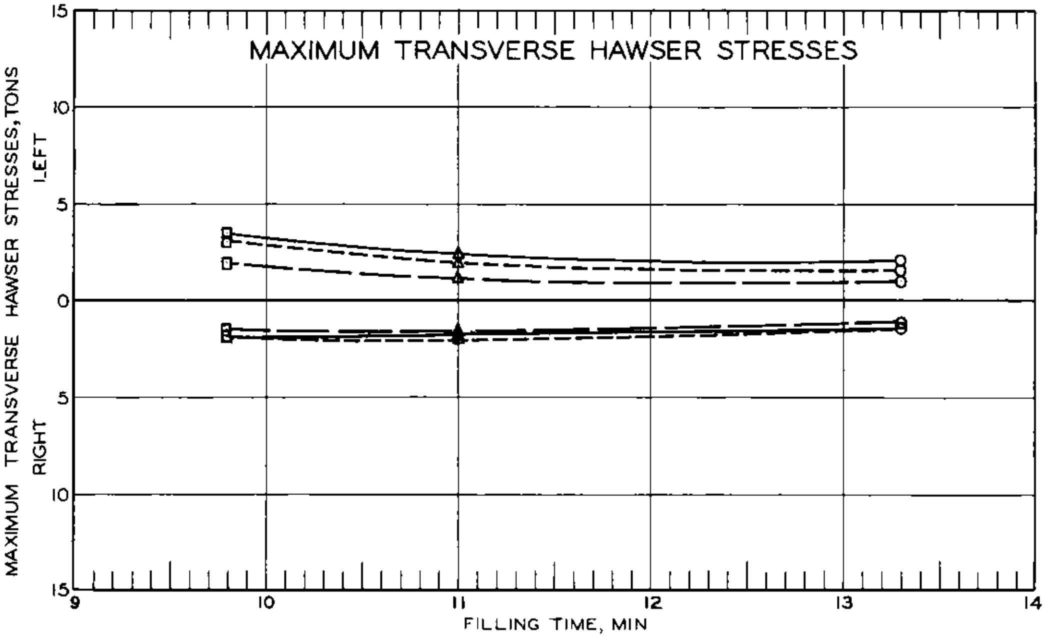
FILLING CHARACTERISTICS
TYPE I (ORIGINAL) MULTIPORT ARRANGEMENT
4-MIN VALVE
14-FT SUBMERGENCE, 62-FT LIFT



NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0)
4-BARGE TOW POSITIONED 30 FT BELOW UPSTREAM MITER GATE PINTLES.
CULVERT AT VALVES: 10 FT X 10 FT.
SUBMERGENCE IS THE DIFFERENCE IN ELEVATION BETWEEN LOWER POOL AND THE LOCK CHAMBER FLOOR (EL 428.0).

EMPTYING CHARACTERISTICS
TYPE I (ORIGINAL)
MULTIPORT ARRANGEMENT
1-1/2-MIN VALVE
14-FT SUBMERGENCE, 62-FT LIFT





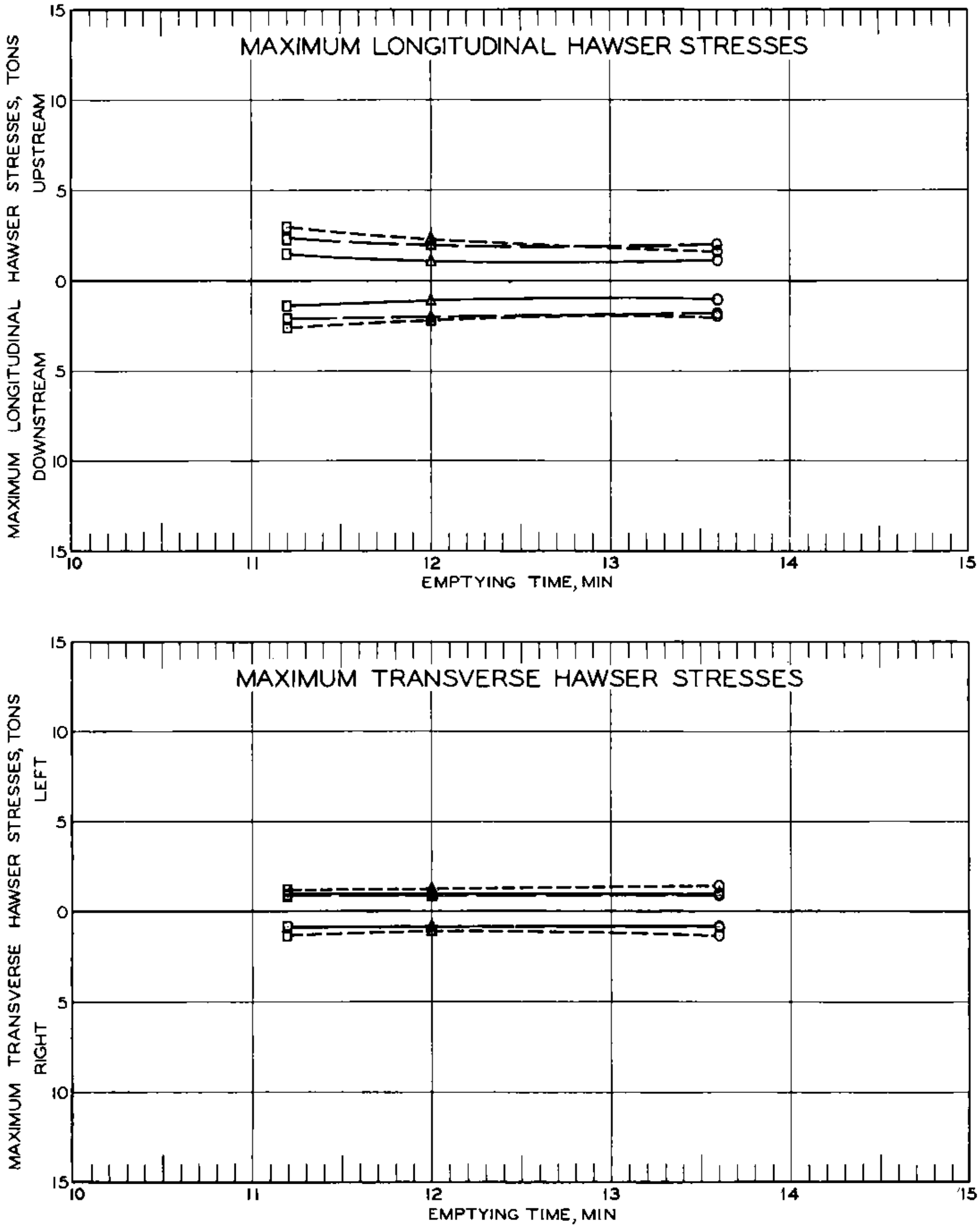
LEGEND	
SYMBOL	VALVE TIME, MIN
□	2
△	4
○	8

NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0).

——— 4-BARGE TOW AT STA 0+30
- - - - 2-BARGE TOW AT STA 0+30
— — — 2-BARGE TOW AT STA 2+25

EFFECT OF FILLING TIME ON MAXIMUM HAWSER STRESSES

MULTIPORT ARRANGEMENT TYPE 1
2- AND 4-BARGE TOWS



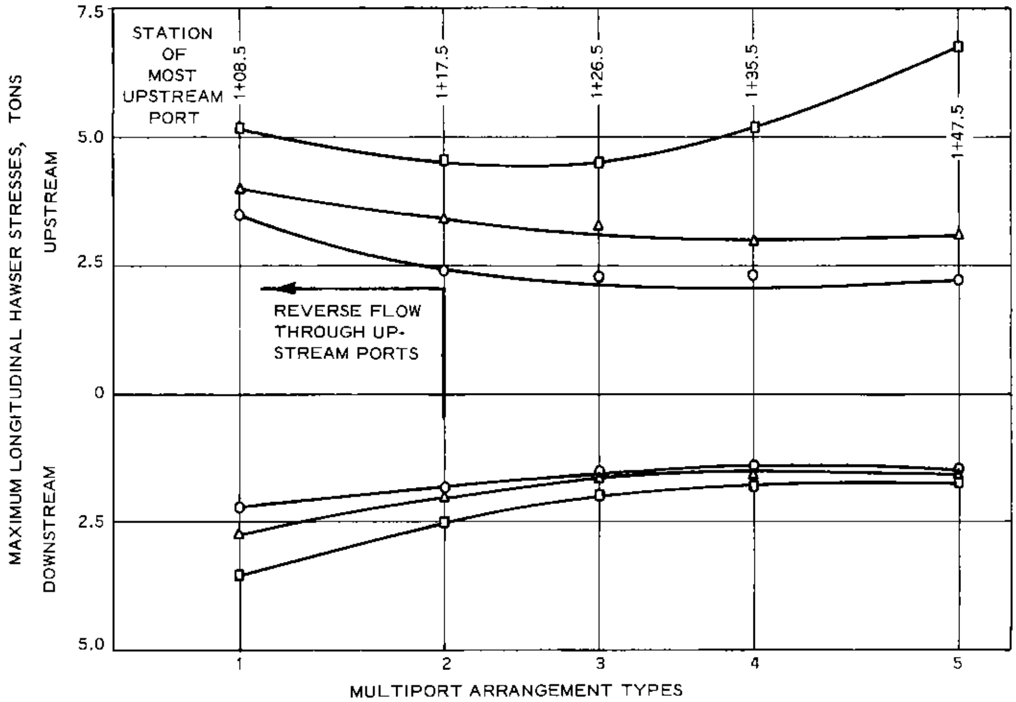
LEGEND	
SYMBOL	VALVE TIME, MIN
□	2
△	4
○	8

NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0).

——— 4-BARGE TOW AT STA 0+30
- - - - 2-BARGE TOW AT STA 0+30
— — 2-BARGE TOW AT STA 2+25

EFFECT OF EMPTYING TIME ON MAXIMUM HAWSER STRESSES

MULTIPORT ARRANGEMENT TYPE I
2- AND 4-BARGE TOWS

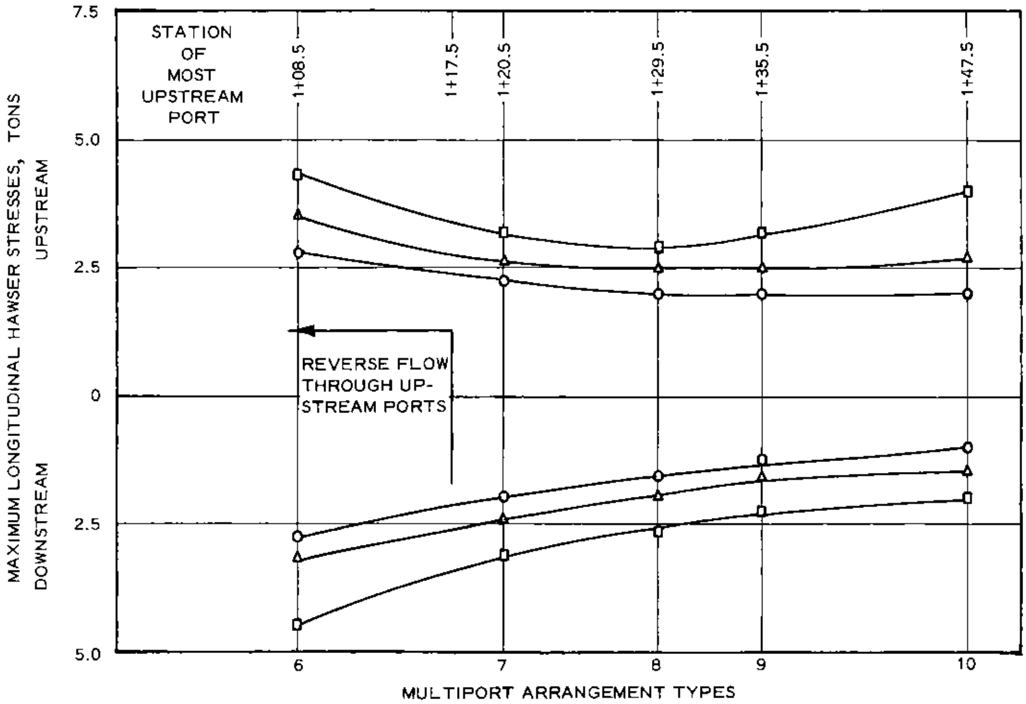


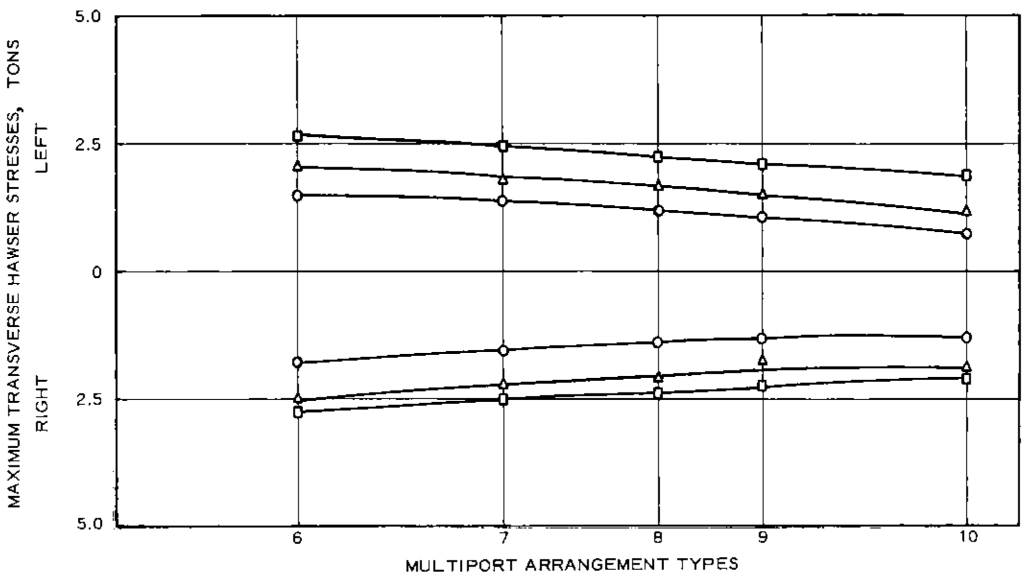
NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0).
14-FT SUBMERGENCE
4-BARGE TOW POSITIONED 30 FT FROM UPSTREAM MITER GATE PINTLES.

O 2-MIN VALVE
□ 4-MIN VALVE
Δ 8-MIN VALVE

MAXIMUM HAWSER STRESSES DURING FILLING

MULTIPORT ARRANGEMENT TYPES 1-5



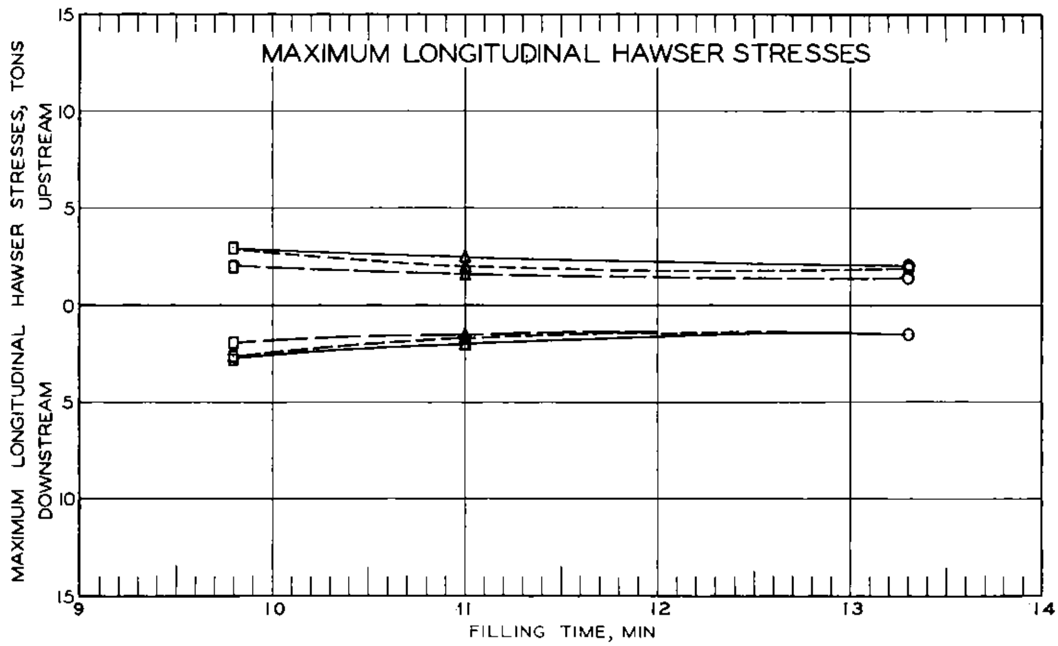


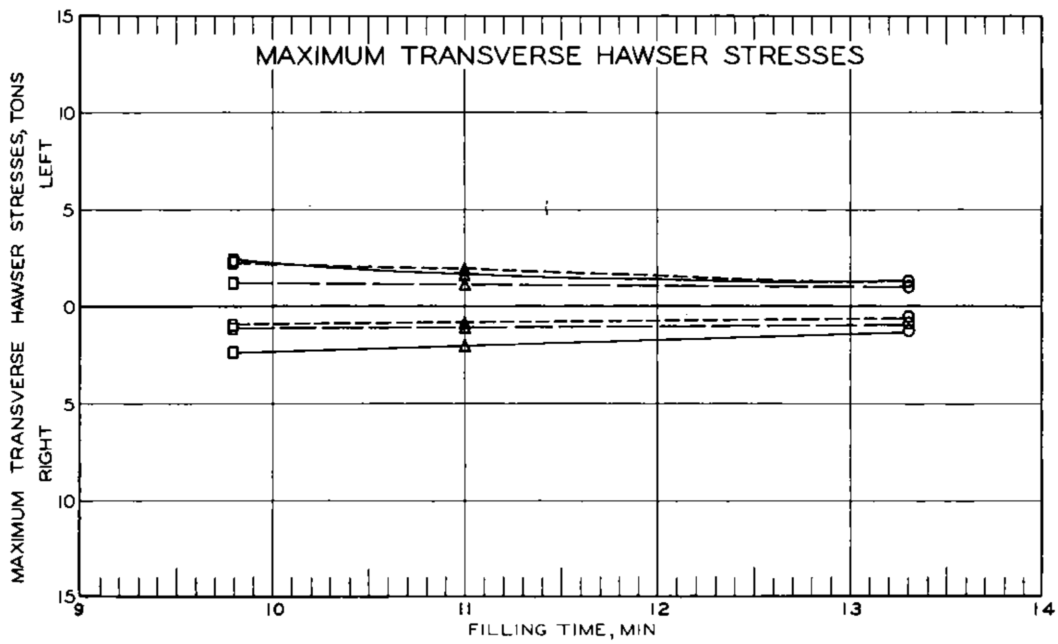
NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0).
4-BARGE TOW POSITIONED 30 FT FROM UPSTREAM MITER GATE PINTLES. MITER GATES ARE SHIFTED DOWN-STREAM 21 FT (STA 0+30, STA 4+80).

□ 2-MIN VALVE
Δ 4-MIN VALVE
O 8-MIN VALVE

MAXIMUM HAWSER STRESSES DURING FILLING

MULTIPORT ARRANGEMENT TYPES 6-10





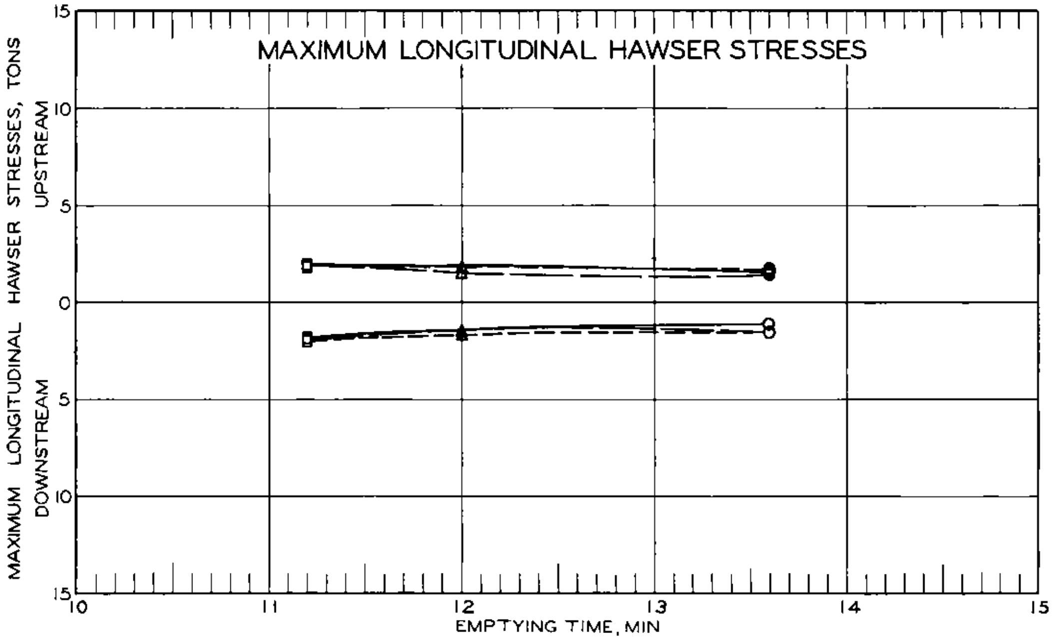
LEGEND	
SYMBOL	VALVE TIME, MIN
□	2
Δ	4
O	8

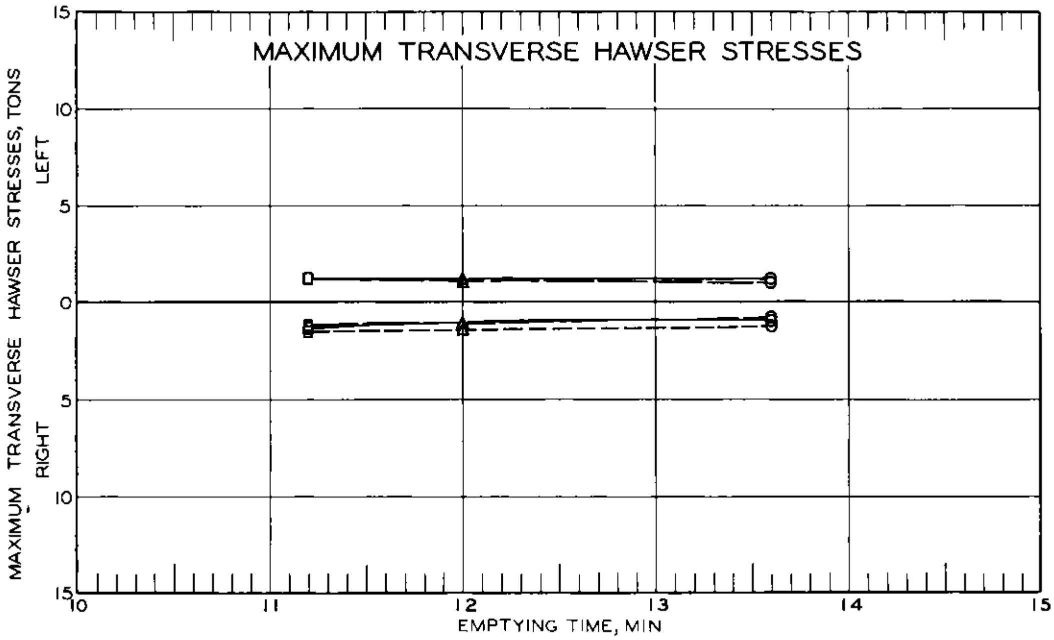
NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0).

———— 4 BARGES AT STA 0+30
– – – – 2 BARGES AT STA 0+30
—— —— 2 BARGES AT STA 2+25

MAXIMUM HAWSER STRESSES DURING FILLING

MULTIPORT ARRANGEMENT TYPE 8
2- AND 4-BARGE TOWS





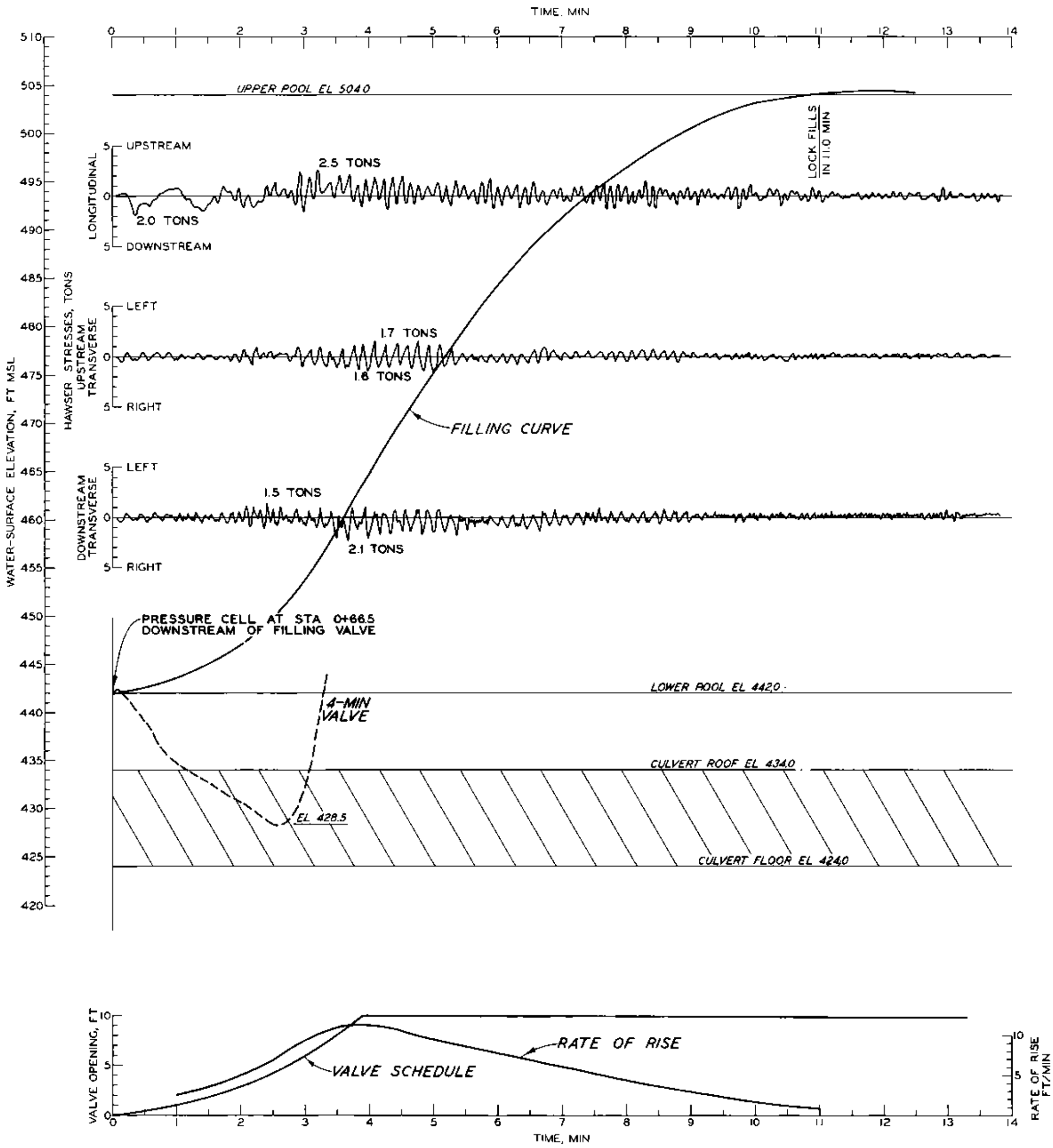
LEGEND	
SYMBOL	VALVE TIME, MIN
□	2
Δ	4
O	8

NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0).

——— 4 BARGES AT STA 0+30
– – – – 2 BARGES AT STA 0+30
— — — 2 BARGES AT STA 2+25

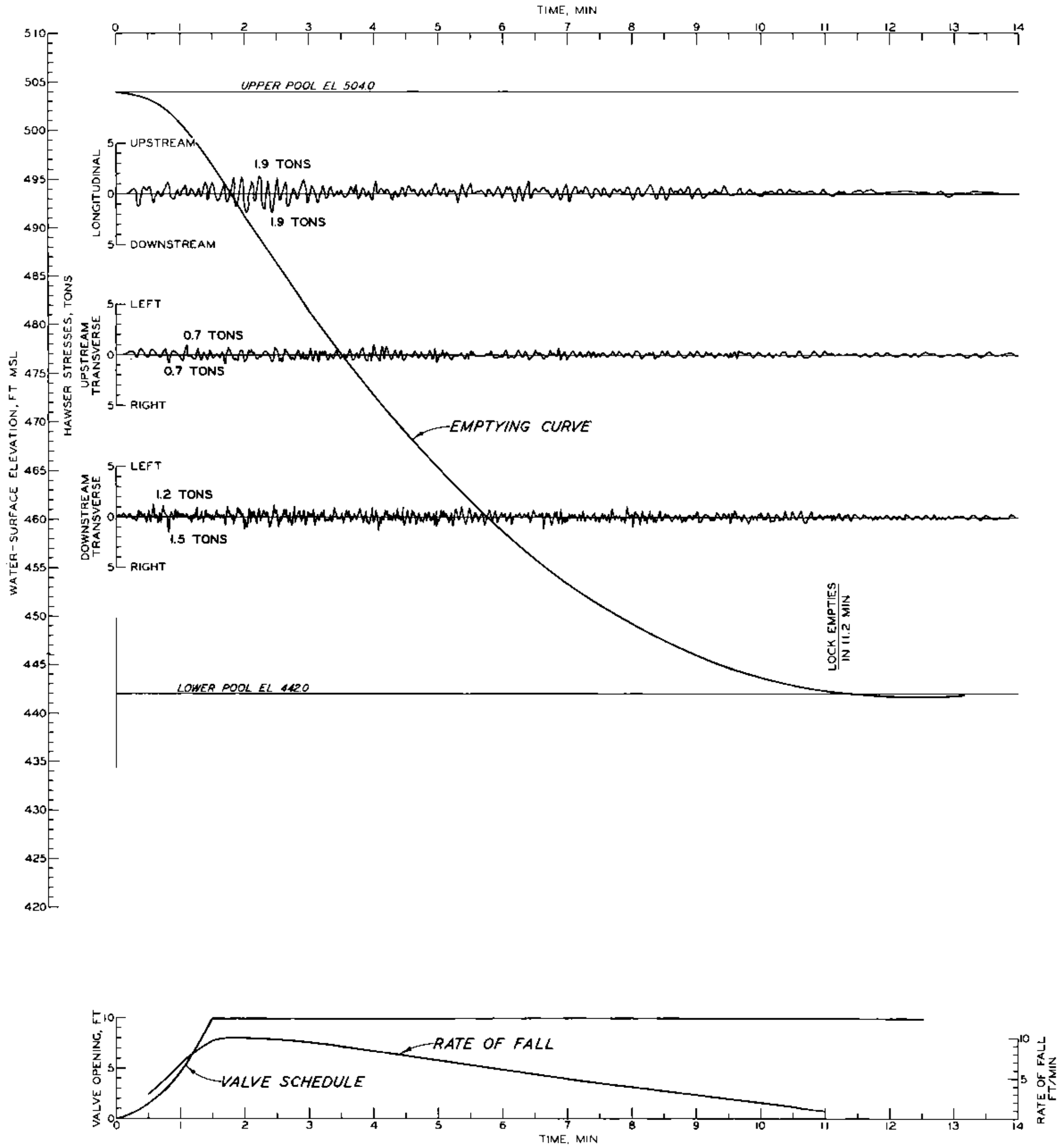
MAXIMUM HAWSER STRESSES DURING EMPTYING

MULTIPORT ARRANGEMENT TYPE 8
2- AND 4-BARGE TOWS



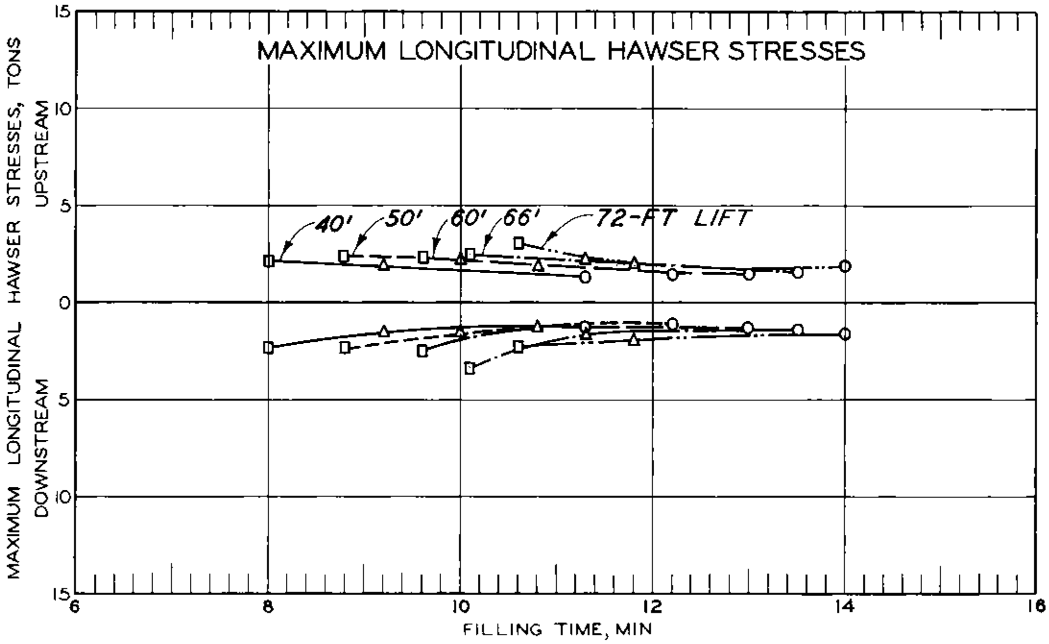
NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0)
4-BARGE TOW POSITIONED 30 FT BELOW UPSTREAM MITER GATE PINTLES.
CULVERT AT VALVES; 10 FT X 10 FT.
SUBMERGENCE IS GIVEN FROM LOCK FLOOR EL 428.0.

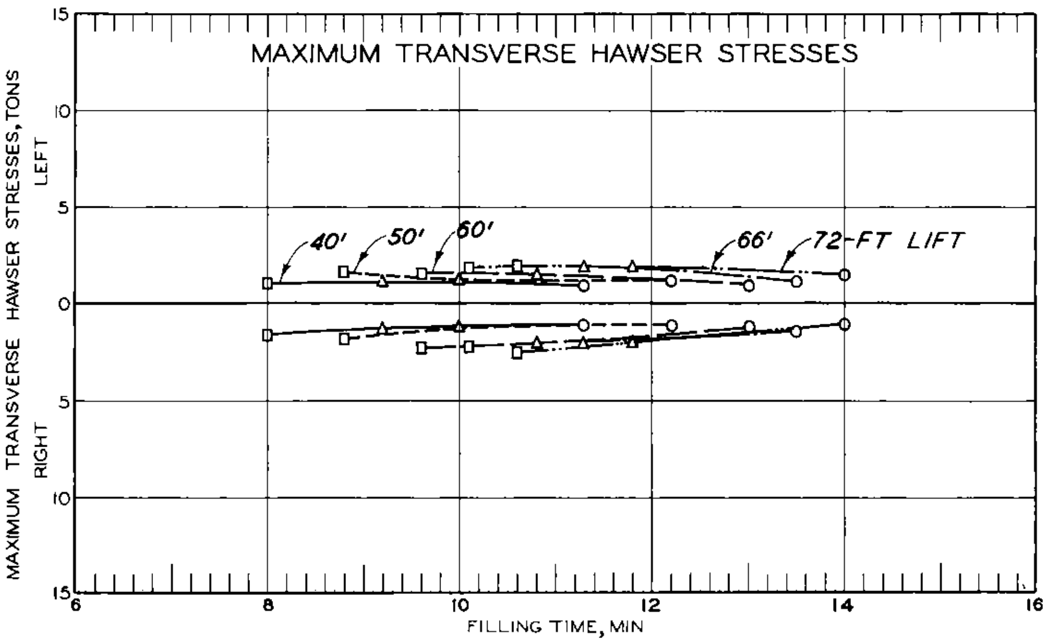
FILLING CHARACTERISTICS
TYPE 8 MULTIPORT ARRANGEMENT
4-MIN VALVE
14-FT SUBMERGENCE, 62-FT LIFT



NOTE 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0)
4-BARGE TOW POSITIONED 30 FT BELOW UPSTREAM MITER GATE PINTLES.
CULVERT AT VALVES, 10 FT X 10 FT.
SUBMERGENCE IS GIVEN FROM LOCK FLOOR EL 428.0.

EMPTYING CHARACTERISTICS
TYPE 8 MULTIPORT ARRANGEMENT
1-1/2-MIN VALVE
14-FT SUBMERGENCE, 62-FT LIFT





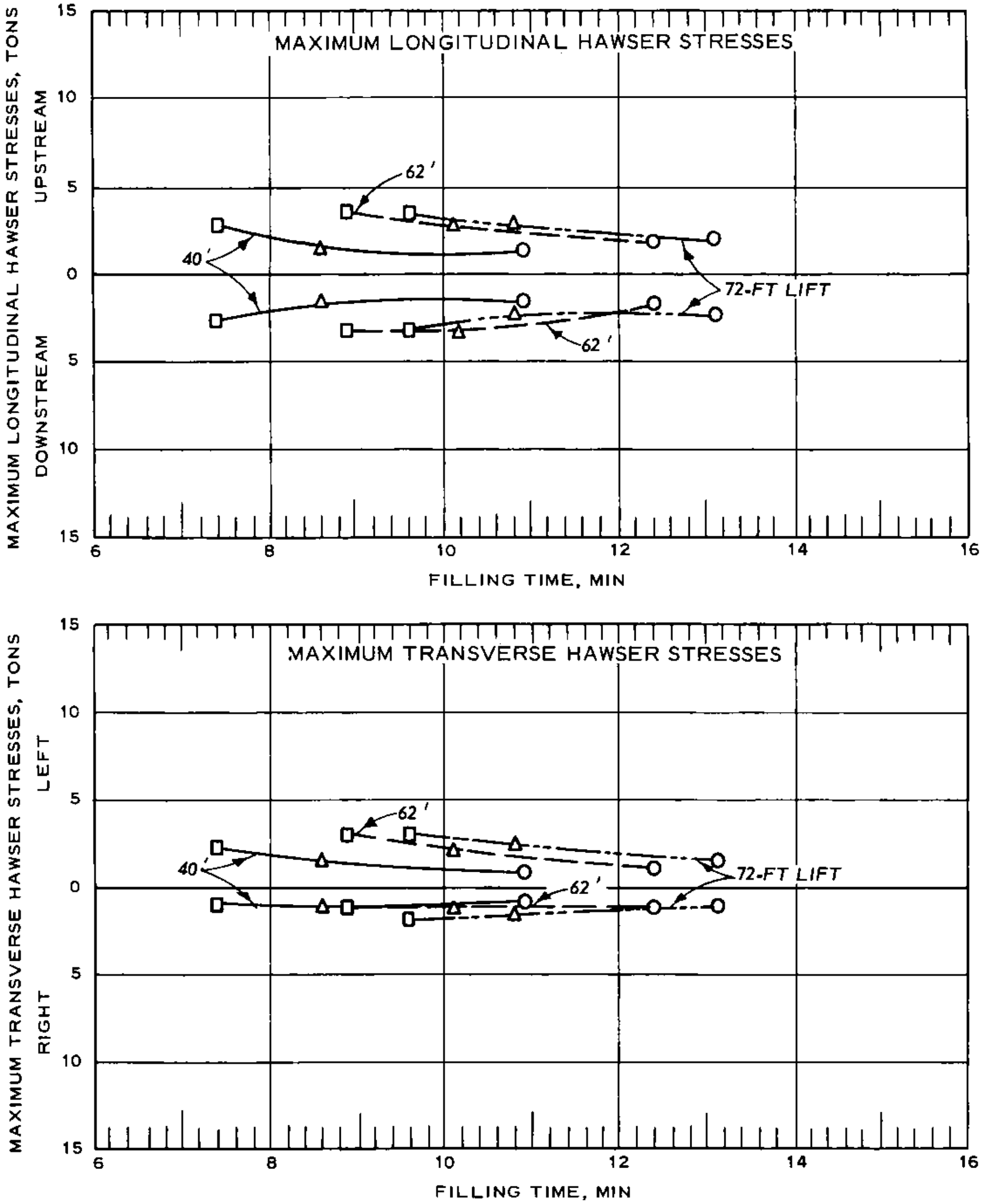
LEGEND	
SYMBOL	VALVE TIME, MIN
□	2
Δ	4
O	8

NOTE: LOWER POOL EL 442.0 .

4-BARGE TOW POSITIONED 30 FT BELOW UPSTREAM MITER GATE PINTLE (7280 TONS DISPLACEMENT).

EFFECT OF LIFT ON MAXIMUM HAWSER STRESSES DURING FILLING

MULTIPORT ARRANGEMENT TYPE 8
40-, 50-, 60-, 66-, AND 72-FT LIFTS
14-FT SUBMERGENCE



LEGEND

SYMBOL	VALVE TIME, MIN
□	2
△	4
○	8

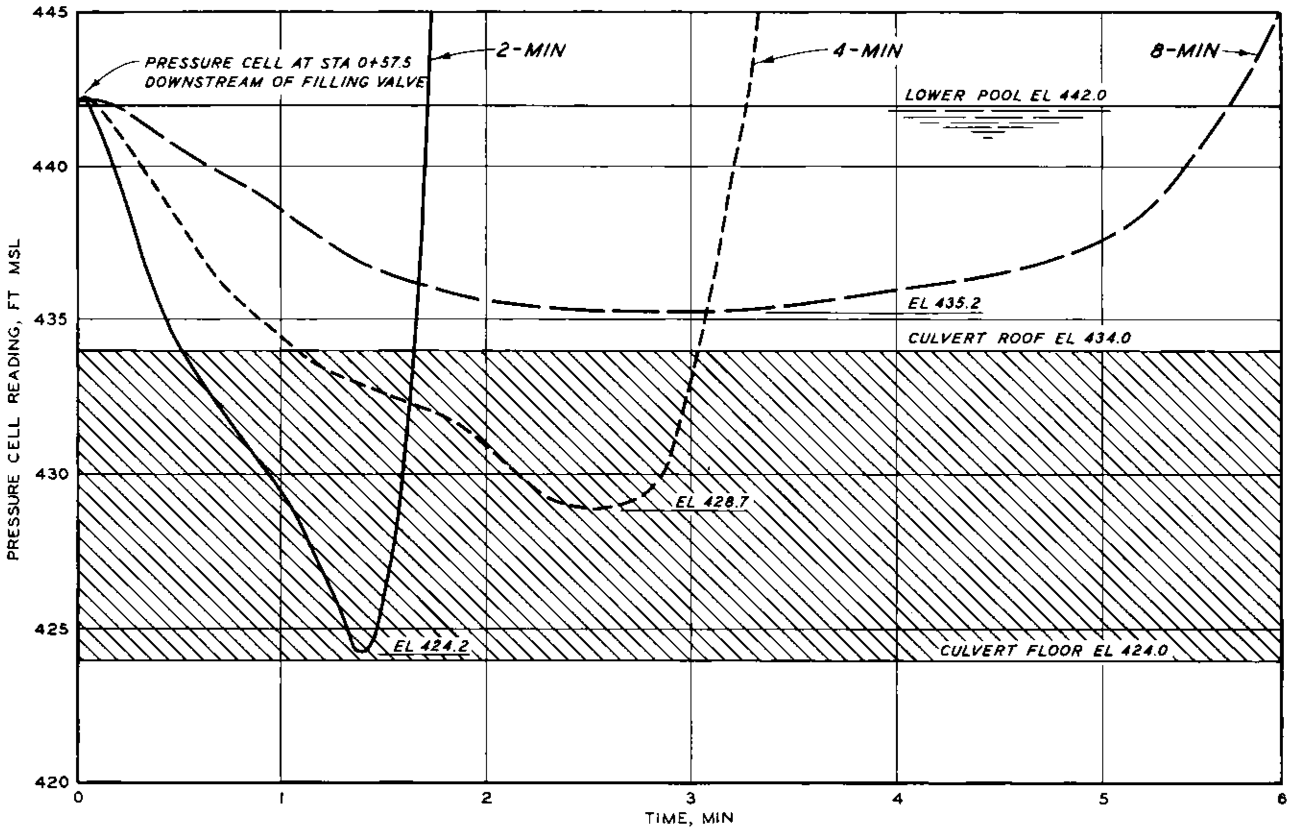
NOTE: LOWER POOL EL 442.0 .

4-BARGE TOW POSITIONED 30 FT BELOW UPSTREAM MITER GATE PINTLE (7280 TONS DISPLACEMENT).

EFFECT OF LIFT ON MAXIMUM HAWSER STRESSES DURING FILLING

MULTIPORT ARRANGEMENT TYPE II
40-, 62-, AND 72-FT LIFTS
14-FT SUBMERGENCE

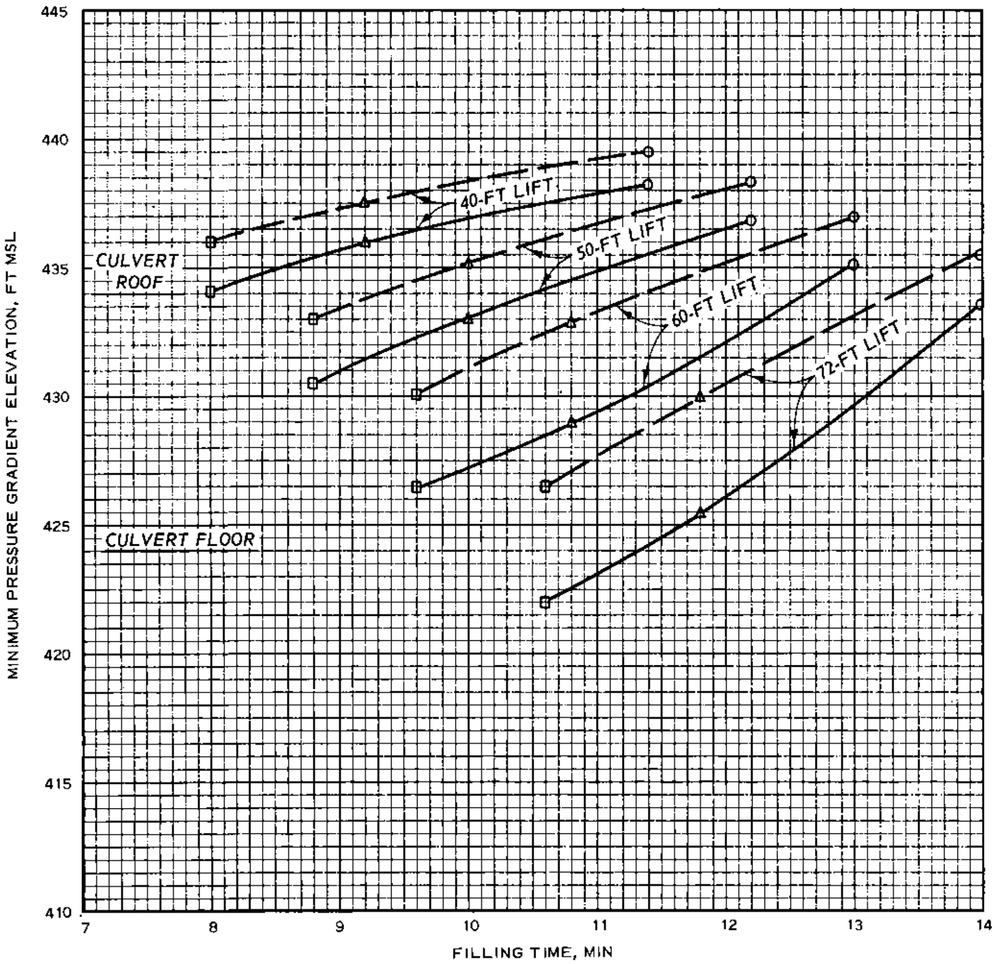
PLATE 20



NOTE: CULVERT SIZE 10 FT X 10 FT.
UPPER POOL ELEVATION 504.0
SUBMERGENCE IS GIVEN FROM
LOCK FLOOR EL 428.0.

CULVERT PRESSURES DOWNSTREAM
OF FILLING VALVES

TYPE I (ORIGINAL) MULTIPORT ARRANGEMENT
14-FT SUBMERGENCE, 62-FT LIFT



LEGEND

□ 2-MIN VALVE
△ 4-MIN VALVE
○ 8-MIN VALVE

TRANSITION SECTION
D/S OF FILLING VALVE

——— ORIGINAL
– – – – ALTERNATE

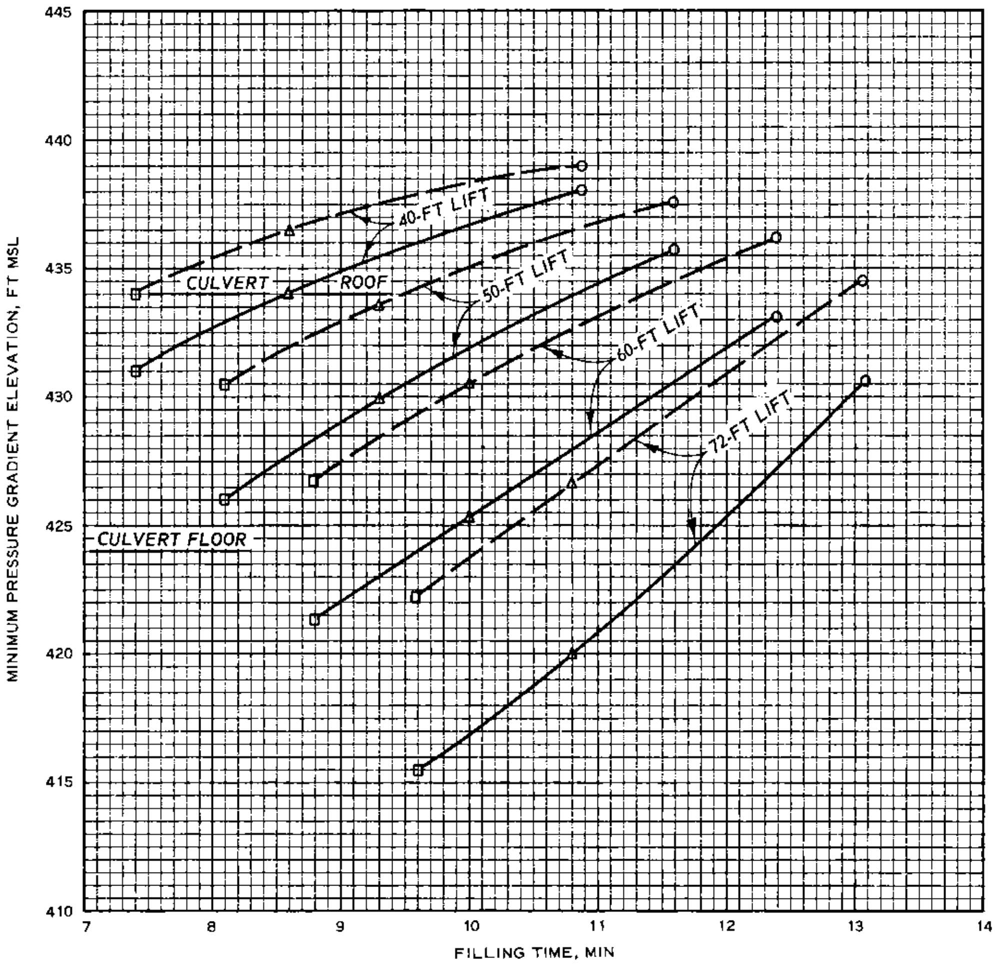
NOTE: PRESSURE GRADIENT ELEVATIONS SHOWN ARE BASED ON AVERAGE PRESSURE CELL READINGS.

SUBMERGENCE 14 FT ABOVE LOCK FLOOR.

PORT AREA/CULVERT AREA = 0.75

CULVERT ROOF PRESSURES DOWNSTREAM OF FILLING VALVES

MULTIPORT ARRANGEMENT TYPE 8



LEGEND

□ 2-MIN VALVE
Δ 4-MIN VALVE
O 8-MIN VALVE

TRANSITION SECTION
D/S OF FILLING VALVE

——— ORIGINAL
– – – ALTERNATE

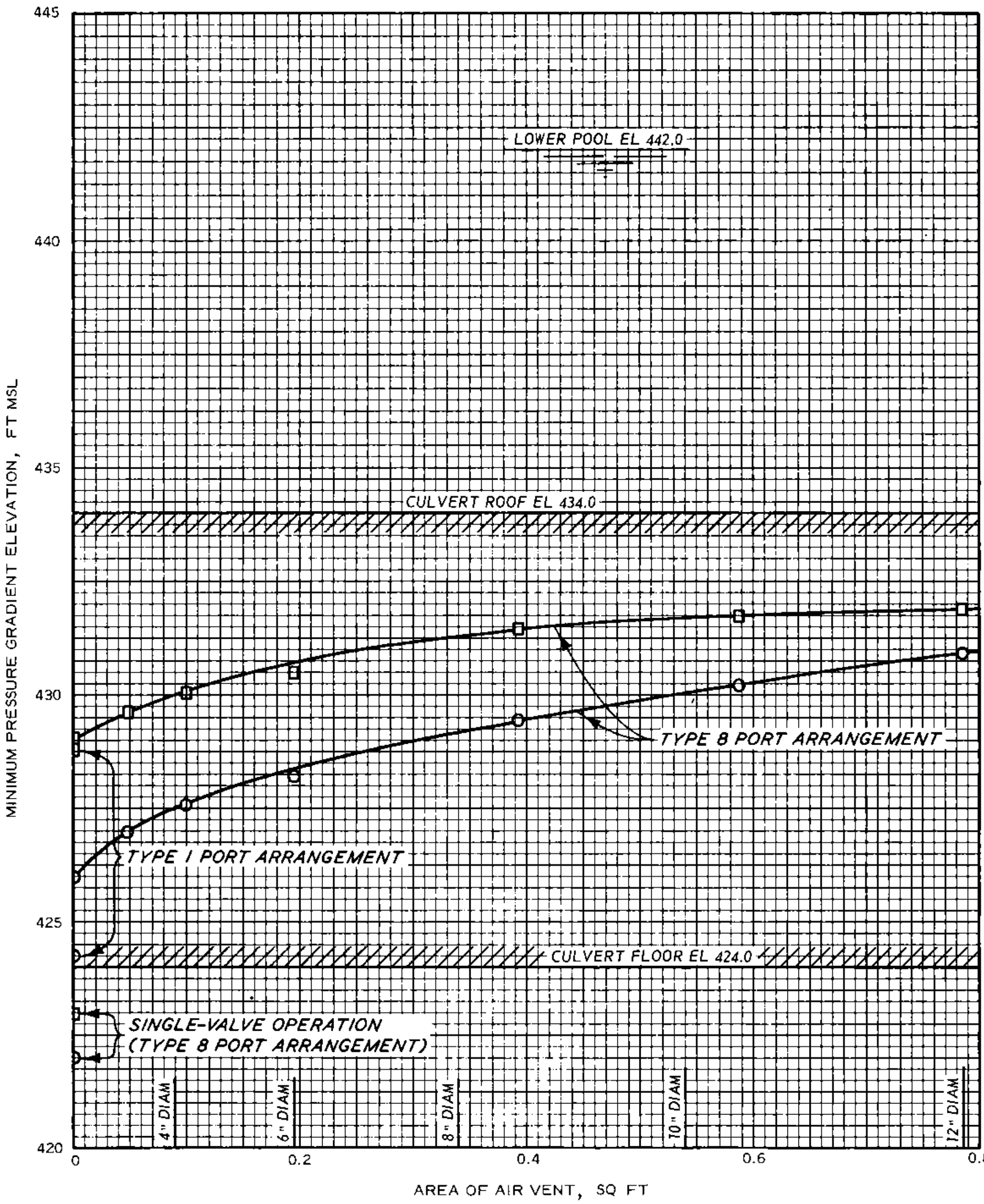
NOTE: PRESSURE GRADIENT ELEVATIONS SHOWN ARE BASED ON AVERAGE PRESSURE CELL READINGS.

SUBMERGENCE 14 FT ABOVE LOCK FLOOR.

PORT AREA/CULVERT AREA = 0.95

CULVERT ROOF PRESSURES DOWNSTREAM OF FILLING VALVES

MULTIPORT ARRANGEMENT TYPE II



LEGEND

O 2-MIN VALVE

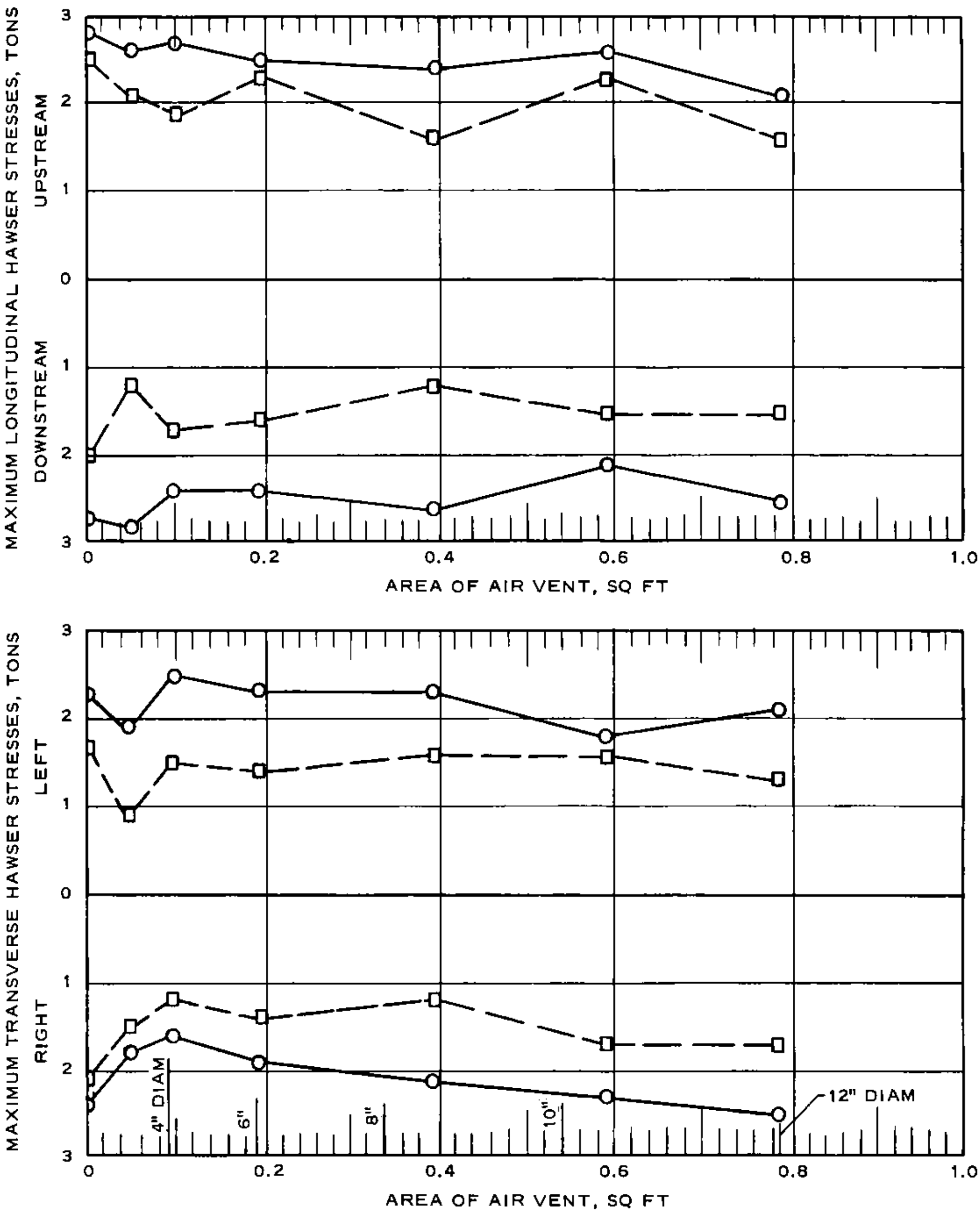
□ 4-MIN VALVE

NOTE: PRESSURE GRADIENT ELEVATIONS SHOWN ARE BASED ON AVERAGE PRESSURE CELL READINGS.

MINIMUM INSTANTANEOUS PRESSURES ABOUT 5 FT LOWER.

EFFECT OF AIR-VENTING ON CULVERT ROOF PRESSURES DOWNSTREAM OF FILLING VALVES

62-FT LIFT

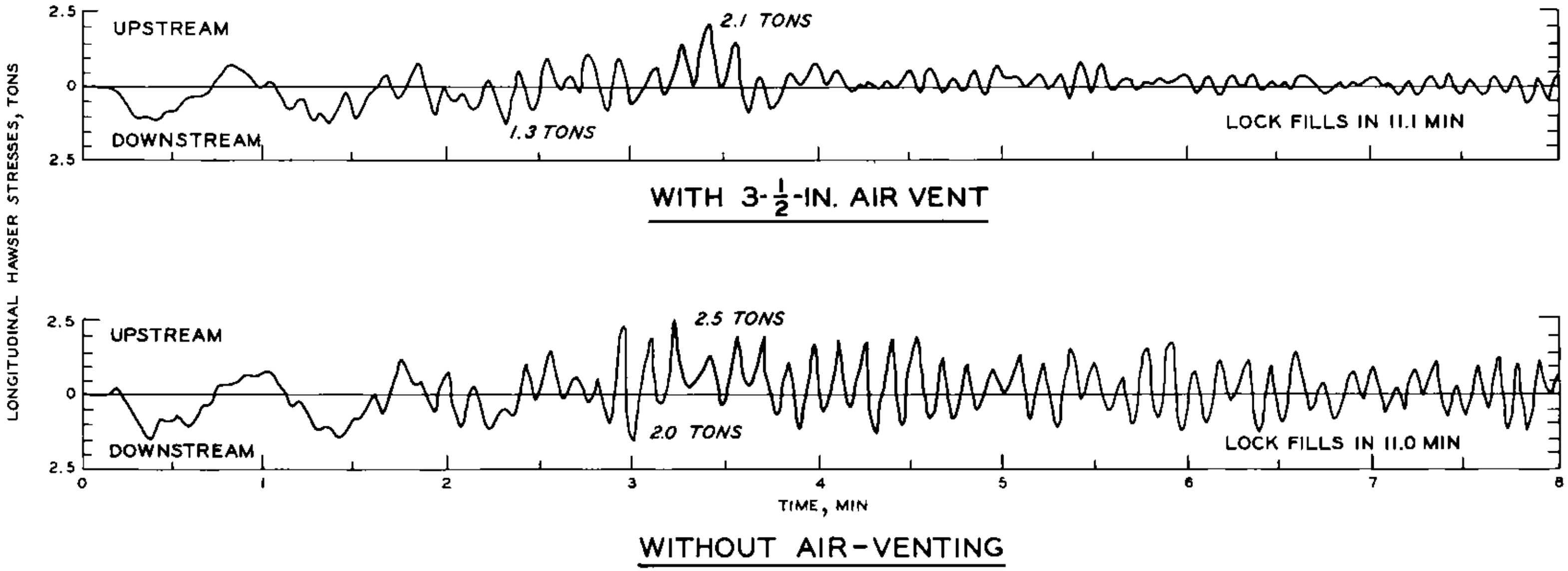


LEGEND

SYMBOL	VALVE TIME MIN	FILLING TIME MIN
O	2	9.8
□	4	11.0

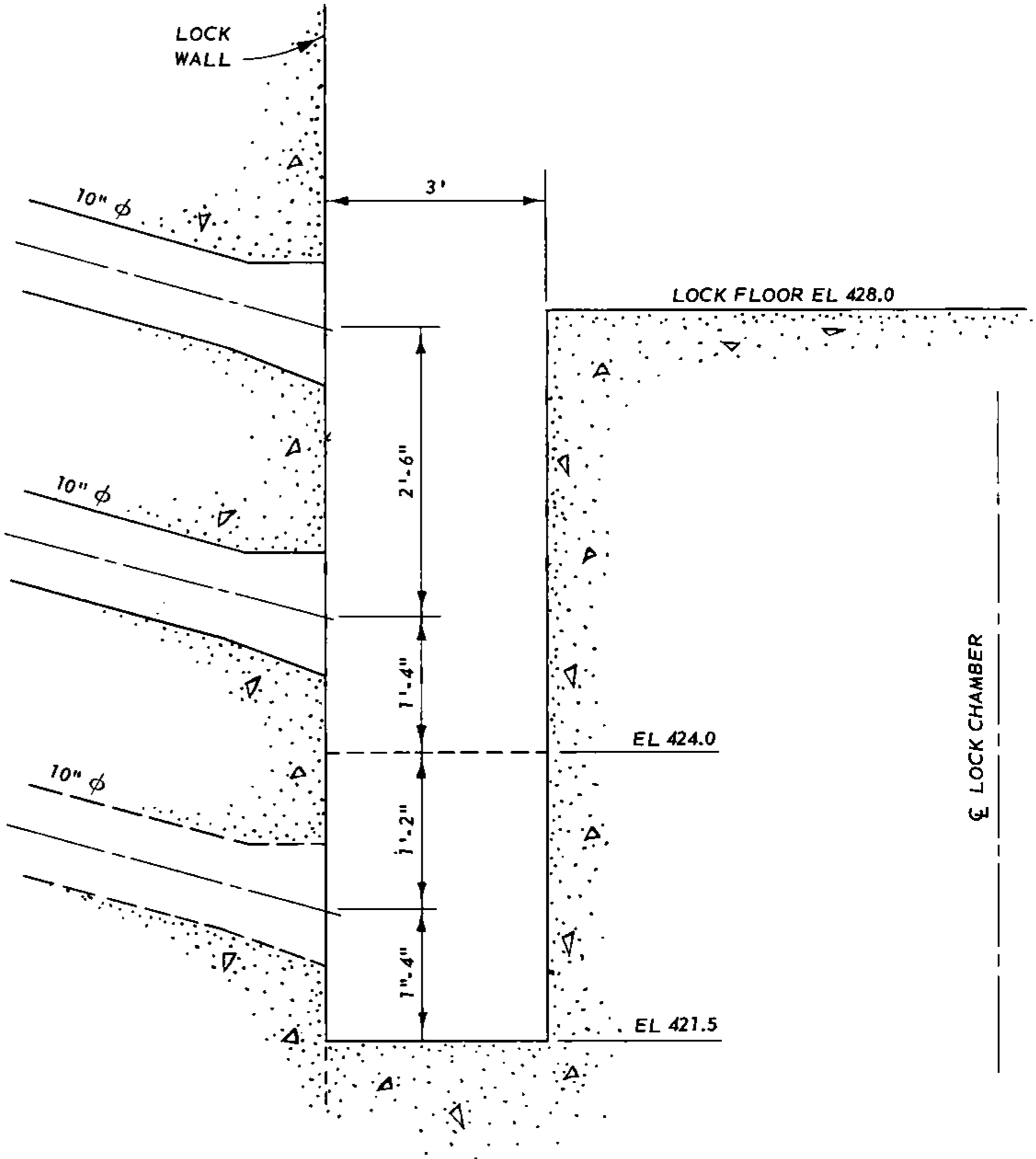
EFFECT OF AIR-VENTING ON MAXIMUM HAWSER STRESSES DURING FILLING

MULTIPORT ARRANGEMENT TYPE 8
62-FT LIFT



NOTE: 62-FT LIFT, 14-FT SUBMERGENCE.
UPPER POOL EL 504.0, LOWER POOL EL 442.0.
4-BARGE TOW POSITIONED 30 FT BELOW UPSTREAM MITER GATE PINTLES.

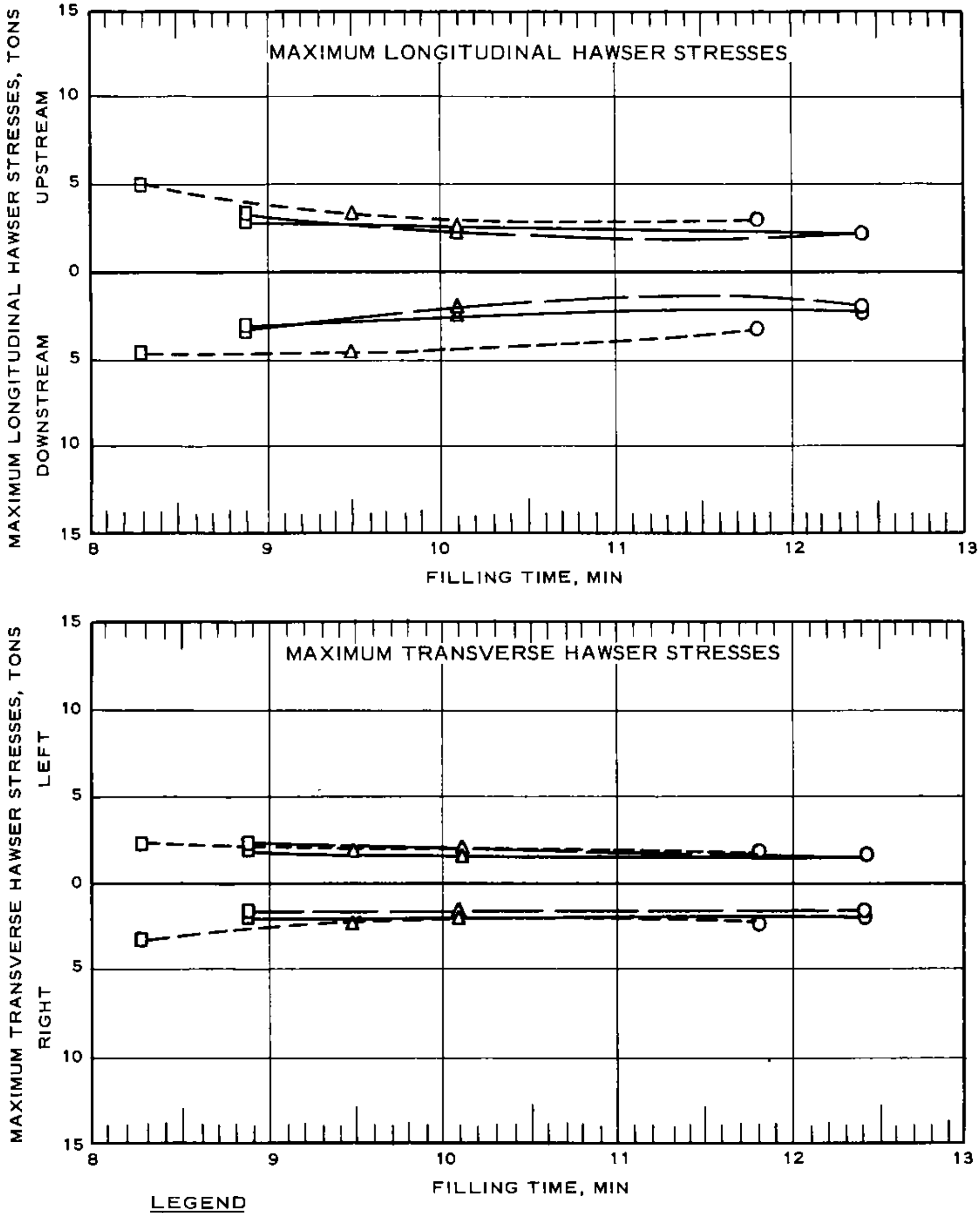
HAWSER STRESSES DURING FILLING
MULTIPORT ARRANGEMENT TYPE 8
4-MIN VALVE



ARRANGEMENT TYPE	NUMBER OF PORTS OPEN* TOP ROW	MIDDLE ROW	BOTTOM ROW	TRENCH DEPTH FT
12	87	87	0	6.5
13	87	87	0	4.0
14	91	91	44	6.5

* EXTRA PORTS OPENED FOR RESISTANCE CORRECTION ARE NOT INCLUDED.

MULTIPORT ARRANGEMENT TYPES 12-14



LEGEND

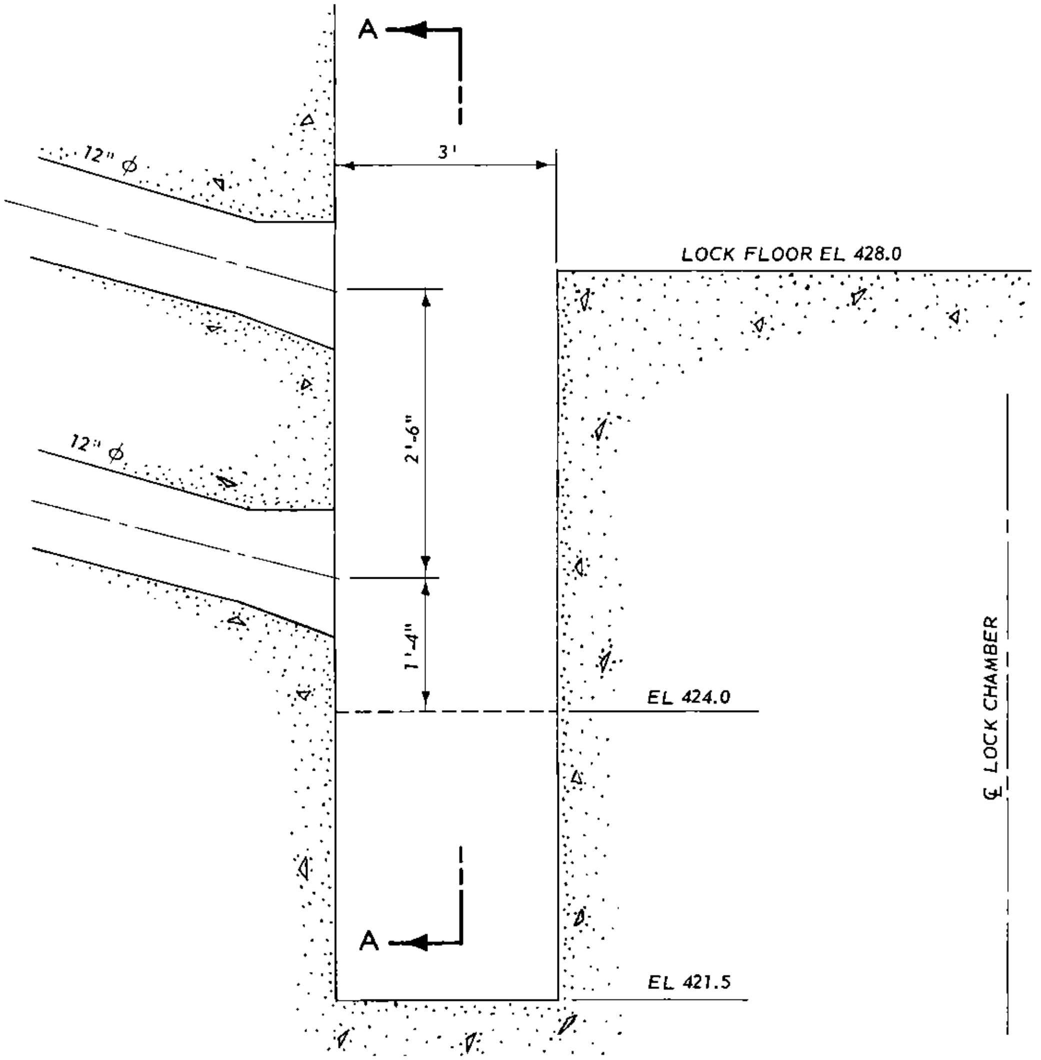
SYMBOL	VALVE TIME, MIN
□	2
Δ	4
O	8

NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0).

———	TYPE 12
— —	TYPE 13
-----	TYPE 14

MAXIMUM HAWSER STRESSES DURING FILLING

MULTIPORT ARRANGEMENT TYPES 12–14
4-BARGE TOW

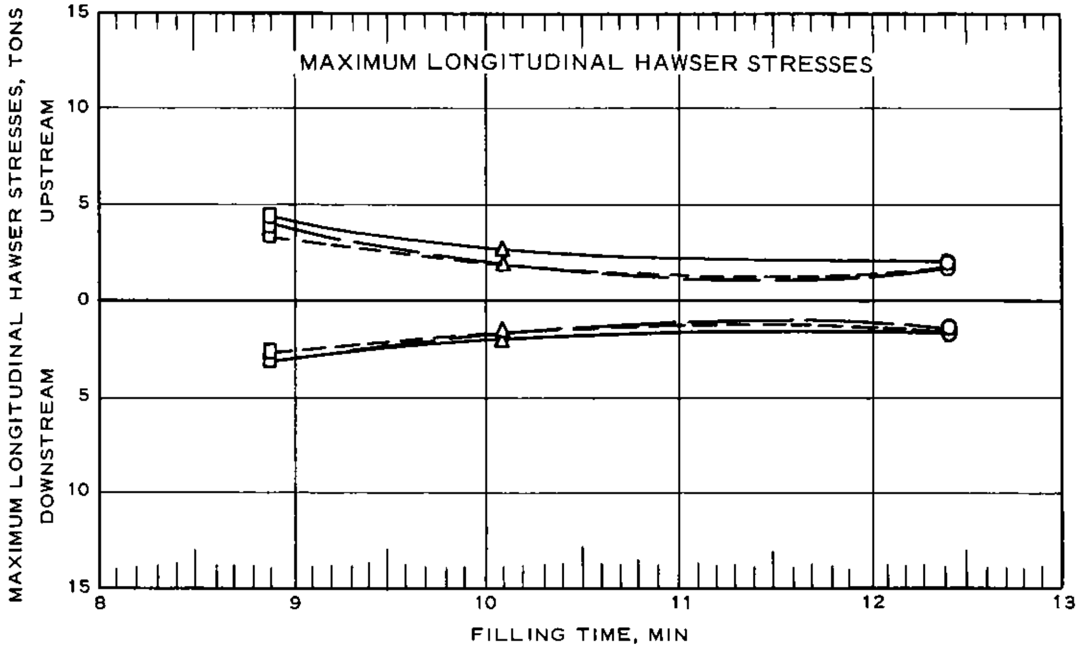


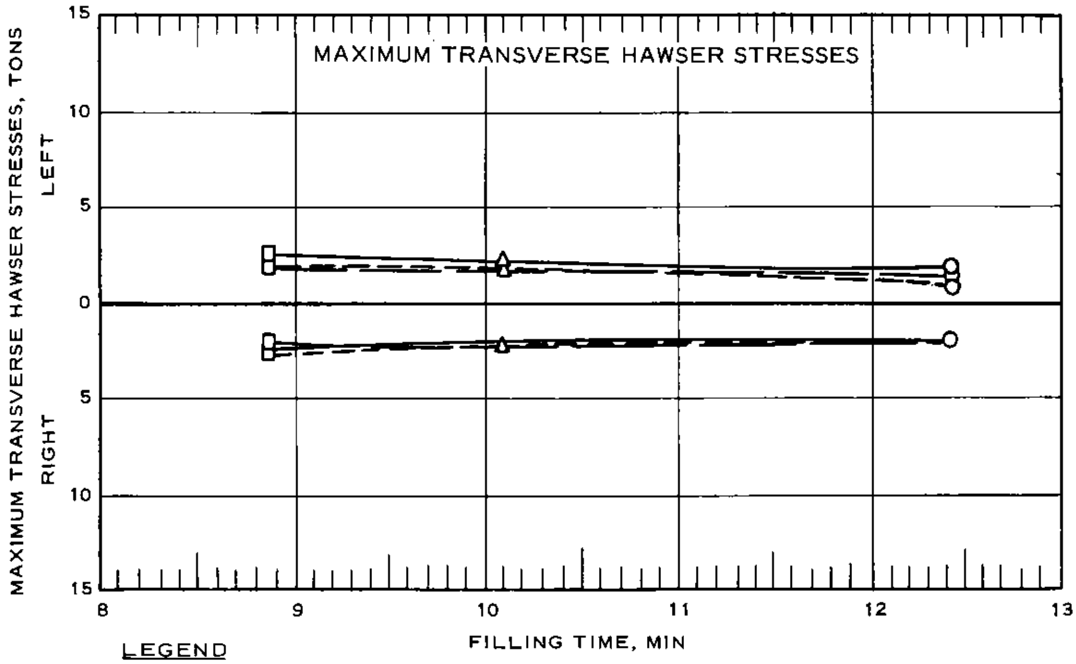
ARRANGEMENT TYPE	NUMBER OF PORTS OPEN* TOP ROW	BOTTOM ROW	SECTION A-A MULTIPORT PATTERN (3 FT ON CENTERS)	TRENCH DEPTH FT
15	60	61	○ ○ ● ○ ○ ● ○ ○ ● ○ ○ ●	4.0
16	89	32	○ ○ ○ ○ ○ ○ ● ● ○ ● ● ○	4.0
17	89	32	○ ○ ○ ○ ○ ○ ● ● ○ ● ● ○	6.5

* EXTRA PORTS OPENED FOR RESISTANCE CORRECTION ARE NOT INCLUDED.

● PORT CLOSED.

MULTIPORT ARRANGEMENT TYPES 15-17





LEGEND

SYMBOL	VALVE TIME, MIN
□	2
△	4
○	8

NOTE: 62-FT LIFT (UPPER POOL EL 504.0, LOWER POOL EL 442.0).

———	TYPE 15
— —	TYPE 16
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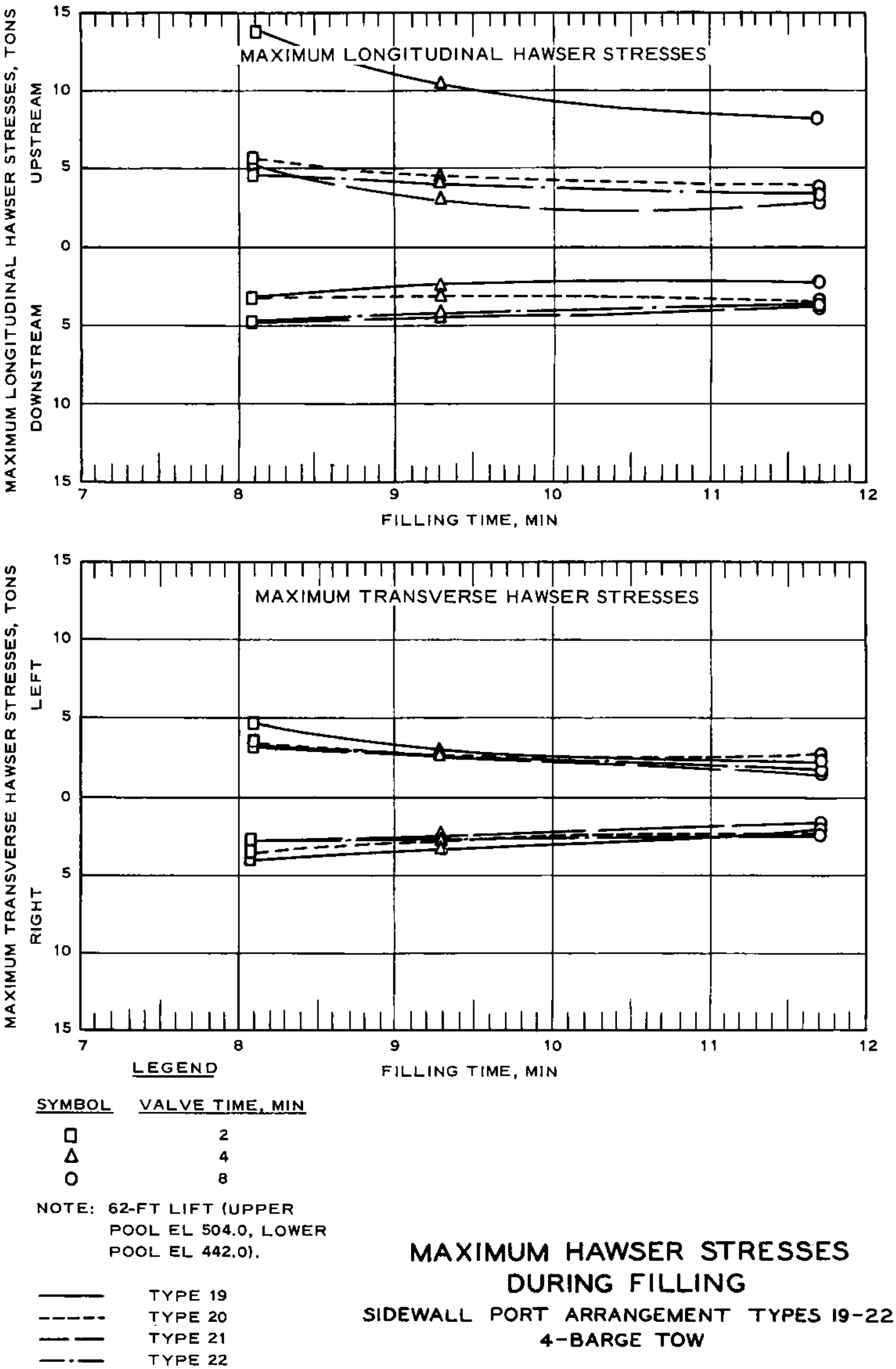
MULTIPORT ARRANGEMENT TYPES 15-17

4-BARGE TOW



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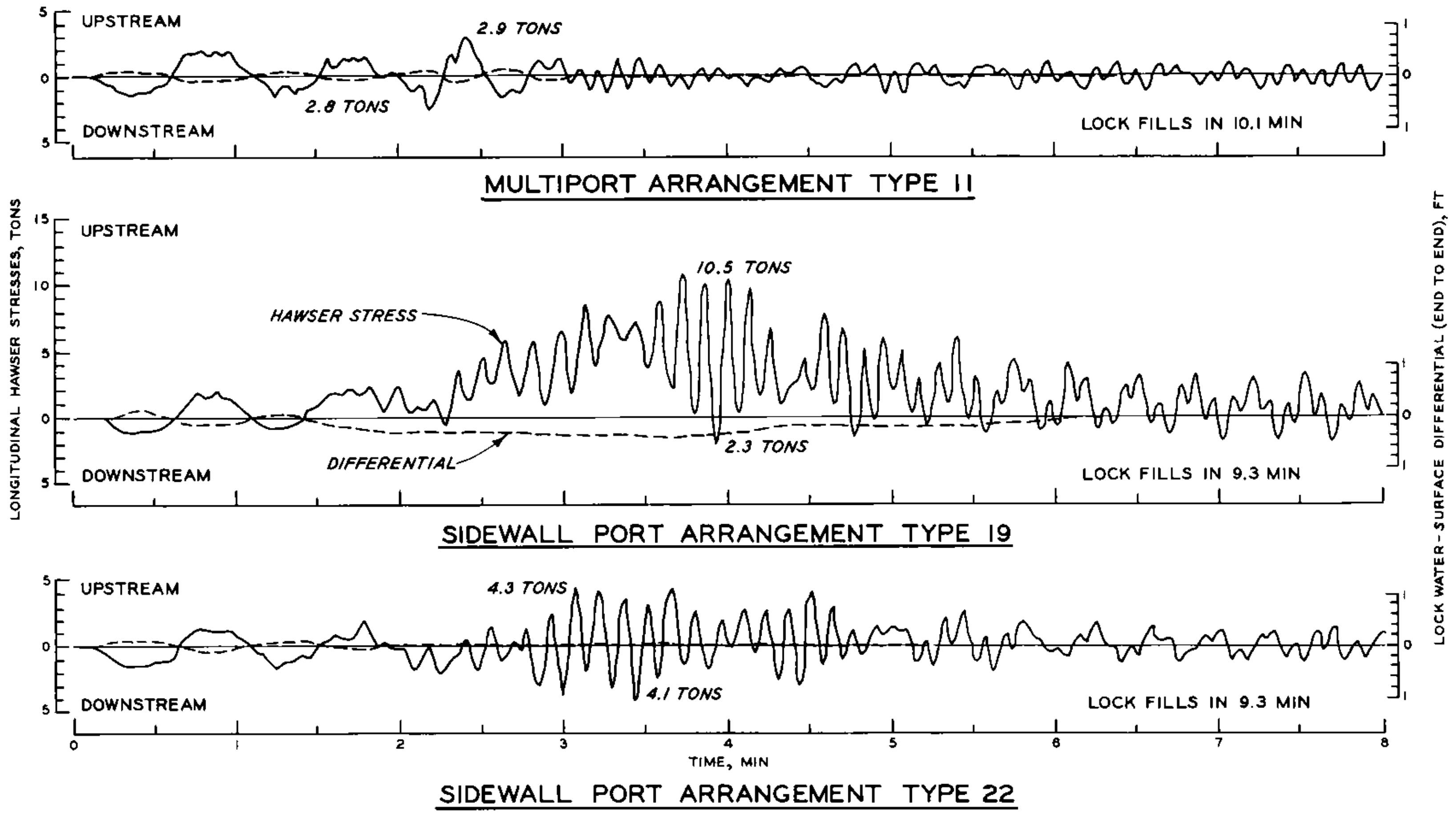
SIDEWALL PORT ARRANGEMENT TYPES 19-22

4-BARGE TOW



NOTE: 82-FT LIFT, 14-FT SUBMERGENCE.
UPPER POOL EL 504.0, LOWER POOL EL 442.0.
4-BARGE TOW POSITIONED 30 FT BELOW UPSTREAM MITER GATE PINTLES.

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Final report

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13. ABSTRACT Cordell Hull Lock will be 84 ft wide by 450 ft long and will have a normal lift of 59 ft with a maximum lift of 62 ft occurring about 5 percent of the time. Model study (scale 1:25) of the filling and emptying system proposed for this lock was confined to the portion of the hydraulic system between the filling and emptying valves. Performance of the type 1 (original) multiport arrangement was, in general, satisfactory even though it was evident from test results that certain improvements could be made in the system. The lock chamber manifold includes three horizontal rows of seventy-two 8-in.-diam ports resulting in an overall port area/culvert area ratio of 0.75 based on the culvert area at the valves. The manifold extends over 48 percent of the chamber length and is centered about 3.9 percent of the chamber length upstream from the midpoint of the chamber. The ports discharge into a 3-ft-wide by 6.5-ft-deep trench along the toe of the lock wall. With the proposed filling-emptying system the lock can be filled in 11.0 min (4-min valve) and emptied in 11.2 min (1.5-min valve) with acceptable hawser stresses and turbulence conditions in the chamber. Consideration of the performance of the system and construction schedules at the project resulted in its adoption for use at the Cordell Hull project. However, additional tests of the multiport system were conducted since this type of system was under consideration for use at another project. These tests resulted in several suggestions for improvements in the system. Port arrangements in which conventional sidewall ports discharged into a trench at the toe of the lock wall were also investigated, but their performance did not compare favorably with that of the better multiport arrangements.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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