CORPS OF ENGINEERS

U. S. ARMY

REPORT ON THE

CLOSURE OF THE SECOND-STEP COFFERDAM
Mc NARY LOCK AND DAM

Columbia River, Oregon and Washington

OFFICE OF THE DISTRICT ENGINEER

WALLA WALLA, WASHINGTON

JULY 1951

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Prepared by Walla Walla District
Corps of Engineers
July 1951

SYLLABUS

The present report describes the McNary Second-Step Cofferdam closure operation from the time of awarding the contract to the completion of the river diversion.

The McNary closure was a very difficult engineering problem which was solved by an ingenious method never used before. The present report describes the application of the method, the changes made on the basis of model experiments and the developments which assisted the ultimate success of the operation.

The report concludes that the McNary method can be applied on other difficult river diversions and suggests possible improvements.

TABLE OF CONTENTS

SYLLABUS

CHAPTER I - GENERAL

Paragraph		Page
1	Purpose	1
2	Hydrology and Streamflow	1
5	Summary Hydrograph	1
6	Cofferdam Layout	2
8	Magnitude of Closure Problem	3
9	Government Responsibility	3

CHAPTER II - THE PRE-CONSTRUCTION PHASE

11	McNary General Model	5
14	Selection of Precast Blocks	6
15	Design Section of Fill	6
16	Contract Award	7
18	McNary Tetrahedron Studies	7
19	Office Investigations	8
22	Seattle Model Experiments	9
23	Field Experiments	10
24	Bonneville Sectional Models	10
29	Construction Model	12
32	Operation of Construction Model	13
33	Prototype Experiments	14

Paragraph		Page
	CHAPTER III - CONSTRUCTION METHODS AND EQUIPMENT	
34	Tetrahedron Casting	15
36	Specific Gravity of Tetrahedrons	16
37	Main Cableway	16
42	Loading of Tetrahedrons	18
43	Grid System	18
44	Spotting of Payloads	19
46	Field Control of Drops	19
49	Observations of Downstream Drift	20
50	Hauling of B-Stone	21
	CHAPTER IV - THE CLOSURE OPERATION	
51	FIRST TETRAHEDRON FILL	22
55	Effect of First Tetrahedron Fill	23
56	Bulking Experiment	24
57	Start of First Sounding Survey	24
61	Contractor's Difficulties	25
62	Setback of Closure Operation	26
64	Completion of First Sounding Survey	27
65	Shape of First Tetrahedron Fill	27
66	First Experiment on Construction Model	28
68	Second Experiment on Construction Model	28
70	Third Experiment on Construction Model	29
72	SECOND TETRAHEDRON FILL	30
77	Second Sounding Survey	32

Paragraph		Page
78	Fourth Experiment on Construction Model	32
79	Fifth Experiment on Construction Model	33
80	Difficulties in Simulation on Model	33
81	Completion of Fifth Experiment on Construction Model	34
82	THIRD TETRAHEDRON FILL	34
85	Sixth Experiment on Construction Model	36
87	Seventh Experiment on Construction Model	37
89	Final Experiment on Construction Model	37
90	FOURTH TETRAHEDRON FILL	38
92	The Turning Point	38
94	Third Sounding Survey	39
95	Computations of the Permeability	40
96	Completion of B-stone Fill	40
97	FIFTH TETRAHEDRON FILL	41
100	Emergence and Closure	42
102	SIXTH TETRAHEDRON FILL	42
104	First Permeability Measurement	43
106	Actual vs. Computed Spillway Flow	44
107	Actual Flow Distribution	44
108	Completion of Zone III	44
111	Sealing of Closure Fill	45
119	Crib Construction	47
120	Unwatering of Cofferdam Area	48
126	Characteristics of Tetrahedron Fill	50
129	Construction Report	50

Paragraph		Page
130	COST OF CLOSURE	51
	CHAPTER V - DISCUSSION	
	BASIC FACTORS OF McNARY CLOSURE	
132	Planning	54
133	Novel Method	54
134	Selection of Equipment	55
135	Resourcefulness	55
	POSSIBLE IMPROVEMENTS	
139	Engineering Analysis	56
141	Model Studies	57
145	Field Preparations	58
146	Field Observations	58
	APPLICATION TO OTHER PROJECTS	
149	Foundation Problems	59
151	Shapes and Specific Gravity of Precast Blocks	60
153	Procedure for Placing Rock Fill	61
154	Value of a Construction Model	62
155	Importance of Sealing	62
	CHAPTER VI - CONCLUSIONS	

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18 PLATES (See List of Plates)

50 PHOTOGRAPHS

CHAPTER I - GENERAL

1. Purpose. - The purpose of the present report is to describe the McNary Second-Step Cofferdam Closure in sufficient detail so that the experience gained may be used to best advantage in connection with other similar projects of the Corps of Engineers.

2. Hydrology and Streamflow. - The Columbia River at the McNary damsite has a drainage area of 215,000 square miles, varying in elevation from approximately 250 feet above mean sea level at the site to above 10,000 feet at the top of numerous peaks within the area. The mean annual precipitation for the Columbia River Basin above the McNary damsite is 24.2 inches. The annual precipitation is more than 50 inches in the mountains; at high elevations a large part of the precipitation falls in the form of snow.

3. Large floods are due to snowmelt and usually occur in late May or early June. The maximum on record in 72 years occurred on 6 June 1894 and attained 1,200,000 c.f.s. (cubic feet per second). Another disastrous flood occurred in 1948 and attained a peak of 980,000 c.f.s. on 31 May.

4. The low water season extends usually from September to February; during this period the average discharge is approximately 90,000 c.f.s. However, winter rain storms will occasionally result in abnormally high flows of short duration at any time after about 10 November. One such flood occurred in December 1933 at the beginning of construction of the Bonneville project and attained 368,000 c.f.s. at The Dalles.

5. Summary Hydrograph. - Plate 1 shows the derived minimum,

maximum and average daily discharge at the McNary damsite for the months of September, October, November and December for the period from 1894 to 1947 inclusive. In accordance with this summary hydrograph, September and October would have been the logical months for the closure operation, as discharges of approximately 90,000 c.f.s. might have been expected during the more difficult part of the closure; however, the fall runs of salmon preclude a closure during those two months. The 10th of October was therefore established as the earliest time at which operations could be started, and the time available for the completion of the rockfill portion of the closure was thus limited to less than 60 days in order that the fill could be brought above water surface before the possible occurrence of winter storms. Such storms could have resulted in flows in excess of 150,000 c.f.s. which was the upper limit of river flow for which closure operations were considered feasible.

6. Cofferdam Layout. - Plate 2 shows the general layout of the Second-Step Cofferdam and the location of the 240-foot gap in the Oregon channel in which the closure had to be made. The navigation lock and the Washington portion of the spillway were built, and the first cofferdam had been removed. The ogees in the first 12 bays were concreted to elev. 250, or 41 feet below the ultimate crest. Temporary fish ladders in bays 1 and 13 left 11.7 bays actually available for the passage of the river flows.

7. Plate 3 shows the gap proper, together with contours of the river bed based on sounding data taken in 1935, and with soundings taken along the upstream and downstream legs of the cofferdam after the flood of 1948. The floor of the gap consisted of two shelves at

approximately elev. 235, with a deep trough in between, in which the maximum depth at low water was approximately 53 feet. The major flood which occurred in 1948 removed the top of Artesian Island and apparently deposited some material in the deepest portion of the Oregon channel, resulting in some upward changes of the contours in the bottom of the channel.

8. Magnitude of Closure Problem. - The severe combination of great water depth, large river discharges with resulting high water velocities, and very limited available time, made the McNary closure one of the most difficult river diversions in construction history. The constriction of the river flow through the 11.7 low spillway bays would create pool differentials of 16 to 18 feet for discharges from 100,000 to 150,000 c.f.s.

9. Government Responsibility. - In view of the magnitude of the problem and the difficulties connected with it, the Corps of Engineers decided to assume the responsibility for the design of the closure by specifying the general method of procedure. The operation was included in the contract for the Oregon Shore work, for construction of the substructure of the powerhouse units 1 and 2, in order that construction of the remainder of the powerhouse could be initiated immediately after the flood of 1951 to meet the specified schedules for generation of power.

10. Various closure methods were considered in the early design stage and in successive discussions. Studies on methods of river closure were initiated in 1945 and closure by use of floating timber cribs was originally contemplated. Extensive model studies were made in order to determine the optimum order of work, that is, whether the

final closure should be in the Oregon or Washington channels or across the relatively high ground at Artesian Island, and also to determine the magnitude of hawser pulls during placing of the cribs. These studies indicated that the optimum order of closure with cribs, considering minimum hawser pulls, would consist of initial construction of all upstream cribs, except for those in the Oregon and Washington channels, then closing the Oregon channel and making final closure in the Washington channel. Hawser pulls of almost 1,000,000 pounds for the final crib in each channel were indicated. If the Oregon channel were closed last, the hawser pulls for final crib in the Oregon and Washington channels were indicated to be approximately 2,500,000 pounds and 400,000 pounds, respectively. Further study of the hazards and time involved in use of the crib method resulted in its abandonment and studies were made based on use of steel cells. Difficulties inherent in holding the template for and driving the final closure cells against a differential head of about 20 feet, together with the relatively great height of cell of 90 feet, and difficulty of sealing against overhanging sides of the underwater canyon in the Oregon channel, raised considerable doubt of the dependability of closing the river by steel cells. Finally, the design was adopted which consisted of use of steel cells except for the Oregon channel and then closing this 240-foot gap by placing successive lifts of large quarry rock or pre-cast concrete blocks, each lift backed first with large rock from excavation and later the whole backed with finer materials and an impervious layer.

CHAPTER II - THE PRE-CONSTRUCTION PHASE

11. McNary General Model. - Model studies were carried out in 1949 on the 1:100 scale general model of the McNary project at the Bonneville Hydraulic Laboratory at Bonneville, Oregon, to determine the hydraulic characteristics of the closure as a whole, particularly the flow patterns, water surface elevations and velocities at numerous points upstream and downstream from the structures. The closure of the 240-foot gap was simulated by means of impervious precast trapezoidal prisms, each simulating a successive lift 10 feet high; no attempt was made to determine or to simulate the amount of flow which might pass through the closure fill proper. River discharges covering the range from 75,000 to 250,000 c.f.s. were simulated.

12. The experiments with a river discharge of 100,000 c.f.s. indicated that the maximum velocity through the 240-foot gap at the beginning of the closure would be 12 f.p.s. (feet per second) and that the maximum velocity over the crest at any time during the construction of the fill would be 24 f.p.s. In addition, the experiments indicated the presence of a submerged plunging jet with velocities up to 35 f.p.s. near the toe of the slope.*

13. Experiments with a river discharge of 150,000 c.f.s showed maximum velocities of 15 f.p.s. at the beginning of the closure, 28 f.p.s. over the crest and 38 f.p.s. near the toe, leading to the conclusion that a closure with this discharge might not be feasible.*

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* Twelfth Preliminary Report, McNary General Model, dated 26 May 1949.

14. <u>Selection of Precast Blocks</u>. - The size of the stone or concrete blocks was based on data available regarding the weight of stones required for stability in water flowing at various velocities. The prototype data obtained in 1936 in connection with the Passamaquoddy project, as shown in plate 4, were considered especially applicable; they showed that stones weighing 16,000 pounds each would be stable in velocities up to 31 f.p.s. Based on estimated costs of quarrying rock of that size, the use of concrete blocks was selected, and the tetrahedron shape was decided upon under the assumption that this would have the best shape factor against rolling and sliding, both during placing and during periods of cofferdam submergence by the spring floods.

15. <u>Design Section of Fill</u>. - Bids for the Oregon Shore contract were called on 6 June 1949 and included making of the closure in accordance with plate 5. The procedure specified was to construct the first Zone I fill with class A meterial (precast 8-ton concrete blocks) with backing of B-stone (minimum weight 1 ton), then proceed to the second Zone I fill with similar backfill, and continue in this manner to elev. 270. Upon attainment of this elevation the fill was to be backed with C-stone (ungraded rock spoil from excavation), then with a 4-foot layer of spalls, a heavy layer of impervious material, a 2-foot filter blanket, and finally a 3-foot revetment of dumped C-stone on a 1 on 3 slope. The top of the fill was to be raised later from elev. 270 to elev. 302 by means of timber cribs filled with bank-run gravel or rockfill on the downstream side and with impervious material on the upstream side. The successful bidder was permitted to submit an alternate plan of his own, but did not elect to do so.

16. <u>Contract Award.</u> - The contract for the Oregon Shore work was awarded on 5 August 1949 to McNary Dam Contractors — a combine of Guy F. Atkinson Co., Ostrander Construction Co., and J. A. Jones Construction Co. — on a total bid of $15,835,539.50. The quantities and bid prices for the principal items involved in the closure fill were the following:

4,500	8-ton concrete tetrahedrons, in place	$ 120.00 each
3,500	Tons of B-stone from excavation in place	3.50 per ton
15,000	Tons of B-stone from quarry, in place	5.50 per ton
50,000	Tons of C-stone, in place	2.60 per ton

17. The contractor proposed to place the closure materials by means of a cableway. Field and office studies were therefore initiated to determine the location of the dropping points and the optimum sequence.

18. McNary Tetrahedron Studies. - Tetrahedron experiments were made in the field at McNary in June 1949. A tug was held stationary at various points over Artesian Island on the centerline of the upstream leg of the Second-Step Cofferdam; the water was approximately 20 feet deep and the velocity at 0.2 depth was 12.3 f.p.s., decreasing slightly toward the bottom. Five tetrahedrons were dropped in all, three weighing 1,000 pounds each, one weighing 2,000 pounds and one weighing 3,000 pounds. The drops were made from a launching platform located on the stern of the tug; each tetrahedron had a colored double-cone buoy fastened by means of 75 feet of 1/8" airplane cable. Figures 1 and 2 illustrate the launching device. The position

of the tug was sighted in from the shore and the launching occurred in accordance with the prearranged signals. The position of the buoys after launching was determined by instruments from the shore. The observations indicated little or no movement after the tetrahedrons had reached the bottom and were discontinued after a few days because the buoys had broken loose. No observations were made at the time of the experiments or after recession of the summer flood to determine the downstream drift below the launching point.

19. <u>Office Investigations</u>. - The various office studies undertaken did not give any reliable results as to the downstream drift of the tetrahedrons. Our present understanding of the many factors involved is altogether inadequate to solve the problem mathematically. In the course of the investigation several factors were brought to light, e.g. that the unsteady motion of a simple body even in a stationary and continuous fluid is not yet clearly understood and is therefore forming the subject of a continuing research program at a well-known hydraulic research center in the Middle West. The introduction of a varying shape factor and the transition from one medium to another complicated the problem further, especially as even the analysis of the water-entry of a sphere has only recently been investigated with some system.

20. The engineering factors involved in the closure formed the subject of numerous conferences between engineering personnel of the Walla Walla District and the Contractor's representatives. Two important changes resulted; the first consisted of accepting the contractor's offer to substitute 12-ton tetrahedrons for the original 8-ton units and decreasing the number from 4,500 to 3,000, without

changing the contract price of $30.00 per cubic yard of concrete in place; the second consisted of making the top of each tetrahedron fill 20 feet wide instead of sharp-crested (see plate 5). The Contractor's representatives made several other suggestions which did not meet with approval, e.g. that tetrahedrons with higher specific gravity (using iron ore as aggregate or with some pig iron mixed in and weighing 10 to 16 tons, but having the same volume as 8-ton tetrahedrons) be substituted for ordinary concrete tetrahedrons, also that the number of 12-ton tetrahedrons be substantially increased.

21. In May 1950 a line 90 feet downstream from the centerline of the cofferdam and a dropping elevation of 30 feet above the water surface were selected for the construction of the first tetrahedron fill; the drops for the successive fills were left open for future determination in the light of the experience with the first fill.

22. Seattle Model Experiments. - During the months of July and August one of the hydraulic engineers of the Walla Walla District Office, who had made extensive studies of closure operations in general and was deeply concerned about the success of the McNary closure, carried out a personal research program at the University of Washington in Seattle. A special model flume was built, which simulated a width of 52 feet in the deepest section of the Oregon channel and which permitted the construction of the various fills on a scale of 1:24 (see fig. 3). The sectional model was operated in accordance with the data contained in the Twelfth Preliminary Report, McNary General Model, dated 26 May 1949, which gave the controlling water surface elevations and velocities for the flows under consideration. The experiments indicated that the fill in accordance

with the proposed plans could not be carried above elev. 240 approximately (see fig.4) and suggested changes, principally the use of blocks of greater specific gravity, which would insure its success.* The presentation of the findings was followed by showings of the moving pictures taken in the course of the experimental work and by numerous conferences.

23. Field Experiments. - Attempts were made to find locations on natural streams or existing projects in which to simulate the conditions which would exist during the critical construction stage of the closure fill. Some field experiments were actually carried out at two natural locations on the Clearwater River near Greer and Orofino, Idaho, respectively, but conditions turned out to be so different as to render the results inconclusive and of no value. Thereafter, all experimental work was limited to locations where fully controllable laboratory conditions would be available at all times.

24. Bonneville Sectional Models. - In order to check the results of the Seattle experiments, additional model tests were carried out at the Bonneville Hydraulic Laboratory in the McNary spillway flume. The central portion 52 feet wide of the Oregon Channel was simulated on a 1:24 scale by construction of a longitudinal partition. An experiment was made based on the data contained in the Twelfth Preliminary Report (see par. 12), simulating a river discharge of 100,000 c.f.s. The experiment showed that the fill could be raised with tetrahedrons to elev. 230 without difficulty, but beyond that stage gains in elevation could be attained only in small lifts, with the critical stage occurring

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Second-step Cofferdam Closure - Model Experiments by A. J. Gilardi July-September 1950 between elev. 240 and 250. The results obtained at the Bonneville Hydraulic Laboratory confirmed the results of the Seattle experiments by showing that the closure as planned would reach a critical point at about elev. 240. This appeared to be the point at which the effect of submergence on the overflowing sheet of water decreased substantially and free overflow began.

25. The Bonneville experiments were witnessed by numerous representatives of the North Pacific Division, Portland District Office, Walla Walla District Office, McNary Project Office and McNary Dam Contractors (see fig. 5 and 6). The opportunity was thus offered to all concerned to observe and discuss the behavior of the tetrahedrons and the formation of the various fills; this proved of great value and led to the development of several plans to improve the construction technique and better assure success of the closure (see fig. 7).

26. The experiments were expanded later by removing the longitudinal partition and using the full 5-foot width of the McNary spillway flume. Two experiments were then run, simulating the 100,00 c.f.s. flow and the 150,00 c.f.s. flow conditions, respectively.

27. The experiment simulating a river discharge of 100,000 c.f.s. (see fig. 8) showed that the construction of the closure fill in the 5-foot flume was still more difficult than in the 26-inch flume; the experiment brought out also the importance of placing the dropping points closer together to minimize the gulley action, and the necessity of frequent soundings as a guide to subsequent drops.**

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*Memorandum Report 1-1, McNary Cofferdam Sectional Closure Model, dated 17 October 1950.

**Memorandum Report 1-2; McNary Cofferdam Sectional Closure Model, dated 25 October 1950.

28. The second experiment made in the 5-foot flume simulated a river discharge of 150,000 c.f.s. This experiment showed that the completion of the closure fill with such high flows would be much more difficult than under the 100,000 c.f.s. condition; in fact, a point was reached in which it was impossible to raise the fill any higher by dropping tetrahedrons from a skip, unless some means of anchoring them was provided.*

29. Construction Model. - A 1:24 scale construction model of the entire 240-foot closure gap was built at the McNary damsite. This model was to serve several purposes, such as to simulate the flow conditions in still greater detail, especially those at the ends of the fill, to provide for field engineering forces and contractor's personnel information and visual, three-dimensional, observations of the flow characteristics at various stages of construction, especially in the underwater regions, as well as to be fully prepared for any unforeseen developments. The approval of the construction model was secured on 6 October, i.e., only 4 days prior to the scheduled start of the prototype closure operation. The design and construction were expedited in every possible manner; much credit was earned by the personnel of the Bonneville Hydraulic Laboratory, the McNary Project Office and McNary Dam Contractors for completing the construction model and having it ready for preliminary runs by 25 October, or only 19 days after approval.

30. The model was located on the Oregon Shore immediately downstream from the Oregon Shore cofferdam, on a compacted fill built to

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*Memorandum Report 1-3; McNary Cofferdam Sectional Closure Model, dated 26 October 1950.

elev. 265, i.e., sufficiently high to permit operation at river stages up to about 350,000 c.f.s. (see fig. 9). The water supply was obtained by means of two 20" - 100 h.p. cofferdam unwatering pumps with a capacity of approximately 12,300 g.p.m. (27.5 c.f.s.) each under a head of 30 feet. The pumps were supported on a platform located on top of the Oregon shore cofferdam between cells A28 and A29, the water being conveyed to the model by means of two 20" overhead steel pipelines each about 175 ft. long with suitable valve controls. Bypass conduits and a pipeline for filling the model were also provided.

31. The model proper simulated approximately 1,200 feet of the Oregon channel and had an overall length of 105 feet, a maximum width of 55 feet and a width of 24 feet at the downstream end. The bottom of the test section in the model was formed in compacted sand by means of sheetmetal templates and was topped with a layer of mortar. The prototype roughness was simulated by means of pebbles embedded in small dabs of mortar. The entire model was laid out in such a manner that an observer could see both the model and the prototype closure gaps simultaneously and with the same orientation. The tailwater elevation was controlled by a large timber-and-steel tailgate hinged on the bottom and adjustable by means of a 3-ton chain hoist. No provision was made for measuring the discharge through the model because no prototype data were available for comparison, and also in order to simplify the construction. The waste water was passed through an underground corrugated pipe and was led back to the river.

32. <u>Operation of Construction Model.</u> - The general program for the operation of the construction model consisted of three general phases, as follows:

a. Determine the reliability of the model by performing a major operation at different times and ascertaining whether the model would duplicate itself.

b. Check with the prototype, i.e., perform on the model the same operations as had already been carried out on the prototype, and compare the results of both.

c. Determine the best method of prototype procedure, beginning with known conditions as determined by soundings and leading to a successful closure.

This comprehensive program was left flexible, so as to cope with day-to-day developments and exigencies.* The operation of the model having thus been so closely related to the prototype closure, the further description of the experiments will be presented concurrently with that of the prototype work and, generally speaking, in chronological order.

33. Prototype Experiments. - Two experimental drops were made in the field using actual 12-ton tetrahedrons. The first drop was made from the trestle between cribs 4 and 5; the height of the drop was 26.5 feet; the water was 25 feet deep and flowed at velocities of 13.7 f.p.s., decreasing to 12.5 f.p.s. The observed drift was 39 feet. A second drop was made on 7 October 1950 from the cableway at Station 160 and Range 830; the depth of the water was 55 feet and the velocity approximately 12.5 f.p.s. at 10-foot depth, decreasing to 6.0 f.p.s., at 50-foot depth. The observed drift was 40 feet.

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*First Preliminary Report, McNary Cofferdam Closure Model, Bonneville Hydraulic Laboratory, 1 May 1951

CHAPTER III - CONSTRUCTION METHODS AND EQUIPMENT

34. Tetrahedron Casting. The tetrahedrons were cast on the Oregon shore just south of the powerhouse assembly bay (see plate 7 and fig. 11). The concrete was mixed in the central mixing plant using 4 sacks of Portland cement per cubic yard. Bank-run gravel was used originally, but did not prove satisfactory on account of poor grading and formation of gravel pockets, and was replaced by graded and washed aggregates with a maximum size of three inches. The water-cement ratio was 6 gallons per sack of cement, and the contractor chose to use an admixture of Darex air entraining agent in the proportion of 1.25 ounces per sack of cement, although the specifications did not require its use. The concrete was hauled 1/8 of a mile from the mixing plant in four cubic yard buckets mounted three at a time on a flat railroad car. The buckets were lifted by a 50-ton whirley crane used for the powerhouse construction and the concrete was poured through a hopper into the forms. The tetrahedrons were cast base down on fixed wooden platforms; heavy wooden forms were used for the sides, an opening being left near the apex for pouring and for inserting the lifting eye; 80 forms and 183 bases were available. Electric vibrators handled by two men each were used. Plate 6 shows the principal dimensions and other details of the 12-ton tetrahedrons, also a size comparison with a heavy automobile.

35. Casting of the tetrahedrons was carried out intermittently 24 hours a day; the maximum number of tetrahedrons cast in 24 hours was approximately 100. The forms were generally removed 24 hours after casting (see fig. 12). The tetrahedrons were transferred three or four days after casting to the storage yard about 0.4 of a mile away (see

fig. 13). Curing was performed by the Hunts process membrane treatment applied by spraying upon the removal of the forms.

36. Specific Gravity of Tetrahedrons. - The specific gravity of the tetrahedrons was determined in the field from about 20 representative pieces of approximately one cubic foot each and was found to vary considerably. The average specific gravity was found to be 2.48, corresponding to 155 pounds per cubic foot. Since model tests in progress indicated the desirability of obtaining the maximum practicable specific gravity, the use of Darex was discontinued after 2,042 tetrahedrons had been cast; the weight of the tetrahedrons was thereby increased by approximately 600 pounds, giving a specific gravity of 2.54 corresponding to 158.6 pounds per cubic foot.

37. Main Cableway. - The construction of the closure fill was carried out by means of the main cableway, located as shown in plate 7. The span was 1,500 feet; the track cable was of the locked-coil type and had a diameter of 3 inches. The two towers were 100 feet high; the top of the headtower was at elev. 397 and that of the tailtower at elev. 379, being 105 feet and 87 feet, respectively, higher than the top of the cofferdam cells.

38. The structural steel portion of each tower above the sockets weighed 50 tons; the four base trucks, including the machinery for the lateral movement of the towers, weighed together approximately 70 tons. The operating machinery in the headtower, including all motors and transformers, weighed approximately 130 tons; the concrete counterweights, including four tetrahedrons, added 485 tons, making a total moving weight of 735 tons on the tracks for the headtower. The tailtower had no operating machinery, except in the trucks, and had concrete counter-

weights, including six tetrahedrons, weighing approximately 650 tons, making a total moving weight on the tracks of about 770 tons.

39. Both cableway towers were movable laterally on heavy tracks permitting a maximum travel of 260 feet. The front tracks of each tower were supported on an inclined and continuous concrete slab for better distribution of the thrust. The rate of travel of the towers was 100 feet per minute and that of the skip with full load was 1,200 feet per minute. The cableway was operated entirely from a control booth located in the headtower; however, a tender was stationed in the tail-tower to check its proper functioning at all times.

40. The payload was carried in a skip 12 feet by 12 feet in plan, which was suspended with 7/8" diameter hoist cables running in two double sheaves; each of these sheaves was operated by a separate hoist cable, in such a manner that either end of the skip could be lowered independently from the other. The skip was open in front; the sloping back was 6 feet high and the sides varied from 6 feet in the rear to 2 feet in front. The skip was of steel construction and weighed approximately seven tons when empty. A steel liner 1/2" thick was fastened on corrugated transversal supports; the liner was further reinforced by means of wearing strips which were intended to facilitate sliding of the load. This type of construction did not prove very satisfactory under the impact of B-stone dumped from trucks; 4" planks were substituted later and proved more satisfactory, although their useful life when handling B-stone was only about 48 hours.

41. The cableway had originally been used for construction work at Terminal Island with a span of 800 feet; the same main cable was re-used. At McNary the rated capacity was 16 tons of payload, which

corresponded to two of the originally planned 8-ton tetrahedrons dropped simultaneously. However, payloads up to 30 tons were hauled occasionally by suspending directly from the hoist cable, i. e. without use of the skip.

42. Loading of Tetrahedrons. - The tetrahedrons were hauled from the storage yard to the loading skip by means of two 12-ton capacity Tournacranes in which the boom had been shortened to 4 feet; each Tournacrane was pulled by a DW-10 tractor. For loading at the storage yard the hook was lowered and inserted manually into the lifting eye of the tetrahedron; the tetrahedron was then lifted so that the base was approximately 3 feet above the ground, and the leg was tilted forward to make one edge of the tetrahedron bear against the rear timber facing, which in turn prevented the tetrahedron from swinging laterally during the trip. Loading of the skip occurred near the water's edge on the Oregon shore; the cableway operator lowered the skip to the ground and the Tournacrane operator backed the tetrahedron and lowered it approximately on the center of the platform, whereupon the hook was disengaged manually (see fig. 14). The complete round trip of a Tournacrane required approximately four minutes, exclusive of waiting time. Two Tournacranes were generally used; in this manner the second Tournacrane would usually arrive at the skip while the first tetrahedron was being placed.

43. Grid System. - A grid system was used in accordance with the layout shown in plate 7. The positions on lines parallel to the tower tracks were designated as stations, and the positions on lines at right angle thereto were designated as ranges. The combination of tower movement and skip travel permitted accurate placement of a load in any position of the closure fill.

44. Spotting of Payloads. - The stationing of the towers was determined visually by the intersection of sight lines on each tower with graduated baselines located near the sloping front tracks.

45. The range of the skip was determined by means of a travel indicator placed next to the headtower operator and showing the travel distance by means of an inner dial reading in hundreds of feet and an outer dial reading in feet (see fig. 15 and 16). The travel indicator was actuated from a sprocket mounted concentrically on the 4-foot sheave of the 1-1/8" diameter continuous haul cable and placed on top of the headtower; the sprocket drove a selsyn generator through a roller chain and a 30:1 reduction gear. The selsyn generator was in turn coupled to a selsyn motor which operated the hand of the foot dial directly and the hand of the hundred-foot dial by means of a clock mechanism. This travel indicator operated very satisfactorily, and provided accuracy within about two feet from the desired point for all positions of the load. The sprocket drive was designed and installed after the original friction drive between the revolving drum of the haul cable and a rubber roller had proved unsatisfactory; the slip of the cable on the drum caused unreliable readings, even with zeroing prior to each haul.

46. Field Control of Drops. - A central control station located in a small portable building on cell A21 of the Oregon Shore cofferdam was used for directing the operation and for recording its progress. The location of the building and the adjacent 30-foot observation tower on top of cell A22 permitted a sweeping view of the closure gap and of the area downstream from it.

47. The central control station was staffed by a dispatcher acting directly under the authority of the Resident Engineer or his

assistant. An inspector was stationed in the control booth of the headtower and two transitmen were stationed on the Oregon shore cofferdam and Artesian Island, respectively.

48. Direct conversation among the four stations was carried out at first through portable radios (walkie-talkies) and later through field telephones; the latter proved much more reliable and satisfactory. The dispatcher ordered each successive tetrahedron drop, in accordance with the schedule or modifications thereof, and the inspector relayed the instructions to the headtower operator who then spotted the tetrahedron over the desired point. The original friction drive was used for the travel indicator during the construction of the first fill and some difficulty was experienced in spotting the tetrahedrons; this, in addition to other initial difficulties with the checking technique, resulted in some uncertainty as to the exact position of the actual dropping points of the first tetrahedron fill.

49. Observations of Downstream Drift. - Observations of the downstream drift on some of the tetrahedrons were made at typical stages of the closure operation. The method of observation was the following: A double-cone buoy was fastened with an 1/8" diameter airplane cable 200 feet long to the eye of a tetrahedron while the skip was stationed on the Oregon shore; the tetrahedron was then hauled out to its dropping point, with the cable and buoy trailing behind. The current swiftly carried the buoy downstream and tightened the cable. The tetrahedron was held stationary for a minute or two, giving to transitmen an opportunity to cut in the position of the buoy by instrument. After dropping of the tetrahedron, the new position of the buoy was cut in. Displacement downstream was designated as the downstream drift. The

procedure was not exact, but was probably the only practical one to use and gave an indication of sufficient accuracy for construction purposes.

50. Hauling of B-stone. - The B-stone was stockpiled on the Oregon shore in a locality adjacent to the tetrahedron storage, as shown in plate 7. The B-stone was loaded by means of a power shovel on Euclid dump trucks weighing approximately 23 tons empty and handling payloads of approximately 18 tons each. Each truckload was weighed on platform scales on its way to the loading skip and a tab showing the total weight and the tare was given to the driver, who in turn gave it to an inspector at the skip. The inspector observed the load during the dumping and noted the estimated weight, if any, of the material which was below the permissible minimum of 2,000 pounds for each stone and for which no payment was allowed (see fig. 25). Four or five Euclids were sufficient at all times to keep the cableway well supplied with B-stone.

CHAPTER IV - THE CLOSURE OPERATION

51. FIRST TETRAHEDRON FILL. - The closure operation proper started on 10 October 1950 at approximately 4 p.m. The river discharge was 96,000 c.f.s. and the water surface elevation at gate 7 (see plate 7) was 255.3. The spillway was passing a substantial proportion, perhaps 20 to 25 percent, of the total flow. No measurements were made due to the high velocities and turbulence.

52. A dropping schedule had been prepared in accordance with the indications of the sectional model experiments made up to that date. This schedule called for the dropping of 628 tetrahedrons based on the volume of the theoretical cross-section with allowance of 10% for loss outside of the section and assuming bulking of the tetrahedrons at 33 1/3 percent, as a factor of safety. In this connection tests with small scale models indicated actual bulking of the tetrahedrons would be almost 50% when dropped in a container. Shaking of the container resulted in reduction of the bulking to about 40% of the net volume. The purpose of the dropping schedule was to form a flat-crested fill to elev. 230, with slopes of 1 on 2 upstream and downstream, and with a centerline at 103 feet downstream from the centerline of the cofferdam, as shown in plate 5. The drop line was located 60 feet downstream from the centerline of the cofferdam, and the distance between drop points was 14 to 15 feet. The total number of tetrahedrons to be dropped at each point is given in parentheses in plate 8; however, the drops were made in several passes, for the purpose of obtaining the most uniform crest elevation possible (see fig. 17 and 18).

53. Due to the paucity of data regarding the possible rebound of

the main cable and secondary stresses caused therein by the sudden release of such heavy loads, the Contractor preferred to operate the cableway with minimum stresses; therefore, the tetrahedrons were hauled about 12 feet above the water surface, giving a sag ratio of about 12:1. This procedure had the disadvantage that the lowering of the front hoist cable to release the tetrahedrons caused the front of the skip to dip considerably and occasionally plunge several feet into the fast moving water; when this occurred, the skip and tetrahedron were displaced downstream, sometimes perhaps as much as 10 feet.

54. The fill construction was carried out continuously and on a 24-hour basis; the average time interval between successive tetrahedron drops was about 5 minutes. A buoy fastened to one of the last tetrahedrons and dropped at point C (see plate 8) drifted approximately 10 feet.

55. Effect of First Tetrahedron Fill. - During the construction of the first fill, the water surface upstream rose faster than expected; at 3:30 p.m. on 12 October 439 tetrahedrons had been dropped and the water surface at gage 7 had risen to elev. 258.6, or 3.3 feet, of which about 0.3 of a foot was due to the increase in the discharge of the river from 98,000 to 102,000 c.f.s. A spectacular standing wave about 6 feet high and approximately 100 feet long had formed almost parallel to the centerline of the cofferdam and 80 feet downstream from it, with two long tongues of fast water issuing diagonally around the end cells (see fig. 19 and 20). In view of the circumstance that the contractor had a considerable amount of work to perform before the upper pool could be raised any further, the decision was reached to consider the first tetrahedron fill as completed.

56. <u>Bulking Experiment</u>. - The greater-than-expected rise in the water surface led to the conclusion that the tetrahedrons must have formed a ridge higher than anticipated and that this was due to the fact that the slopes of the fill were much steeper than the theoretical cross-section, that loss of tetrahedrons from the section during this phase was negligible, and that allowance for bulking had been very conservative. A rough test was made at the McNary site to check the bulking allowance. This test consisted of dropping model tetrahedrons (1:24 scale) in a 55-gallon barrel full of water and containing 7.342 cu. ft. of water at the start. It was found that 245 tetrehedrons were required to fill the barrel and that they had displaced 3.095 cu. ft. of water. The remaining 4.247 cu. ft. of water represented the volume of the voids between the tetrahedrons and corresponded to 57.8% of the fill volume, or vastly more than assumed.

57. <u>Start of First Sounding Survey</u>. - Preliminary soundings to determine the position and shape of the first tetrahedron fill began on 12 October, immediately upon completion of the tetrahedron drops. The cableway skip was used for the soundings and carried a crew of about 10 men. A small hoist was tack-welded to the side for handling the sounding weights, and a meter derrick was fastened to the bottom of the skip for operating the current meter (see fig. 21 and 22). Spotting of the skip over any desired point was attained by means of a portable radio and by flagging. The position of each sounding and velocity measurement was determined by instrument from the two shores.

58. Considerable difficulty was experienced at the beginning, because the sounding weights became wedged among the tetrahedrons, resulting in breakages of the 1/8" airplane cables used. Streamlined and

triangular-shaped lead-filled pipe weights were used; the heaviest of the latter, weighing 400 pounds each and provided with fins, resulted in least losses and performed more satisfactorily than the other types.

59. The preliminary soundings and velocity measurements were continued in the swingshift of 12 October and the dayshift of 13 October, and were completed in the middle of the afternoon of 13 October. The tetrahedron fill was found to be a high and sharp ridge across the deepest portion of the channel, with a few pinnacles extending to elev. 247 or 248. The position of the crest was practically parallel to the centerline of the first fill as planned, but nearly 30 feet upstream from it. The center of gravity of the section was 80 feet downstream from the centerline of the cofferdam, whereas the drop-point had been 60 feet downstream, indicating an average drift of 20 feet. The slopes of the fill were found to be very steep; in particular, the upstream slope was steeper than 1 on 1 in places.

60. The results disclosed by the preliminary soundings generated considerable over-optimism and even scattered suggestions that a few hundred tetrahedrons should be dropped at once to bring the fill above the water surface. However, the decision was taken in the end to place B-stone before proceeding with further tetrahedron drops; the stone fill was ordered to be placed well upstream from the first tetrahedron fill, to prevent any material reduction of its great permeability. A total of 2,200 tons of B-stone was placed on 13 and 14 October, the average rate being approximately 200 tons per hour.

61. Contractor's Difficulties. - Due to the very tight closure schedule, the contractor had planned to carry out the completion of the north portion of the second-step cofferdam concurrently with the con-

struction of the closure fill. This plan did not work out as expected, for several reasons. Difficulty was experienced in closing off the flow through the 30-foot openings between the timber cribs; the round, reinforced concrete stoplogs 38 feet long and 3 feet in diameter tended to roll to the bottom because the water pressure was insufficient to hold them against the cribs, and because no other provision had been made to hold them in place. T-shaped steel guides were added, but the leakage between the individual stoplogs was still excessive; this, together with the rise in the water surface due to the construction of the first fill and the subsequent sharp rise in the river discharge, made very difficult the construction of the cells upstream from the cribs and necessitated complete stoppage of construction work on the closure fill for 16 days, i.e. to 1 November. Some very anxious moments were experienced during that period, for instance, when crib 4 was partially undermined and settled over 1 foot, and when cells 45 and 47, although heavily braced, nearly collapsed during construction of the sheetpiling inclosure and prior to backfilling. Grand Coulee Dam gave some assistance during this critical period, by holding back some of the streamflow in Lake Roosevelt.

62. Setback of Closure Operation. - During this 16-day setback only four tetrahedrons were dropped, bringing the total placed to 443; two of the tetrahedrons were dropped on 27 October on the occasion of the visit of personnel from the Chief of Engineers' Office, and the other two on 28 October during an inspection trip of the American Society of Civil Engineers.

63. The forced delay in the construction of the closure fill occurred during a period of rising river stages, when the discharge at

the Umatilla gage increased from 93,000 c.f.s. on 17 October to 141,600 c.f.s. on 1 November; furthermore, the delay yielded some offsetting and important beneficial results, by permitting the completion of the construction model and performance of the initial experimental work before the second tetrahedron fill could be started.

64. Completion of First Sounding Survey. - The soundings of the first fill were continued on Sunday, 15 October and completed on Sunday, 22 October. This procedure was in accordance with the prior arrangements made with the Contractor, to the effect that the cableway be used during the week for construction work and on Sundays for soundings and velocity measurements. The results confirmed the findings of the preliminary soundings. Plate 8 shows the average shape and position of the first fill.

65. Shape of First Tetrahedron Fill. - The peculiar and unexpected formation of the first tetrahedron fill was probably due to the following circumstances: (a). The closure fill had to be built across a pronounced local depression or pothole in the Oregon channel, which was followed immediately downstream by a sudden rise of nearly 15 feet in the river bed. This circumstance probably caused the bottom velocities in the closure section to be considerably lower than in a normal river section, and reduced the downstream drift of the tetrahedrons accordingly. In the absence of data regarding the vertical velocity distribution, the sectional model studies up to that time had been based on normal channel conditions, and had not made any allowance for the abnormality of the closure site. (b) The fill formed approximately 80 feet downstream from the centerline of the cofferdam; the crest length along an alinement connecting this fill with the end cells

was therefore approximately 320 feet, as compared with the 240-foot width of the closure gap. This lateral spreading decreased the velocities of the water materially and reduced the downstream drift accordingly. The lateral spreading could not, of course, have been reproduced satisfactorily in a sectional model of uniform width.

66. First Experiment on Construction Model. - Operation of the construction model began on 26 October; the operating personnel consisted of a supervisor from the Bonneville Hydraulic Laboratory, four men from the engineering staff of the Walla Walla District Office, and several laborers from McNary Dam Contractors.

67. The first experiment consisted in reproducing the first fill using the same procedure and the same river discharges of 96,000 c.f.s. at the beginning and 101,000 c.f.s. at the end, under which the prototype fill had been constructed. The procedure was necessarily slow, because it was necessary to shut down the model from time to time to determine the average height of the fill for the purpose of establishing a new rating curve corresponding with the observations made on the prototype during the construction of the fill. After placement of 439 tetrahedrons and B-stone as in the prototype, the flow conditions were simulated very satisfactorily in the model as to pattern, water surface elevations and velocities. The shape of the fill and the average elevation of the crest (see fig. 23) were also in satisfactory agreement with the sounding data obtained on the prototype. Figure 24 is a photograph taken in the model to show the depression in which the first fill was constructed, in relation to the much higher sill in the river bed further downstream.

68. Second Experiment on Construction Model. - A second experi-

ment was then performed to simulate the dropping of about 425 tetrahedrons in accordance with a schedule which was intended to raise the crest elevation from an average of 245 (as obtained for the central portion by means of the first fill) to an average of 255 uniformly across the entire gap. This experiment was run with varying discharge; at the beginning 117,000 c.f.s. was simulated in accordance with the then occurring river discharge; this was increased later to 150,000 c.f.s. to simulate a sudden rise in the river, and finally the experiment was completed with the discharge of 117,000 c.f.s. This dropping schedule did not give satisfactory results and was therefore abandoned; in particular, the schedule tended to bring up the central portion of the fill too fast, and to intensify the already severe gulley action at both ends of the fill. However, the results of this schedule would probably not have been quite so unsatisfactory, if the entire experiment had been run with the uniform discharge of 117,000 c.f.s.

69. The 425-odd tetrahedrons which had been placed were then removed without disturbing the original 443 of the first fill; this was done without difficulty, because all model tetrahedrons were numbered and were always dropped in numerical sequence. A new schedule for the second fill was then set up; this schedule was intended basically to first fill in the depressions in the first fill, especially near the end cells, then to raise the crest as uniformly as possible from elev. 245 to 255; however, the schedule was intended to be flexible and subject to such changes as might be indicated by visual observations on the model.

70. Third Experiment on Construction Model. - The second schedule was run in the model on 31 October for a discharge of 117,000

c.f.s. and proved more satisfactory than the previous schedule. This third experiment showed that any local depression in the crest of the fill caused a concentration of flow through it, which in turn appeared distinctly at the water surface as a long tongue of smooth and fast flowing water. It was further found by experience that whenever such a "slick" developed, it was necessary to concentrate the tetrahedron drops at its root until the "slick" had disappeared (see fig. 26). Two or more "slicks" appeared at times; in this case the larger "slick" would be stopped first, then the others. The technique of "watching the slicks" was developed in this experiment as the most effective procedure for the construction of the second fill.

71. After dropping 446 tetrahedrons (bringing the total to 889), the crest had attained an average elevation of 247.2; however, much difficulty was experienced beyond that point. For instance, the next 103 tetrahedrons dropped (bringing the total to 992) were mostly carried away into deep water, especially those placed in the vicinity of cell 17, and raised the average crest elevation only 0.3 of a foot. This led to the conclusion that the closure could not be carried to completion by simply dropping additional tetrahedrons. B-stone was then added on the upstream side to form a berm 40 feet wide at elev. 235, or approximately 12 feet below the average crest of the second tetrahedron fill; the purpose of this step-down was to provide a foundation for the third tetrahedron fill and to reduce the velocity for its construction.

72. SECOND TETRAHEDRON FILL. - The construction of the second tetrahedron fill in the prototype began at 3:20 p.m. on 1 November, without additional B-stone beyond that described in paragraph 60.

The river discharge was 141,600 c.f.s. and still rising slowly; the readings of gage 20 and the Ferry gage were 263.0 and 254.9, respectively, giving a head differential of 8.1 feet. The tetrahedrons dropped for the second fill had short yellow stripes on all three sides.

73. The dropping schedule was essentially the one which had just been tested in the model, and consisted of first filling in the depressions near the end cells, then others which might become apparent. The schedule was to serve merely for general guidance and was to be modified, if necessary, by "watching the slicks" as they developed on the prototype. The longest tongue occurred near cell 17 and had shown the highest velocities in the surveys; it was found necessary to maintain the crest in that locality rather high, to offset the natural tendency of the overflowing sheet to break out over and over again in that vicinity.

74. The construction of the second tetrahedron fill continued on a 24-hour basis on 2 November and 3 November. During this period the difficulties increased considerably, because the rising river discharge attained 149,650 c.f.s. on 3 November at 4 p.m.; although the operators had been able to maintain a fairly regular and smooth crescent-shaped overflow crest most of the time, a long "slick" persisted in the center for many hours during the night of 2 November and morning of 3 November, before it finally could be stopped. The closure was obviously passing through a critical stage, as evidenced by the fact that a tetrahedron dropped at point N (see plate 9) with an attached buoy showed a downstream drift of 85 feet. Grand Coulee Dam was unable to assist the closure operation at that time, because Lake Roosevelt was completely full.

75. The second tetrahedron fill was pronounced complete at 2:45 p.m. on 3 November; by that time 544 tetrahedrons had been dropped, bringing the cumulative total to 987 (see fig. 27 and 28). The cumulative distribution of the drops at each point is shown on plate 9. Gages 7 and 20 read 264.6 and the Ferry gage 255.4, corresponding to a head differential of 9.2 feet. The increase of 1.1 feet from the start of the second fill was due partially (0.5 ft.) to the increase in discharge, leaving a net gain of only 0.6 of a foot for the entire second fill.

76. Dropping of B-stone was started at 4 p.m. on 3 November and carried on continuously until midnight of the 4th, for the purpose of constructing a foundation to elev. 235 on which to place the successive fills. A total of 5,746 tons was placed, making a cumulative total of 7,962 tons. On 4 November the river discharge attained a peak for the closure period of 157,000 c.f.s. at 10:15 a.m., which was close to the record flow for that date.

77. Second Sounding Survey. - The following day, Sunday, 5 November, was spent in taking soundings and determining the contours of the water surface in the vital area. Plate 9 shows the average cross section of the fill and its position; a comparison of this with the cross section shown in plate 8 indicates that the average crest elevation obtained with the second fill was no greater, and possibly somewhat lower than after completion of the first fill.

78. Fourth Experiment on Construction Model. - Operation of the construction model had continued in the meantime. A fourth experiment was run to determine whether the closure fill could be completed with a river discharge of 117,000 c.f.s. by successive drops of

tetrahedrons and B-stone, holding the latter fill about 10 feet lower than the crest of the tetrahedron fill. On 1 November a schedule was tested, which consisted of placing 342 tetrahedrons from a line 35 feet downstream from the centerline of the cofferdam, and which was expected to bring the average crest of the tetrahedron fill to elev. 255. The distribution of the dropping points below the centerline was varied when tetrahedrons were carried away; usually, better results were obtained by moving the dropping point further upstream. After placement of 418 tetrahedrons (making a total of 1,410) the average elevation of the crest was 253.1. Increasing difficulties were being experienced, especially in the vicinity of cell 17 (see fig. 29); after placement of a berm 40 feet wide of B-stone to elev. 245, it was possible to carry the fill to emergence on 2 November, with a total of 1,846 tetrahedrons (see fig. 30).

79. Fifth Experiment on Construction Model. - A fifth experiment was run on the model to determine whether the closure could be effected by using the same procedure as in the fourth experiment, i.e. of keeping the B-stone about 10 feet below the crest of the tetrahedron fill, but simulating the then expected discharge of 150,000 c.f.s. at the start and decreasing to 140,000 c.f.s. This experiment was started on 3 November and completed on 7 November.

80. Difficulties in Simulation on Model. - Some difficulty was experienced in simulating the first two fills in the model; although the headwater and tailwater checked quite accurately, there was a tendency for the tetrahedrons to form a high point in the middle with two small depressions on the sides. The difficulty might have been due to one or more of the following causes; (a) uncertainty as to the exact

position and the sequence of the prototype drops, (b) the already mentioned occasional downstream drift of the prototype skip, (c) the lower prototype plunging velocity, (d) the probably slightly greater specific gravity of the model tetrahedrons which were used over and over again and soaked for a few minutes prior to dropping, and (e) differences in topography and in surface roughness.

81. Completion of Fifth Experiment on Construction Model. - The crest obtained in the model after dropping 987 tetrahedrons wad adjusted to conform to the prototype soundings and the experiment was continued. Many of the following 225 tetrahedrons were carried away; after the total number of tetrahedrons had attained 1,366 and an average crest elevation of 250.7 had been reached, a critical stage was noticeable, in which the dropping of a tetrahedron in one place would dislodge another elsewhere. More B-stone was added at that stage, to form a berm 40 feet wide at elev. 241. The experiment was completed on 7 November, when it was found that no further difficulty would be experienced in completing the closure; a total of 2,275 tetrahedrons had been required to attain a crest elevation of 267.4 and a water surface elevation of 274 at gage 20.

82. THIRD TETRAHEDRON FILL. - In view of the observations made during the construction of the second prototype fill and those made on the model for the successive fills, it was decided to widen considerably the prototype B-stone foundation at elev. 235 before beginning with the third tetrahedron fill. A total of 4,562 tons of B-stone was placed on 6 November and during the night shift of 7 November. The widening of this foundation caused a slight rise in the water surface at gage 7, with an accompanying drawdown and acceleration before reaching the

crest of the tetrahedron fill (see fig. 31). At the same time the pipe sleeves for threading the two-inch holding cables between cells 15 and 16 on the Oregon side, and between cells 17 and 18 on the Washington side were rushed to completion, as they were expected to be needed sooner or later. The tentative method of anchoring the tetrahedrons is shown on plate 10. The contractor received order to proceed with the casting of an additional 500 12-ton tetrahedrons, bringing the total to 3,500.

83. Prior to beginning the third tetrahedron fill, the main cable was tightened in order to compensate for the rise in the upper pool and also to place the tetrahedrons without dipping the skip into the stream. The third prototype tetrahedron fill was started on 7 November upon completion of the B-stone fill. The schedule for the third tetrahedron fill called for the placement of 392 tetrahedrons from a line parallel to the centerline of the cofferdam and 25 feet downstream from it; the cumulative number of tetrahedrons scheduled to be placed at each point is shown in parenthesis on plate 11. The goal of the third tetrahedron fill was to raise the average crest to elev. 255. The tetrahedrons dropped for the third fill had short white stripes on all three sides.

84. Progress on 7 November was limited to the placement of six tetrahedrons, due to difficulties with the skip and main cable. Excellent progress was made on 8 November, when 320 tetrahedrons were dropped in 21 hours, corresponding to an overall rate of one tetrahedron in slightly less than four minutes. At some of the points in the center which required less manipulation of the controls, drops were made at the rate of almost one every two minutes. In the middle of the afternoon the former water surface drop and standing wave below had

changed to a smooth long slope, indicating a correspondingly flat tetrahedron slope below. The third tetrahedron fill was completed in the morning of the 9th, a total of 403 tetrahedrons having been dropped (see fig. 32). The river discharge had dropped by that time to 138,800 c.f.s. and the head differential between gage 20 and the Ferry gage was 10.8 feet. Dropping of B-stone started immediately upon completion of the tetrahedron fill. A total of 4,050 tons was scheduled to be placed for the purpose of attaining an average elevation of 242. The drops were continued until 2.p.m. on 10 November, an actual total of about 4,250 tons having been placed. The head differential was increased thereby from 10.9 feet to 11.1 feet.

85. Sixth Experiment on Construction Model. - The sixth experiment was started on 7 November, to determine whether the number of tetrahedrons required for the closure could be reduced by placing the B-stone in successive lifts level with the corresponding average crest of the tetrahedron fill. After removal of all tetrahedrons with the exception of 987 corresponding to the first and second fills, B-stone was added to elev. 240 to simulate a trapezoidal section as shown on the contract drawings (see plate 5).

86. The experiment was run simulating a river discharge of 150,000 c.f.s. at the beginning and decreasing to 140,000 c.f.s. at the end. Considerable difficulty was experienced several times in raising the crest of the tetrahedron fill, especially in the vicinity of cell 17; at times this experiment indicated that a larger number of tetrahedrons would be required for the closure, but finally a crest elevation of 264.7 was attained on 8 November with 1,879 tetrahedrons. At that point it became apparent that no further difficulty

would be experienced in making the closure by this method; however, the average crest was nearly three feet lower than in the fifth experiment, using a setback of about 10 feet. In view of this circumstance, it would appear that the total number of tetrahedrons required for making a completeclosure would have been substantially the same with either method.

87. <u>Seventh Experiment on Construction Model.</u>- On 10 and 11 November all tetrahedrons above number 987 were removed and a seventh experiment was run which consisted of a repetition of the fifth experiment. The purpose of this re-run was to determine whether the model would duplicate itself. The experiment was continued until the same number of 2,275 tetrahedrons had been placed; the duplication turned out very satisfactory over the entire range of the operation and from every standpoint.

88. The river bed in the model in the vicinity of the closure gap was later modified in accordance with the probings obtained in November 1948. The change was mostly on the shelf on the Oregon side; the average raise over the area affected was about 2 1/2 feet and the maximum about 5 1/2 feet.

89. <u>Final Experiment on Construction Model.</u> - Beginning on 13 November, the final model experiment was made which consisted of simulating the river discharges and dropping schedules actually used for the prototype closure until the prototype stage was attained; from that point on the model was kept current with the prototype progress until the final closure was attained. Difficulties were again experienced in simulating the second fill, because in the model the crest of the tetrahedrons had a tendency to build up considerably more than in the

prototype. No adjustment was made in the model at the end of the second tetrahedron fill; as a result the construction of the third tetrahedron fill brought the crest well above the water surface at one point. Adjustment was made at that stage to make the model conform with the prototype soundings; the model closure operation was then continued to completion without too much difficulty.

90. FOURTH TETRAHEDRON FILL.- The fourth tetrahedron fill was started on the prototype on 10 November, immediately upon completion of the third B-stone fill. The river discharge was 131,400 c.f.s. Gage 20 and the Ferry gage read 265.4 and 254.3, respectively, giving a head differential of 11.1 ft. The schedule called for the placement of 256 tetrahedrons from a drop line 5 feet downstream from the centerline of the cofferdam and was intended to raise the average crest elevation from 248 to 255. The scheduled cumulative drops at each point are shown in parenthesis on plate 12. The tetrahedrons used for this drop had short black stripes painted on the three sides.

91. Within a few hours the progress of the operation became distinctly noticeable, as a few dimples appeared in the water surface at several points and some tetrahedrons became visible below the water surface in the vicinity of the end cells (see fig. 34). The fourth tetrahedron fill was completed at 8:45 a.m. on 11 November; 278 tetrahedrons had been dropped, bringing the total to 1,664; the distribution of the actual drops at each point is shown on plate 12. The river discharge was practically unchanged at 131,800 c.f.s. Gage 7 and the Ferry gage read 266.7 and 254.35, corresponding to a differential of 12.35 feet and a gain of 1.25 feet for the fourth tetrahedron fill.

92. The Turning Point. - The fourth tetrahedron fill had thus

marked a definite turning point in the closure operation. Although the experience with the Rhone River closure at Genissiat had shown that in the construction of a submerged fill a stage is reached in which the slope steepens rapidly, the pronounced improvement due to the fourth fill had come so suddenly as to be difficult of satisfactory explanation at the time. The decrease in discharge and the extreme permeability of the fill were generally credited with the improved outlook. At any rate, the conclusion was reached that no more tetrahedrons were to be cast; the stop order to the contractor became effective when 280 tetrahedrons had been cast on the supplementary order, making a total of 3,280.

93. The fourth B-stone fill began at 8:55 a.m. on Saturday, 11 November; the schedule called for a drop of 9,600 tons distributed in such a manner as to bring the fill to elev. 247 extending to a line parallel to the centerline of the cofferdam and 40 feet upstream from it. The placement of the B-stone proceeded very rapidly for the remainder of the day; due largely to the minimum of maneuvering required for the skip, the hourly rate attained 300 tons part of the time.

94. Third Sounding Survey. - The following day, Sunday, 12 November 1950, was spent in taking soundings, making velocity measurements and determining water surface elevations in the closure gap. Observations made from the skip indicated that the general action of the overflowing sheet of water was considerably less violent than on preceding similar occasions and that the roar of the water had decreased materially. Some of these changes were due to the decrease of the river discharge to 126,200 c.f.s.; however, the points of numerous tetrahedrons were visible through the water and a pronounced breaking up of the overflowing sheet was noticeable at several points. Velocity observa-

tions in general were also lower than on the preceding sounding surveys.

95. Computations of the Permeability. - Computations were made at the time to check the assumption that the decided improvement in outlook was due largely to the extreme permeability of the fill. The computations were based on the observations made on the 1:100 general model; a rating curve for the spillway was prepared accordingly, which showed that for a river discharge of 128,300 c.f.s. and the observed prototype headwater at gage 22 the spillway discharge was 62,300 c.f.s., which in turn showed that the total flow through the closure gap was 66,000 c.f.s. Since correlation curves obtained from the 1:100 general model for the flow distribution indicated that the discharge through the gap for an impervious closure fill was 38,000 c.f.s., the leakage was considered to be equal to the difference between this figure and the total flow of 66,000 c.f.s. through the gap, i.e. 28,000 c.f.s. The basic assumption was therefore considered at the time as being fully confirmed.

96. Completion of B-stone Fill. - Placement of B-stone continued on Monday, 13 November and Tuesday, 14 November and was completed during the night shift of 15 November. A total of about 9,600 tons was placed, bringing the total to about 26,350 tons. Four tetrahedrons were dropped in the morning of 13 November near cell 16 on the occasion of the visit of Col. William E. Potter, Acting Assistant Chief of Engineers for Civil Works, O.C.E., and other dignitaries. Upon completion of the placement of B-stone the readings of gage 7 and the Ferry gage were 266.3 and 253.6, giving a head differential of 12.7 feet; a small portion of this head differential was due to the decrease of the river discharge to 116,300 c.f.s.

97. FIFTH TETRAHEDRON FILL. - The fifth tetrahedron fill was started on Wednesday, 15 November at the beginning of the night shift. The schedule called for the placement of 195 tetrahedrons to be dropped from a line 15 feet upstream from the centerline of the cofferdam and parallel to it, and to be distributed as shown in parenthesis on plate 13. The purpose of this schedule was to raise the average fill elevation from 257 to 270. The tetrahedrons used for this drop were marked with short red stripes on all three faces.

98. After dropping approximately 100 tetrahedrons, it became apparent that the central portion of the tetrahedron fill was being raised excessively and the flow was being concentrated too much near the end cells, resulting in loss of tetrahedrons when dropped near the ends. The schedule was therefore discontinued and a plan was substituted which consisted in taking full advantage of the favorable turn of events and making the closure with utmost rapidity before the river discharge could increase materially. The remainder of the fifth drop was placed in accordance with the instructions given by the central control station which had been transferred to the top of cell 16. The general procedure was to drop tetrahedrons at each point where tongues of fast water were visible; the drops were usually made as far upstream as possible in order to minimize the tetrahedron loss, and were continued till the tongue had practically disappeared (see fig. 35).

99. Drops near cell 17 were directed on one occasion by observers stationed there and communicating through a portable radio with the central control station, which in turn relayed the instructions to the inspector in the headtower. For placement of tetrahedrons and B-stone in the immediate vicinity of cell 17 the skip was turned around so as to

discharge facing north (see fig. 36).

100. <u>Emergence and Closure.</u> - The construction of the fifth tetrahedron fill was continued during the night shift of Thursday, 16 November. At 8 a.m. on that day the prototype closure was declared successful; a total of 2,088 tetrahedrons had been placed by that time, and completion could have been accomplished with B- and C-stone. Gage 7 and the Ferry gage read 268.10 and 253.05, respectively, giving a head differential of 15.05 feet. The river discharge had dropped to 111,000 c.f.s.

101. The appearance of the crest at the time of the official closure is shown in fig. 37 and 38. The stage might have been designated more appropriately as the "Emergence Stage", because the surface flow was not actually cut off in its entirety at the time; in addition, the upper pool was still nearly 3 feet below the desired elevation of 271. However, taking into consideration the difficulties encountered and the vicissitudes overcome, the designation of the emergence stage as the point of closure is easily understood and appears justifiable.

102. <u>SIXTH TETRAHEDRON FILL.</u> - The sixth tetrahedron fill began immediately thereafter; the purpose of this sixth fill was to place sufficient tetrahedrons to construct ultimately a berm to elev. 270 and about 40 feet wide downstream from the centerline of the cofferdam. The project was inspected by General Lewis A. Pick, Chief of Engineers, in the early afternoon of that day (see fig. 39); approximately 2,150 tetrahedrons were then in place, both on the prototype and in the construction model. The sixth prototype tetrahedron fill was continued without interruptions until 5 p.m. of the following day, Friday, 17 November, when it was stopped temporarily; by that time 427 tetrahedrons

had been dropped, making an over-all total of 2,515 tetrahedrons (see fig. 40 and 41).

103. Placement of C-stone (ungraded rock spoil from excavation) began at 6:30 p.m. on Friday, 17 November, and continued until midnight of the following day, when it was stopped temporarily; by that time a total of about 7,840 tons had been placed.

104. First Permeability Measurement. - A permeability measurement was made on the prototype in the early afternnon of Saturday, 18 November. The river discharge was approximately 118,000 c.f.s.; the readings of gage 20 and the Ferry gage were 269.35 and 253.80, respectively, giving a head differential of 15.55 feet. The measurement section was located across the Oregon channel between cell A26 of the Oregon shore cofferdam and a jutting point on Artesian Island. A temporary cableway with a span of approximately 600 feet and a Price current meter were used. The leakage was determined to be approximately 10,600 c.f.s., or about 9% of the then occurring flow; prior to placement of the C-stone the leakage is estimated to have been approximately 12,500 c.f.s.

105. A permeability measurement was made on the construction model on 18 November. The model was set up exactly as the prototype, i.e. with 2,515 tetrahedrons and 26,300 tons of B-stone, but no C-stone had been placed. The average headwater elevation was 269.5 and the average tailwater was 253.55, giving a head differential of 15.95 feet. The measurement was made with a midget current meter in the section corresponding to the prototype. The leakage was found to be 4.09 c.f.s, corresponding to 11,500 c.f.s. on the prototype; this value may be considered as a reasonably good approximation of the estimated prototype leakage of

12,500 c.f.s. prior to the placement of C-stone.

106. Actual vs. Computed Spillway Flow. - The great discrepancy between the measured leakage and the computed value showed that the improved outlook observed during the placement of the fourth fill was due only partially to the permeability of the fill. Further analysis of the problem led to the discovery that the rating curve for the spillway as computed on the basis of observations made on the 1:100 general model was approximately 25,000 c.f.s. too low. The cause of the wide discrepancy lay in the fact that the approach channel to the spillway bays was approximately at the same elevation of 250 as the temporary crest, and the extremely high velocity of approach brought about flow at critical depth over the crest, instead of turbulent flow.

107. Actual Flow Distribution. - Mr. F. B. Campbell, Hydraulic Engineer, of the Omaha Office, Corps of Engineers, who was stationed at McNary during the entire closure operation and had followed developments very closely, prepared a revised rating curve for the spillway under the assumption of critical depth control over the spillway, and considered the 3 bays on the left end to be dependent on the reading of gage 23, and that gage 22 affected the remaining 8.7 bays. On the basis of this revised rating curve and other data available, Mr. Campbell prepared the very interesting set of curves reproduced in plate 15, showing the distribution of the river flow during the closure operation, as follows:

1. Flow through the spillway.
2. Flow over the top of the closure fill.
3. Leakage through the closure fill.

108. Completion of Zone III. - Placement of C-stone continued on

20 and 21 November (see fig. 42), followed by continuation of the sixth tetrahedron fill from 21 November to 27 November, when the last tetrahedron was dropped, bringing the total to 3,271 for the entire closure operation (see fig. 43). Placement of C-stone was continued on 27 and 28 November. An access road to Artesian Island was built toward the end of November across the top of the tetrahedron fill, just downstream from the location of the timber cribs.

109. A second permeability measurement was made on 29 November, after placement of approximately 25,000 tons of C-stone. The leakage was found to be 2,529 c.f.s., or approximately 10,000 c.f.s. less than before placement of the C-stone.

110. The placement of C-stone was carried out continuously and was completed on 2 December. The placement of the 4-foot layer of spalls started on 2 December and continued intermittently until completion on 7 December, when a total of approximately 9,900 tons had been placed.

111. Sealing of Closure Fill. - The original plan, as shown in plate 5, specified a thick layer of impervious material over the spalls, with a filter zone placed between the spalls and impervious material if deemed necessary. A 2-foot filter blanket and a 3-foot revetment of C-stone was specified over the impervious fill to finish the embankment.

112. Since the gradation of the spalls made placing of impervious material in immediate contact with the layer of spalls undesirable, a filter zone consisting of a 6-foot layer of bank-run sand and gravel was placed over the spalls by dumping between 5 December and 8 December; a total of about 11,570 cubic yards was placed. The grading of this

material was very poor; in accordance with analysis, 68% of it was larger than #4 mesh and 31% passed through #30 mesh. As a result of the deficiency of intermediate grain sizes, the fines were washed through the coarser material during placement, resulting in a pervious layer of gravel ranging in sizes from #4 mesh to almost 6 inches.

113. A 4-foot layer of graded and washed concrete gravel ranging from 3/4" to #4 mesh was placed by lowering the skip through the water; the operation started 8 December and ended on 18 December; a total of about 7,100 cubic yards was placed. Upon completion of the placement, the entire surface of the gravel blanket was smoothed out with a 3,000-lb. steel drag 16 feet wide, which was lowered to the bottom of the slope by means of the cableway, and pulled up the slope by a drag line stationed on the berm.

114. A permeability measurement was made on 19 December in a restricted section of the Oregon Channel in the vicinity of cell 72. The leakage through the closure fill was found to be approximately 850 c.f.s. or 0.7 percent of the then prevailing discharge of 118,950 c.f.s.

115. A 4-foot layer of washed concrete sand ranging from #4 mesh to #200 mesh was then placed over the gravel by lowering the loaded skip slowly through the water and dumping after lifting the lip a few feet above the bottom. Upon completion, the sand blanket was smoothed out with the steel drag. Soundings indicated that this careful procedure of placing and dragging had resulted in a very uniform and smooth blanket; the leakage had been reduced to the extent that it was no longer measureable.

116. At this juncture instructions were received to attempt

placing the impervious layer of silt over the entire upstream face of the fill, by dumping this material on top of the embankment and bulldozing it over the edge. The material was expected to reach its angle of repose, which was estimated to be 1 on 3 or flatter. The procedure was applied at the south end of the fill, where approximately 4,000 cubic yards of material were placed on 22 December. The result was very unsatisfactory, because the material first piled up with an upstream vertical face more than 25 feet high, then sloughed suddenly; this was accompanied by the appearance of muddy water on the downstream side of the fill. Later inspections by a diver showed that a substantial portion of the 4-foot layer of sand had been gouged out and that the material of the slide had settled near the bottom, where it had formed a very flat and somewhat beneficial blanket sloping upstream. About 860 cubic yards of the sand blanket was replaced.

117. The use of silt for the impervious layer was then abandoned and bank-run sand and gravel with the deficiency in grain sizes between the #4 and #30 meshes eliminated by addition of "rifle-range" sand was placed in a layer ranging from 8 feet at the top to 12 feet at the bottom, by very careful lowering of the loaded skip through the water and releasing it as close to the bottom as practicable. The upstream slope of this layer was 1 on $2\frac{1}{2}$.

118. The closure embankment was completed with a 3-foot layer of dumped stone extending from the top down to elev. 250; this revetment was placed during the early part of January 1951. A stationary barge was used as a platform to enable trucks to dump some of the stone in places inaccessible with the cableway.

119. Crib Construction. - The cribs were constructed during the

second half of January 1951. The cribs are of heavy timber construction and set on top of the closure fill (see fig. 45). The location of the cribs and the type of fill material are shown on plate 16. The top of the timber cribs is at elev. 302, or 10 feet higher than the remainder of the Second-Step Cofferdam; the purpose of this extension is to protect the closure fill from scour during the summer floods (see fig. 46).

120. Unwatering of Cofferdam Area. - The unwatering of the cofferdam area started on 19 January 1951 with one 20" - 100 h.p. propeller pump. The number of pumps was gradually increased to 5 and the water level was lowered by 12.5 feet 5 days later. A sixth pump was installed on 5 February and the water surface in the Oregon Channel was lowered to elev. 232, or approximately 26 feet below the initial level. A considerable amount of leakage water entered the cofferdam area through the downstream leg of the second-step cofferdam, apparently due to poor contact of the sheetpiling with the rocky bottom, together with inadequate grading or placement of the fill material in the steel cells; many of the leaks were distinctly visible in the form of jets and boils.

121. A plan was developed for sealing the large leaks in the downstream leg of the cofferdam by constructing steel sheetpiling pockets on the water side of cells 52 to 56, and filling them with bank-run sand and gravel. This plan was abandoned later, and an attempt was made instead to place bank-run sand and gravel, blended with "rifle-range" sand, with an 8-inch tremie along the rock contact on the outside of the steel cells. The experiment did not succeed, because the tremie clogged continually; the material was finally placed by using a clamshell bucket lowered slowly to the bottom, then opened gradually; this procedure resulted in a satisfactory reduction of the leaks.

122. The large leaks through cells 74 to 77 were sealed satisfactorily by constructing steel sheetpiling pockets or "blisters" on the dry side of the cells and placing about 4 feet of concrete in the bottom through a tremie.

123. The upper pool level attained elev. 283.6 on 13 February, when the discharge had increased unseasonably to 274,200 c.f.s.; the water surface elevation in the Oregon Channel inside the cofferdam attained 235.4, corresponding to a maximum head differential on the closure fill of 48.2 feet. On that date the amount of water pumped out of the cofferdam area in 24 hours was approximately 284 acre-feet, corresponding to an average pump discharge of 143.7 c.f.s.

124. During the latter part of February 1951 a small temporary dam was constructed in the Oregon Channel to form a separate pool downstream from the closure fill. Three 20-inch 200 h.p. propeller pumps were installed to lower the water surface in the pool as much as possible, for the purpose of inspecting the lower part of the tetrahedron fill, and to determine the amount of leakage through the closure fill. Pumping began on 21 February and continued until 25 February; the lowest level attained was elev. 217.4 on 24 February; the water could not be lowered further, because the leakage through the small temporary dam was excessive. The upper pool was at elev. 276.2 and the head difference on the closure fill was 58.8 feet. The leakage through the closure fill proper was estimated at 54 c.f.s. (see fig. 47).

125. The cofferdam is constructed to protect against a flood of approximately 400,000 c.f.s. and is therefore expected to be overtopped in May 1951. Complete unwatering of the cofferdam area will form part of the completion contract and is expected to take place shortly after the

1951 summer floods (see fig. 50).

126. Characteristics of Tetrahedron Fill. - Observations made on the prototype tetrahedron fill after unwatering and up to the present time show similar characteristics as the model, i.e. the steep downstream slope of approximately 1 on 1, the sharp break at approximately elev. 240 about 115 feet downstream from the centerline of the cofferdam, a flat slope averaging approximately 1 on 9 for about 90 feet, and a steeper slope averaging 1 on 1.5 extending to elev. 270.

127. Figure 48 shows the appearance of the toe of the tetrahedron fill when the water surface in the Oregon Channel had been lowered to elev. 218.4, corresponding to a head of approximately 57.5 feet on the closure fill. Figure 49 shows the general appearance of the Oregon Channel under the same conditions.

128. Plate 18 shows the results of a partial planetable survey of the exposed face of the tetrahedron fill, indicating the ultimate position of the high points of a limited number of tetrahedrons. A total of 139 tetrahedrons were spotted below the downstream edge of the roadway fill; out of this total, 44 tetrahedrons or nearly 1/3 originated from the second fill and showed an average drift of about 36 ft. The first fill contributed 25 tetrahedrons (18%), the third fill 29 (21%), the fourth fill 37 (26.6%), and the fifth fill only 4, or 2.7%. The survey could not be completed, at first because snow and ice conditions made movements on the sloping surfaces too dangerous, and later because the Contractor covered a large area of the tetrahedron fill to construct the lower access road shown in fig. 47.

129. Construction Report. - A separate report has been prepared

by the McNary Project Office to cover in greater details all construction phases of the closure operation.*

130. COST OF CLOSURE. - A preliminary and partially estimated compilation of the cost of the McNary Second-Step Cofferdam closure is given in the tabulation following:

a. PROTOTYPE COST

Description	Bid Quantity	Actual Quantity		Unit Cost	Total
12-ton concrete tetrahedrons, in place	3,000	3,000	ea.	$180.00	$540,000.00
12-ton concrete tetrahedrons, in place	500	280	ea.	135.00	37,800.00
B-stone from excavation, in place	3,500	15,975	ton	3.50	55,912.50
B-stone from quarry, in place	15,000	11,578	ton	5.50	63,679.00
C-stone, in place	50,000	46,177	ton	2.60	120,060.20
Spalls, in place	7,500	9.923	ton	3.50	34,730.50
Impervious material, in place	30,000	12,674	c.y.	1.10	13,941.40
90% Pit run Gravel with 10% "Rifle Range" Sand, in place		32,712	c.y.	1.10	35,983.20
Sand from "Rifle Range"		3,900	c.y.	1.10	4,290.00
Filter Blanket, in place		7,846	c.y.	2.50	19,615.00
Concrete Gravel (#4-3/4") in place		7,121	c.y.	5.68	40,447.28
Concrete Sand, in place		9,619	c.y.	5.68	54,635.92
		Carried Forward			1,021,095.00

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*Report on Construction of the Second-Step Cofferdam Closure Fill at McNary Dam — 2 April 1951.

Description	Bid Quantity	Actual Quantity	Unit Cost	Total
			Brought Forward	$1,021,095.00
Concrete Sand and Gravel, (50% sand, 50% gravel), in place		1,042 c.y.	$ 5.68	5,918.56
Dumped Stone Revetment, in place	7,000	18,283 ton	2.00	36,566.00
Timber Crib		Job		86,200.00
Use of Cableway for Soundings (Contractor's Cost)		Job		12,527.00
				$1,162,306.56
Engineering, supervision inspection & overhead				104,607.59
Total Prototype Cost				$1,266,914.15

b. MODEL COST

18 Precast blocks for Clearwater River experiments (Contractor's Cost)		334.13
Costs for Sectional Model Studies (Bonneville Hydr. Laboratory)		5,868.08
Construction Model at McNary (Contractor's Cost)	21,394.94	
McNary Project Office charges for labor and material	7,235.54	
Portland District Costs	10,314.50	
Walla Walla District Costs including overhead	6,814.20	45,759.18
Total Cost of Model Studies		$51,961.39

c. SUMMARY

Total Prototype Cost	$1,266,914.15
Total Cost of Model Studies	51,961.39
Total Cost of Second-Step Cofferdam Closure	$1,318,875.54

CHAPTER V - DISCUSSION

BASIC FACTORS OF McNARY CLOSURE

131. Generally speaking, the McNary Second-Step Cofferdam closure was a complete success. The problem presented unusual difficulties, yet it was solved by a combination of skillful planning, an ingenious method, proper selection of equipment and aggressive resourcefulness.

132. Planning. The skillful planning was evidenced by the selection of the Oregon Channel for the site of the closure. Generally speaking, there were three principal locations for the closure site. The first was the Washington side, the second was across Artesian Island, while the third was across the Oregon Channel. The selection of the first or the second site would have had the advantage of permitting final closure in water of lesser depth but with velocities substantially the same as if final closure were made in the Oregon Channel and without material benefit in conditions during diversion of the main flow of the river from the Oregon Channel. Furthermore, navigation and passage of fish would have been interfered with for a considerably longer period of time. By selecting the site across the Oregon Channel just upstream from the centerline of the dam, it was possible to concentrate the closure operation to a relatively narrow and deep gap; this provided sufficient cross-sectional area to eliminate the danger of excessive velocities, and permitted the solution of the two very difficult problems of diverting the main flow of the river and closure with one single operation.

133. Novel Method. The ingenious method of making the closure by successive drops of precast concrete blocks and backfilling with

material of various sizes, had the advantage of gradual effectiveness and flexibility. The gradual effectiveness was attained by first filling the bottom of the channel until a submerged sill of uniform elevation was attained across the entire closure gap, then raising this sill in several low horizontal layers until emergence was attained. By using this procedure the water flowing through the gap was always forced to spread in a gradually thinning sheet over the entire width of the gap and was never concentrated at one or more points, as would have occurred by end dumping, by construction of steel pile cells, or by using cribs floated into place and sunk. The flexibility consisted in being able to shift the dropping points to any location where the overflowing sheet of water showed signs of undesirable local convergence.

134. Selection of Equipment. The proper selection of the equipment was clearly evidenced, especially by the main cableway and appurtenant devices for loading and unloading of the precast concrete blocks and other materials required for the closure fill. The cableway layout was such as to permit placement of the tetrahedrons, B-stone and other types of material at any point of the closure fill and in any desired sequence or elevation, including deep submergence. No other piece of construction equipment would have been capable of such flexibility of operation and such "pin-point" accuracy of placement; however, the provision of longer tracks for the cableway would have been desirable for handling possible unforeseen work.

135. Resourcefulness. The aggressive resourcefulness was demonstrated on numerous occasions during the last four months of 1950, for instance when extensive experimental work was rushed through, when unforeseen difficulties caused a serious delay in the closure operation,

when the river flow attained a near-record stage, and when all preparations were made for anchoring the tetrahedrons as the success of the operation appeared endangered.

POSSIBLE IMPROVEMENTS

136. In common with any other major construction operation performed without the benefit of precedents, the McNary cofferdam closure could have been improved quite materially, in the light of later experience.

137. A report covering such a major construction operation would be incomplete if it omitted a discussion of the ways and means whereby the same problem might have been solved better, easier, or more economically. Such a discussion should not be interpreted as a criticism of the manner in which the problem was solved, but as a constructive effort to point the way in which similar problems of the Corps of Engineers might be expedited or in other manner benefited through the experience gained at McNary.

138. For the purpose of facilitating the presentation of this discussion, the various items will be classed into four groups, namely: (1) Engineering Analysis, (2) Model Studies, (3) Field Preparations, (4) Field Observations.

139. Engineering Analysis. The method selected for the McNary closure had never been used before and no data were available on which to base the design of the fill or the procedure for constructing it. In the absence of such data, the design was based on three assumptions, namely, that the Passamaquoddy data were applicable, that tetrahedrons would not tend to roll or slide as readily as other shapes, and that

slopes of 1 on 2 could be attained. None of the three assumptions was verified; in particular, no account was taken of the fundamental and far-reaching difference between the Passamaquoddy data and the McNary conditions, i.e., that the Passamaquoddy data applied to the simple resistance to movement or inertia of stationary bodies when exposed to a stream of water, whereas the McNary problem was just the reverse and much more complicated, because it involved two-dimensional acceleration of a falling body, followed by three-dimensional retardation. In addition, the Passamaquoddy data had been determined with stones weighing 165 lbs./ cu. ft., whereas the weight of ordinary concrete is about 150 lbs./ cu. ft.; the buoyant weight of the latter is therefore 15% less than for dense stone.

140. Doubts were expressed occasionally as to the feasibility of the proposed design under the admittedly difficult conditions to be expected; however, these expressions of doubt were insufficient to cause any material changes.

141. Model Studies. Model experiments of the river diversion as a whole had been made in the 1:100 McNary General Model, but the data obtained were only general in character. No experiments were made to analyze in detail the construction of the closure fill, since it was considered that such experiments would need to be made on such an elaborate and expensive scale to assure the dependability of results that the cost thereof was not warranted .

142. Concern regarding the feasibility of the proposed design began to be felt when the results of some personal experiments made in Seattle with a sectional model were reported. Several experiments in a stream and with sectional model were then carried out in hurried

sequence. A construction model was decided upon a few days before beginning of the actual closure operation.

143. Sectional model studies would have indicated the advantage of the highest practicable specific gravity, the best shape and size of the precast concrete blocks, the most desirable cross section of the fill and the best procedure for its construction.

144. A complete and detailed model of the entire construction area, including low spillway bays, on a sufficiently large scale, say 1 : 24 or 1 : 30, utilizing the data obtained from the sectional model studies, would have shown that the closure could have been made without undue difficulty with the equivalent of about 1,800 12-ton tetrahedrons. Additional advantages of such a model would have been to furnish reliable data regarding the permeability of the fill and the distribution of flow between the closure gap and the low spillway bays channel, thus eliminating some of the uncertainties and incorrect assumptions which prevailed until after the closure was actually completed and a prototype permeability measurement was made.

145. Field Preparations. The necessity of adequate preparation for the actual construction work is too obvious and well understood to require emphasis at this point. However, tight construction schedules can at times cause considerable difficulty, even to highly experienced contractors. At McNary the planned simultaneous construction of the closure fill and completion of the upstream leg of the cofferdam had to be discarded a few days after the beginning of the closure.

146. Field Observations. One phase of the observations which caused difficulty was the determination of the controlling water surface elevations. The location of the principal gages is shown in plate 7.

Staff gages were used throughout, reading directly in feet above mean sea level. Several of these gages were affected by impingement of the water or by wave action. Gage 8 could only be estimated roughly, as the wave action was excessive; gage 9 was practically worthless, as the wave action exceeded 2 feet at times. The Ferry gage had therefore to be used in determining the head differential between the upstream and downstream sides of the closure fill; this reduced the accuracy of the data still further, because the Ferry gage is located 0.9 mile downstream from the closure fill. Difficulty was also experienced with the accurate determination of the river discharge; the official Umatilla gage, located 2.8 miles downstream from the closure fill, is a staff gage in several sections; the section which had to be used at the time of the closure was heavily coated with mud and had to be read at a considerable distance, thus resulting in low accuracy.

147. The importance of accurate gage readings, preferably by means of recording gages at the strategic points, cannot be overemphasized.

APPLICATION TO OTHER PROJECTS

148. The McNary method of cofferdam closure is applicable to the construction of other similar projects. In view of the fact that every project has different characteristics, the method would probably have to be modified to attain best results.

149. Foundation Problems. At McNary the closure fill rested entirely on solid basalt; this had the advantage of great resistance to erosion, but probably permitted some of the tetrahedrons in the bottom layer to slide more than they would on erodible material.

150. The McNary method appears applicable to any type of foundation material which has sufficient bearing capacity for the submerged fill; the danger of scour in erodible material is reduced to a minimum by the circumstance that a large and slow roller develops which, together with the leakage stream, forms a protective cushion at the toe of the fill.

151. Shapes and Specific Gravity of Precast Blocks. Shapes of precast blocks other than the tetrahedron, such as slabs or prisms, could offer some advantages, particularly in their resistance to "sailing" in very fast water; however, the advantages of the tetrahedron shape were aptly demonstrated, e.g. its resistance to dislodgement by overflow after placement, its large bulking factor (50%-60%) with resultant decrease in cost of fill in place, and its ease of handling. In view of the demonstrated desirability of making the precast blocks as heavy as possible, consideration should be given subject to cost limitations, to the use of the heaviest available aggregates, possibly ore or smelter slag, and densest possible mixtures. The use of admixtures, such as air entraining agents, which reduce the specific gravity of the concrete, should be avoided.

152. Where very fast velocities are to be encountered, consideration might be given to the use of "self-anchoring units", each consisting of a concrete block of very high specific gravity cabled to an ordinary concrete block; by a suitable design and placement procedure such units would provide a relatively steep and very stable "back-bone" for the fill and might permit substantial savings of cost for the closure fill as a whole, by reducing the quantity of high-specific-gravity blocks which would otherwise be required.

153. Procedure for Placing Rock Fill. Experience gained in the McNary closure has indicated that such an operation can be performed without use of large blocks in as great a portion of the section as was done in that case. Depending on availability, it is indicated that an appreciable amount of the initial fill could be made with quarry-run stone or rock from required excavation. Since it is practically impossible to accurately determine the location or shape of the fill actually in place by either soundings or visual means, it is necessary to depend on gage readings and the surface appearance of the flow over the closure for interpretation of results. With that in mind, the most economical rock available should be placed first until the velocity of the water increases to the extent that the additional rock being placed is being carried over the crest of the fill without increase in height of crest. This point can be determined by practical cessation in rise of the upstream water surface. At this point an adequate shelf of rock, for support of the heavy blocks, should be constructed. Quantities and point of placing must be estimated from soundings, both before and after placing the rock fill. The large blocks, of the size, specific gravity, and shape previously determined should then be placed so as to drop near the indicated edge of the fill. The success of this operation again should be closely checked by gage readings. When rate of rise of water surface again declines or if the predetermined volume of blocks have been placed, the rock shelf should again be extended to form a support for additional blocks in order to keep their number to a minimum. Results at McNary have indicated that this shelf should be carried practically to the top of the layer of blocks in place for optimum retention of the next layer of blocks. Dropping of blocks should be carefully controlled

to eliminate formation of "slicks" which indicate fast moving water through a depression in the fill and which can be very difficult of closing if permitted to become pronounced. This procedure can be repeated until the fill emerges above the water surface, provided the blocks are of sufficient size and specific gravity.

154. Value of a Construction Model. The provision of a construction model at the site proper is advisable for most closure operations of a difficult nature. Among the advantages of such a construction model can be cited the visualization of the problem and improved understanding on the part of the local engineering force and contracting personnel of the problems involved, and the availability for developing solutions if emergencies arise. At McNary the construction model proved of inestimable value and was a major contribution to the ultimate success of the prototype closure operation.

155. Importance of Sealing. The sealing of the interstices in the closure fill is a difficult operation requiring great care in design and construction. The design should be governed by considerations of soil mechanics, including stability analyses and protection against wave action or other erosion. Because of the existence of flowing water inherent in this type of closure, and the tendency of material being deposited through such flowing water to become separated into relatively uniform size bands, it is necessary to avoid a large range in particle size for any one layer in order to prevent practically total loss of the finer material in the layer being placed. For this reason, it was found necessary to place the seal blanket, after the spall layer was in place, in four separate layers; the first layer consisting of bank-run sand and gravel of which only the particles above the #4 mesh were

retained; the second layer consisting of well-graded aggregate from 3/4 inch to #4 mesh; the third layer consisting of graded sand; and the fourth layer containing fine sand and silt. This procedure, coupled with careful dragging of each separate layer, will compensate for any probable segregation and formation of pervious pockets. The use of fine silt and clay should be discouraged, because their inherent characteristics in the presence of water make their behavior too unpredictable.

CHAPTER VI - CONCLUSIONS

156. The successful completion of the McNary Second-Step Cofferdam closure solved one of the most difficult engineering problems in construction history.

157. It is believed that the McNary method, consisting of successive drops of precast concrete blocks and backfilling with rocks, will permit successful and economical closure even under the most difficult conditions likely to be encountered in practice, provided, however, that such changes and adaptations are made as may be required to fit specific conditions.

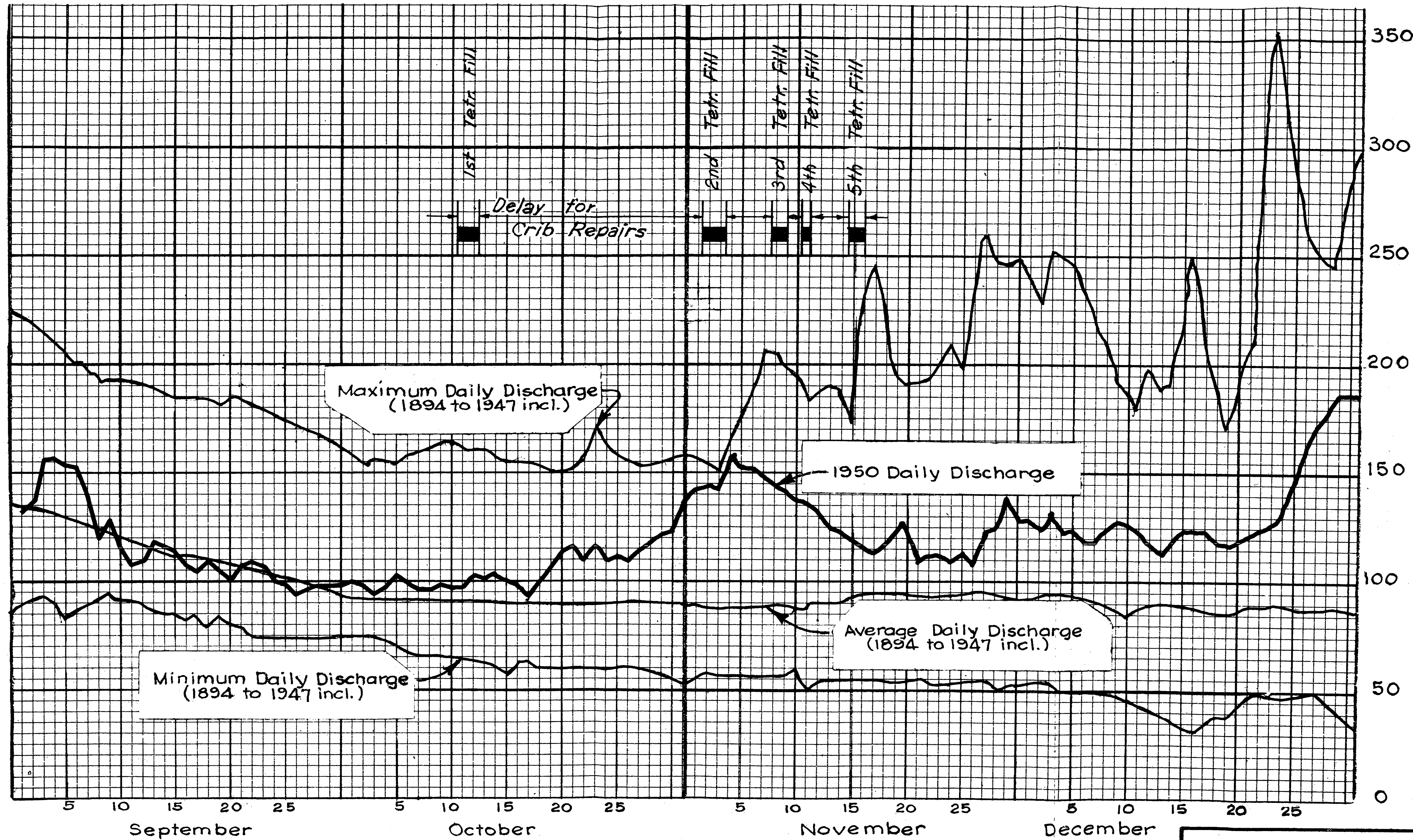
158. Each major river diversion presents different features and different engineering problems, which require individual analysis and adequate preparation for emergencies.

159. The engineering analysis should be verified with such model studies which may be warranted, in order to reduce to the minimum the uncertainties and the cost of the field operation.

PLATES

LIST OF PLATES

No.	Title
1	Summary Hydrograph - Columbia River at McNary Dam
2	General Layout of Cofferdam
3	Details of Closure Gap
4	Stability of Stones in Flowing Water
5	Design Section of Closure Fill
6	Details of 12-Ton Tetrahedrons
7	Map of Closure Area
8	First Tetrahedron Fill
9	Second Tetrahedron Fill
10	Teatative Anchorage of Tetrahedrons
11	Third Tetrahedron Fill
12	Fourth Tetrahedron Fill
13	Fifth Tetrahedron Fill
14	Closure Progress Chart
15	Actual Flow Distribution
16	As-Built Section of Closure Fill
17	Comparison of Design and As-Built Sections
18	Location of Tetrahedrons After Unwatering



Basic plate prepared by McNary Construction Division Office

McNARY LOCK AND DAM

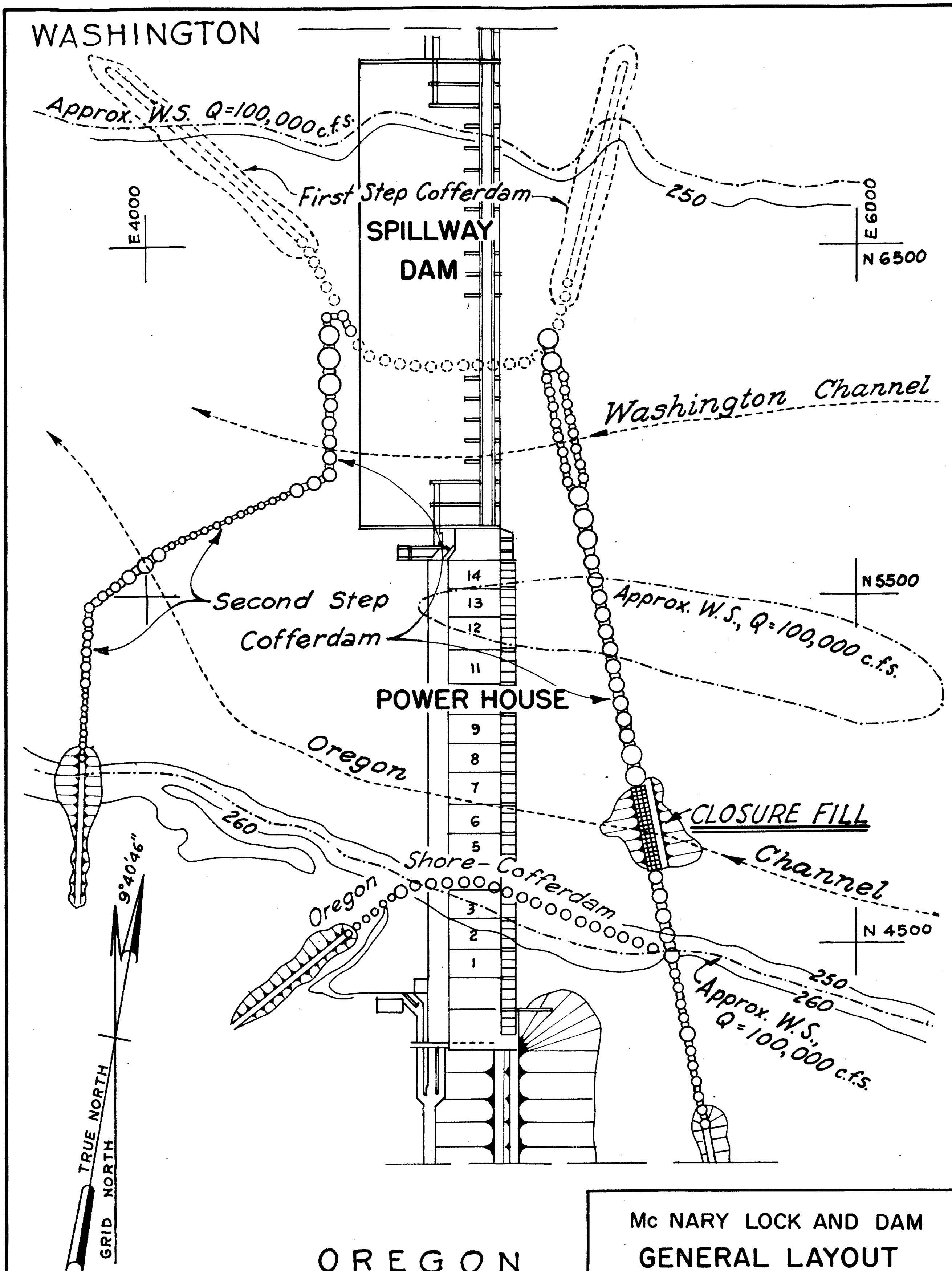
SUMMARY HYDROGRAPH

COLUMBIA RIVER AT McNARY DAM

NO SCALE

TO ACCOMPANY REPORT DATED JULY 1951, REPORT ON McNARY COFFERDAM CLOSURE

PLATE 1



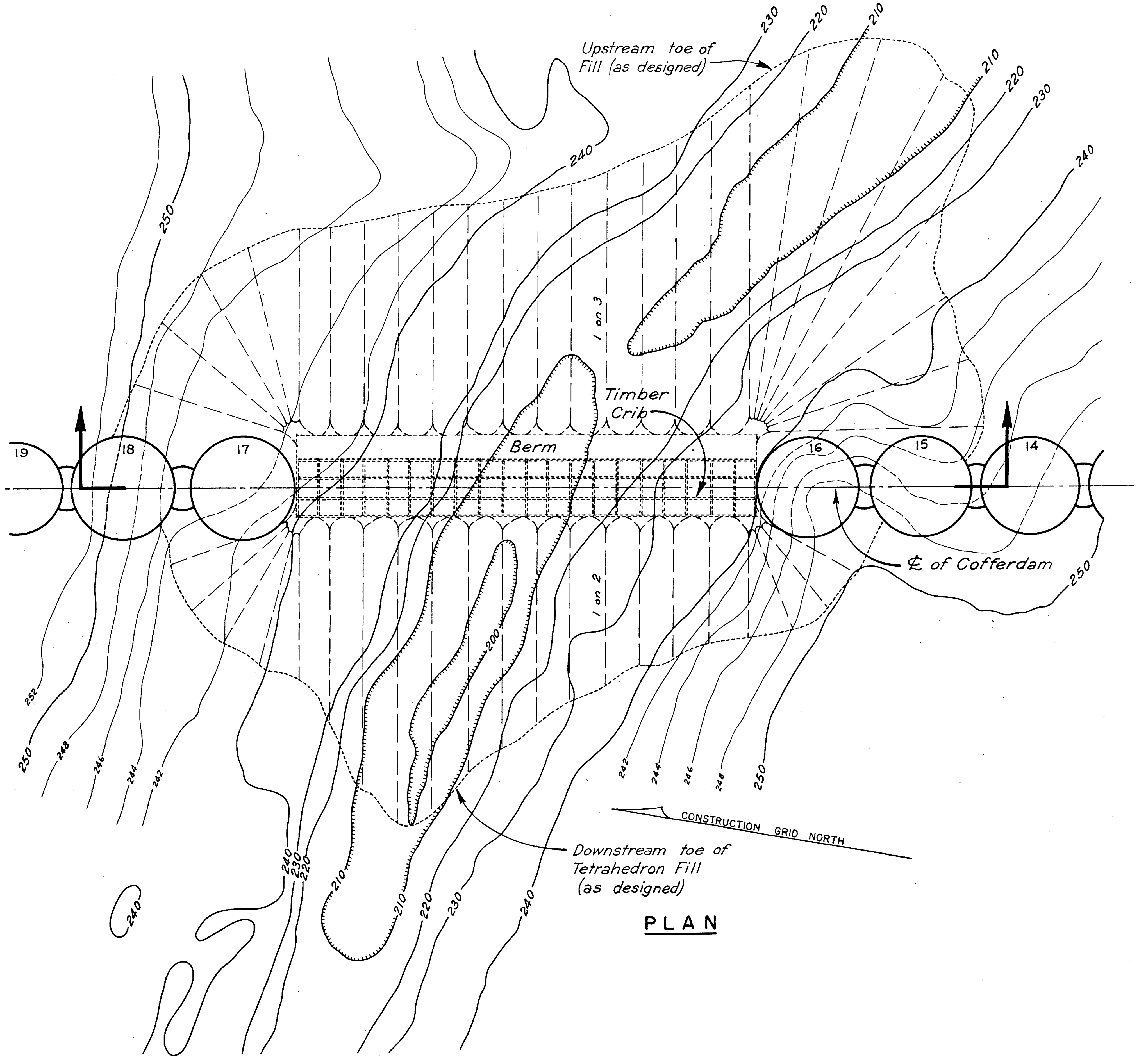
Mc NARY LOCK AND DAM

GENERAL LAYOUT OF COFFERDAMS

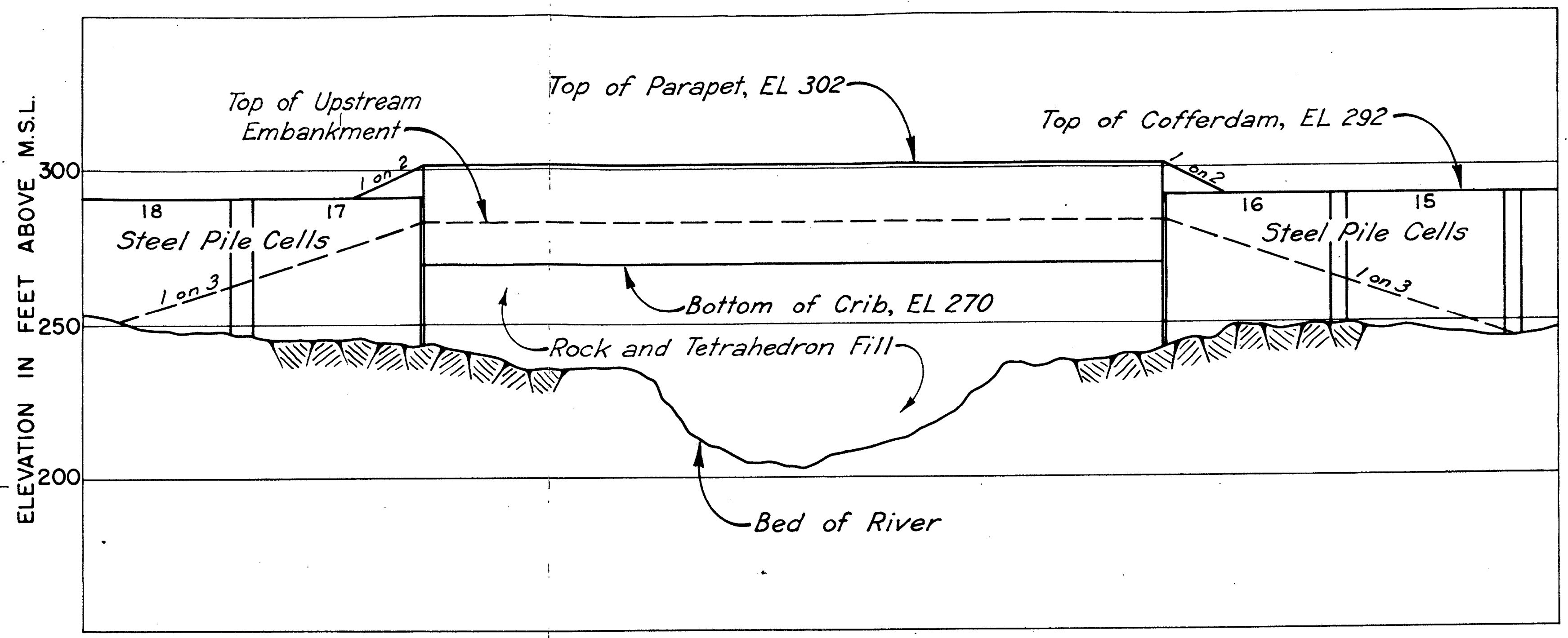
SCALE: 1"=400'

TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON Mc NARY COFFERDAM CLOSURE"

PLATE 2



PLAN



SECTION ON ℄ OF COFFERDAM

(AS DESIGNED)

Mc NARY LOCK AND DAM

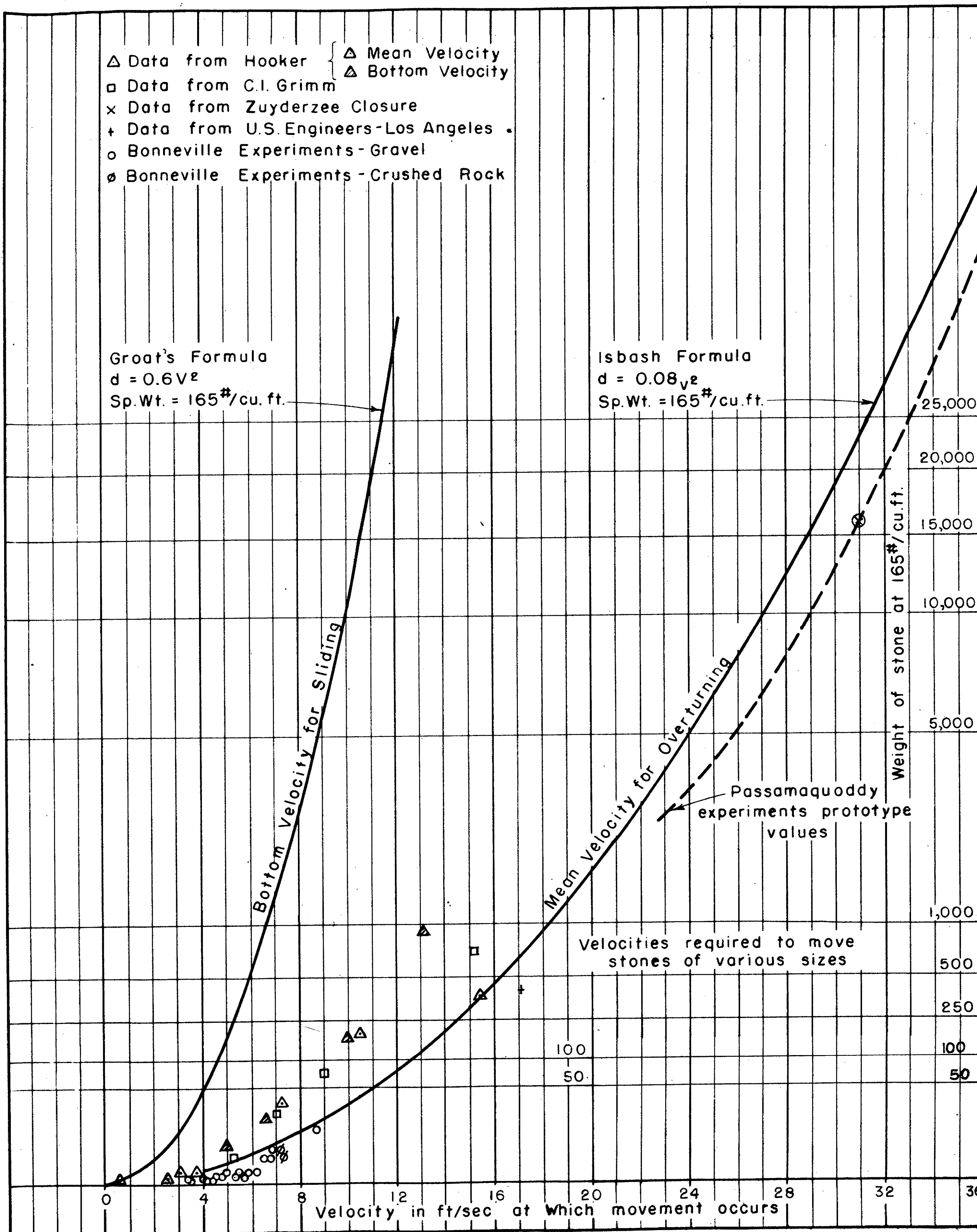
DETAILS OF CLOSURE GAP

SCALE IN FEET

50 0 50 100

TO ACCOMPANY REPORT DATED JULY 1951 "REPORT ON Mc NARY COFFERDAM CLOSURE"

PLATE 3



NOTE:
Original plate prepared by U.S. Engineer Office, North Pacific Division, Portland, Oregon, 24 October, 1938.

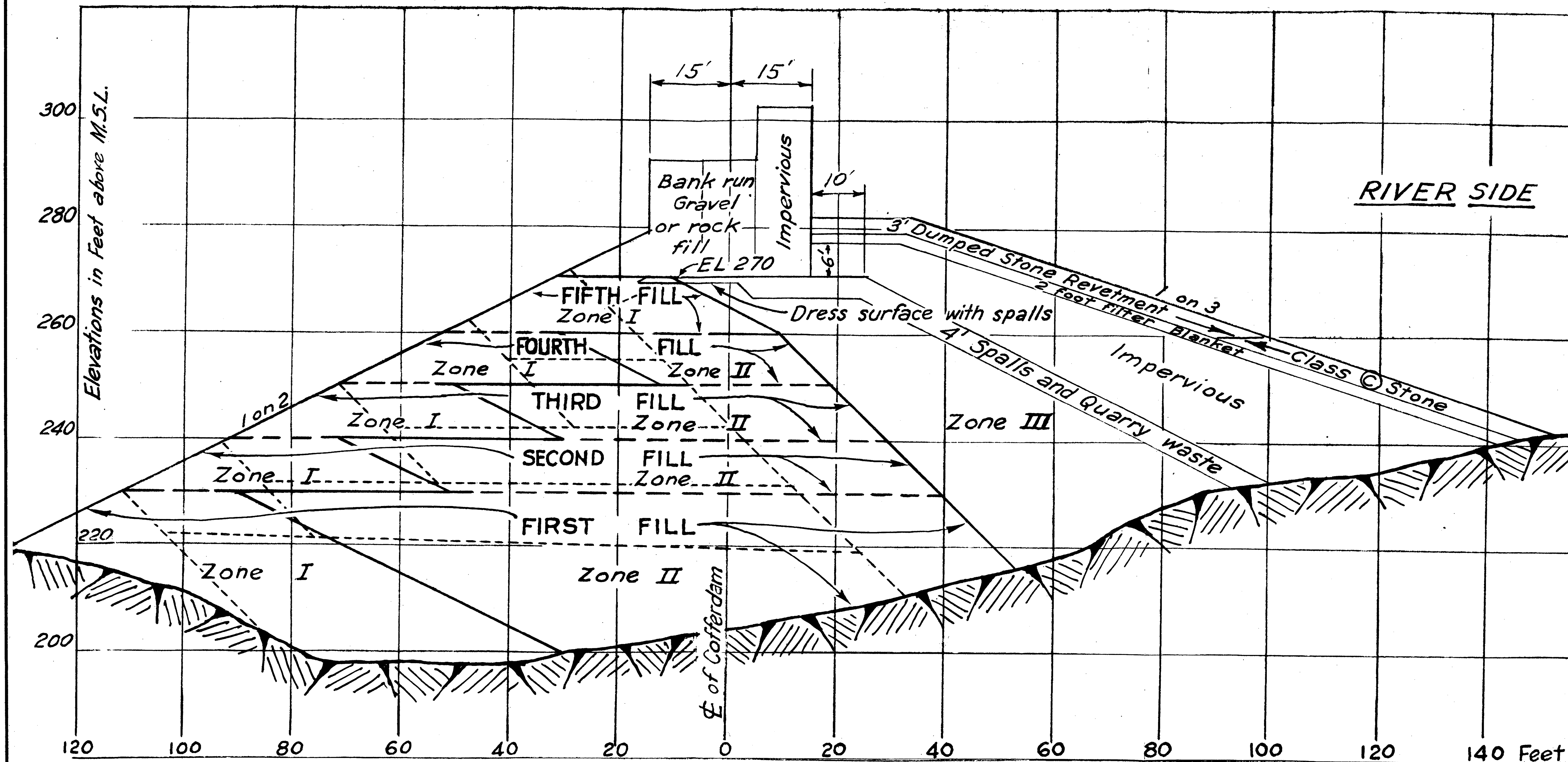
Mc NARY LOCK AND DAM

STABILITY OF STONES IN FLOWING WATER

NO SCALE

TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON MC NARY COFFERDAM CLOSURE"

PLATE 4



The Design Section, as revised 15 August 1950, is made up as follows:

Zone I = 12-ton Tetrahedrons
Zone II = B-stone (min. weight 2000 lbs.)
Zone III = C-stone (ungraded rock spoil from excavation.)

NOTES:

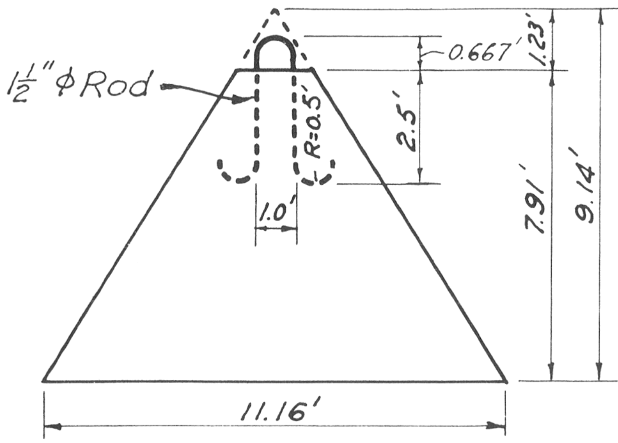
1. *Dotted lines indicate Zone Limits in accordance with Contract Drawings dated 25 May 1949.*
2. *Solid lines indicate Zone Limits as revised. 15 August 1950.*
3. *For location of Design Section see PLATES 3&7.*

McNARY LOCK AND DAM

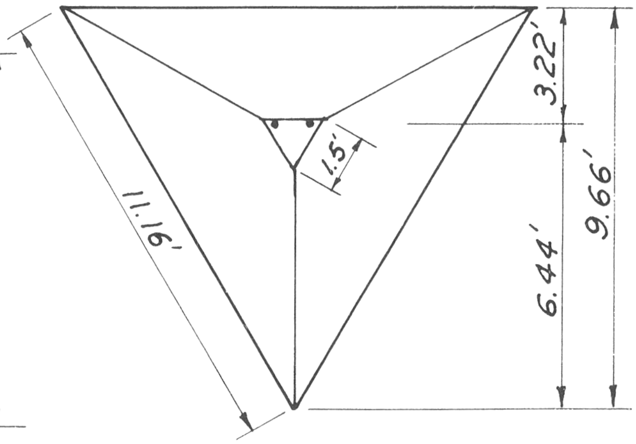
DESIGN SECTION OF CLOSURE FILL

SCALE: 1"=20'

TO ACCOMPANY REPORT DATED JULY 1951 "REPORT ON McNARY COFFERDAM CLOSURE"

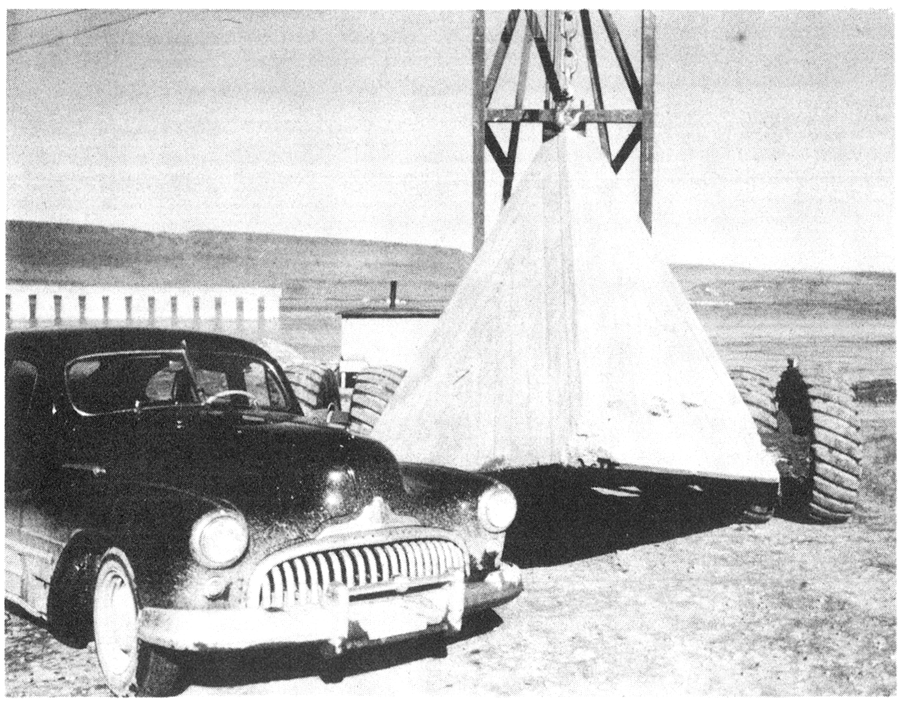


PLAN



ELEVATION

NOT TO SCALE

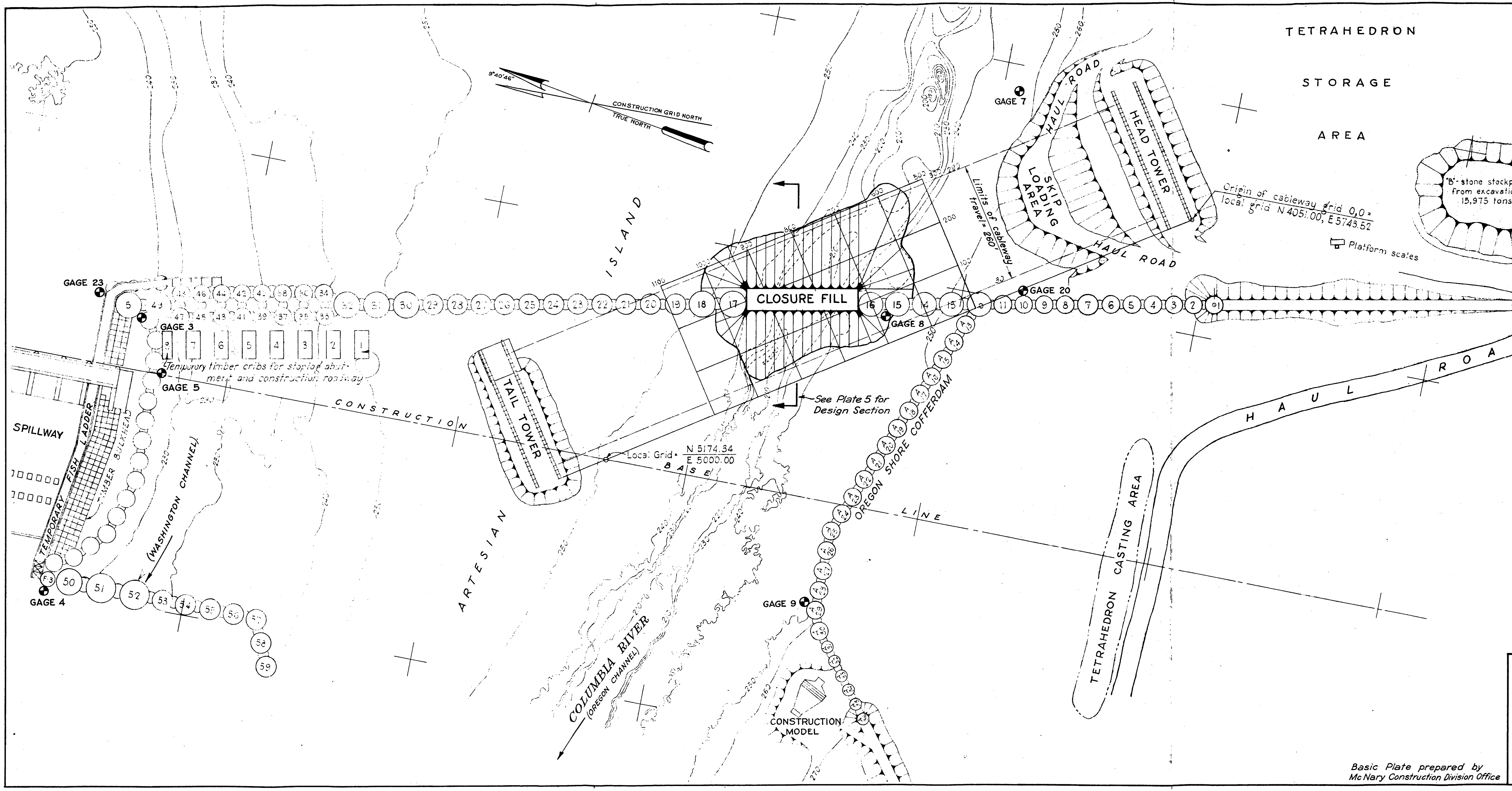


COMPARISON OF SIZES

McNARY COFFERDAM CLOSURE

DETAILS OF
12-TON TETRAHEDRON

TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON McNARY COFFERDAM CLOSURE"



Basic Plate prepared by Mc Nary Construction Division Office

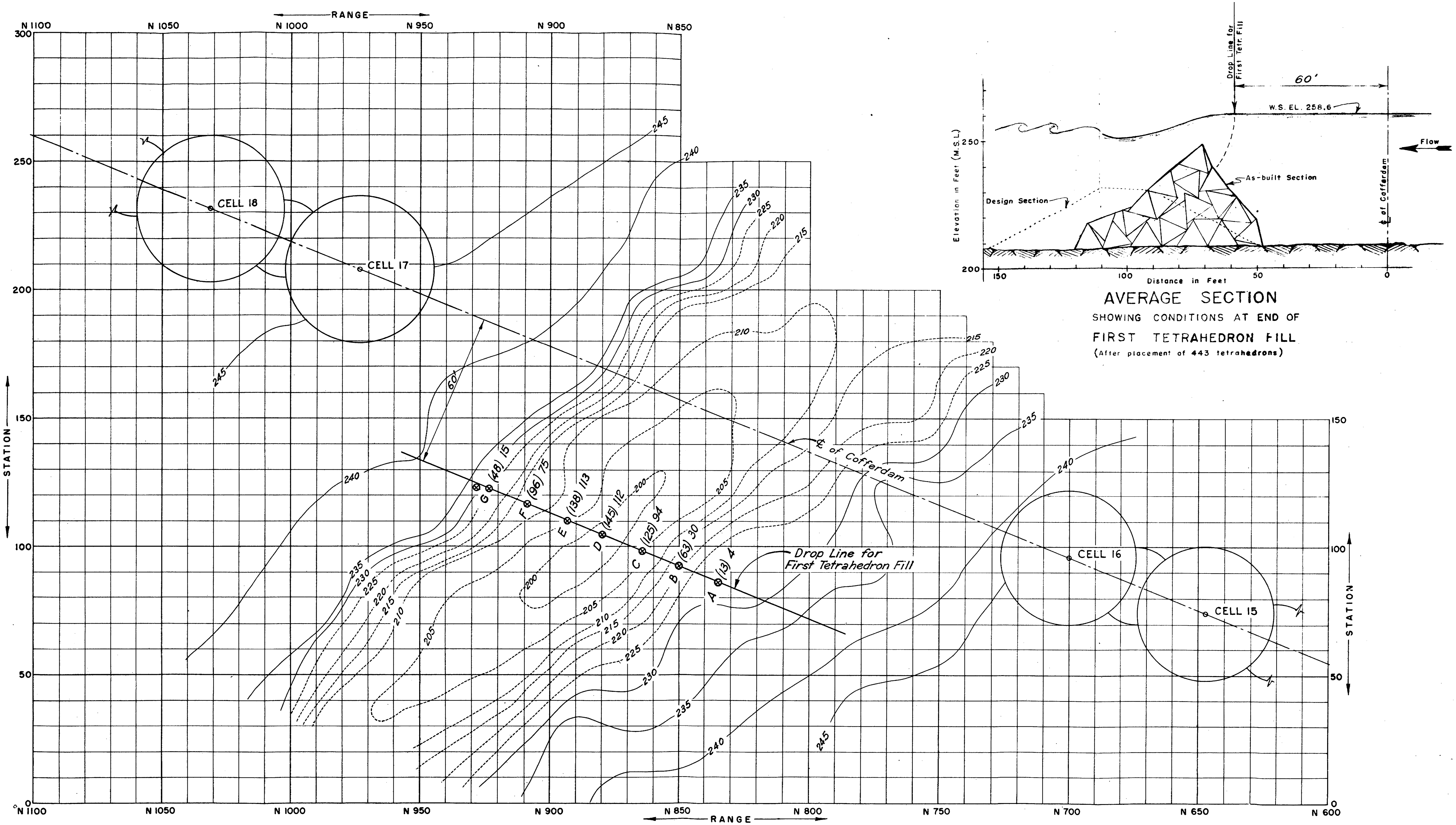
Mc NARY LOCK AND DAM

MAP OF CLOSURE AREA

SCALE IN FEET
100 0 100 200 300

TO ACCOMPANY REPORT DATED JULY 1951: "REPORT ON Mc NARY COFFERDAM CLOSURE"

PLATE 7



NOTES:

Figures in parentheses, e.g.(125), indicate the number of 12-ton tetrahedrons scheduled to be dropped at each particular point. The figures following, e.g. 94, indicate the number of tetrahedrons actually dropped.

Contours show natural conditions. Contours below EL. 230 are of limited accuracy.

McNARY LOCK AND DAM

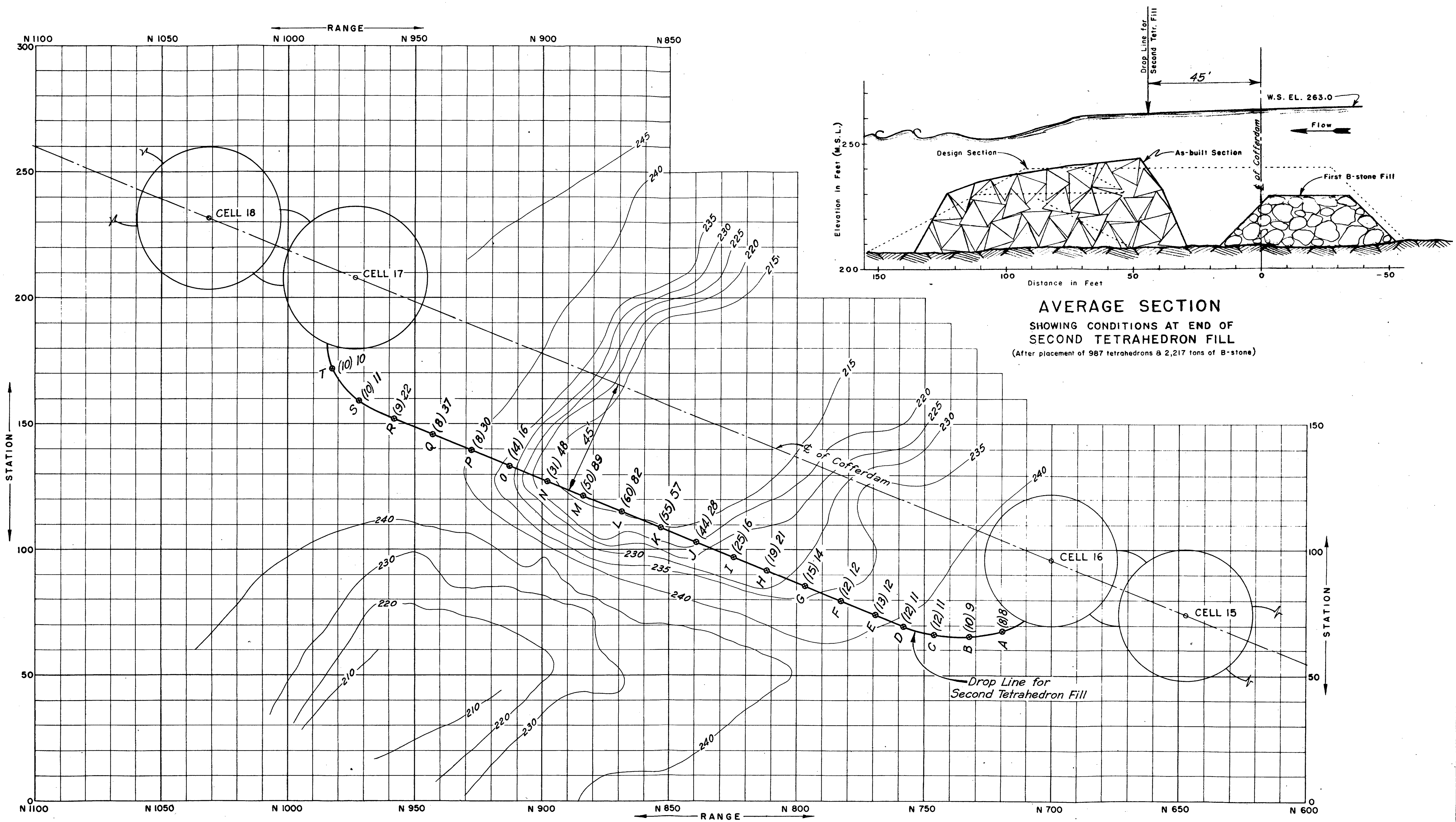
FIRST

TETRAHEDRON FILL

SCALE IN FEET

20 0 20 40 60

TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON McNARY COFFERDAM CLOSURE"



AVERAGE SECTION

SHOWING CONDITIONS AT END OF SECOND TETRAHEDRON FILL

(After placement of 987 tetrahedrons & 2,217 tons of B-stone)

NOTES:

Figures in parentheses, e.g. (44), indicate the number of 12-ton tetrahedrons scheduled to be dropped at each particular point.

The figures following, e.g. 28, indicate the number of tetrahedrons actually dropped.

Contours show approximate topography at beginning of Second Tetrahedron Fill.

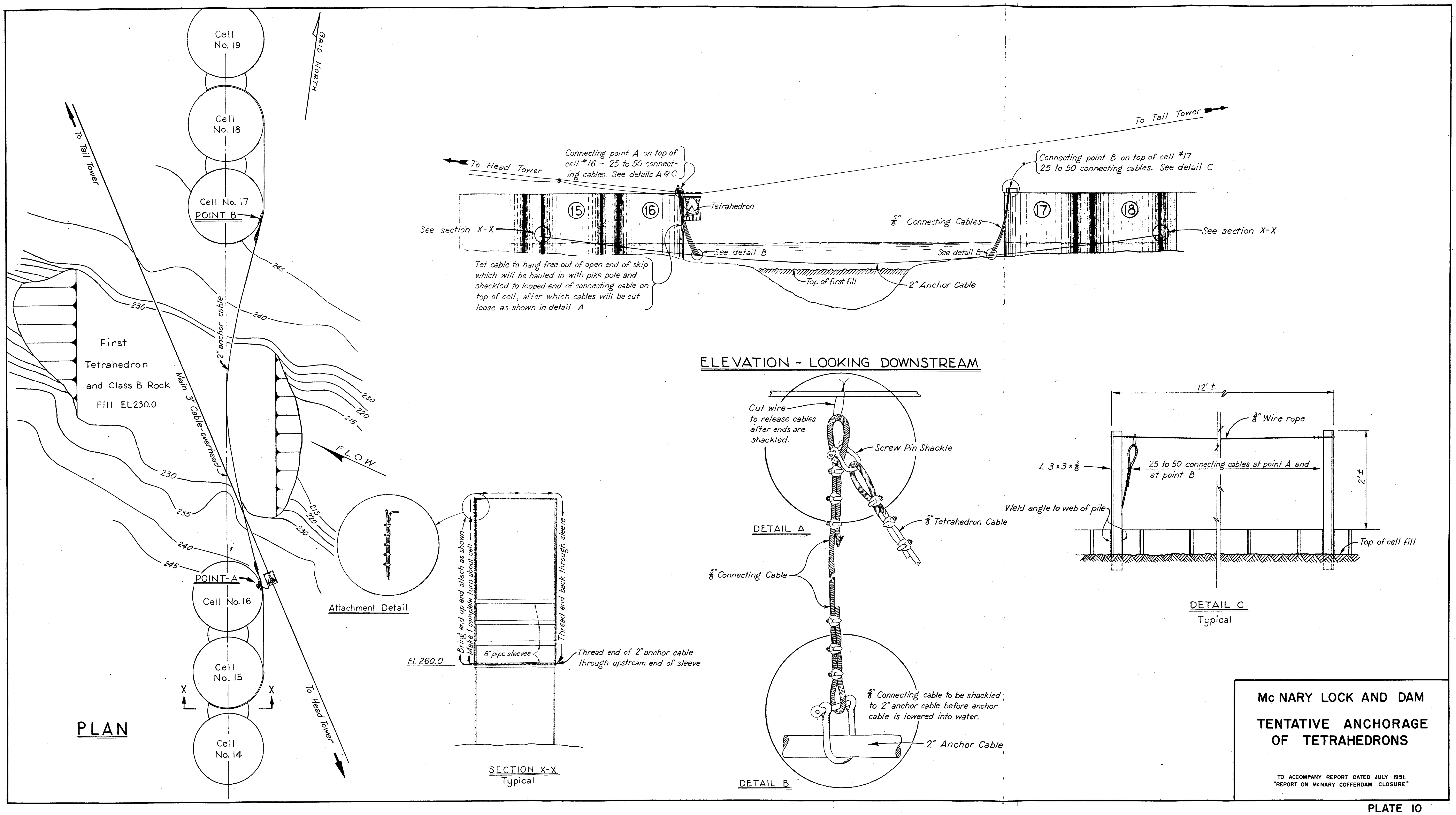
Mc NARY LOCK AND DAM

SECOND TETRAHEDRON FILL

SCALE IN FEET

20 0 20 40 60

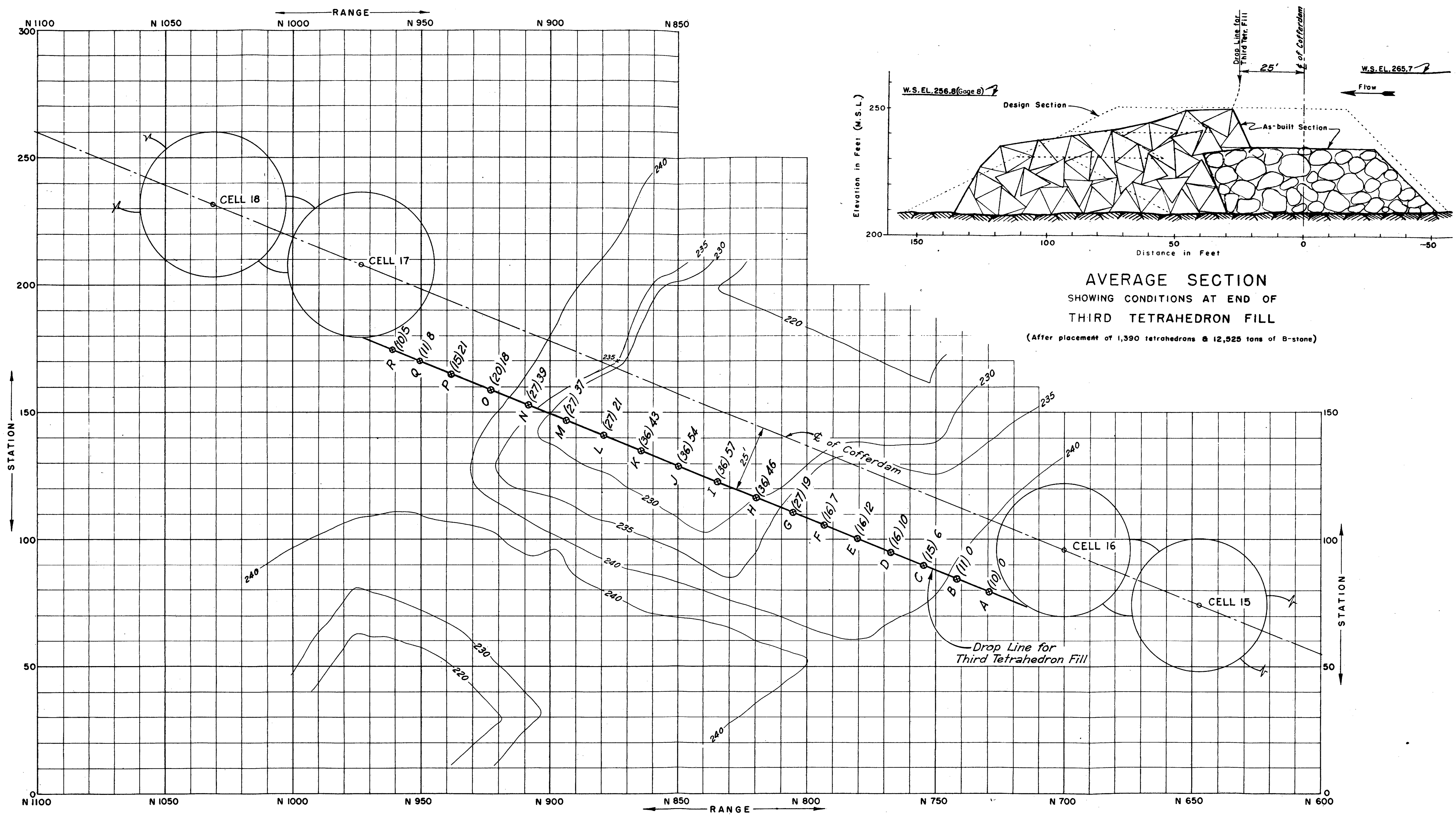
TO ACCOMPANY REPORT DATED JULY 1951 "REPORT ON McNARY COFFERDAM CLOSURE."



McNARY LOCK AND DAM

TENTATIVE ANCHORAGE OF TETRAHEDRONS

TO ACCOMPANY REPORT DATED JULY 1951: "REPORT ON McNARY COFFERDAM CLOSURE"



AVERAGE SECTION
SHOWING CONDITIONS AT END OF
THIRD TETRAHEDRON FILL
(After placement of 1,390 tetrahedrons & 12,525 tons of B-stone)

NOTES:
Figures in parentheses, e.g. (10), indicate the number of 12-ton tetrahedrons scheduled to be dropped at each particular point. The figures following, e.g. 5, indicate the number of tetrahedrons actually dropped.

Contours show approximate topography at beginning of Third Tetrahedron Fill.

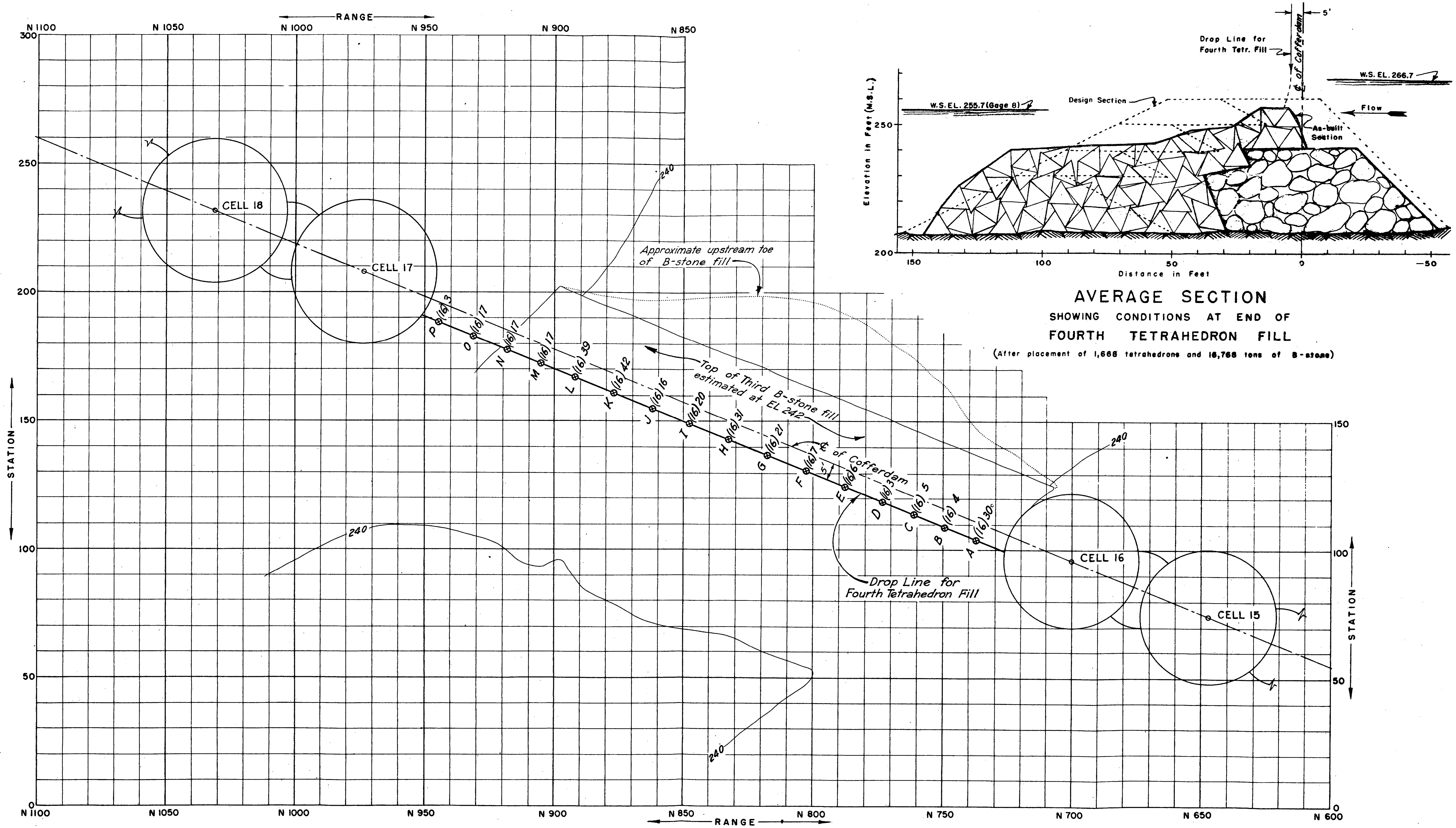
Mc NARY LOCK AND DAM

THIRD

TETRAHEDRON FILL

SCALE IN FEET
20 0 20 40 60

TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON McNARY COFFERDAM CLOSURE



AVERAGE SECTION

SHOWING CONDITIONS AT END OF

FOURTH TETRAHEDRON FILL

(After placement of 1,668 tetrahedrons and 16,768 tons of B-stone)

NOTES:

Figures in parentheses, e.g. (16), indicate the number of 12-ton tetrahedrons scheduled to be dropped at each particular point. The figures following, e.g. 3, indicate the number of tetrahedrons actually dropped.

The 240' contours are based on soundings made up to 5 November 1950, and prior to completion of the Second B-stone Fill and placement of the Third B-stone Fill.

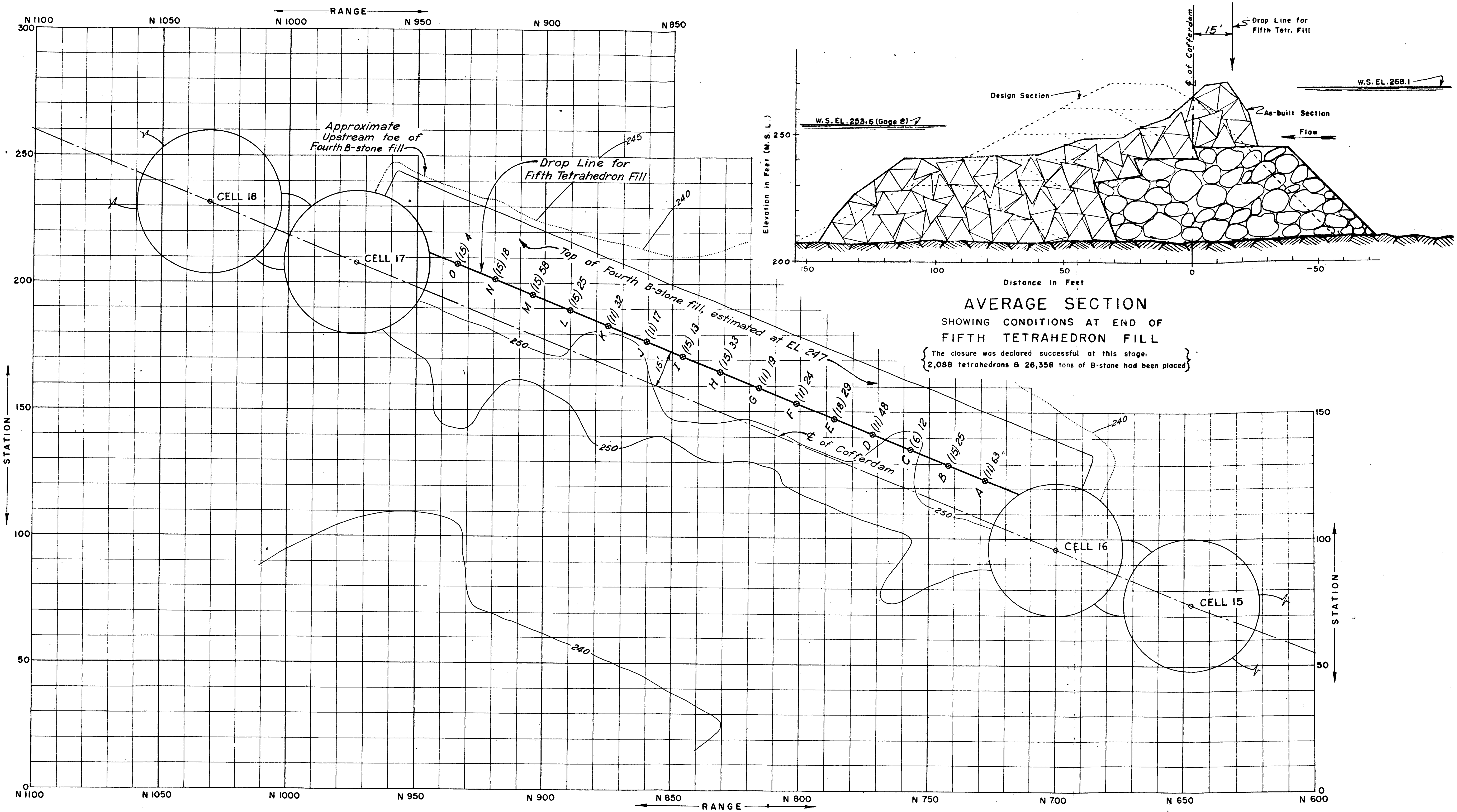
Mc NARY LOCK AND DAM

FOURTH TETRAHEDRON FILL

SCALE IN FEET

20 0 20 40 60

TO ACCOMPANY REPORT DATED JULY 1951 "REPORT ON McNARY COFFERDAM CLOSURE"



AVERAGE SECTION

SHOWING CONDITIONS AT END OF
FIFTH TETRAHEDRON FILL

{ The closure was declared successful at this stage: 2,088 tetrahedrons & 26,358 tons of B-stone had been placed }

NOTES:

1. Figures in parentheses, e.g. (18), indicate the number of 12-ton tetrahedrons scheduled to be dropped at each particular point. The figures following, e.g. 29, indicate the number of tetrahedrons actually dropped.
2. Drops were controlled visually and the range for each dropping point was varied as required.
3. Contours show approximate topography at the beginning of the Fifth Tetrahedron Fill.

Mc NARY LOCK AND DAM

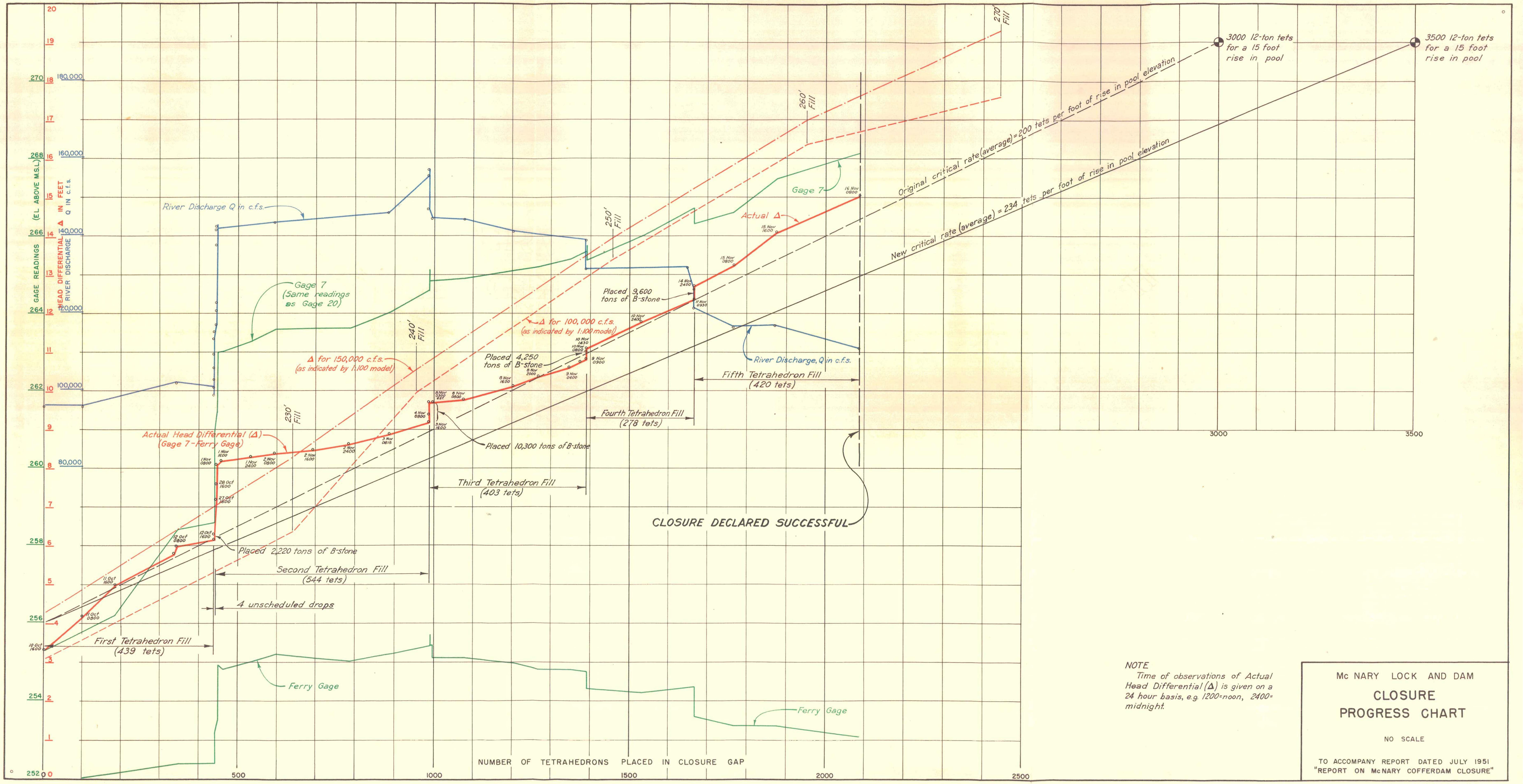
FIFTH

TETRAHEDRON FILL

SCALE IN FEET

20 0 20 40 60

TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON McNARY COFFERDAM CLOSURE"



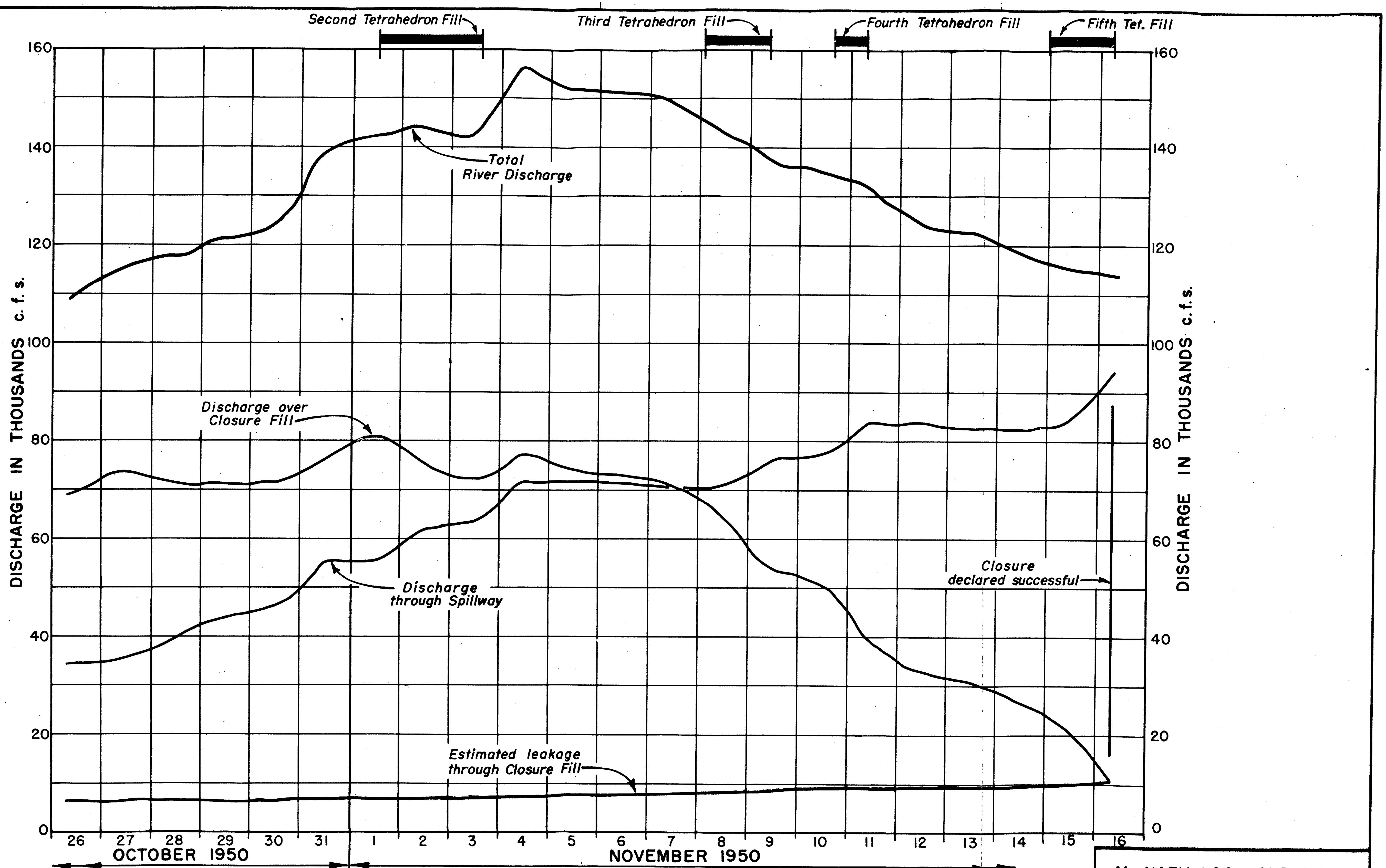
McNARY LOCK AND DAM

CLOSURE PROGRESS CHART

NO SCALE

TO ACCOMPANY REPORT DATED JULY 1951 "REPORT ON McNARY COFFERDAM CLOSURE"

PLATE 14



Original Chart prepared by
Mr. F. B. Campbell, Hydraulic Eng'r.
Omaha Office, Corps of Engineers

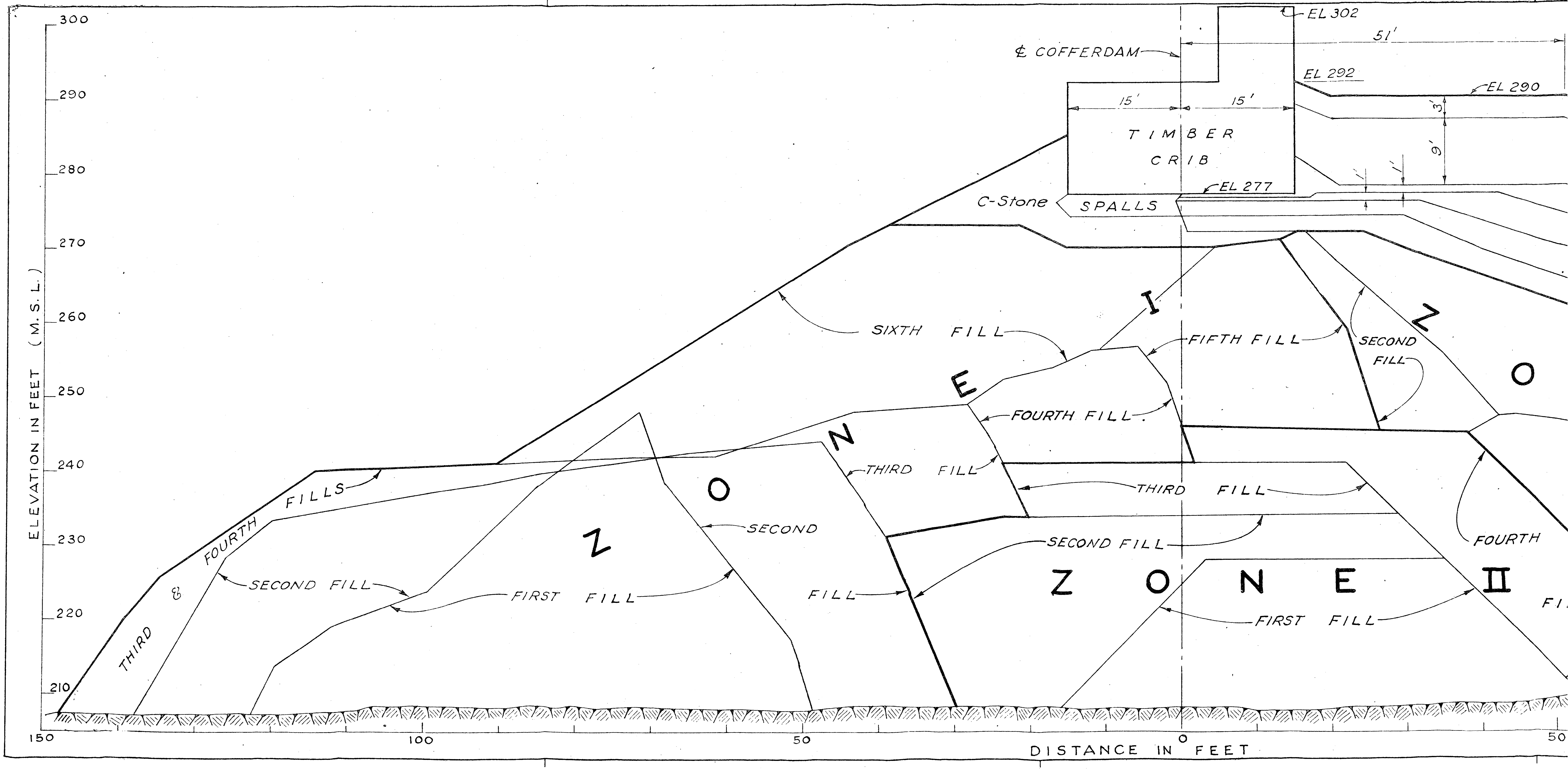
Mc NARY LOCK AND DAM

ACTUAL
FLOW DISTRIBUTION

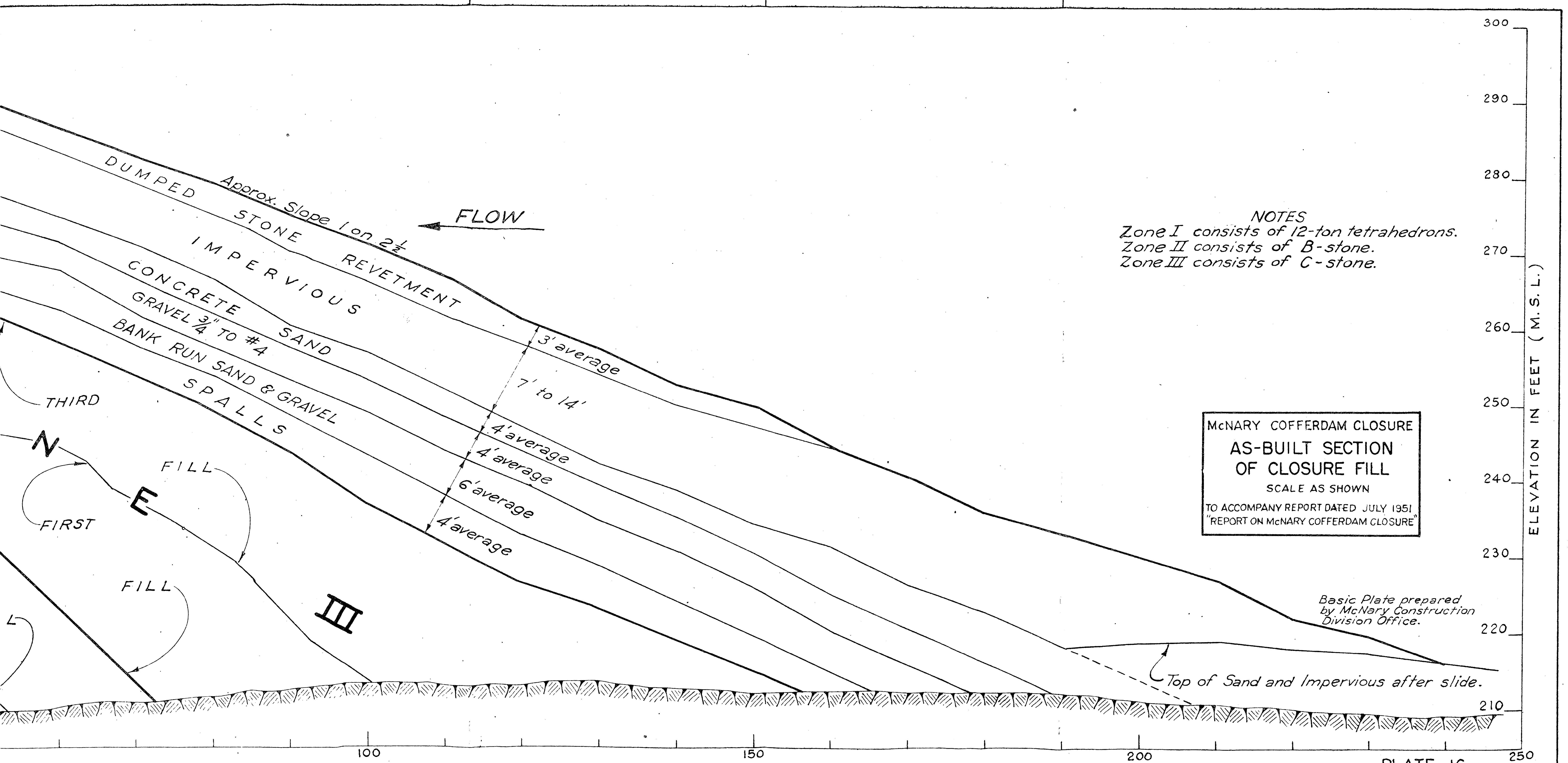
NO SCALE

TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON McNARY COFFERDAM CLOSURE"

PLATE 15

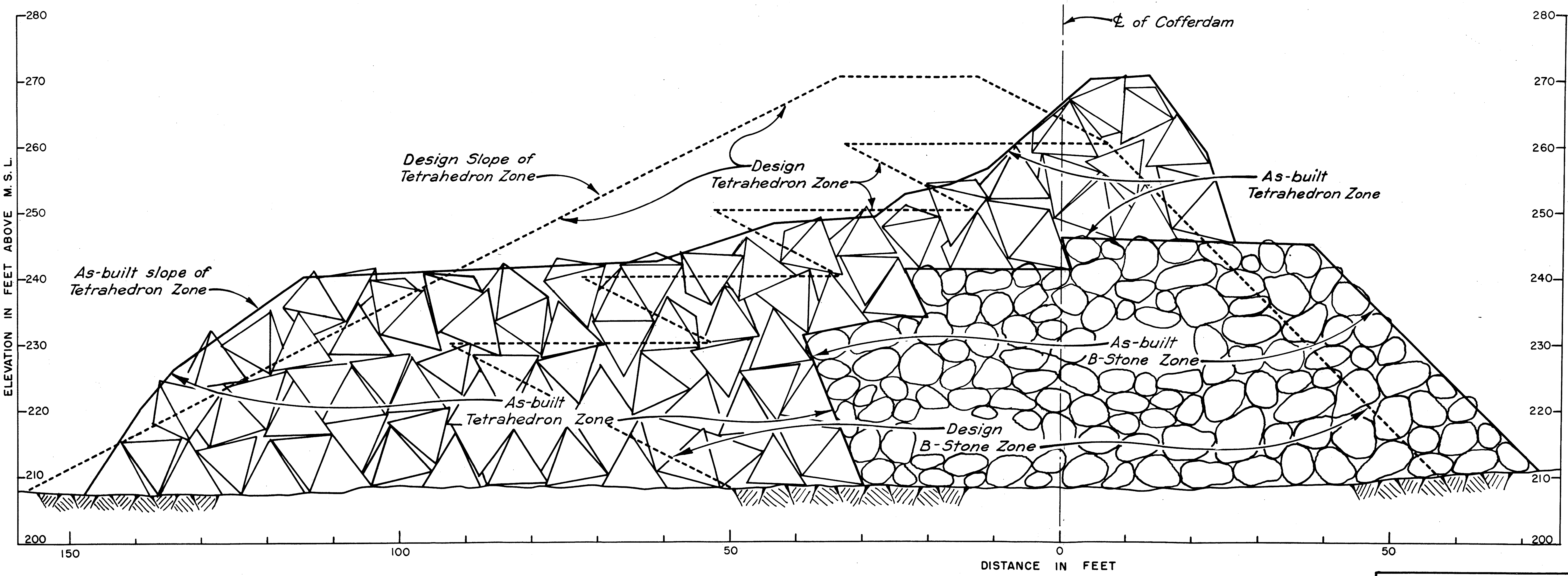


EL 302
51'
℄ COFFERDAM
EL 292
EL 290
15'
15'
TIMBER CRIB
3'
9'
1'
1'
EL 277
C-Stone
SPALLS
ZONE I
ZONE II
ZONE II
SIXTH FILL
FIFTH FILL
SECOND FILL
FOURTH FILL
THIRD FILL
THIRD FILL
THIRD & FOURTH FILLS
SECOND FILL
FIRST FILL
SECOND FILL
SECOND FILL
FIRST FILL
FOURTH
ELEVATION IN FEET (M. S. L.)
300
290
280
270
260
250
240
230
220
210
150
100
50
0
50
DISTANCE IN FEET



NOTES
Zone I consists of 12-ton tetrahedrons.
Zone II consists of B-stone.
Zone III consists of C-stone.
McNARY COFFERDAM CLOSURE
AS-BUILT SECTION
OF CLOSURE FILL
SCALE AS SHOWN
TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON McNARY COFFERDAM CLOSURE"
FLOW
Approx. Slope 1 on 2½
DUMPED STONE REVETMENT
IMPERVIOUS
CONCRETE SAND
GRAVEL ¾" TO #4
BANK RUN SAND & GRAVEL
SPALLS
3' average
7' to 14'
4' average
4' average
6' average
4' average
THIRD
FIRST
FILL
FILL
N
E
III
Top of Sand and Impervious after slide.
Basic Plate prepared by McNary Construction Division Office.
ELEVATION IN FEET (M.S.L.)
300
290
280
270
260
250
240
230
220
210
100
150
200
250

PLATE 16



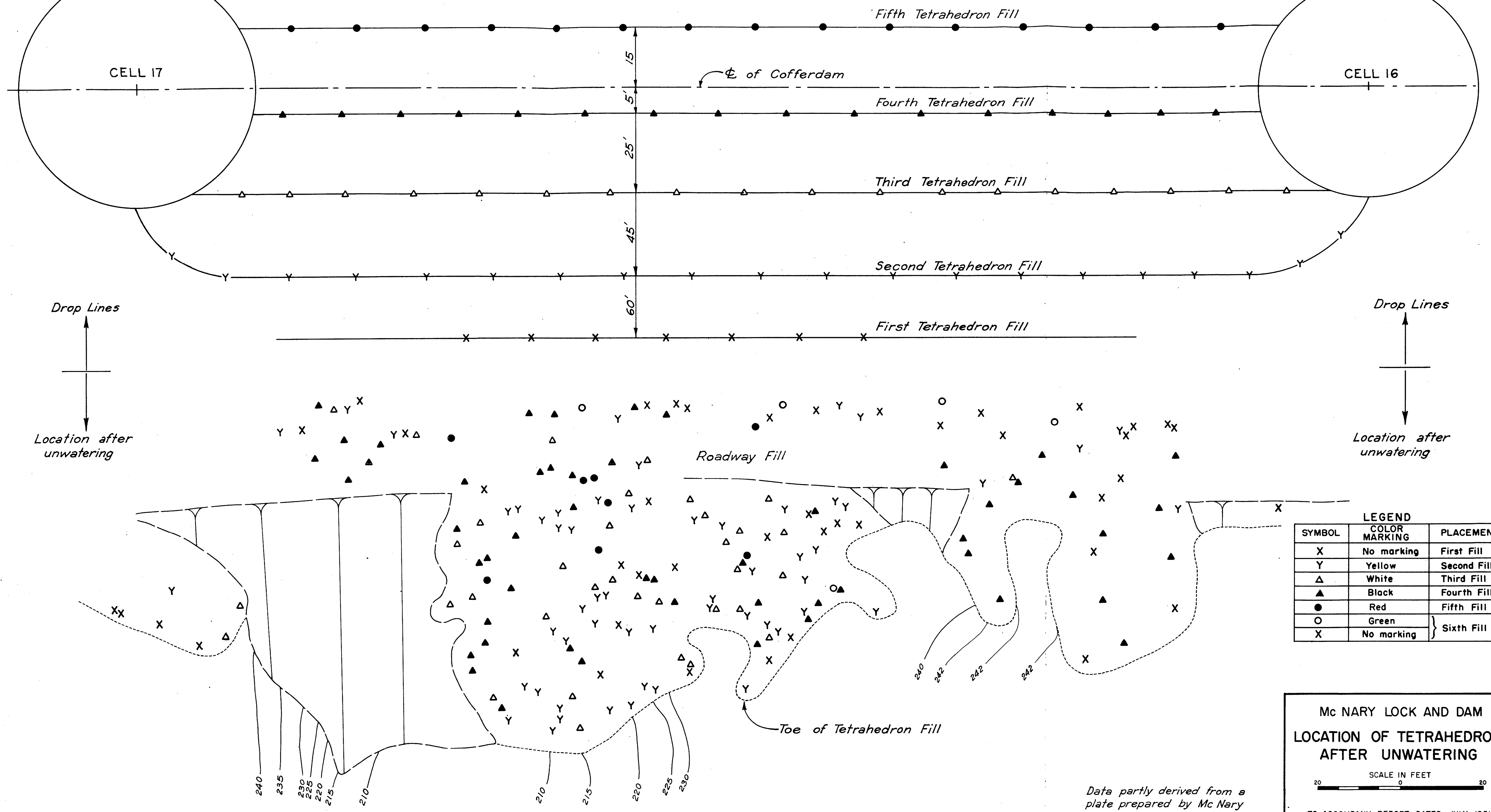
NOTE:
The Sixth Tetrahedron Fill was placed in the dry after closure and is not shown. (See Plate 16)

Mc NARY LOCK AND DAM

COMPARISON OF DESIGN AND AS-BUILT SECTIONS

SCALE AS SHOWN

TO ACCOMPANY REPORT DATED JULY 1951 "REPORT ON Mc NARY COFFERDAM CLOSURE"



LEGEND

SYMBOL	COLOR MARKING	PLACEMENT
X	No marking	First Fill
Y	Yellow	Second Fill
△	White	Third Fill
▲	Black	Fourth Fill
●	Red	Fifth Fill
○	Green	Sixth Fill
X	No marking	Sixth Fill

Data partly derived from a plate prepared by Mc Nary Construction Division Office.

Mc NARY LOCK AND DAM

LOCATION OF TETRAHEDRONS AFTER UNWATERING

SCALE IN FEET
20 0 20

TO ACCOMPANY REPORT DATED JULY 1951
"REPORT ON Mc NARY COFFERDAM CLOSURE"

PHOTOGRAPHS

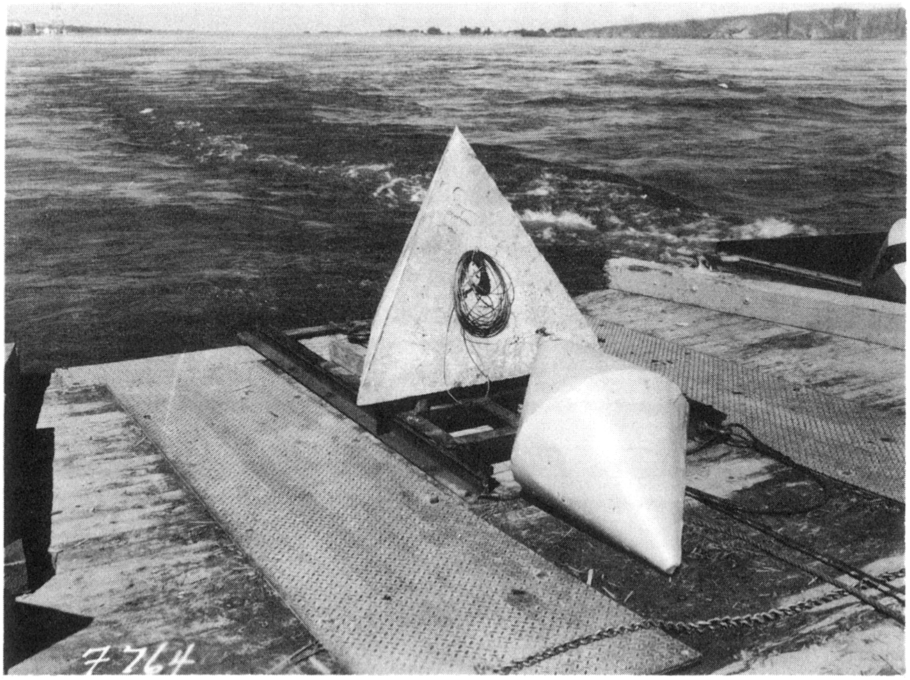


Fig. 1 - Tetrahedron Studies on Columbia River at McNary
Shows 1000-lb. tetr. on launching platform 12 June 1949

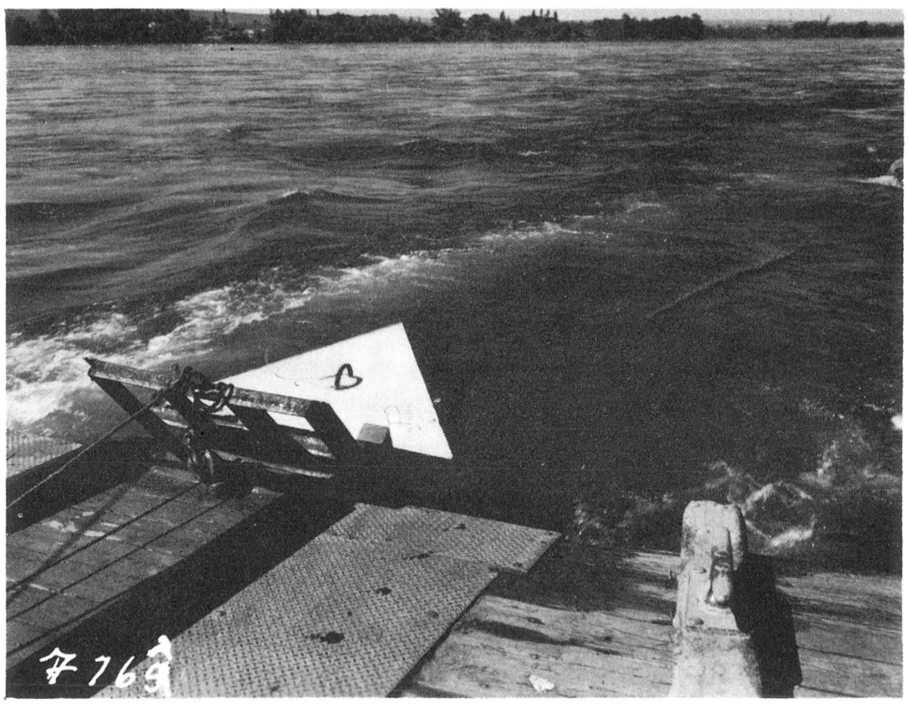


Fig. 2 - Tetrahedron Studies on Columbia River at McNary
Shows tetrahedron being launched 12 June 1949

Fig. 3 - Seattle Model Experiments
General View, looking upstream

31 Aug. 1950

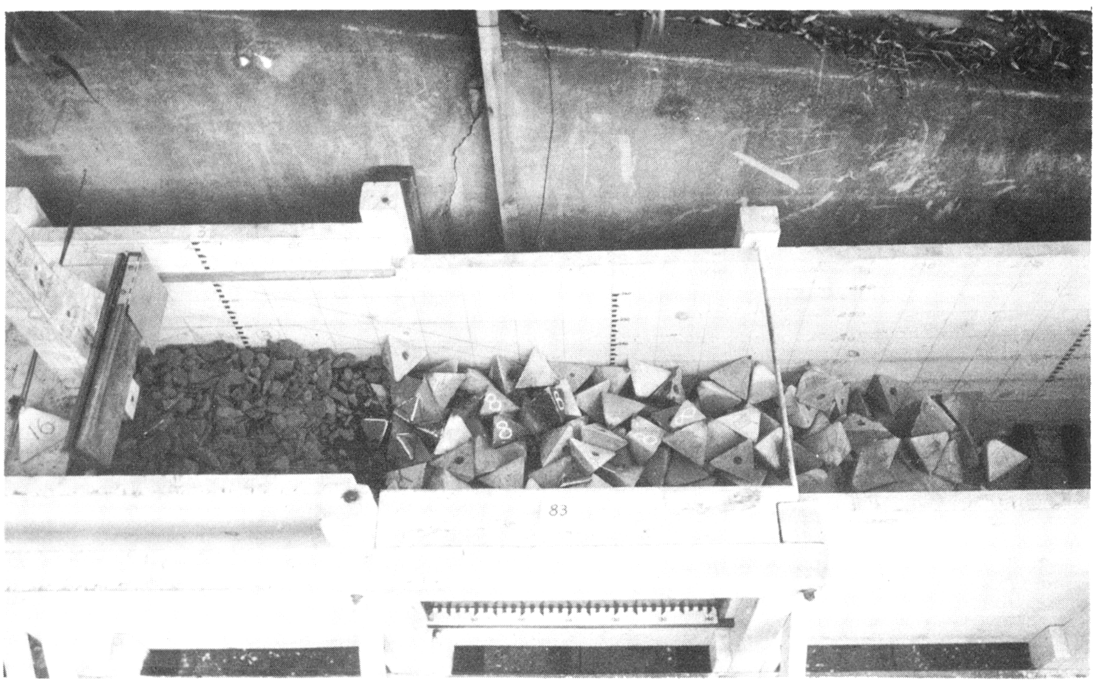


Fig. 4 - Seattle Model Experiments
Top View of Fill, Crest El. 240±

1 Sept. 1950

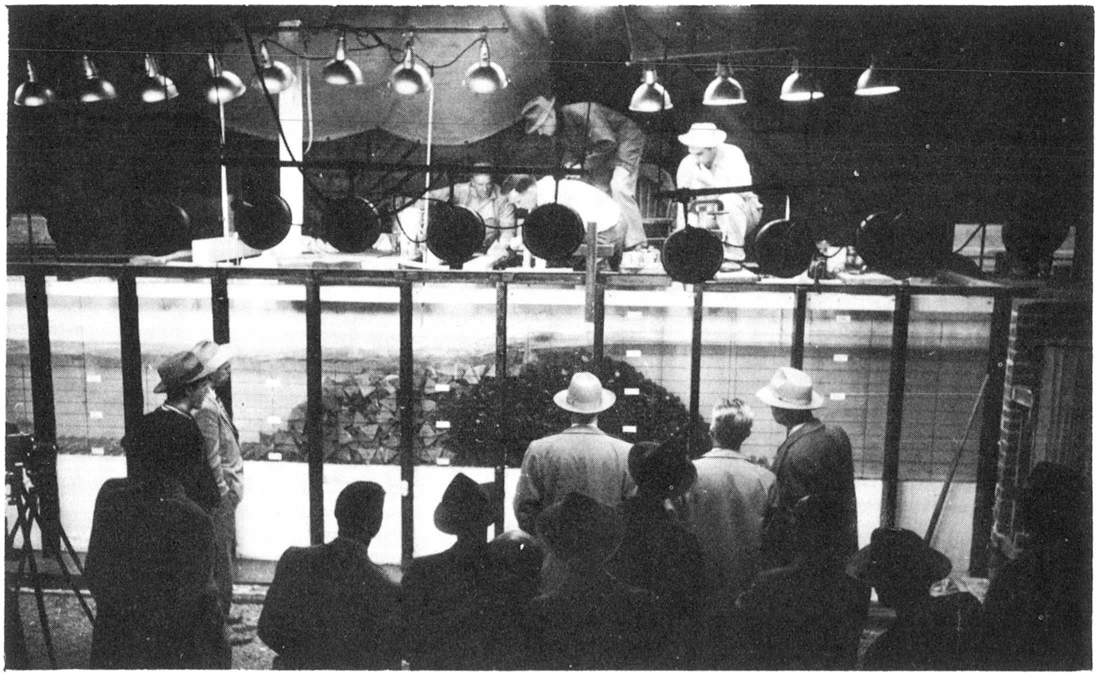


Fig. 5 - Bonneville Sectional Model (26" width)
General View of Apparatus 5 Oct. 1950

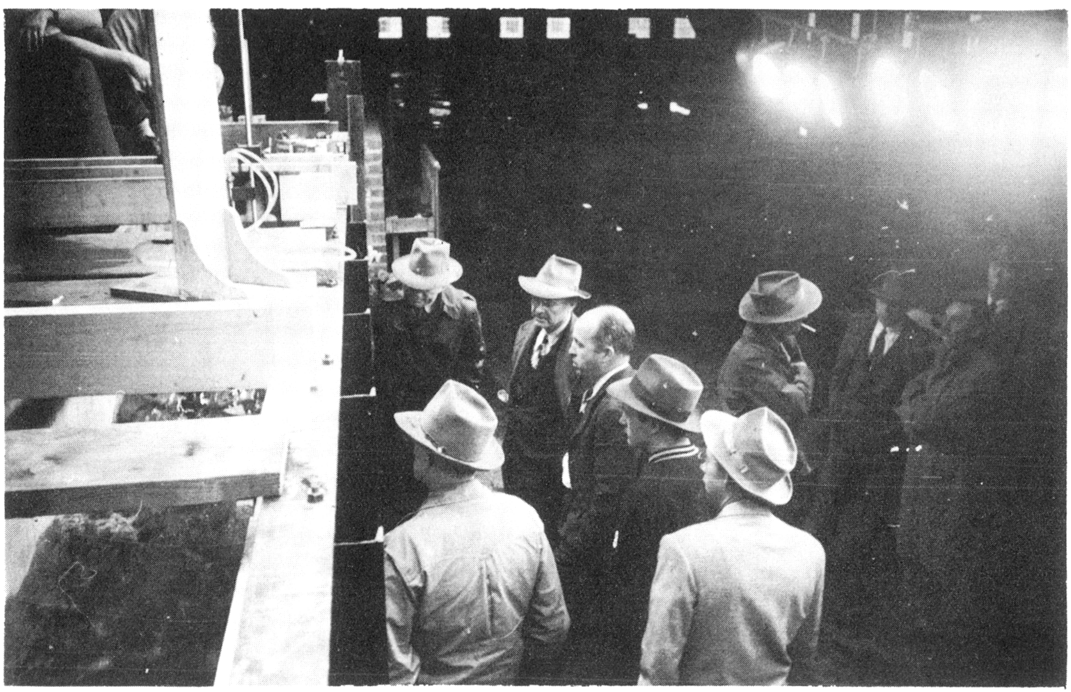


Fig. 6 - Bonneville Sectional Model (26" width)
Discussion of observations 5 Oct. 1950

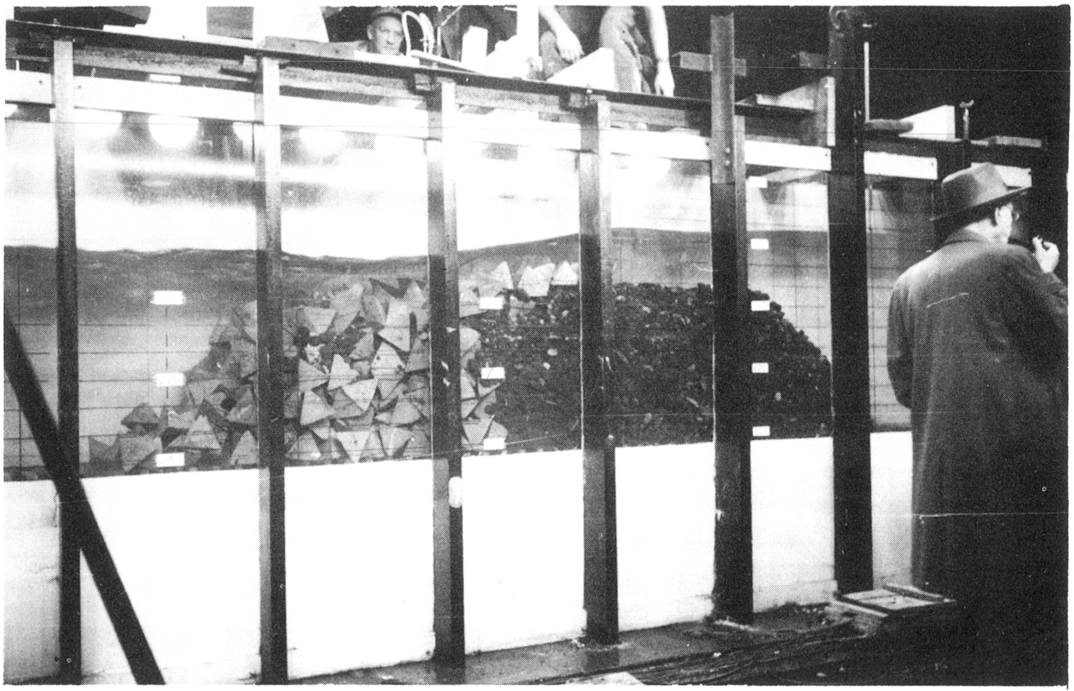


Fig. 7 - Bonneville Sectional Model (26" width)
Raising fill by experimental procedure 5 Oct. 1950

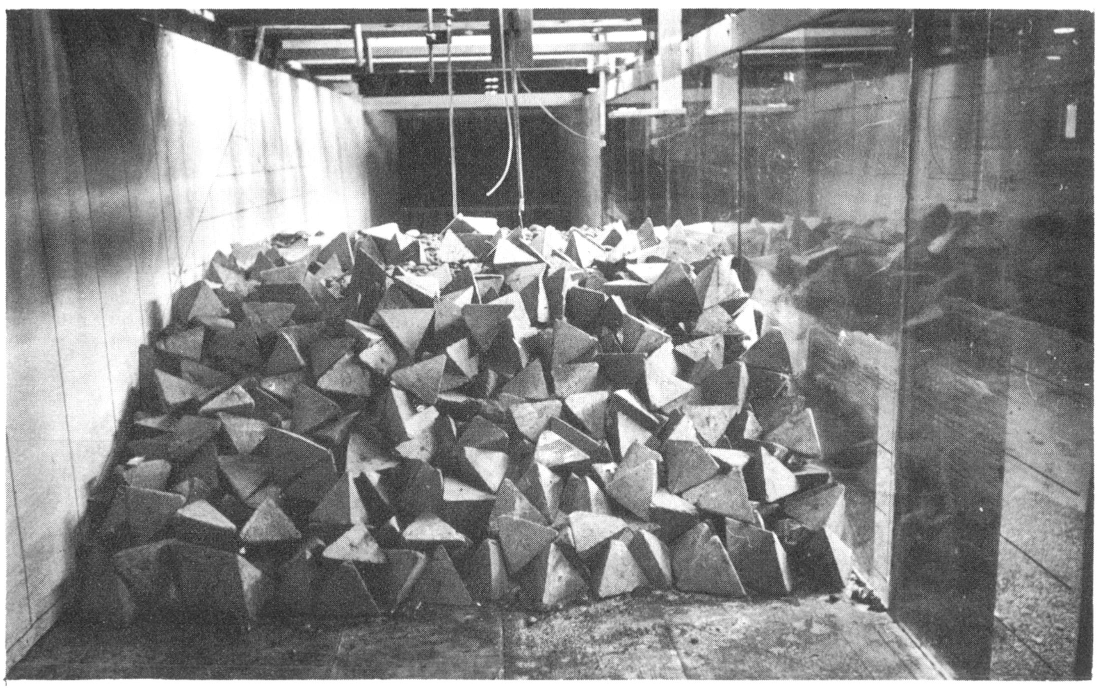


Fig. 8 - Bonneville Sectional Model (60" width)
Unwatered tetrahedron fill, looking upstream 10 Oct. 1950

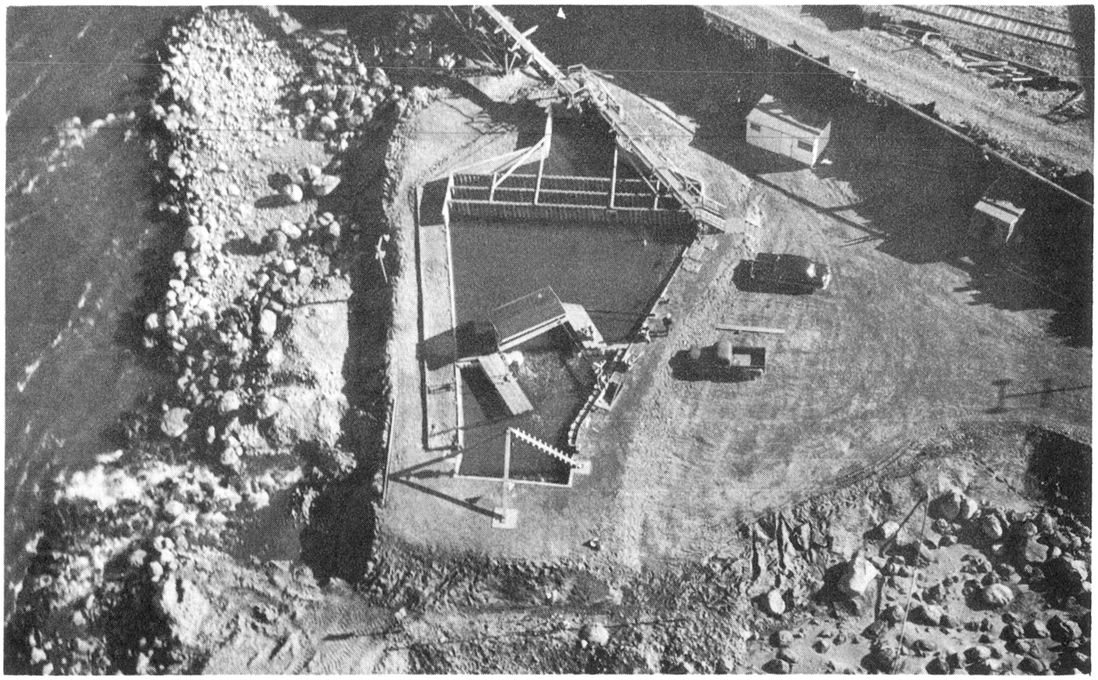


Fig. 9 - Construction Model at McNary
Aerial view   9 Nov. 1950

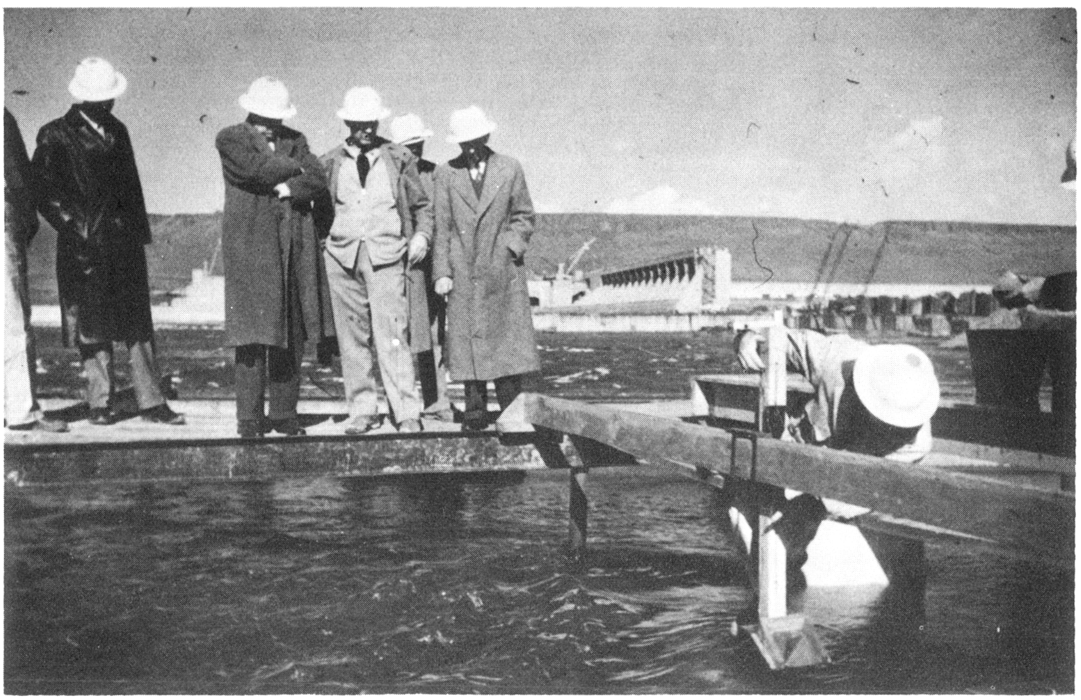


Fig. 10 - Construction Model at McNary - Operation in
presence of Officers and Civilian Engineers   30 Oct. 1950

Fig. 11 - View from top of cableway head tower
Shows tetrahedron casting yard 25 July 1950

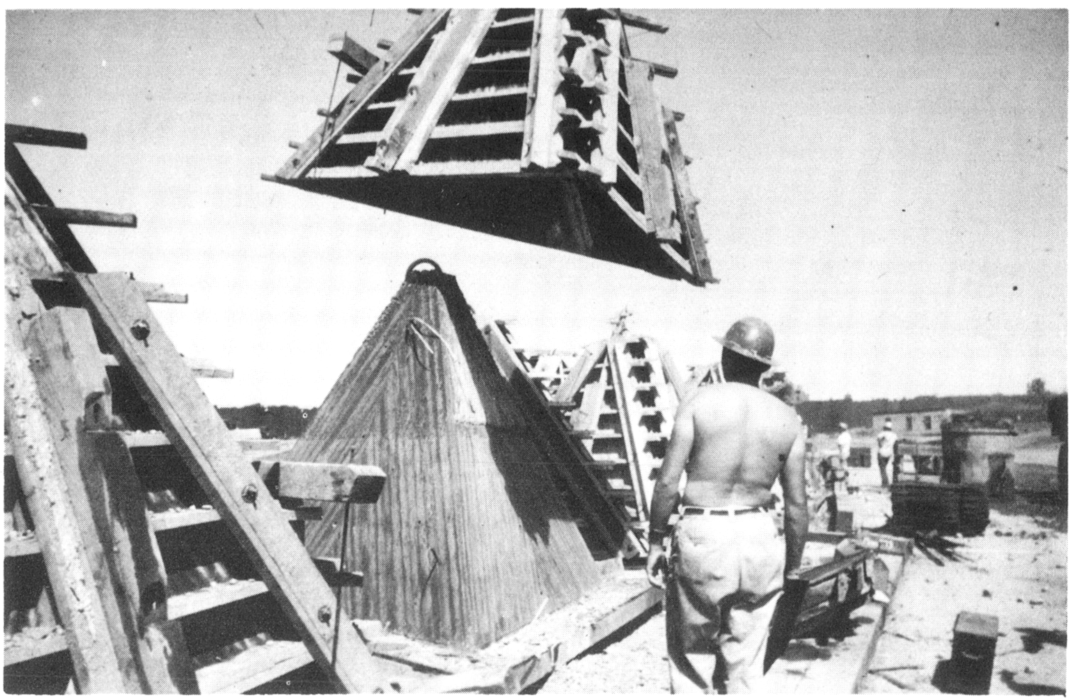


Fig. 12 - Tetrahedron Casting Yard
Removal of a wooden form 25 July 1950

Fig. 13 - General Aerial View. Shows tetrahedron casting, storage yard, cableway and closure gap 9 Nov. 1950

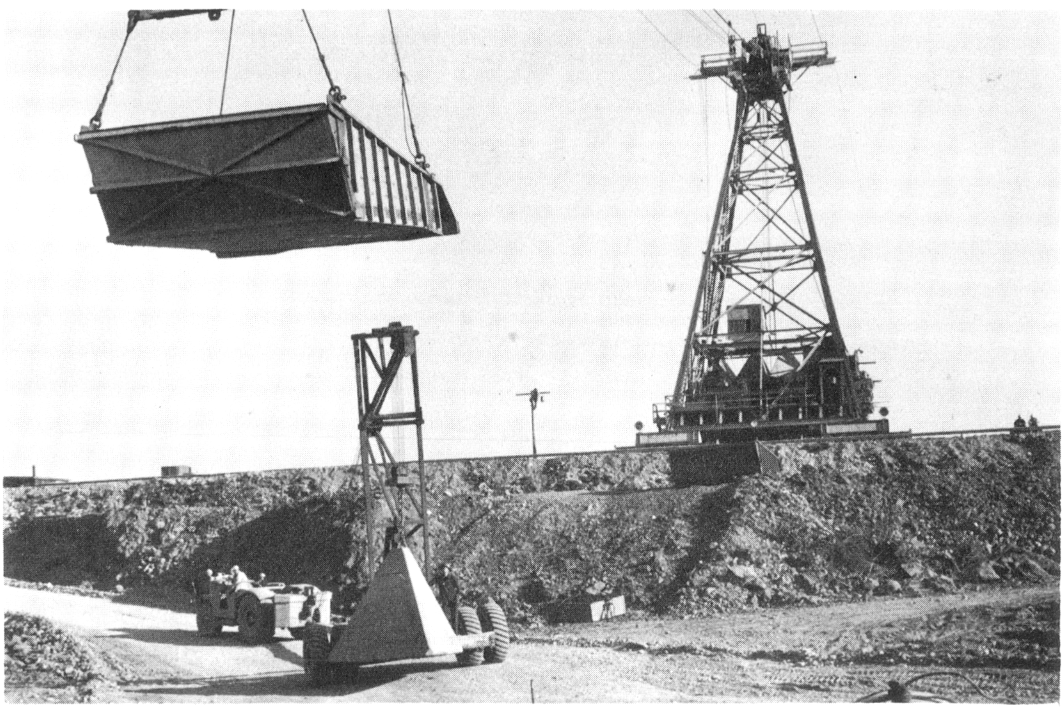


Fig. 14 - Tetrahedron Handling. Tournacrane with tetrahedron waits as skip is lowered by cableway 11 Oct. 1950

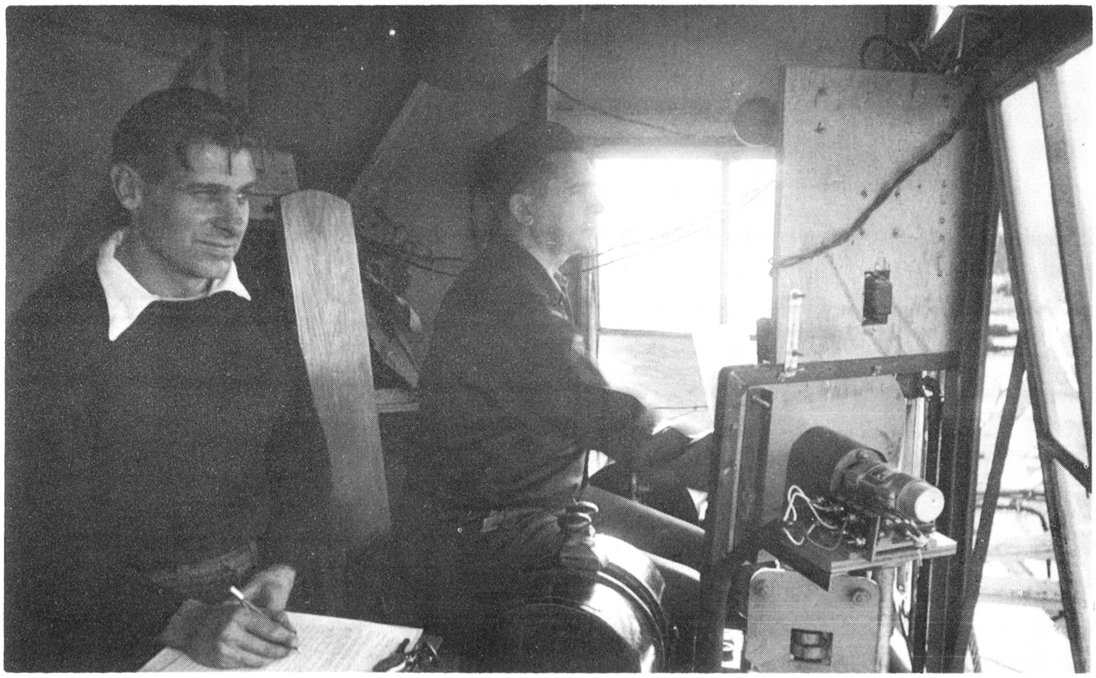


Fig. 15 - Interior of Cableway Control Booth
Cableway operator at right; inspector at left 8 Nov. 1950

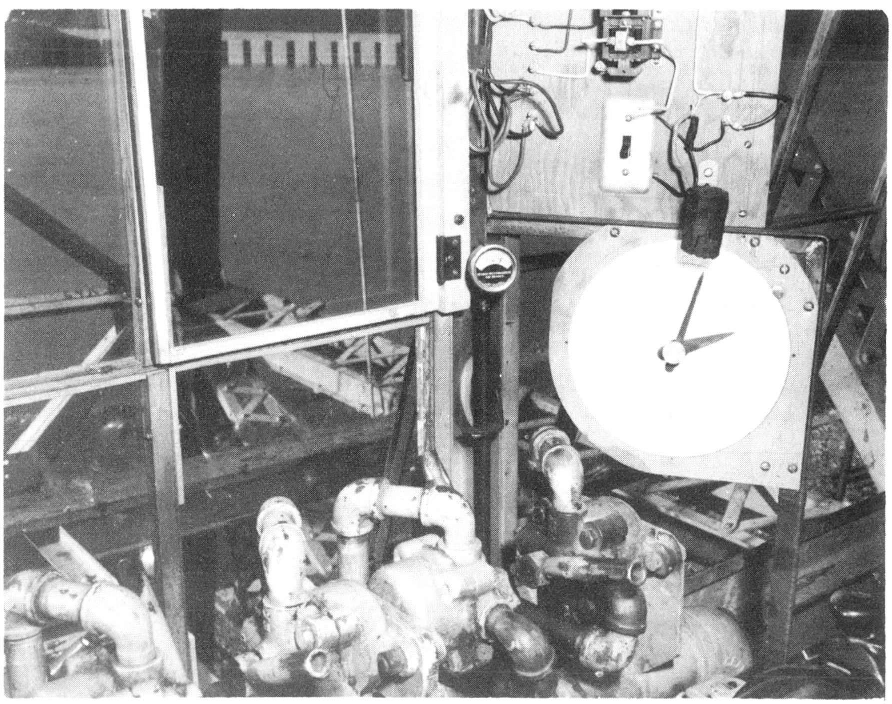


Fig. 16 - Interior of Cableway Control Booth
Details of skip-travel indicator Oct. 1950

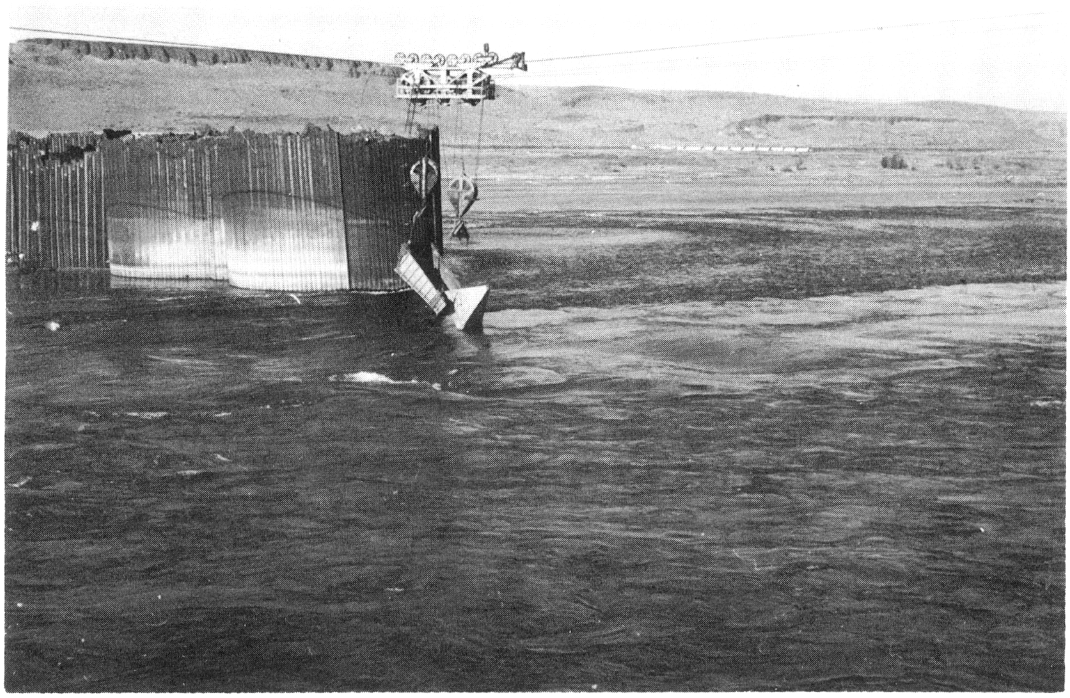


Fig. 17 - First Tetrahedron Fill
12-ton Tetrahedron sliding into water 11 Oct. 1950

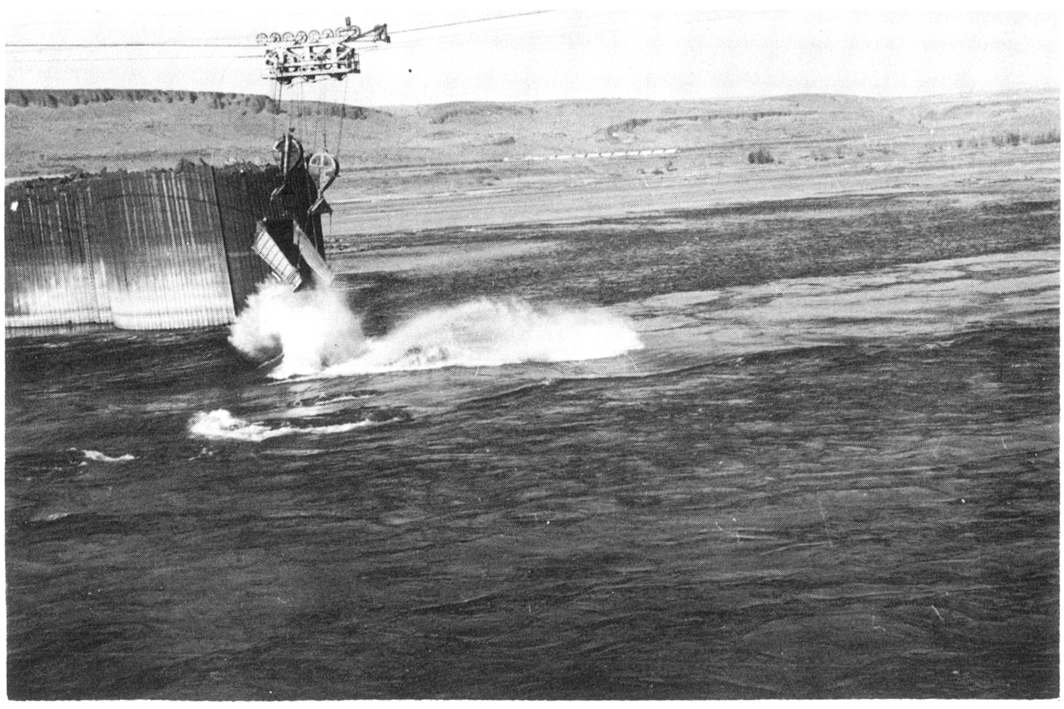


Fig. 18 - First Tetrahedron Fill
Cableway rebound and splash 11 Oct. 1950

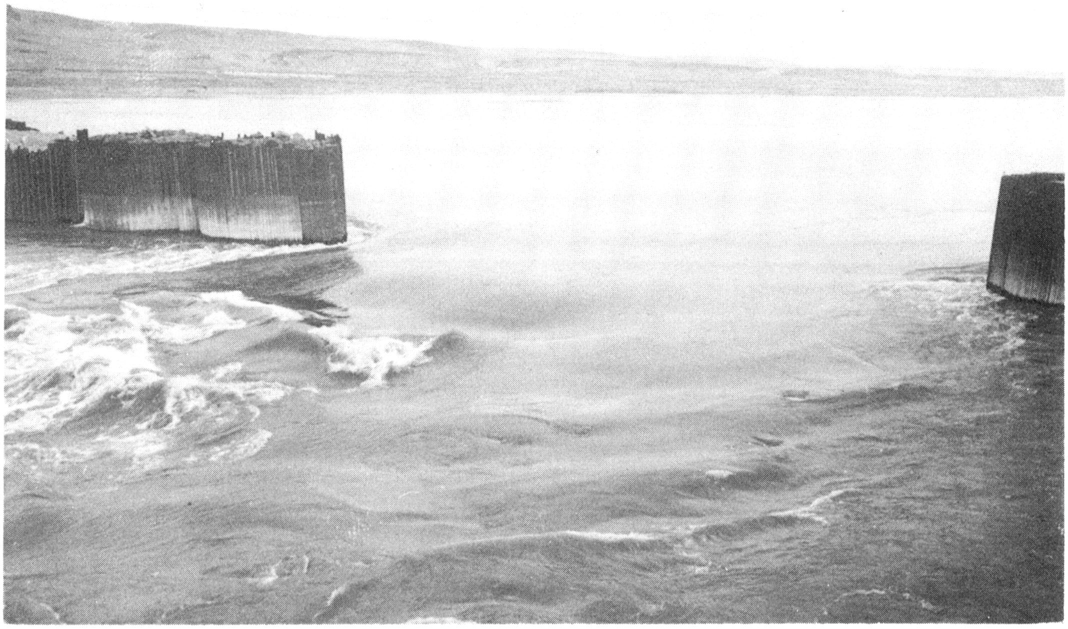


Fig. 19 - First Tetrahedron Fill
View of Water Surface after completion 31 Oct. 1950

Fig. 20 - First Tetrahedron Fill
Detail of wave action 15 Oct. 1950

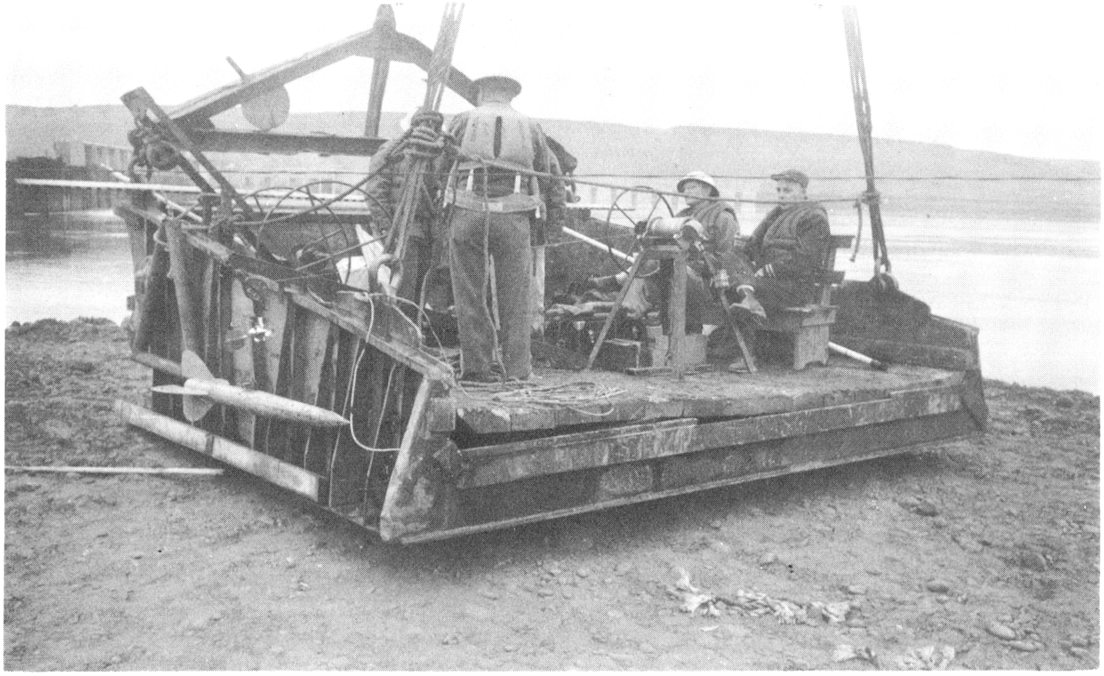


Fig. 21 - Skip converted for sounding work
Shows equipment used 12 Nov. 1950

Fig. 22 - Sounding party at work after completion
of First Tetrahedron Fill 15 Oct. 1950

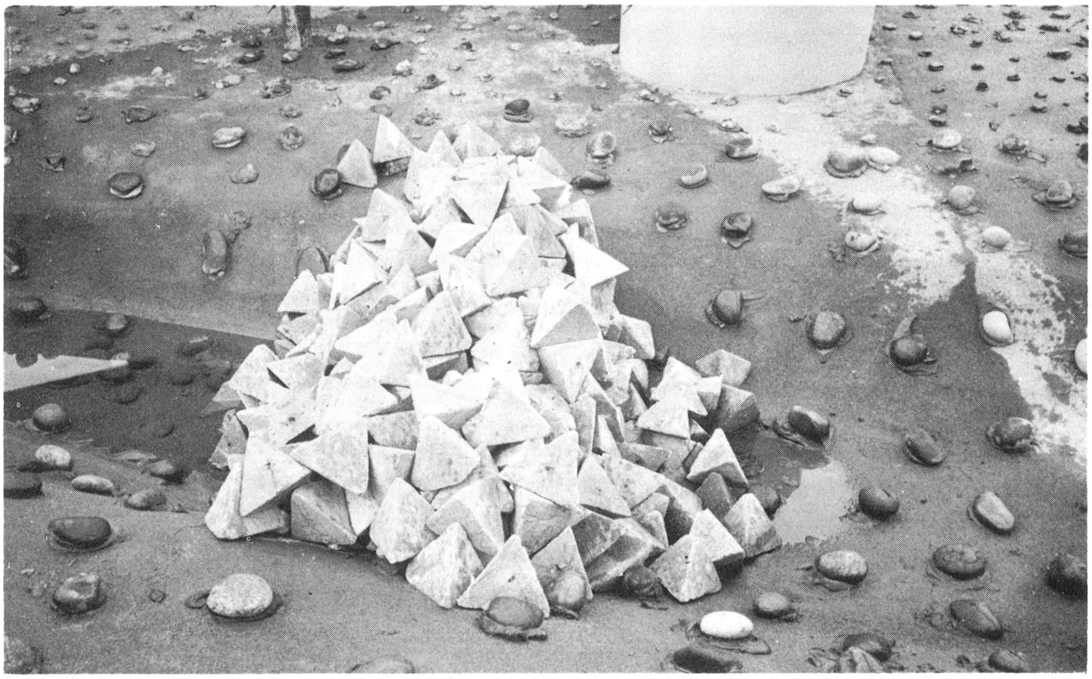


Fig. 23 - First Tetrahedron Fill in Construction Model
View after unwatering 28 Oct. 1950

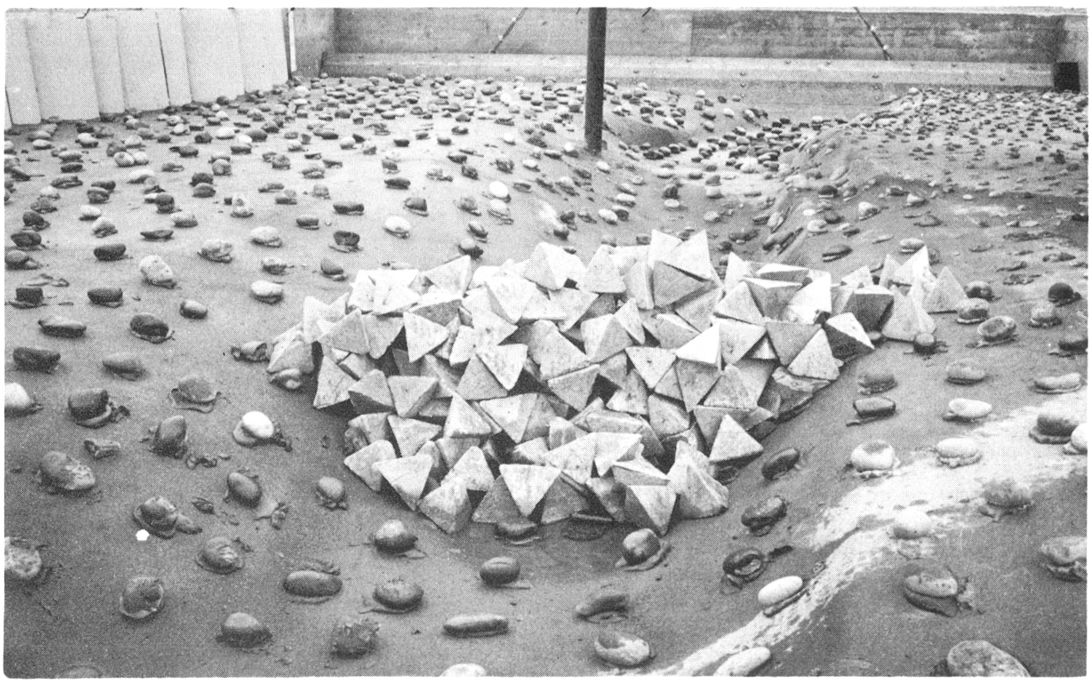


Fig. 24 - Similar to Fig. 21 above
Shows rise in river bed downstream 28 Oct. 1950

Fig. 25 - Typical Samples of B-stone
assembled at the platform scales 28 Feb. 51

Fig. 26 - Construction Model - Third Experiment
Typical "slick" formation. 4 Nov. 1950

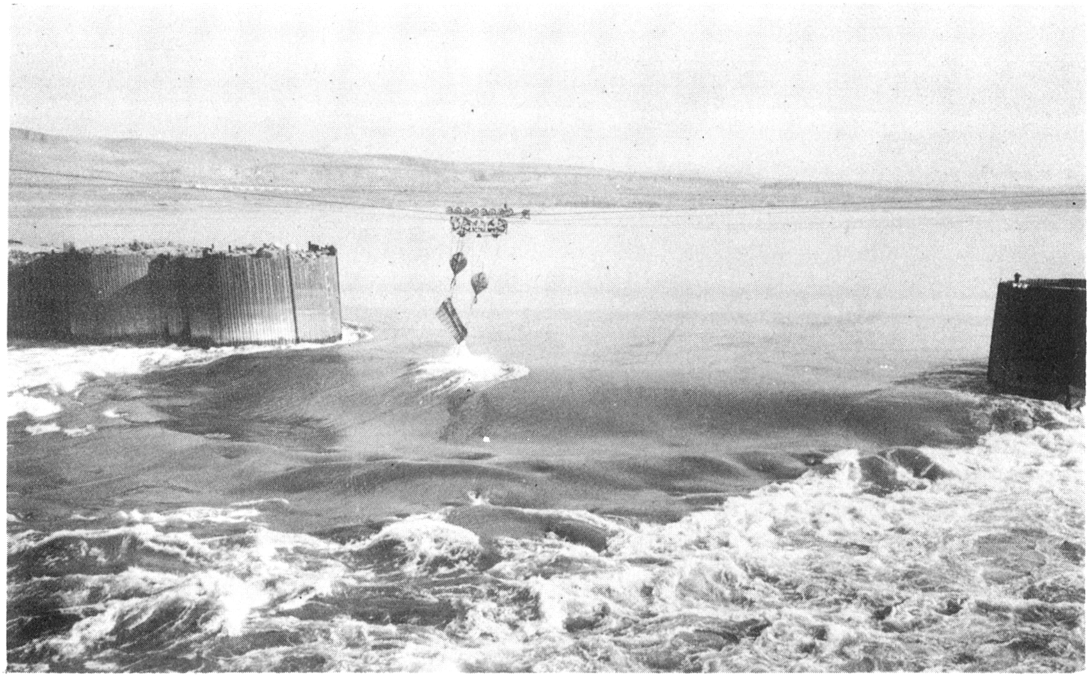


Fig. 27 - Second Tetrahedron Fill nearing completion
View of Water Surface 3 Nov. 1950

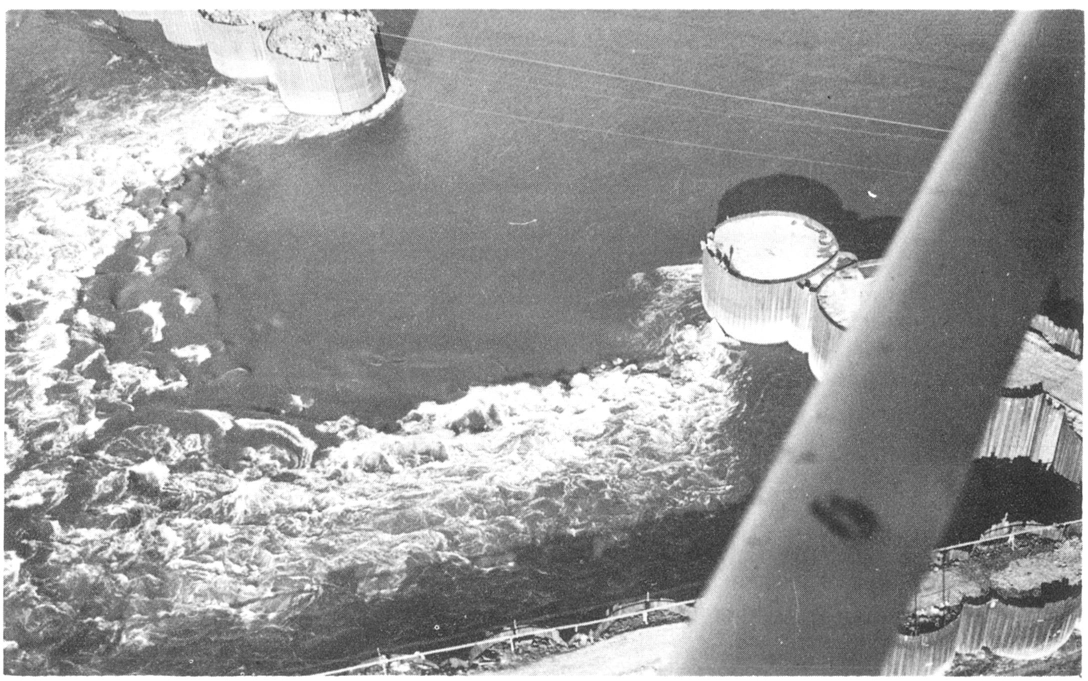


Fig. 28 - Second Tetrahedron Fill nearing completion
Aerial view of Water Surface 3 Nov. 1950

Fig. 29 - Construction Model - Fourth Experiment
Water Surface with 1722 tetrahedrons 2 Nov. 1950

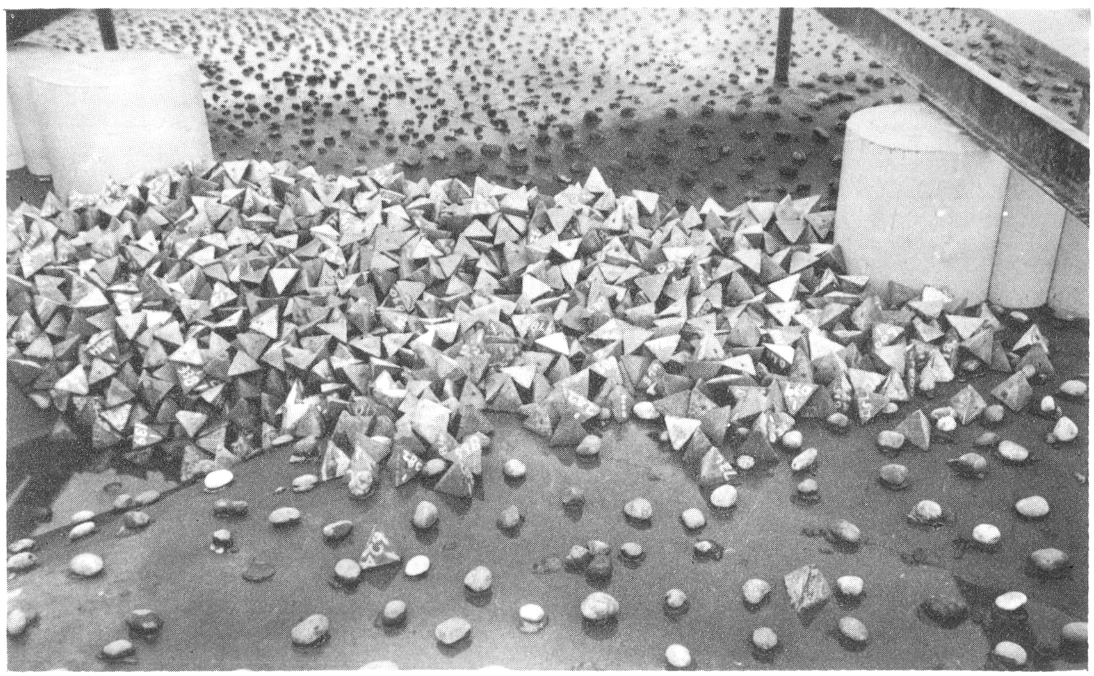


Fig. 30 - Construction Model - Fourth Experiment
View of Fill with 1846 tetrahedrons 2 Nov. 1950

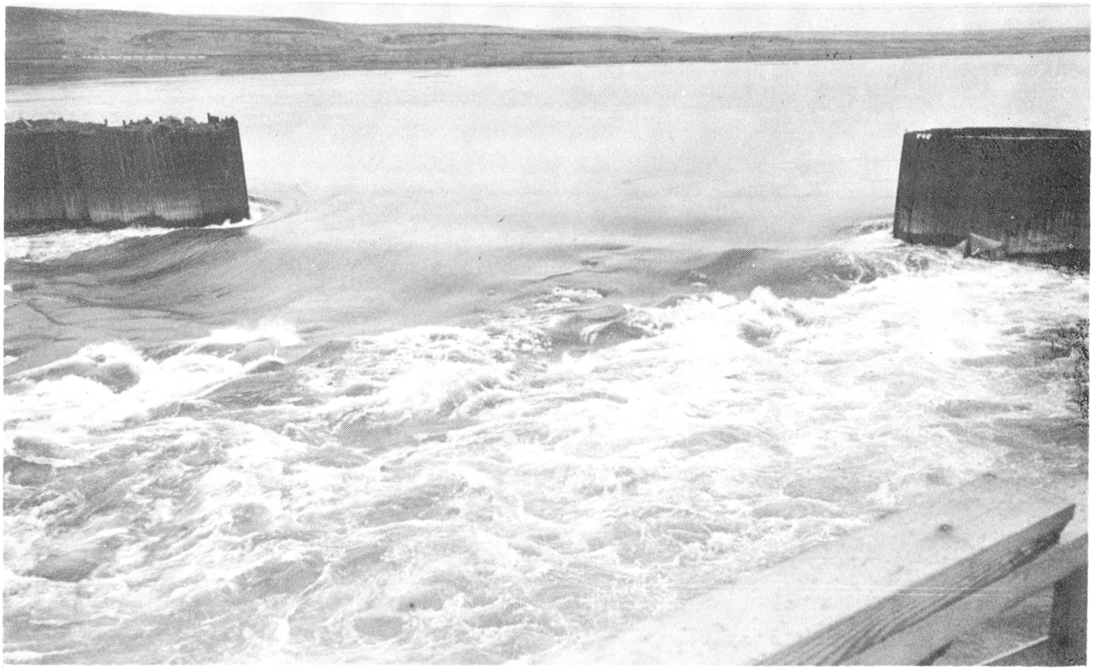


Fig. 31 - Second Tetrahedron Fill. Upstream drawdown caused by placement of B-stone (Compare with Fig. 27) 7 Nov. 1950

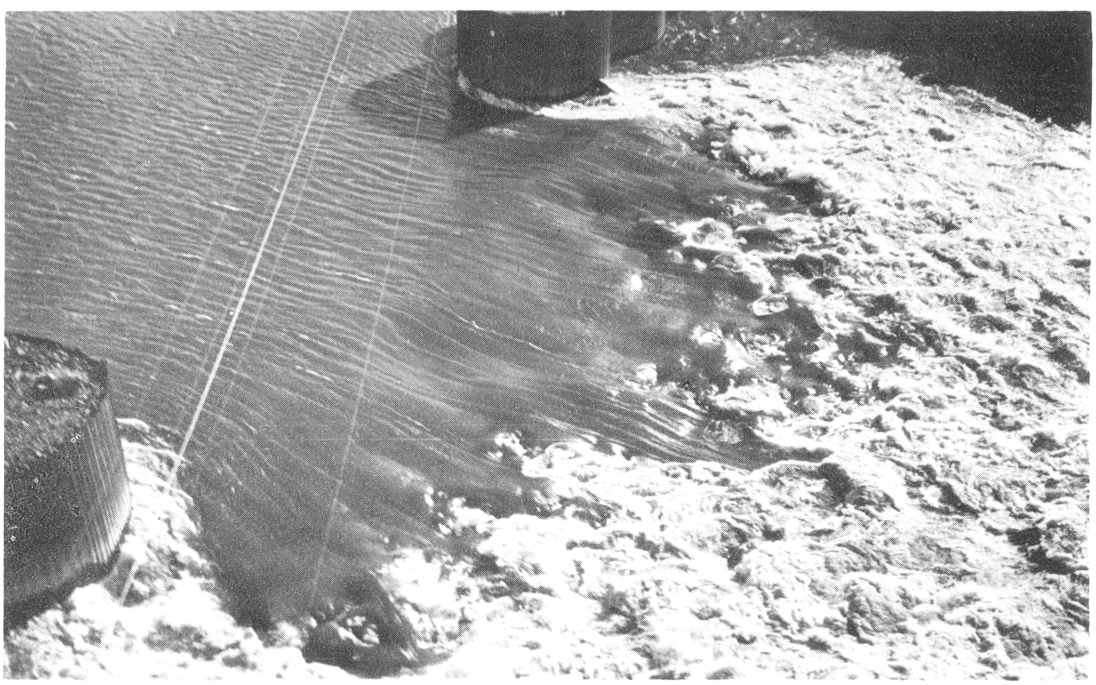


Fig. 32 - Third Tetrahedron Fill
Aerial View of Water Surface upon completion 9 Nov. 1950

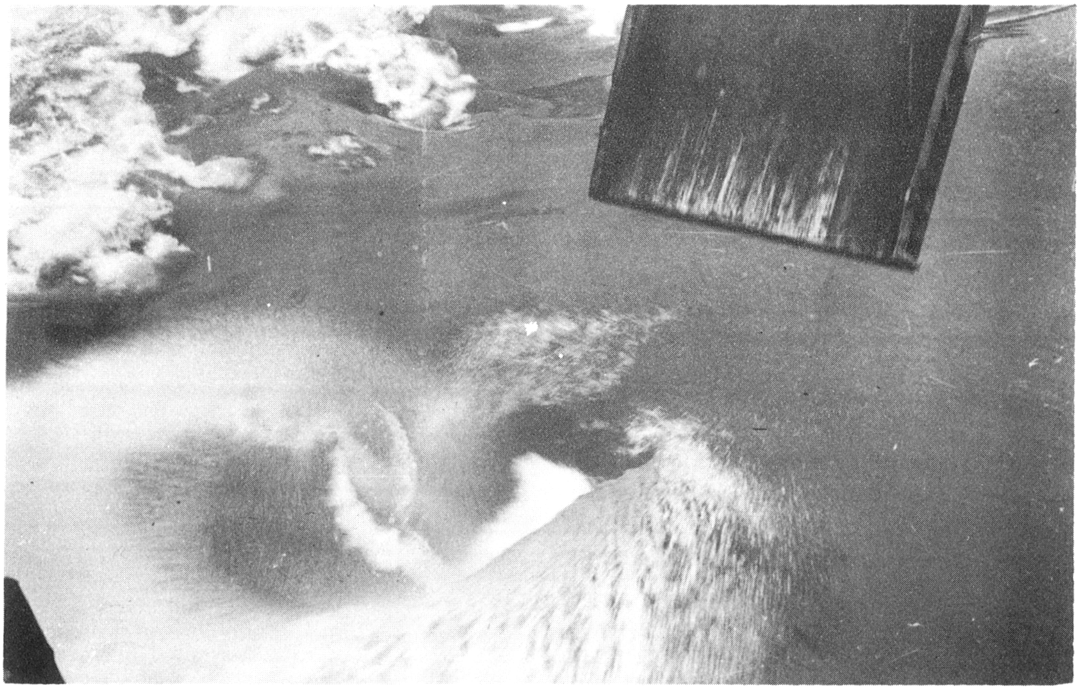


Fig. 33 - Fourth Tetrahedron Fill
Close-up of typical water-entry cavity 11 Nov. 1950

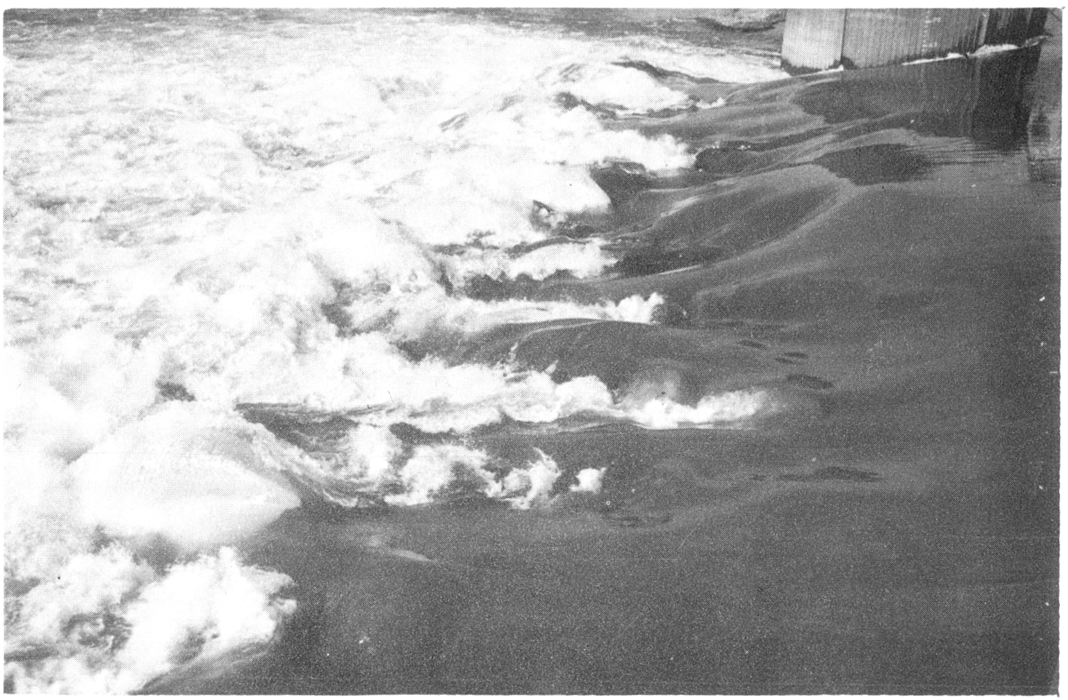


Fig. 34 - Fourth Tetrahedron Fill
Breaking up of overflowing sheet 13 Nov. 1950

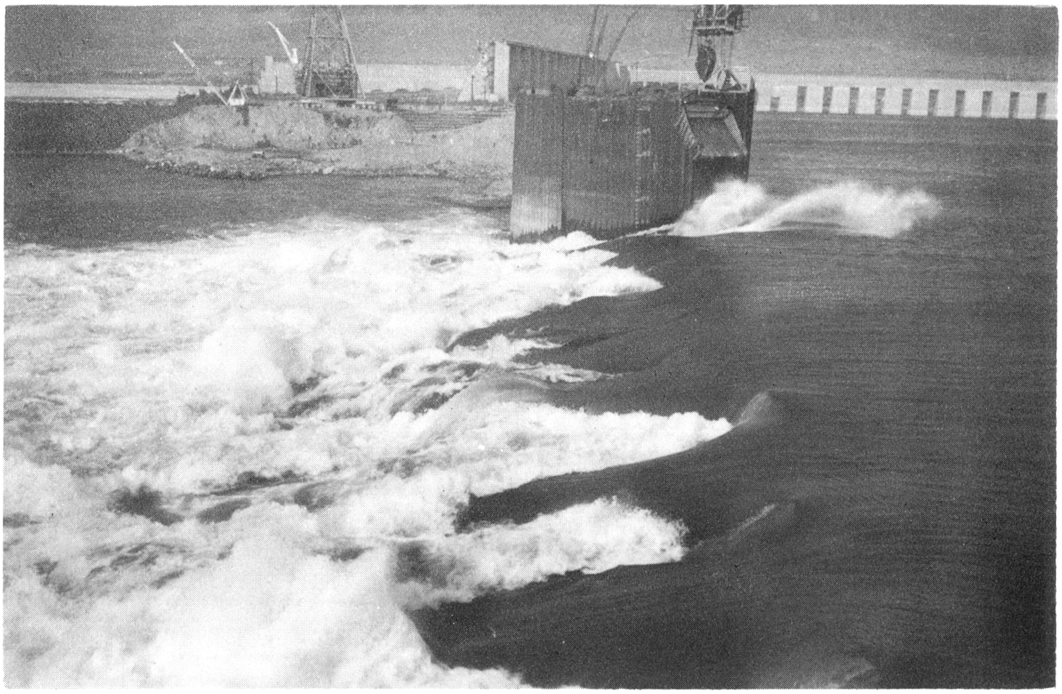


Fig. 35 - Fifth Tetrahedron Fill in progress. Shows several points, also drop to stops "slick" near Cell 17 15 Nov. 1950

Fig. 36 - Fifth Tetrahedron Fill in progrees. Drops to stop "slick" near Cell 17 15 Nov. 1950

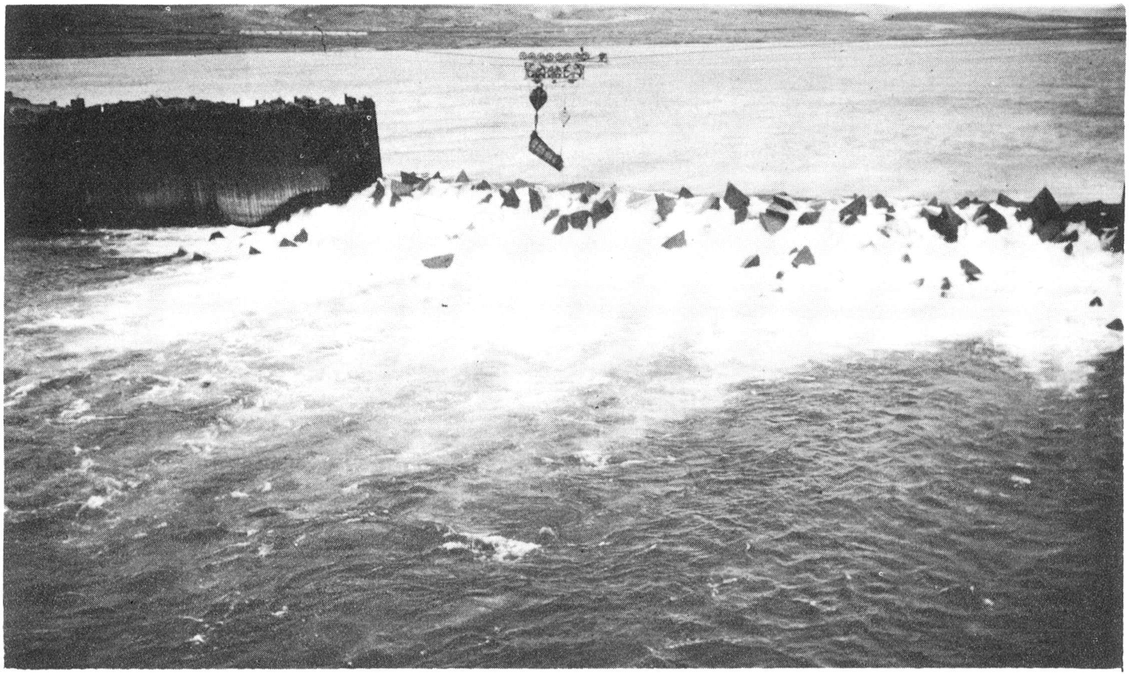


Fig. 37 - Fifth Tetrahedron Fill completed (2,088 tetrs. in place)
Closure officially declared successful 16 Nov. 1950

Fig. 38 - Similar to Fig. 37 above 16 Nov. 1950

Fig. 39 - General Pick, Chief of Engineers, and other dignitaries inspect closure operation 16 Nov. 1950

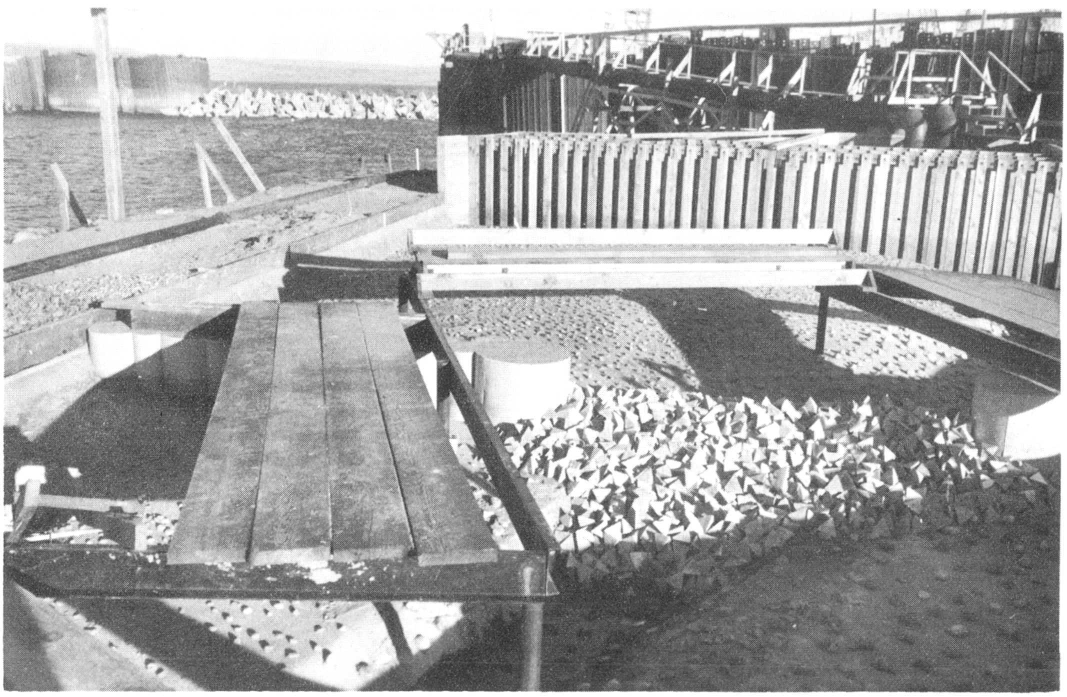


Fig. 40 - Sixth Tetrahedron Fill under construction (2,515 tets.) on both Prototype and Construction Model 17 Nov. 1950

Fig. 41 - Sixth Tetrahedron Fill under construction
Looking upstream 17 Nov. 1950

Fig. 42 - Sixth Tetrahedron Fill under construction
with some C-stone in place 21 Nov. 1950

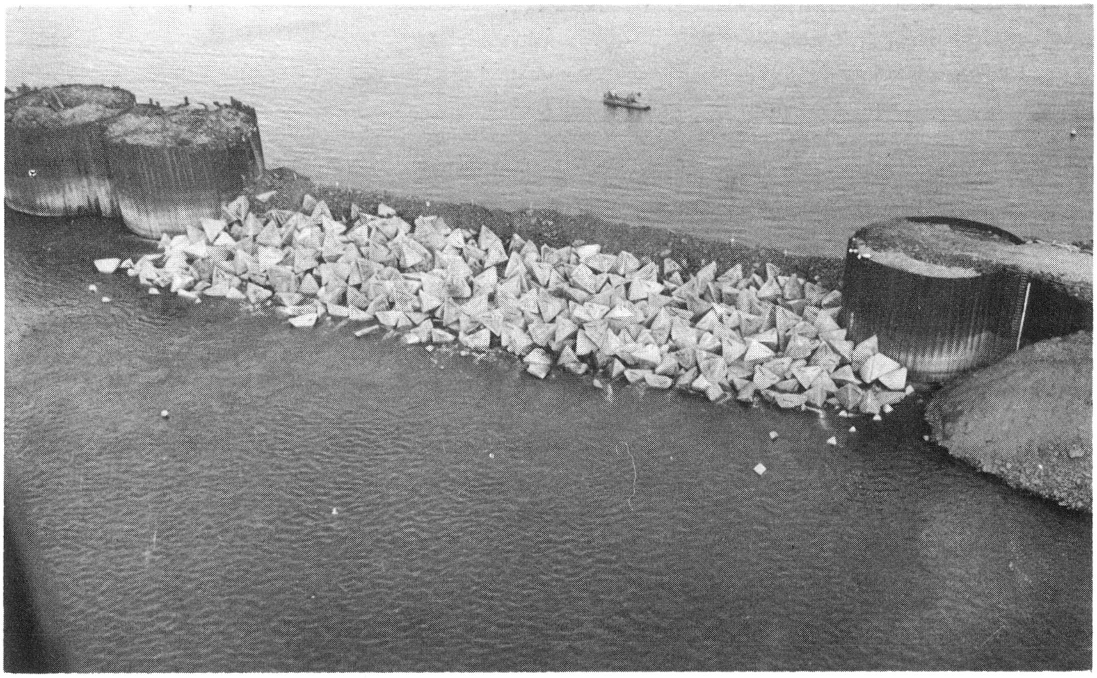


Fig. 43 - Closure Fill nearing completion
Aerial view looking upstream 22 Nov. 1950

Fig. 44 - Columbia River flow diverted
through low spillway bays 22 Nov. 1950

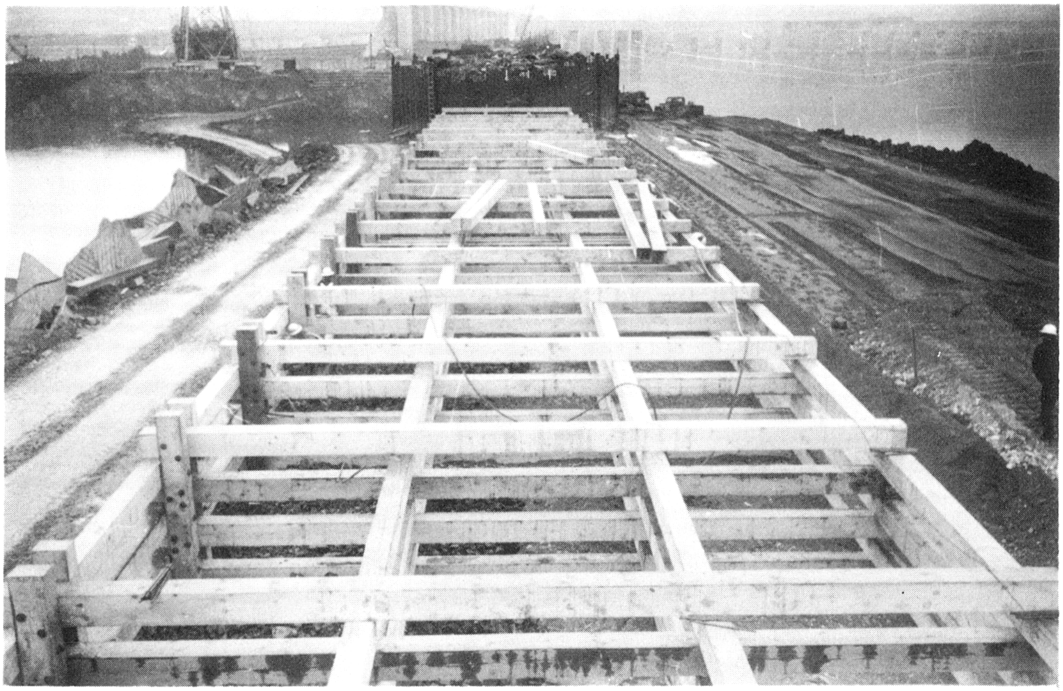


Fig. 45 - Timber Crib under construction

10 Jan. 1951

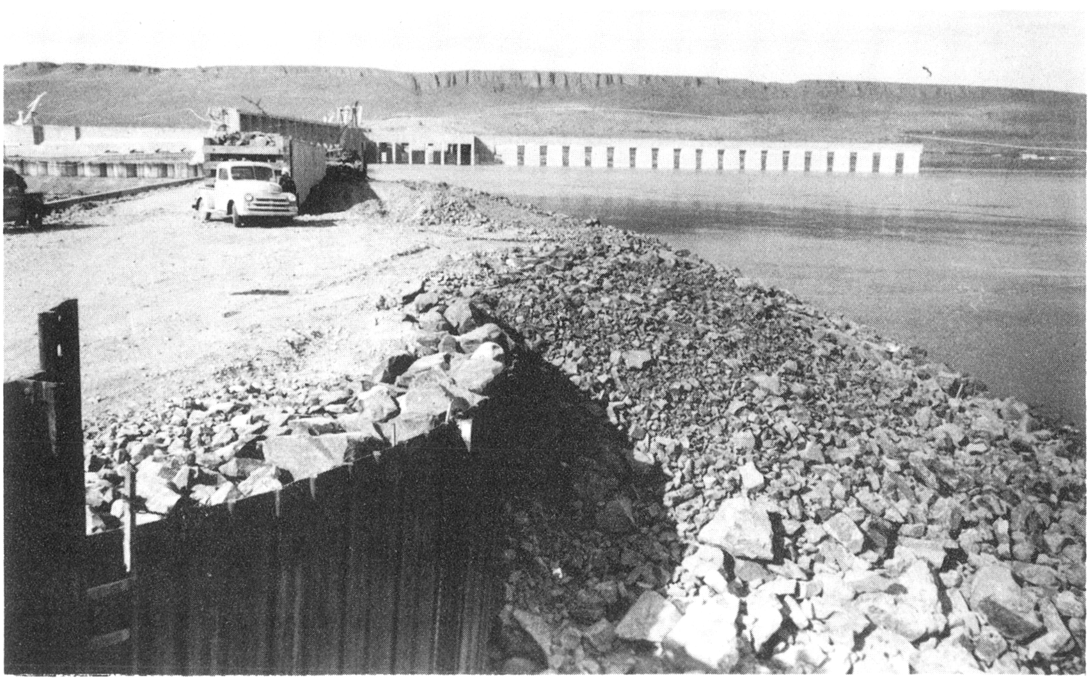


Fig. 46 - Closure Fill and Timber Crib completed

27 Feb. 1951

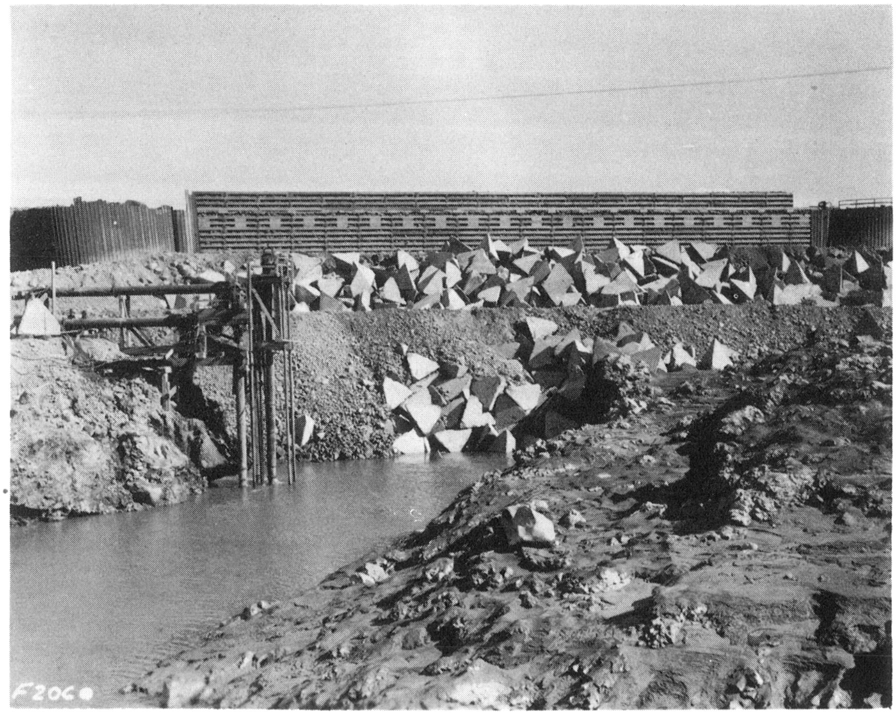


Fig. 47 - Downstream View of Closure Fill after unwatering (W.S. El. 218.4) 25 Feb. 1951

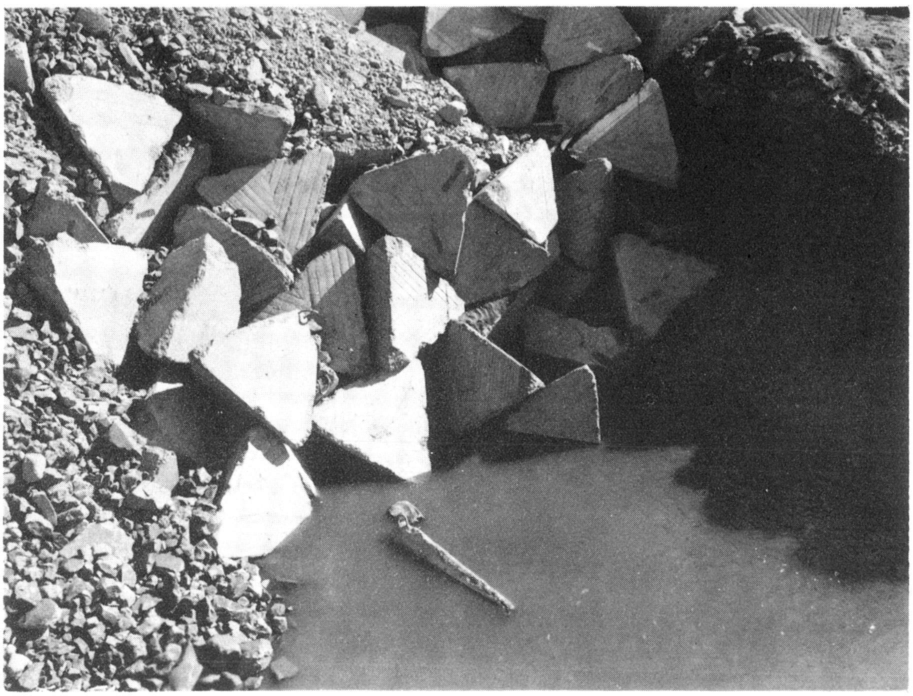


Fig. 48 - Toe of Tetrahedron Fill after unwatering (W.S. El. 218.4) 25 Feb. 1951

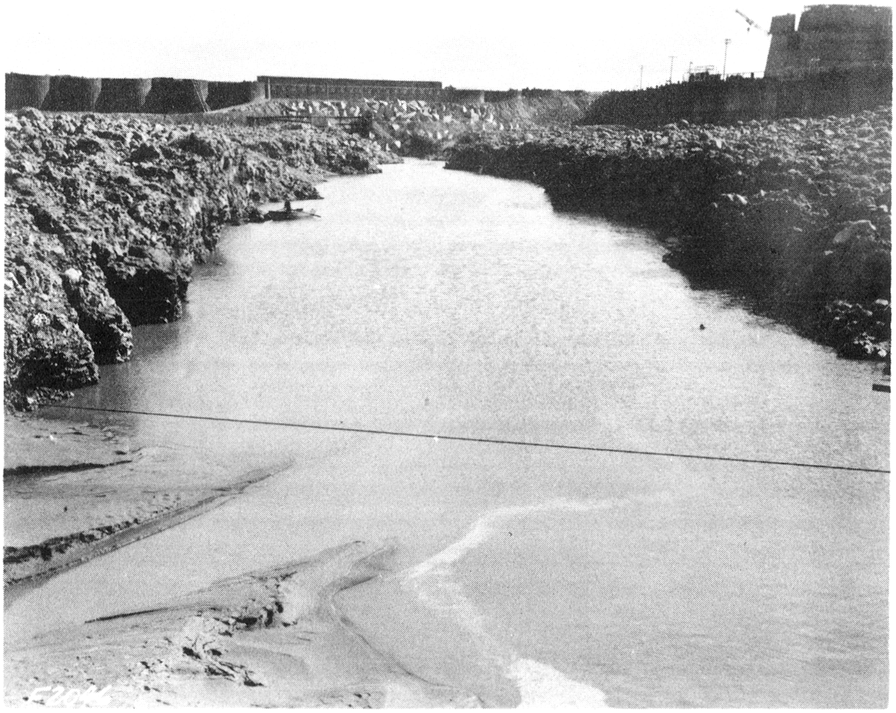


Fig. 49 - Oregon Channel unwatered to El. 2184
Looking upstream 25 Feb. 1951

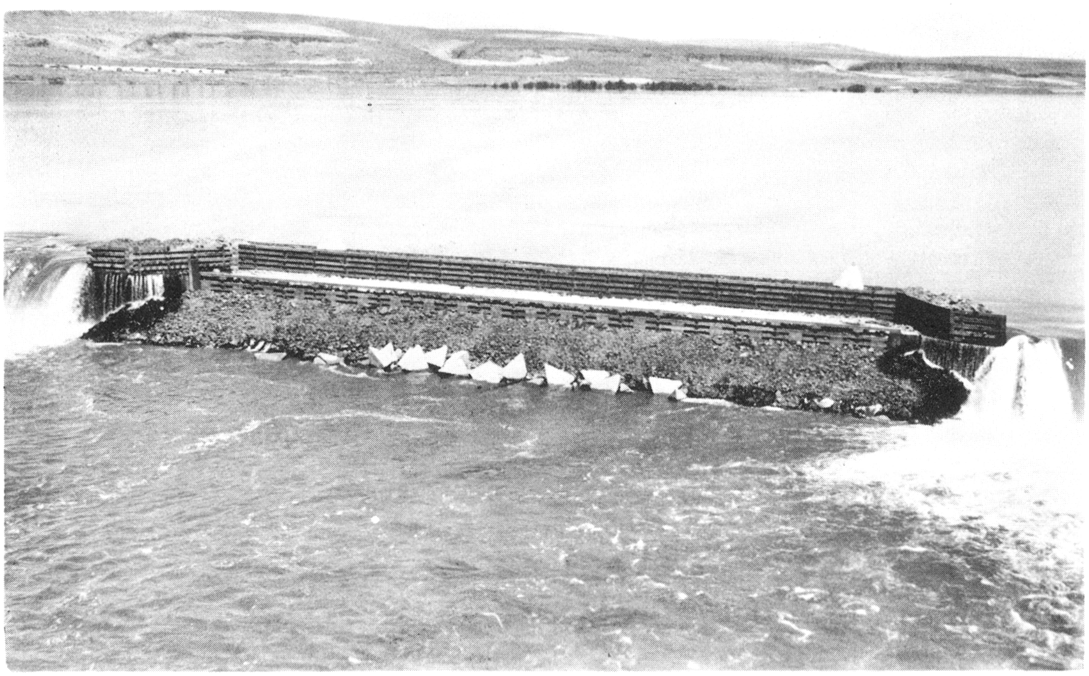


Fig. 50 - Closure Fill during 1951 high water
Looking upstream 18 May 1951