UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

PROGRESS REPORT ON STUDIES OF THE FLOW OF WATER IN OPEN CHANNELS WITH HIGH GRADIENTS

Hydraulic Laboratory Report No. Hyd.-35

RESEARCH AND GEOLOGY DIVISION

HYD 35

BRANCH OF DESIGN AND CONSTRUCTION
DENVER, COLORADO

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Denver, Colorado, July 27, 1938

MEMORANDUM TO CHIEF DESIGNING ENGINEER
(C. W. Thomas)

Subject: Progress report on studies of the flow of water in open channels with high gradients.

1. Introduction. The phenomenon of open channel flow has long been an interesting subject, particularly to the hydraulic engineer, and when this flow is in a channel with a high gradient it is fascinating even to a layman. Empirical formulas have been developed for determining the hydraulic properties of an open channel of relatively low gradient. Changes in existing formulas and development of new formulas have resulted in giving the engineer tools with which to design and build structures of this type economically and with a marked degree of assurance that the hydraulic operation will be satisfactory. The data from which these formulas were derived have been extrapolated and the results used for design of channels with high gradients. To some this appears logical while others follow precedent for want of a better procedure. There has been a concensus of opinion that additional data are necessary to confirm the formulas used in current practice or from which to develop new formulas.

2. Previous work by laboratory section. The subject has been reopened for discussion in the hydraulic laboratory section within the past year. The term reopen is used because the subject was approached previously but was not developed to any great extent because of the urgency of solution of more specific problems. The subject was not forgotten and data were collected from time to time as it presented itself. When the subject was being discussed previously, three angles to the problem were considered:

(1) Is air present in the flow and, if so, to what extent?
(2) What is the mechanics by which air might enter the water?
(3) What factors enter into the retarding of the velocity of the flow in the channel?

The results of these studies are summarized briefly. In regard to (1), air was present in the flow, but at the location tested the amount as measured by two different methods was found to be a very small percentage of the total flow. In (2) the mechanics by which the air enters the flow was not satisfactorily explained. A study of L. Prandtl's analysis was made. His suggestion is that if a difference in velocity occurs between two layers of fluid flowing past one another, the boundary surface does not remain smooth, but first assumes a wave form, then curls back on itself and finally assumes the shape of a vertex. In the case of open channel flow, where the water surface is in contact with the atmosphere, these vortices form at the contact plane and carry air into the water. Turbulence within the flow then distributes the air. This turbulence was explained by E. W. Lane, then head of the laboratory, to be a factor in the air distribution. Also turbulence propagated from the sides and bottom of the channel was instrumental in trapping the air in the water. He states: "As the water starts down the steep section of a chute, the portion of it which is not close to the bottom or sides, is rapidly accelerated and soon attains a high velocity. There is a narrow zone on the bottom and sides, however, in which the velocity adjacent to the walls and floor is zero and that at the outside of the zone reaches that of the center section. In this narrow boundary layer there is, therefore, a rapid increase in velocity with increasing distance from the side walls, or in other words, there is a high velocity gradient. In the side strips the flow is very turbulent and air is entrained, giving the water a white appearance, * * * * . There is a similar zone in contact with the bottom but it is not as apparent since it is not in contact with the atmosphere, and air is therefore not entrained. This boundary layer, both on the bottom and sides, is narrow at the top of the chute but widens as the water flows down. The water in the central swift-flowing portion has a relatively smooth surface, and the acceleration resulting from moving down the chute is retarded but little by the effect of friction on the sides. This central portion becomes narrower and thinner as the boundary layer increases in thickness, and if the chute is long enough a point is reached where the velocity throughout the entire cross-section is considerably retarded by side friction. When this point is reached the surface becomes rough, since the turbulent zone has extended through to the water surface". Further study in relation to this phenomenon was advised at that time. Considering (3) in regard to factors opposing the flow, first consideration was given to the dimensions and characteristics of the channel. Some tests were made in an existing structure and the results were analyzed on the basis of determining a value of "n" in Manning's formula. The value was found to agree very closely with values previously determined for similar canal lining on flat slopes. An extensive program of tests to determine the flow conditions existing on the face of overfall dams was outlined. Only a small portion of this program was executed because of more urgent work. Friction between the surface of the flow and the atmosphere was known to exist and was recognized as a retarding factor to the velocity of the flow. An outline of tests was prepared and an estimate submitted in an effort to secure authorization for a study to be made to determine if possible the magnitude of the retarding factor. The program was not approved, not because of lack of interest, but because of lack of time for the laboratory personnel to conduct it. Since the previously described work was accomplished, small amounts of data have been collected. These consist primarily of personal observations and photographs of flow.

3. Scope of current work. The subject has been revived because structures now being designed are of such proportions that available hydraulic design data cannot be applied with a reasonable degree of assurance that the conditions of flow through the completed structure will be entirely satisfactory. An investigation of the characteristics of flow in open channels with high gradients and on the face of overfall dams is being conducted at the present time to supplement the available design data. These current studies may be divided into three divisions: (1) An extensive study of the literature of this and foreign countries to ascertain the extent of written material available on the subject; (2) development work to evolve a method of accurately measuring high velocity flow, and (3) a program of field measurements on an existing structure.

4. Study of literature. A study of the literature disclosed very little on the subject and the explanations by the authors differ greatly. The mode of attack on the problem has been dealt with primarily from the empirical standpoint although applied mathematical solutions have been tried. No attempt will be made to give a lengthy discussion of the views of the different authors, other than to say that they may be divided generally into two schools of thought. The first group are of the opinion that the hydraulic properties of channels on high gradients may be calculated by the use of the same formulas as used for determining the hydraulic properties of channels on flat grades providing of course that the correct values of the component parts of the formulas are used. This procedure assumes the presence of air to be negligible or its effect to be included in the friction factor used. The other group prefers the hypothesis that water flowing in an open channel begins to absorb or entrain air at a velocity which is stated to be between 6.6 and 14.8 feet per second depending upon the type of structure under consideration. At higher velocities the percentage of air by volume in the flow may be as much as 80 percent. Due to this entrainment of air in the flow, the velocity is somewhat less than that calculated by standard formulas. The area of the cross section of the flow is found to be much greater. Also the presence of air in the flow with a consequent increase in internal friction and decrease in density may result in a maximum or terminal velocity.

The exact magnitude of this velocity has not been determined although one author states, "The maximum velocity heretofore observed at which a water-air mixture flows in a steep chute is 77.1 feet per second, and that portion of the water-air mixture occupied by the water amounts to from 20 to 55 percent of the total volume". The mechanics by which this air enters the flow has not been satisfactorily explained due to lack of sufficient observations. Opinion differs as to the rate of absorption of air. Regardless of the mechanics by which the air enters the flow, its presence in the discharge is certain to cause a difference in the hydraulic properties of the channel. Many authors recognize the presence of air in the flow but feel that since "n" is a relative value of friction it can contain the losses due to this air. However, some of these experimenters find a relatively high value of "n" for concrete on a steep slope. Since the formulas were intended for use with a value of "n" determined experimentally for each type of material, it does not readily follow that concrete channel lining placed under similar conditions on a flat slope should have a roughness factor less than that laid on a steep slope. The study of the literature may be summarized by saying that the science of flow in open channels with high gradients is an almost unexplored field. Although it is not a new subject the difficulties encountered and the number of variables present in such flow conditions have greatly retarded the progress toward a comprehensive analysis of the problem. Also the formulas developed by the older experimenters have grown into very general usage and have been accepted as standard. This condition renders the propagation of any new formulas or method of attack difficult. During the time that the problem has been considered, conversation with many design, construction and operating engineers disclosed that at various times some field measurements have been attempted but due to lack of suitable equipment, difficulties encountered in conducting the tests, and apparent discrepancies, the results have not been published. A much better conception of the subject could probably be obtained if this condition did not exist.

5. Flow on the face of an overfall dam. Water flowing down the face of a high overfall dam is a form of open channel flow, yet practically nothing is known of the conditions that exist in this type of flow. Only recently have structures been built to such height that this problem has become manifest. The design of these structures has been based on precedence established by lower structures and by model studies of the contemplated design. The height of overfall dams has increased until it may not be considered sound practice to extrapolate the known facts further. There are no empirical formulas which may be used to determine accurately the qualities of the flow on the face of high overfall dams. This circumstance exists because there have been no structures from which to obtain the data necessary for evolving such

formulas. Even if structures had been available, it is doubtful if any large amount of data could have been collected due to the intermittent operation and the extreme conditions under which the data would have to be obtained. To what extent data obtained from flow in open channels with relatively narrow section is applicable to flow conditions on the face of an overfall dam is purely a matter of conjecture. The efficacy of this data can be determined only by the conduct of tests on an existing structure whose dimensions are within the range of the proposed structures. This may not be possible for a period of time because of the aforementioned deficiency of structures. In the meantime a correlation of present data and a study of existing structures that approach the size of contemplated designs is very desirable.

6. Limitations of current methods of measuring high-velocity flow. Some of the early experiments have failed completely and others were incomplete or questionable because of the equipment or methods used in obtaining the data. Accurate measurements of velocity and elevation of water surface are necessary to properly analyze flow conditions in channels and the means employed to secure these measurements must be reliable. The current meter has been generally adopted in this country for use in measuring low velocities. The pitot tube has found general use in measuring the higher velocities. Each of these two instruments require calibration before using. This calibration must be conducted under conditions similar to those for which it is intended to be used. The degree of accuracy of the results depends upon the care exercised in the calibration. With these thoughts in mind the planning of a series of field measurements necessitated a careful choice of methods and equipment. Water flowing at high velocity, even in relatively small quantities, presents a rather unruly mass to handle. The kinetic energy of this mass is great, consequently any equipment that is used must be designed to withstand severe action. Equipment designed for field use must be compact and possess a degree of portability. It must be made such that a minimum of component parts are employed which are easily accessible and may be repaired with a small amount of equipment and under field conditions. The principles upon which the equipment functions must be basically sound and the technique employed in handling it must be such that a maximum return is gained from a minimum of effort and time. The use of commercial current meters in high velocity flow is not practical. They would not withstand the abuse to which they would be exposed. Special types of meters have been developed to meet certain requirements and still others might be evolved. Were it possible to obtain a sturdy instrument, it is still necessary to obtain a rating. As has been said before the accuracy of the instrument depends upon the degree of care exercised during the calibration and upon the similarity of conditions under which the instrument is rated and those existing where it will be used. The latter of these two requirements is hard to meet. Since certain experi-

menters have found air present in high velocity flow it was reasonable to expect that that condition does exist. The extent and distribution of the air became part of the problem. It was obvious that existing conditions could not be foretold nor duplicated. The rating obtained for a properly designed current meter or pitot tube, although carefully made, may not be applicable to field conditions if methods in current use are followed. By methods in current use is meant the practice of moving the instrument through still water at a known rate of speed. This method is not basically wrong but the fallacy lies in the fact that the still water would normally be devoid of air. The water would have a density somewhat above that of a water-air mixture depending of course upon the percentage of air present. Since this percentage is not known it is impossible to correct for the difference in density and hence the rating will be in error. Furthermore, in the case of a pitot tube the presence of air in the flow is a source of annoyance and unless extreme care is exercised air may trap in the leads or in the instrument and cause erroneous readings. Another factor that must be considered is what effect, if any, the turbulent water found in high velocity flow will have upon the accuracy of the instrument. It is not logical to expect exactly the same results as those obtained in quiet water where streamline flow past the instrument prevails. The introduction of color into the flow and a measurement of the time required for the passage of the color between two or more points, separated by known distances, has been used. This method is not entirely satisfactory because of the error introduced in the time measurement and the difficulty of the human eye to detect the exact boundary of the colored mass. In very turbulent water where the surface is mixed with air, the flow appears very white and the presence of spray above the surface renders it almost impossible to see any foreign body in the flow. Users of this method report inconsistencies in the results. Timing surface or sub-surface floats over a known reach of channel, chemical titration, impact devices, electrical dissipation from a hot wire in the flow, traveling screen, and in closed conduits, a salt-velocity method of measuring discharge have been used. All, except the latter, were considered impractical for the type of flow to be measured.

7. The salt-velocity method. The salt-velocity method has been used extensively in determining the flow through power penstocks in turbine acceptance tests. A test technique and method of analysis have been fairly well perfected. In closed conduit studies, the method consists of the introduction of a brine solution into the conduit by a quick-acting pop valve. The time is recorded at the time this valve opens. The brine solution is carried down-

stream in the form of a cloud within the flow. At a selected station downstream two electrodes are placed near the center of the conduit and connected to an electromotive force. An ammeter is included in the circuit. As the brine cloud passes the station, the flow of current between the two electrodes is increased due to the presence of brine in the water. The time at which the brine cloud passes the electrode station is recorded. By carefully determining the volume of the conduit between the point of introduction of the brine and the electrode station, and the elapsed time of travel from the valve to the electrode, the discharge per unit of time may be determined. If the velocities in the conduit are relatively low or the distance between pop valve and electrode is sufficient, the measurement of time may be made with an accurate stop watch. However, if high velocities are encountered or short reaches are used, the accuracy of the flow measurement depends largely upon the timing element employed. A careful study of this method and the results obtained through its use led to the belief that the general principles involved could be applied to velocity measurement in open channel flow. The technique employed in the application must necessarily be different. Since the presence of air in open channel flow is evident, it was not advisable to use the method as a means of measuring discharge. Moreover, the volume occupied by the flow in an open channel may vary between wide limits depending upon the velocity and discharge. In a closed conduit one variable is eliminated since the volume remains constant. The portion of the method applying to velocity measurement, with certain changes in technique, seemed equally applicable to open or closed conduits.

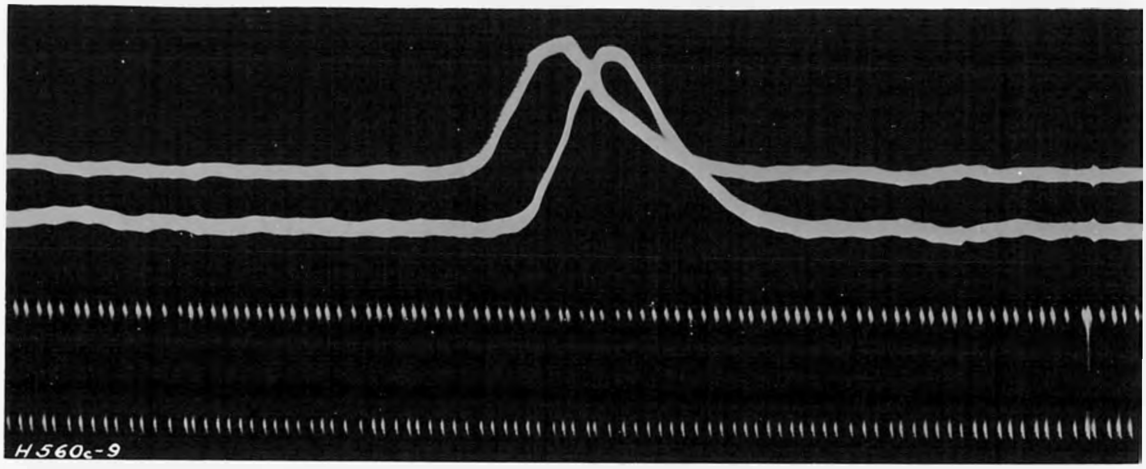
8. Initial tests in laboratory. A technique applicable to open channel flow and equipment to execute the tests was necessary before any field measurements could be attempted. This development was started in the laboratory. In addition to measuring the velocity, it is necessary to secure water-surface measurements in the channel for computing air content and energy gradient. Some satisfactory means of obtaining these measurements was also sought. It was found that the technical section of the Denver office was constructing an oscillograph and this instrument would be available for use as a time-measuring device almost as soon as other equipment could be assembled for starting the tests. A hydraulic model of a chute on the Sun River project, Montana, was being tested in the laboratory. The chute has a cross section of approximately 6 inches deep by $9\frac{1}{2}$ inches wide. Velocities in this model were from ten to fifteen feet per second and the section was of sufficient length to permit preliminary investigation of the method. Copper electrodes were fastened to the inside of the chute and wire leads carried to a convenient location for the oscillograph.

The electrodes used ranged in width from 1/4 inch to 3/4 inch and were spaced from six inches to two feet apart, measured parallel to the center line of the chute. Two electrodes were used at each point, one on each side of the flume. The original strips extended from the floor to the top of the sides but some of these were later shortened to extend only part way up the sides in order that they would not project above the water surface. Others were extended part way across the floor and up the sides. Electrodes were later made by using No. 7 flathead, brass, wood screws with only the surface of the head exposed to the flow.

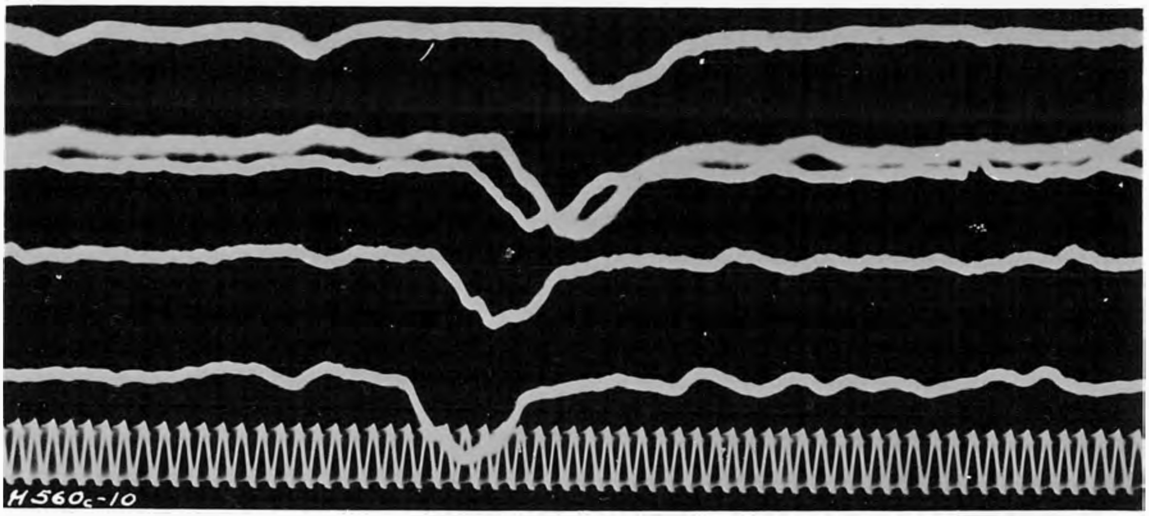
9. Description of the oscillograph. The oscillograph used consisted essentially of three moving coil galvanometers, an optical system, and a motor-driven camera. The current supply for the fields of the galvanometers was derived from a six-volt storage battery and the moving coils were excited from dry cell batteries in the test circuit. The vibration of the moving coils was damped by oil. The optical system employed two small flash light bulbs as light sources, a cylindrical lens to reduce the light supply to a horizontal band, three small cylindrical lenses (one in front of each galvanometer) to focus the horizontal band on tiny mirrors fastened to the moving coils of the galvanometers and to change the reflected bands to vertical bands, and a cylindrical lens to focus the vertical bands as points on the film in the camera. The camera was belt-driven by a six-volt shunt motor. The record was made on standard No. 122 camera film in 37-inch lengths, wound on daylight loading spools. One length was used for each record. The film was drawn through the camera at right angles to the vibrating light beam.

10. Laboratory procedure. Two pairs of electrodes were separately connected by wiring systems to two of the galvanometers in the oscillograph. The third galvanometer was connected to the 110-volt, 60-cycle, A. C. light supply to provide a time base on the record film. The power supply to operate the galvanometers included one or two dry cell batteries, depending upon the base current needed, and the circuits were closed by the water between the electrodes. After all circuits were properly balanced the camera was started and salt solution dumped from glass containers into the flow. A saturated solution was used and the amount introduced varied during the tests from one-fourth pint to one quart. It was usually introduced at the upper end of the flume but in some instances the introduction was made close to the first set of electrodes. From three to five measures of brine could be emptied into the flow during the ten seconds required for the film to pass through the camera.

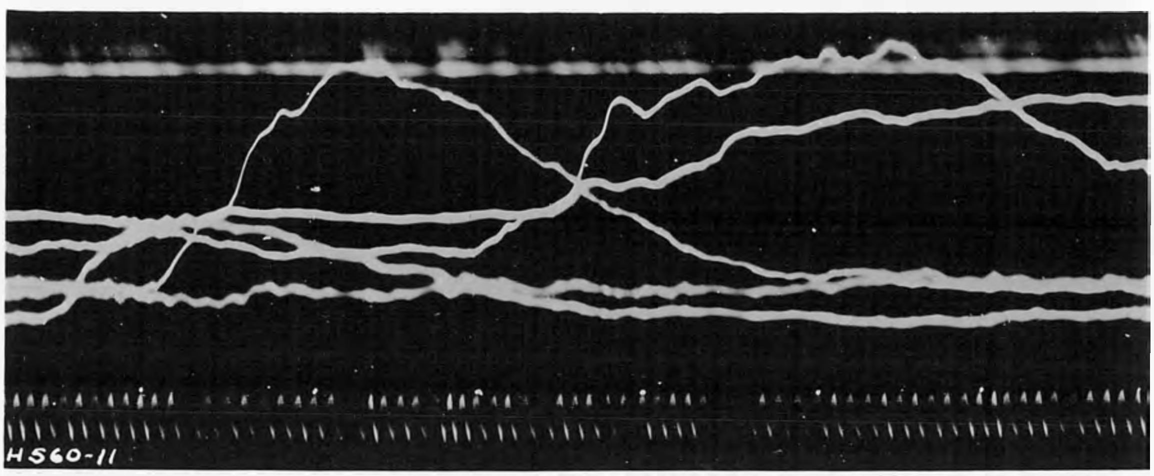
11. <u>Results of initial laboratory tests.</u> Since the oscillograph was arranged to provide visual observation, very few film records were made. The type of electrodes, the number of dry cells necessary in the circuit, the amount of salt, and the point of induction were studied visually on the ground glass of the oscillograph. When the test circuit was connected to the oscillograph the galvanometers registered a base deflection due to the passage of some current through the flowing water. The amount of this current was dependent upon the area of the electrode exposed to the water and the amount of electromotive force supplied by the dry cell batteries. As the brine solution passed between the electrodes, the conductivity of the water was increased and the flow of current increased. The windings in the galvanometers were calculated to give a deflection of the light beam on the film of one inch per five milliamperes change in current. The base current amounted to from one to three milliamperes and during the passage of the brine was increased to approximately eight milliamperes. The instantly responding moving coil galvanometer and the optical system produced a current-time record on the film, in which distance along the film was proportional to time; and the deflection of the beam of light was proportional to the instantaneous value of current passing through the galvanometer vibrator. The record obtained by such an arrangement is so long that it is not feasible to reproduce it here. However, a portion of an actual record is shown on plate 1. No attempt was made to measure accurately the value of the current since it had little bearing on the results. The distance between the curves produced by the passage of the salt, as measured by the time scale imposed on the film by the 60-cycle alternating current, corresponded to the time necessary for the flow to travel the distance between the pairs of electrodes. This distance was accurately measured in the flume. The distance between the curves on the film was taken in three different ways. The distance between the centers of gravity of the curves, the distance between the points where the curves left the base lines, and the distance between similar points on the curves were measured. The distances all agreed very closely and no trend was evident of one measurement indicating a higher velocity than another. The measured velocities checked the calculated average velocities very closely. The electrodes with greater exposure to the flow produced a greater base deflection in the galvanometers but this could be diminished by decreasing the voltage in the circuit. The electrodes extending above the water surface were sensitive to waves on the surface of the flow. This caused extraneous deflections in the galvanometers which were at first considered to be objectionable but were later found to be readily distinguishable from the deflections caused by the brine. It was concluded that strip electrodes fastened to sides of the flume or circular electrodes on the sides



A. Oscillogram from Sun River chute model.



B. Oscillogram from 45-degree laboratory chute.



C. Oscillogram from Kittitas Wasteway.

or bottom of the flume would give satisfactory results. The area of electrode was immaterial since it was necessary to balance the current at the instrument before each test, using one, two or three $1\frac{1}{2}$-volt dry batteries. The amount of salt necessary to produce a legible deflection was determined by trial. The quantity of salt solution influenced the deflection produced in two ways. The maximum deflection was increased by an increase in salt solution and the curves extended over a greater elapsed time. Too great a deflection caused the curve to swing beyond the edge of the film and an excessive time interval made the calculations difficult. By determining the correct amount of brine and by dumping it into the flow quickly very readable curves were obtained. The length of flume being used made it possible to introduce the brine at the upper end. The cloud was carried through the flume with very little elongation.

12. Laboratory tests of high velocity flow. A technique necessary to secure and interpret the records obtained by this method of measuring velocity was developed for the low-velocity flume. To expand this technique, a wooden flume was constructed on a 45-degree slope. This flume was 9.6 inches wide by 10.5 inches deep, inside dimensions. The length was 17 feet $2\frac{1}{2}$ inches, measured along the slope. The water was delivered to the flume by a 12-inch centrifugal pump and was admitted to the flume under pressure from a rounded-edge slide gate. The maximum discharge of $8\frac{1}{4}$ second-feet produced velocities of approximately 50 feet per second. The electrodes installed in this flume were $\frac{1}{2}$-inch brass disks, placed flush with the inside surface of the chute. Nine sets (two disks per set) were placed in the floor of the chute, 18 inches between sets, measured along the center line of the floor. Nine sets of electrodes were placed in the sides of the chute at the same spacing and in line with the bottom electrodes. The leads from the electrodes were carried to a central switchboard at the oscillograph. The connection from the board to the instrument was made by short leads fitted with tip jacks. The brine was introduced into the flow from a pressure tank with an outlet immediately downstream from the slide gate and controlled by a quick-acting valve. The introduction was made at the surface of the flow. The technique followed during these tests was essentially the same as that in the low-velocity chute. Three additional elements installed in the oscillograph made it possible to measure the velocity over longer reaches and to trace the action of the salt cloud through a greater distance. The base current through the circuits was found to be slightly less than that in the low-velocity chute, probably due to the relatively small electrode area, hence a larger amount of brine was necessary to produce a suitable record. The brine could be introduced more rapidly with

the quick-acting valve so the initial cloud in the flow was evidently quite similar to the cloud in the low-velocity chute. However, there was more elongation as it passed down the chute which was expected since the turbulence in the flow was greater and high velocities prevailed. Near the close of the test program finely ground salt was used instead of a brine solution. The cloud, as registered by a milliammeter, was slightly longer than the brine cloud but was very little greater in concentration. Evidently the highly turbulent flow dissolved the salt rapidly and distributed it throughout the cross section in a short distance. Although it increased the work necessary in making an analyis of the oscillogram curves, this method was considered more desirable because of the simple manner in which the powder could be introduced into the flow. Since the method was being developed for field use, simplicity of equipment was essential.

13. Results of laboratory tests of high-velocity flow. The series of tests although not extensive led to some definite conclusions. Oscillograms produced were easy to interpret (plate 1). The brine cloud was carried the length of the flume in a sufficiently compact mass to give good results. The results obtained from the electrodes placed in the side of the chute checked those from the bottom electrodes so closely that there was no evidence of disagreement. This indicated that the brine was well distributed throughout the cross section and the equipment employed was sensitive to the presence of the brine regardless of the location of the electrodes. Measurements of velocity by the use of either side or bottom electrodes checked the calculated velocity within one percent. The velocity was calculated by the formula $V = Q/A$, where V is velocity in feet per second; Q, discharge in cubic feet per second, and A, area of the cross section in square feet. The discharge was measured over the calibrated laboratory weir and the area of the cross section was carefully measured at the gate. The oscillograms obtained from this chute showed a persistent pulsation in the base current. This pulsation was not periodic and the resulting deflections were not of equal magnitude. Several explanations were offered for this occurrence. It was very possible that splash from the flow wet the insulation of the wire leads and caused a part of the leads to act as electrodes intermittently. Visual observations of flow conditions, however, showed pulsations in the flow itself. There appeared to be regions of high-velocity water separated by regions of lower velocity. These flow pulsations were evidently reflected in the photographic record. Velocity determined from the film by using these minor deflections of current gave consistent results when compared with the deflections caused by the passage of salt. For the purpose of making field measurements, it was concluded that electrodes, if installed in a structure at the time of

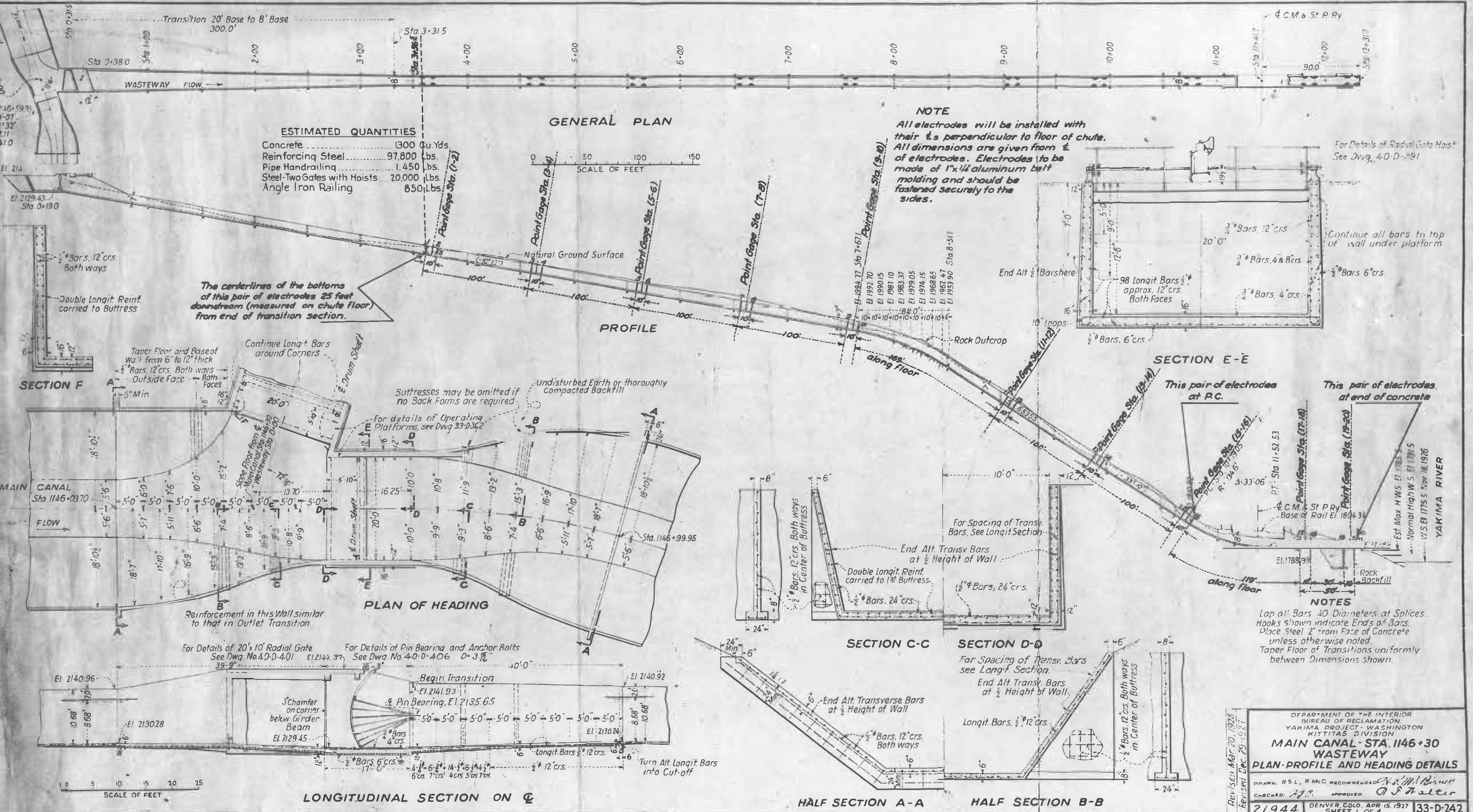
its erection should consist of small plates embedded flush with the interior surface of the channel. The wire leads could then be carried through the walls and to some suitable location for the recording equipment. If, however, the electrodes are for installation in an existing structure, they should consist of metal strips securely anchored to the side walls in such a manner that they would offer a minimum resistance to the flow. They should be installed perpendicular to the floor of the chute and be of sufficient length to extend above maximum water surface so the wire lead could be attached to the upper end. The distance that the electrodes should be separated, either longitudinally or transversely, would necessarily depend upon the section to be tested. From the results obtained in the small chute, it was concluded that finely divided dry or moist salt would dissolve in the turbulent flow very rapidly and would be satisfactory for use in the field. Some development work was done to secure a means of accurately determining the water surface in extremely turbulent flow. The basic principles applied appeared to be satisfactory but insufficient time negated the completion of equipment suitable for field use.

14. Tests on Kittitas wasteway. A program of field measurements was initiated to further develop the method of measuring high-velocity flow and to secure data for the design of the flood spillway for Shasta Dam. After considering the dimensions of existing structures and the possibility of operating them conveniently, the wasteway at station 1146+30 on the Kittitas Main Canal - Kittitas Division - Yakima Project - Washington, was selected as suitable for initial testing (plate 2). In this structure there is a drop of 340.5 feet in a horizontal distance of 1213 feet. All but a small fraction of a foot of this fall occurred in a horizontal distance of 1135 feet. A plan and section of the wasteway is shown in figure 1. With two bottom slopes available for testing in the same structure, the opportunity of securing considerable data with but a single installation was advantageous. Details of the test program were arranged by correspondence between the Denver office and the project office. In order to expedite the tests twenty sets of electrodes were installed in the chute under the direction of the project superintendent prior to the actual initiation of the tests. The location of the electrodes is shown on figure 1. The sets of electrodes were numbered consecutively down the wasteway. It was considered advisable to install the pairs of electrodes at the two different intervals because of the uncertainty of the stability of the salt cloud. Should the dispersion occur quite rapidly the 10-foot reaches could be used to determine the velocity although the 90, 100, or 110 foot reaches would be preferable, if the dispersion should be sufficiently small, because the percentage of error in reading the time would be less. The actual distances

A. Upper section of wasteway. Looking downstream.

B. Lower section of wasteway. Looking downstream.

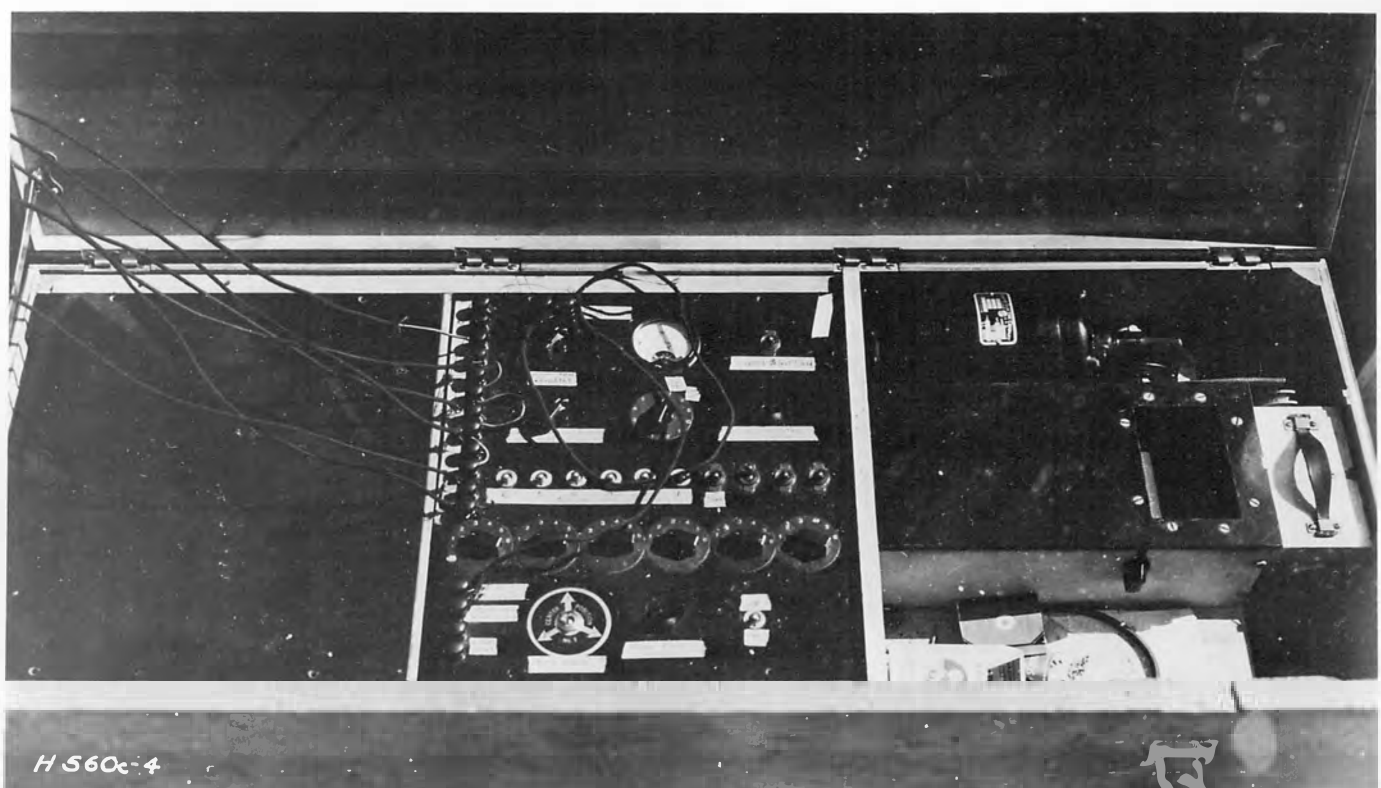
FIGURE 1


GENERAL PLAN
Transition 20' Base to 8' Base 300.0'
WASTEWAY FLOW
ESTIMATED QUANTITIES
Concrete 1300 Cu. Yds.
Reinforcing Steel 97,800 Lbs.
Pipe Handrailing 1,450 Lbs.
Steel-Two Gates with Hoists 20,000 Lbs.
Angle Iron Railing 850 Lbs.
SCALE OF FEET
NOTE
All electrodes will be installed with their ℄s perpendicular to floor of chute. All dimensions are given from ℄ of electrodes. Electrodes to be made of 1"x1/4" aluminum belt molding and should be fastened securely to the sides.
The centerlines of the bottoms of this pair of electrodes 25 feet downstream (measured on chute floor) from end of transition section.
Natural Ground Surface
PROFILE
Rock Outcrop
For Details of Radial Gate Hoist See Dwg. 40-D-391
SECTION E-E
This pair of electrodes at P.C.
This pair of electrodes at end of concrete
YAKIMA RIVER
SECTION F
PLAN OF HEADING
MAIN CANAL Sta 1146+03.70
FLOW
Suttresses may be omitted if no Back Forms are required
Undisturbed Earth or thoroughly compacted Backfill
For details of Operating Platforms, see Dwg 33-D-362
Reinforcement in this Wall similar to that in Outlet Transition
SECTION C-C
SECTION D-D
NOTES
Lap all Bars 40 Diameters at Splices.
Hooks shown indicate Ends of Bars.
Place Steel 2" from Face of Concrete unless otherwise noted.
Taper Floor of Transitions uniformly between Dimensions shown.
For Details of 20'x10' Radial Gate See Dwg No. 40-D-401
For Details of Pin Bearing and Anchor Bolts See Dwg No. 40-D-406
Begin Transition
Pin Bearing, El. 2135.65
Turn Alt. Longit. Bars into Cut-off
LONGITUDINAL SECTION ON ℄
HALF SECTION A-A
HALF SECTION B-B
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YAKIMA PROJECT - WASHINGTON
KITTITAS DIVISION
MAIN CANAL - STA. 1146+30
WASTEWAY
PLAN-PROFILE AND HEADING DETAILS
Revised Mar. 20, 1928
Revised Dec. 29, 1927
21944
DENVER, COLO. APR. 15, 1927 SHEET 1 OF 4
33-D-242

between pairs of electrodes were measured after the installation. The wiring system differed slightly from that used in the laboratory. All electrodes on the left side of the wasteway were connected in series by a single insulated wire leading to the switchboard at the oscillograph. A separate insulated lead connected each of the electrodes on the opposite side of the structure to the board. The dry cell batteries were introduced between the switchboard and the oscillograph.

15. Velocity measurements. The oscillograph used in the laboratory was used for making the tests in the field (plate 3-B). The only change in the instrument was the addition of an electrically driven, 50-cycle tuning fork to provide a time base. The vibrations of the tuning fork were recorded on the film by connecting one of the galvanometers in the tuning fork circuit. The remaining five elements were available for connection to the electrodes. Data were obtained from ten discharges ranging from 89 to 1005 second-feet. The circuits and elements were adjusted until the light beams would register the trace of the current on the film. Flour salt, of a fineness to pass a 140-mesh sieve, was moistened until the particles would cohere when molded by hand into balls. The size of the ball necessary for satisfactory registration on the film was determined by trial and error. When measuring velocities over a reach of 200 feet with the lower discharges, balls two inches in diameter were sufficient. For longer reaches or larger discharges, the size of the balls was increased. At the maximum discharge, with velocities measured over a 400-foot reach, the diameter of the ball was approximately seven inches. After the balls were formed, the recording apparatus was set in motion. The balls were then tossed into the flow a short distance upstream from the test reach. The number of balls used varied from one to five. On short sections five salt balls were used for a single film record. It was found that all the balls did not record because of the relatively short film, so the number was reduced to two for short reaches and a single ball for the longer reaches. Since only five galvanometer elements were available, five records were necessary to cover the entire length of the flume at each discharge. The first five sets of electrodes were connected for the first record; the next five sets for the second, and so on down the wasteway. For all tests, except the first three discharges, one record was made with electrodes 1, 3, 5, 7, and 9 connected and another with electrodes 12, 14, 16, 18, and 20 connected. It was found that by introducing one large ball of salt, the cloud carried over the longer distance in ample time and in a sufficiently compact cloud to give a legible record. In fact visual observations with a milliammeter showed that the salt was carrying the full length of the wasteway in a sufficient concentration to produce records. However, the cloud was greatly elongated.

A. Point gage used for obtaining depth of flow.



B. Oscillograph.

16. Depth measurements. Measurements of the water surface were made with a point gage (plate 3-A). Ten cross sections were measured, one at the mid-point of each of the ten-foot electrode stations (figure 1). Nine observations approximately one foot apart, were made at each cross section. This same procedure was followed throughout except at the higher discharges when excessive spray made it necessary to abandon the first station below the convex vertical curve. At the maximum discharge, it was necessary to also abandon the second station below the curve. After the tests were completed, the width of the channel at each station was carefully measured. Point gage readings of the bottom of the channel were taken with the same instrument and at the same locations at which the water surface observations were made. The depth and area of cross section occupied by the flow was calculated from these measurements.

17. Discharge measurements. The discharge through the wasteway was determined by gaging the flow in the main canal with a current meter. During the greater part of the tests, the total flow of the canal was diverted into the wasteway. For this condition only one gaging station, located above the wasteway turnout was necessary. The remainder of the time some water was passed down the canal for irrigation purposes. A gaging station located in the main canal downstream from the turnout was used to obtain the quantity passing. The difference in discharge as measured at the two gaging stations was used as the quantity passing through the wasteway. The current-meter measurements for each test were made simultaneously with the velocity and point gage measurements. An experienced hydrographer from the project office made all the current-meter measurements. Standard current meter practice was employed and care was taken to attain a high degree of accuracy.

18. Photographs. Photographs were made of the flow conditions for each discharge and a number of these are included in this report. Sixteen millimeter motion pictures were made of all discharges. Most of these pictures were taken with the camera operating at four times normal speed, or 64 frames per second. When projected at normal speed, the action is shown at one-fourth the actual rate of motion. Since the action of the surface water was extremely rapid, this degree of slow-motion permits a much more thorough observation of its characteristics than is possible otherwise. An ultra-high speed camera would have made possible a much more detailed observation. The speed used was the maximum for the camera employed. The films are filed in the hydraulic laboratory and are available for review. The motion pictures are considered a very valuable part of the data collected because they verify certain actions that could otherwise only be assumed as true because of the deficiency of the human eye to see rapid motion.

19. Results of depth measurements. The results of the tests on the wasteway are given in tabular form. The observed depths of flow are given in table 1. The table consists of ten divisions, each division showing the properties of one of the sections observed, (figure 1). In the first column of each division is given the discharge as measured in the main canal during the time the depth observations were being made. The next nine columns give the actual observed depths of flow in feet at distances from the left side wall. In the column headed mean depth, the average of the nine readings across the section is given. The next column (flow area) gives the area of the cross section of flow. This is the product of the depth given in the preceding column and the average width of the channel as measured. This area is corrected for the cross-sectional area of fillets between the sides and bottom of the channel. The last two columns show the wetted perimeter and hydraulic radius as calculated from the preceding values. All observed depths have been included in the table to show the consistency of the results. The choppy water surface and the large amount of spray rendered it difficult to determine where the point of the gage should be to give a reading that would be indicative of the actual depth of flow. The surface conditions also made it difficult to observe the point of the gage. The depth of flow was considered to be at the base of the loosely flying spray and drops of water. The top of the main portion of the flow included numerous small waves or rollers. The water depths given in the table are approximate mean values between the crest of the waves and the troughs between them. The vibration of the point gage was relied upon more than visual observation to insure that the point was at relatively the same position in the flow for successive readings. Two factors may be observed in the depth measurements as given in the table. (1) For the high discharges, the wave due to entrance conditions (plate 4) was reflected in the point gage readings at station 1-2 and 3-4. This wave was not observed beyond that point. (2) The water surface at the sides of the chute was higher than that in the central portion (plate 5). For the higher discharges, this high portion extended slightly over a foot from each wall and was as much as 0.4 foot higher than the central portion of the flow. For this reason, observation of depth by staff gages fastened to the walls of such a structure would be in error. For the two lower discharges, well-developed traveling waves were persistent in the flow, particularly on the steep slope. They were not obvious in the higher flows. These waves formed in the upper transition section and increased in magnitude and velocity as they progressed down the chute (plate 3-A). They are the type of wave observed in numerous structures at low discharges and have been referred to by some authors as "slugs" or "balls" of water. Some interesting observations were made in regard to these waves. Although 25 waves were observed to pass electrode no. 18 in 50.8 seconds with

TABLE 1

DEPTH MEASUREMENTS

Depth in Feet, by Distance from Left Side Wall in Feet

STATION 1-2

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter feet	Hydraulic Radius feet
89	0.42	0.42	0.46	0.48	0.52	0.50	0.55	0.47	0.53	0.49	3.88	8.77	0.44
193	0.82	0.69	0.72	0.79	0.78	0.76	0.79	0.86	0.89	0.79	6.27	9.37	0.67
362	1.17	1.01	0.95	1.14	1.43	1.36	1.31	1.35	1.36	1.23	9.78	10.25	0.95
401	1.18	1.02	1.05	1.03	1.32	1.47	1.46	1.48	1.31	1.26	10.02	10.31	0.97
491	1.53	1.31	1.30	1.40	1.76	1.79	1.66	1.56	1.64	1.55	12.33	10.89	1.13
587	1.84	1.68	1.59	1.83	2.01	1.87	1.74	1.71	1.87	1.79	14.24	11.37	1.25
719	2.20	2.01	2.11	2.23	2.06	1.92	1.87	1.94	1.94	2.03	16.15	11.85	1.36
777	2.60	2.41	2.52	2.44	2.13	2.03	2.01	2.05	2.18	2.26	17.99	12.31	1.46
922	3.16	2.95	2.92	2.56	2.23	2.19	2.21	2.34	2.35	2.55	20.30	12.89	1.58
1005	3.41	3.19	3.11	2.81	2.29	2.29	2.36	2.70	2.49	2.74	21.81	13.27	1.64

STATION 3 - 4

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter feet	Hydraulic Radius feet
89	0.56	0.48	0.49	0.47	0.49	0.51	0.48	0.51	0.49	0.50	3.96	8.79	0.45
193	0.94	0.79	0.75	0.77	0.73	0.81	0.86	0.81	0.85	0.81	6.43	9.41	0.68
362	1.44	1.20	1.16	1.09	1.10	1.14	1.20	1.47	1.57	1.26	10.02	10.31	0.97
401	1.40	1.21	1.11	1.08	1.07	1.20	1.32	1.45	1.59	1.27	10.10	10.33	0.98
491	1.78	1.53	1.34	1.29	1.30	1.39	1.58	1.85	1.95	1.56	12.41	10.91	1.14
587	2.04	1.81	1.56	1.45	1.49	1.64	1.83	2.13	2.31	1.81	14.40	11.41	1.26
719	2.37	1.98	1.79	1.70	1.83	1.87	2.08	2.25	2.35	2.02	16.07	11.83	1.36
777	2.54	2.31	2.10	1.95	1.99	2.08	2.16	2.40	2.50	2.23	17.75	12.25	1.45
922	2.89	2.78	2.40	2.30	2.25	2.20	2.31	2.52	2.65	2.48	19.74	12.75	1.55
1005	3.09	2.97	2.73	2.54	2.51	2.41	2.45	2.62	2.58	2.66	21.18	13.11	1.62

STATION 5 - 6

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter feet	Hydraulic Radius feet
193	0.98	0.80	0.82	0.79	0.84	0.83	0.80	0.70	0.74	0.81	6.44	9.40	0.68
362	1.40	1.25	1.27	1.29	1.29	1.25	1.12	1.07	1.22	1.24	9.87	10.26	0.96
401	1.29	1.26	1.25	1.25	1.36	1.28	1.08	1.16	1.21	1.24	9.87	10.26	0.96
491	1.73	1.52	1.52	1.53	1.57	1.56	1.39	1.44	1.52	1.53	12.18	10.84	1.12
587	1.85	1.68	1.67	1.77	1.76	1.90	1.71	1.79	1.94	1.79	14.26	11.26	1.25
719	2.11	1.83	1.89	1.89	1.99	2.19	2.02	2.09	2.23	2.03	16.17	11.84	1.37
777	2.25	2.05	1.97	2.00	2.15	2.31	2.25	2.37	2.52	2.21	17.61	12.20	1.44
922	2.50	2.32	2.32	2.36	2.52	2.60	2.45	2.60	2.71	2.49	19.84	12.76	1.55
1005	2.62	2.57	2.48	2.58	2.69	2.66	2.58	2.72	2.88	2.64	21.04	13.06	1.61

STATION 7 - 8

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter feet	Hydraulic Radius feet
193	1.03	0.90	0.91	0.88	0.85	0.73	0.77	0.70	0.79	0.84	6.65	9.41	0.71
362	1.52	1.53	1.37	1.20	1.27	1.14	1.05	1.09	1.20	1.26	9.98	10.25	0.97
401	1.50	1.52	1.36	1.21	1.20	1.19	1.16	1.14	1.13	1.27	10.06	10.27	0.98
491	1.90	1.83	1.71	1.48	1.46	1.38	1.39	1.43	1.64	1.58	12.53	10.89	1.15
587	2.19	2.09	1.92	1.73	1.62	1.58	1.53	1.59	1.82	1.79	14.30	11.31	1.26
719	2.37	2.28	2.18	1.96	1.92	1.87	1.89	1.87	2.28	2.07	16.49	11.87	1.39
777	2.50	2.37	2.22	2.05	2.01	2.03	2.12	2.16	2.44	2.21	17.54	12.15	1.44
922	2.66	2.52	2.50	2.38	2.30	2.43	2.46	2.54	2.67	2.50	19.84	12.73	1.56
1005	2.86	2.74	2.65	2.49	2.49	2.62	2.62	2.79	2.78	2.67	21.26	13.07	1.63

STATION 9 - 10

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter ft.	Hydraulic Radius ft.
193	0.84	0.76	0.76	0.78	0.80	0.74	0.83	0.90	0.80	0.80	6.35	9.36	0.68
362	1.29	1.30	1.10	1.15	1.24	1.20	1.17	1.28	1.27	1.22	9.70	10.20	0.95
401	1.03	1.16	1.13	1.14	1.29	1.31	1.33	1.36	1.39	1.24	9.86	10.24	0.96
491	1.71	1.58	1.40	1.47	1.61	1.55	1.55	1.65	1.73	1.58	12.58	10.92	1.15
587	1.99	1.90	1.77	1.61	1.68	1.73	1.75	1.84	1.98	1.81	14.43	11.38	1.27
719	2.35	2.11	2.05	1.94	1.85	1.91	1.96	2.19	2.27	2.07	16.49	11.90	1.39
777	2.58	2.45	2.26	2.13	2.07	2.12	2.25	2.44	2.50	2.31	18.40	12.38	1.49
922	2.83	2.65	2.54	2.34	2.32	2.34	2.40	2.73	2.76	2.52	20.08	12.80	1.57
1005	2.84	2.72	2.61	2.49	2.45	2.51	2.60	2.80	2.84	2.65	21.12	13.06	1.62

STATION 11 - 12

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter ft.	Hydraulic Radius ft.
193	0.88	0.88	0.90	0.90	0.90	0.86	0.90	0.87	1.05	0.90	7.11	9.46	0.75
362	1.51	1.34	1.34	1.26	1.20	1.23	1.36	1.44	1.55	1.36	10.76	10.38	1.04
401	1.50	1.45	1.38	1.24	1.10	1.43	1.55	1.51	1.59	1.42	11.23	10.50	1.07
491	2.21	2.08	1.89	1.68	1.42	1.57	1.92	2.25	2.22	1.92	15.20	11.50	1.32

STATION 13 - 14

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter ft.	Hydraulic Radius ft.
193	1.22	1.11	1.06	1.12	1.21	1.18	1.13	1.13	1.11	1.14	9.02	9.99	0.90
362	1.73	1.77	1.51	1.55	1.60	1.55	1.56	1.65	1.78	1.63	12.90	10.97	1.18
401	1.71	1.56	1.50	1.46	1.56	1.35	1.36	1.74	1.73	1.55	12.27	10.81	1.14
491	2.26	2.15	1.75	1.80	1.81	1.77	1.72	2.08	2.25	1.95	15.44	11.61	1.33
587	2.25	2.37	1.87	1.87	1.89	1.87	1.89	2.05	2.35	2.05	16.23	11.81	1.37
719	2.62	2.41	2.09	1.89	1.93	1.83	2.10	2.32	2.39	2.18	17.26	12.07	1.43
777	2.53	2.57	2.47	2.16	2.10	2.16	2.30	2.42	2.45	2.35	18.61	12.41	1.50
922	2.81	2.66	2.52	2.52	-	-	-	-	-	2.63	20.83	12.97	1.60

STATION 15 - 16

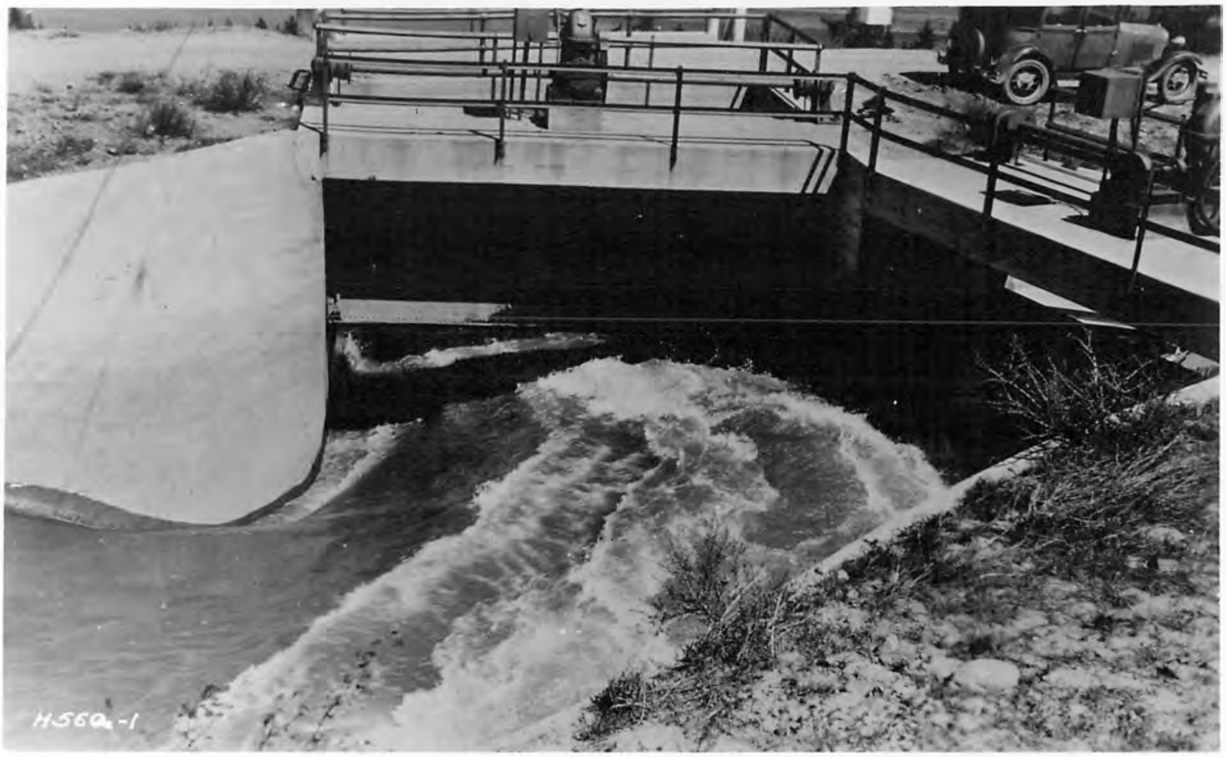
Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter ft.	Hydraulic Radius ft.
193	1.09	1.21	1.11	1.14	1.21	1.06	1.15	1.23	1.17	1.15	9.06	10.02	0.90
362	1.67	1.72	1.55	1.56	1.66	1.53	1.48	1.75	1.76	1.63	12.85	10.98	1.17
401	1.48	1.58	1.45	1.63	1.54	1.42	1.40	1.58	1.54	1.51	11.90	10.74	1.11
491	1.93	1.98	1.74	1.86	1.87	1.67	1.72	1.99	1.90	1.85	14.59	11.42	1.28
587	2.13	2.11	1.92	2.07	2.05	1.98	1.90	2.15	2.08	2.04	16.09	11.80	1.36
719	2.29	2.29	2.13	2.07	2.27	2.16	2.16	2.34	2.36	2.23	17.59	12.18	1.44
777	2.61	2.54	2.24	2.36	2.46	2.31	2.35	2.67	2.62	2.46	19.40	12.64	1.53
922	2.68	2.87	2.63	2.74	2.66	2.65	2.65	2.80	2.87	2.73	21.54	13.18	1.63
1005	3.03	2.85	-	-	-	-	-	-	-	2.94	23.20	13.60	1.71

STATION 17 - 18

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter ft.	Hydraulic Radius ft.
362	1.51	1.45	1.46	1.50	1.58	1.54	1.54	1.59	1.58	1.53	12.04	10.75	1.12
401	1.49	1.46	1.48	1.52	1.54	1.48	1.41	1.48	1.45	1.48	11.64	10.65	1.07
491	1.90	1.83	1.80	1.83	1.91	1.82	1.83	1.84	1.95	1.84	14.49	11.37	1.27
[illegible]	2.06	2.20	2.25	2.17	2.24	2.15	2.15	2.27	2.47	2.22	17.48	12.13	1.44
719	2.41	2.17	2.43	2.26	2.35	2.38	2.37	2.48	2.66	2.39	18.82	12.47	1.51
777	2.61	2.70	2.70	2.59	2.68	2.59	2.44	2.52	2.76	2.62	20.64	12.93	1.60
922	2.74	2.84	3.02	2.97	2.94	2.94	2.85	2.91	2.95	2.91	22.93	13.51	1.70
1005	2.69	2.91	2.99	3.04	3.13	2.93	2.96	2.72	2.79	2.91	22.93	13.51	1.70

STATION 19 - 20

Discharge Second-feet	0	1	2	3	4	5	6	7	8	Mean Depth D ft.	Flow Area ft.^{2}	Wetted Perimeter ft.	Hydraulic Radius ft.
362	1.59	1.57	1.54	1.52	1.49	1.38	1.45	1.52	1.56	1.51	12.02	10.80	1.11
401	1.40	1.61	1.50	1.46	1.41	1.42	1.11	1.20	1.50	1.40	11.14	10.58	1.05
491	1.92	1.79	1.73	1.65	1.66	1.68	1.74	2.01	1.99	1.80	14.33	11.38	1.26
587	2.33	2.09	2.16	2.12	1.90	1.95	1.87	2.09	2.05	2.06	16.41	11.90	1.38
719	2.56	2.42	2.32	2.27	2.25	2.25	2.18	2.27	2.46	2.33	18.56	12.44	1.49
777	2.57	2.64	2.67	2.63	2.56	2.52	2.59	2.69	2.59	2.61	20.80	13.00	1.60
1005	2.95	2.96	2.96	2.88	3.00	2.84	2.83	2.80	2.77	2.89	23.03	13.56	1.70



A. Wasteway entrance. Discharge 922 second-feet.

B. Wave in upper section of wasteway caused by entrance condition. Discharge 922 second-feet.

A. Flow conditions on 10°-12' slope. Discharge 777 second-feet.

B. Flow conditions on 33°-10' slope. Discharge 922 second-feet a discharge of 193 second-feet, they were not periodic. At times two would pass in one second and then a lapse of two or more seconds would occur before another was observed. The average rate of occurrence of these waves at electrode no. 20 for the same discharge was one every 1.6 seconds. Observation and study of the motion pictures showed that the velocity of these waves was considerably greater than the velocity of the intermediate water (plate 7-A & B). The front of the wave was nearly vertical, while the back had a long slope that extended almost to the front of the succeeding wave. The wave front was almost a straight line perpendicular to the direction of flow. The cause of the waves was not definitely observed but the conclusions are that the friction in the fluid being less than that between the fluid and the solid chute caused the upper part of the flow to slide over the lower part and thus attain a higher velocity. This high velocity water overtakes the water flowing at a lower velocity and tends to pile up forming waves. The mechanics of these waves is similar to that of a hydraulic jump. The waves made it difficult to get an average depth of flow for the discharges at which they occurred. Observations were made at the crest of the wave and at an intermediate point and the mean of these readings considered as the depth of flow. Observations of depth for the 89 second-foot discharge have been omitted from the table except for the upper two stations. The magnitude and rate of occurrence of the waves at stations farther down the channel rendered the observations doubtful. It will also be noted that the data is not complete for stations 11-12, 13-14, 15-16. As has been mentioned before, adverse conditions due to spray negated completion of the data (plate 6).

20. Results of velocity measurements. The velocities as calculated from the oscillograms and measurements made in the wasteway are given in Table 2. It was very difficult to read the time interval from the oscillograms for the ten-foot electrode stations and the error involved was high, therefore 90, 100, and 110-foot sections were used almost entirely for determining the velocities. It may be noted in the table that the observed velocities vary as much as 25 percent when measured over the same reach with an apparent constant discharge. The average variation is approximately 7 percent. There are several factors which contribute to this difference in observed velocity. Visual observations and a study of the motion pictures show definite pulsations of velocity in the flow (plate 7-B & C). The apparatus used was evidently sensitive to these pulsations and one record was made of the high-velocity mass while another was made at some lower velocity. Some of the variation was undoubtedly caused by slight errors in reading the oscillograms. The records were not obvious and some deliberation was necessary to determine in each case the exact elapsed time required for the salt to pass over a known distance. In fact velocities could not be satisfactorily determined from some of the records.

OBSERVED VELOCITY

SLOPE 10° - 12'

Distance from Electrode No. 1	0	10'	100'	110'	200'	210'	300'	310'	400'	410'
Number of Electrode	1	2	3	4	5	6	7	8	9	10

Numbers in parentheses are the observed velocities in feet per second. Numbers to right and left of each observed velocity indicate the electrodes between which the velocity was measured.

Discharge Second-feet									
89	1	(35.4)	3	(33.9)	5				
			3	(34.0)	5				
193	1	(37.8)	3	(37.0)	5	(39.1)	9		
					5	(37.8)	7		
362	1	(46.2)	3	(50.3)	5	(51.3)	8	(61.0)	9
	1	(53.4)	3	(54.6)	5	(47.5)	8	(61.7)	9
401	1	(46.8)	3	(53.0)	5				
	1	(46.3)	3	(51.4)	5				
491	1	(52.2)	3	(48.6)	5	(54.4)	8		
			3	(56.0)	5	(56.4)	8		
			3	(51.4)	5	(57.4)	9		
587	1	(55.2)	3	(54.7)	5	(57.5)	7	(62.7)	9
			3	(58.3)	5	(61.0)	7	(65.9)	9
					5	(57.3)	7	(64.0)	9
719	1	(57.9)	3	(57.7)	5	(51.2)	7	(69.5)	9
	1	(57.6)	3	(56.2)	5	(62.0)	7	(67.4)	9
					5	(70.1)	7	(63.6)	9
777	1	(64.6)	3	(62.2)	5	(63.1)	7	(63.0)	9
			3	(64.1)	5	-	7	(64.4)	9
922	1	(72.6)	3	(74.6)	5	(66.1)	7	(68.0)	9
	1	(61.0)	3	(64.9)	5	(60.3)	7	(68.7)	9
			3	(60.7)	5	-	7	(64.7)	9
1005	1	(72.2)	3	(63.4)	5	(72.3)	7	(67.0)	9
	1	(74.2)	3	(71.3)	5	(68.8)	7	(63.5)	9
					5	(66.7)	7	(67.1)	9

SLOPE 33° - 10'

Distance from Electrode No. 11	0	10'	100'	110'	200'	210'
Number of Electrode	11	12	13	14	15	16

Numbers in parentheses are the observed velocities in feet per second. Numbers to right and left of each observed velocity indicate the electrodes between which the velocity was measured.

Discharge Second-feet							
193			12	(55.3)	14	(66.1)	16
			12	(51.4)	14	(67.0)	15
			12	(57.1)	14		
362	11	(78.8)	14	(69.9)	15		
	11	(67.9)	14	(70.3)	15		
			12	(71.0)	14	(65.4)	16
401	11	(74.5)	13	(81.0)	16		
	11	(74.4)	13	(78.8)	16		
			13	(72.5)	16		
491			12	(73.2)	13	(83.6)	15
	11	(79.1)	13	(79.7)	15		
			12	(77.0)	14	(76.3)	16
587	11	(83.9)	13	(79.4)	15		
	11	(79.0)	13	(82.8)	15		
	11	(74.9)	13	(83.8)	16		
			13	(86.1)	15		
719	11	(95.8)	13	(93.4)	16		
	11	(88.2)	13	(80.7)	16		
			13	(82.2)	15		
777	11	(81.7)	13	(116.8)	16		
			13	(106.2)	15		
922			12	(85.3)	13	(93.4)	15
			12	(96.2)	13	(92.5)	15
			12	(87.5)	14	(85.1)	16
1005,			12	(113.1)	15		
			12	(93.1)	15		
					13	(101.3)	15
					13	(102.7)	15
					14	(92.0)	16

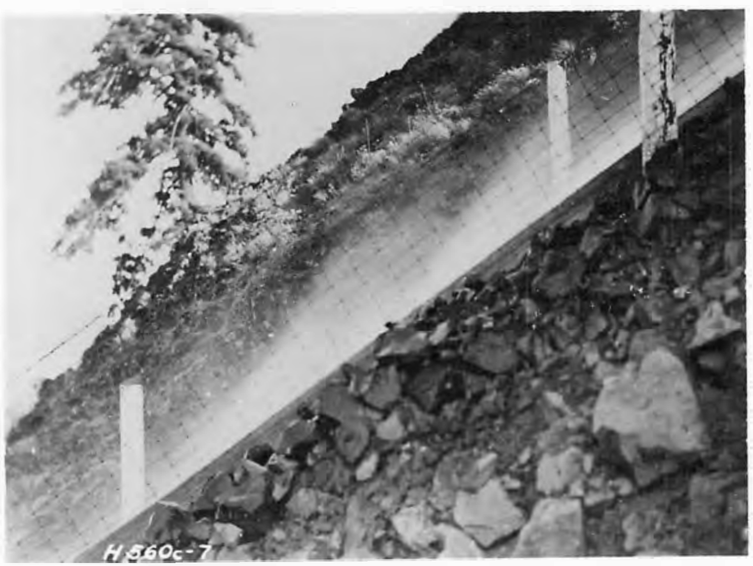
SLOPE 0°- 04'

Distance from Electrode No. 17	0	10'	40'	50'
Number of Electrode	17	18	19	20

Numbers in parentheses are the observed velocities in feet per second. Numbers to right and left of each observed velocity indicate the electrodes between which the velocity was measured.

Discharge Second-feet			
362	18	(42.2)	20
	18	(44.0)	20
	18	(42.2)	20
491	17	(73.8)	20
	17	(59.6)	20
	18	(56.3)	20
587	17	(41.8)	19
	17	(56.2)	20
	17	(74.9)	20
719	17	(83.9)	20
	17	(74.4)	20
	17	(71.3)	19
777	17	(71.4)	19
	17	(62.7)	19
922	17	(72.7)	20
	18	(69.5)	20
1005	17	(77.2)	20
	18	(68.6)	20

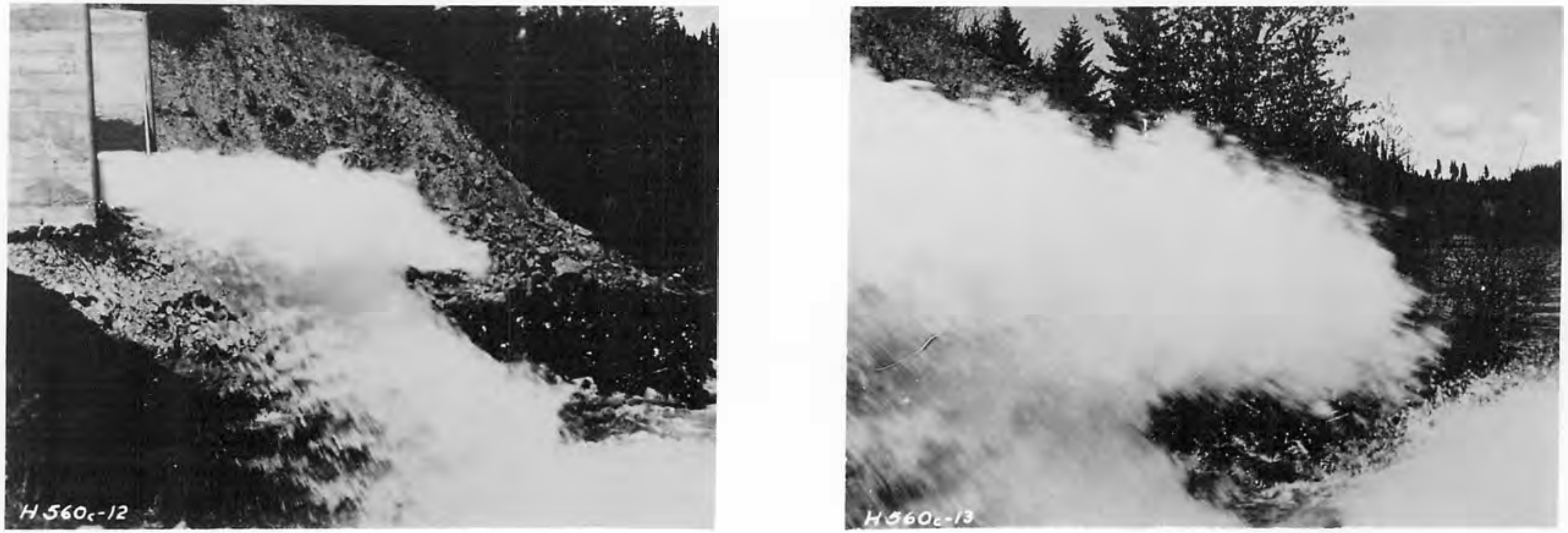
A. Discharge 922 second-feet.



Discharge 1,005 second-feet.

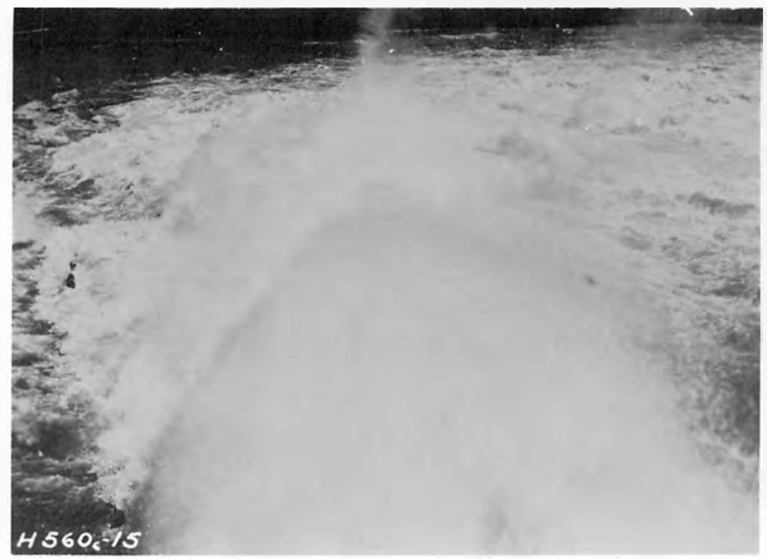
FLOW CONDITIONS AT CHANGE IN GRADE

PLATE 6



A. Discharge 89 second-feet.

B. Discharge 491 second-feet.



C. Discharge 777 second-feet.

JET FROM WASTEWAY ENTERING YAKIMA RIVER

PLATE 7

This accounts for the blank spaces in the table. A large amount of this discrepancy could be eliminated by further improvement of the equipment and technique. Several of the electrodes were damaged and a few were broken off and carried away by the combined action of the high velocity water and rocks and pebbles in the flow. The bent electrodes altered the distance between stations but since comparatively long reaches were used for the actual velocity determinations the error introduced from this source was small. The behavior of the salt cloud as it travels down the wasteway is a subject about which little is known. It may travel from side to side as it progresses down the chute. This inference was gathered from observation of the electrodes after the completion of the tests. It was noted that the electrodes suffered more damage and the concrete showed more erosion on the left wall of the wasteway at one station while at the next station downstream the damage and erosion was on the opposite wall. Such action, although not a symmetrical zigzag pattern, was noted throughout the length of the wasteway. It is possible that some portion of the salt cloud travels continuously in the high velocity center flow and it is this portion which causes the initial deflection of each galvanometer. If this is true the measured velocities are the maximum velocities. The velocities observed between electrode stations 1 and 3, with a discharge of 1005 second-feet, are slightly above the mean velocity calculated from $V = \sqrt{2gh}$. The value of h used was the difference in elevation between the water surface in the canal and the water surface at a point midway between the two stations. No entrance loss or loss due to friction was assumed. These are the only two observed velocities that exceed the velocity calculated by the above formula. Since both observations made under the same conditions exceed the theoretical velocity, it may be that the results were influenced by some unknown factor. It may also indicate that the measured velocity is the maximum velocity in the flow. It has been shown that as the velocity increases in pipes, the maximum velocity approaches the mean cross-sectional velocity in magnitude. This may be assumed to apply in the case of an open channel until further study proves otherwise. The measured velocities are therefore assumed to be mean cross-sectional velocities. Other sources of error, although very small, lie in the fact that the spots from all the elements in the oscillograph cannot be adjusted to lie exactly on a line perpendicular to the center line of the film and the rotation constants of the elements are not identical. Each element deflects slowly at first but with rapidly increasing velocity, partly because the current is increasing and partly because of its own inertia. Hence it is difficult to determine on the film the exact time that a deflection starts. These sources of error are so small that they were considered negligible for the type of work being done.

21. Entrained air. The computed entrained air in percent of total volume of flow is given in Table 3. Station (1-3) refers to the reach between electrode 1 and electrode 3; station (3-5) refers to the reach from electrode 3 to electrode 5, etc. (see figure 1). It is well to emphasize the note (table 3) referring to the calculations for air content on 33° - 10' slope. Because of unavoidable circumstances, water surface readings were not taken at the point gage station 11-12 for discharges above 491 second-feet. Also the observations are not complete for the two high discharges at the next two stations below. Therefore the depth and hence the air content are considered to be that found at the lower stations. The mean depths, hydraulic radii and velocities refer to the mean of all such measurements taken at the ends of and within each reach. In that portion of the table applicable to the 10° - 12' slope, if the two lower discharges are disregarded because of the traveling wave type of flow and particular observation made of the velocities prevailing for discharges 362 to 719 second-feet, inclusive, there appears to be an increase in velocity for each discharge as the flow progresses downstream. This is not apparent for the three higher discharges. This condition may be only a result of errors or velocity fluctuations but seems to be too consistent for that. It may be that for intermediate discharges, constant flow conditions had not been reached in the transition section but for the higher discharges such a condition did prevail. The water-surface measurements show an almost constant depth for each discharge throughout this section of the wasteway. Another reason that the water surface measurements do not agree with the trends shown by the velocity measurements is because the point gage readings covered a considerable period of time and represent the average water surface over this period while the salt cloud employed to measure velocity represents a localized section of the flow and may attain a velocity associated with a single velocity fluctuation. For the high discharges on the 10° - 12' slope and for all discharges on the 33° - 10' slope, there is no consistent increase of velocity for a given discharge and slope as the flow progresses down the wasteway. Hence it is logical to assume that uniform flow conditions prevail. This is not true for the flat slope at the lower end of the wasteway. Here the flow was decelerating and is consequently nonuniform.

22. Summary of all tests on chutes. A summary of all data on air content in chutes is given in Table 4. Information is only given on chutes in which the data is complete. In order to determine the volume of air, the quantity, the velocity, and the area of the cross section must be measured. Other data have been found but in most instances only two of these values

TABLE 3

SLOPE 10° - 12'

Discharge Q Second-feet	Station	Mean Depth D feet	Mean Area A ft.^{2}	Mean Hydraulic Radius R feet	Mean Observed Velocity V ft./sec.	$\frac{Q}{AV}$	Air Content Percent
89	(1-3)	0.49	3.88	0.44	35.4	0.64	36
	(3-5)	0.50	3.96	0.45	34.0	0.66	34
193	(1-3)	0.80	6.35	0.68	37.8	0.80	20
	(3-5)	0.81	6.44	0.68	37.0	0.81	19
	(5-7)	0.83	6.55	0.70	37.8	0.78	22
	(5-9)	.82	6.48	0.69	39.1	0.76	24
362	(1-3)	1.25	9.90	0.96	49.8	0.73	27
	(3-5)	1.25	9.95	0.96	52.5	0.69	31
	(5-8)	1.24	9.85	0.96	49.4	0.74	26
	(8-9)	1.24	9.84	0.96	61.3	0.60	40
401	(1-3)	1.26	10.06	0.98	60.6	0.66	14
	(3-5)	1.26	9.98	0.97	52.2	0.77	23
491	(1-3)	1.54	12.37	1.14	52.2	0.76	24
	(3-5)	1.55	12.30	1.13	52.0	0.77	23
	(5-8)	1.56	12.36	1.14	55.4	0.72	28
	(5-9)	1.56	12.43	1.15	57.4	0.69	31
587	(1-3)	1.80	14.32	1.26	55.2	0.74	26
	(3-5)	1.80	14.33	1.26	56.5	0.73	27
	(5-7)	1.79	14.28	1.26	58.6	0.70	30
	(7-9)	1.80	14.36	1.26	54.3	0.75	25
719	(1-3)	2.02	16.11	1.36	57.8	0.77	23
	(3-5)	2.03	16.12	1.37	57.0	0.78	22
	(5-7)	2.05	16.33	1.38	61.1	0.72	28
	(7-9)	2.07	16.49	1.39	66.8	0.65	35
777	(1-3)	2.24	17.87	1.45	64.6	0.67	33
	(3-5)	2.22	17.68	1.45	63.2	0.70	30
	(5-7)	2.21	17.58	1.44	63.1	0.70	30
	(7-9)	2.26	17.97	1.46	63.7	0.68	32
922	(1-3)	2.52	20.02	1.56	66.8	0.69	31
	(3-5)	2.49	19.79	1.55	66.7	0.70	30
	(5-7)	2.50	19.84	1.55	63.2	0.74	26
	(7-9)	2.51	19.96	1.56	67.1	0.69	31
1005	(1-3)	2.70	21.50	1.63	73.2	0.64	36
	(3-5)	2.65	21.11	1.62	67.4	0.71	29
	(5-7)	2.66	21.15	1.62	69.3	0.69	31
	(7-9)	2.66	21.19	1.62	65.9	0.68	32

SLOPE 33° - 10'

Discharge Q Second-feet	Station	Mean Depth D feet	Mean Area A ft.^{2}	Mean Hydraulic Radius R feet	Mean Observed Velocity V ft./sec.	$\frac{Q}{AV}$	Air Content Percent
193	(12-14)	1.02	8.07	0.83	54.6	0.44	56
	(14-16)	1.14	9.04	0.90	60.1	0.32	68
	(14-15)	1.14	9.04	0.90	57.0	0.32	65
362	(11-14)	1.50	11.83	1.11	73.3	0.42	58
	(12-14)	1.50	11.83	1.11	71.0	0.43	57
	(14-15)	1.63	12.80	1.17	70.1	0.40	60
	(14-16)	1.63	12.80	1.17	65.4	0.43	57
401	(11-13)	1.49	11.75	1.11	74.4	0.46	54
	(13-16)	1.53	12.08	1.12	77.4	0.42	58
491	(12-13)	1.94	15.32	1.32	73.2	0.44	56
	(11-13)	1.94	15.32	1.32	79.1	0.41	59
	(12-14)	1.94	15.32	1.32	77.0	0.44	56
	(13-15)	1.90	15.02	1.30	81.6	0.40	60
	(14-16)	1.90	15.02	1.30	75.3	0.43	57
587	(11-13)	2.05*	15.23*	1.37	79.3	0.42	54
	(13-15)	2.05	15.16	1.37	82.6	0.44	56
	(13-16)	2.05	15.16	1.37	83.8	0.43	57
719	(11-13)	2.18*	17.25*	1.43	92.0	0.45	55
	(13-15)	2.20	17.42	1.43	82.2	0.50	50
	(13-16)	2.20	17.42	1.43	87.1	0.47	53
777	(11-13)	2.35*	18.61*	1.50	81.7	0.51	49
	(13-16)	2.40	19.00	1.51	111.5	0.37	63
922	(12-13)	2.63*	20.83*	1.60	90.8	0.49	52
	(12-14)	2.63*	20.83*	1.60	87.5	0.51	49
	(13-15)	2.68	21.26	1.61	93.0	0.47	53
	(14-16)	2.68	21.26	1.61	85.1	0.51	49
1005	(12-15)	-	-	-	103.1	-	-
	(13-15)	-	-	-	102.0	-	-
	(14-16)	2.94*	23.20*	1.71	92.0	0.47	53

* Point gage readings made only at the end of the section on account of spray.

SLOPE 0° - 04'

Discharge Q Second-feet	Station	Mean Depth D feet	Mean Area A ft.^{2}	Mean Hydraulic Radius R feet	Mean Observed Velocity V ft./sec.	$\frac{Q}{AV}$	Air Content Percent
362	(18-20)	1.52	12.03		42.8	0.70	30
491	(17-20)	1.82	14.41		66.7	0.51	49
	(18-20)	1.82	14.41		56.3	0.60	40
587	(17-19)	2.14	16.95		41.8	0.83	27
	(17-20)	2.14	16.95		60.6	0.57	43
719	(17-19)	2.36	18.69		71.3	0.54	46
	(17-20)	2.36	18.69		73.2	[illegible]	51
777	(17-19)	2.61	20.76		67.1	0.56	44
922	(17-20)	2.91	22.93		72.7	0.55	45
	(18-20)	2.91	22.93		69.5	0.57	43
1005	(17-20)	2.90	22.98		77.2	0.57	43
	(18-20)	2.90	22.98		68.6	0.64	36

have been determined and the third calculated from the formula $Q = AV$. Generally the discharge was calculated from measured cross-section and measured velocity. This, of course, gives a quantity that includes the air and hence is in excess of the true water volume. For this reason numerous experimenters have found a value for "n" for Manning's formula that is very close to that expected, whereas if the actual water discharge were used, some other value might have been found. Only those data based on measured values of all three factors have been included in the table. It is possible that some of the observations were made in regions where stable flow conditions had not been attained. The data under number 26 undoubtedly belongs in this class. Observations and pictures show that at this location, white flow prevailed only near the sides of the structure while the center portion of the flow was darker colored. The data under number 27 was taken on a slope preceded by a steeper slope (No. 26). A comparison of the measured velocities indicates that the flow was decelerating at this section. Other data may have been influenced by similar conditions but details are not available.

23. Velocity of flow in chutes. In attempting to establish some relationship between the hydraulic factors in a channel, an equation based on the analysis of observed data must be established. Ehrenberger found

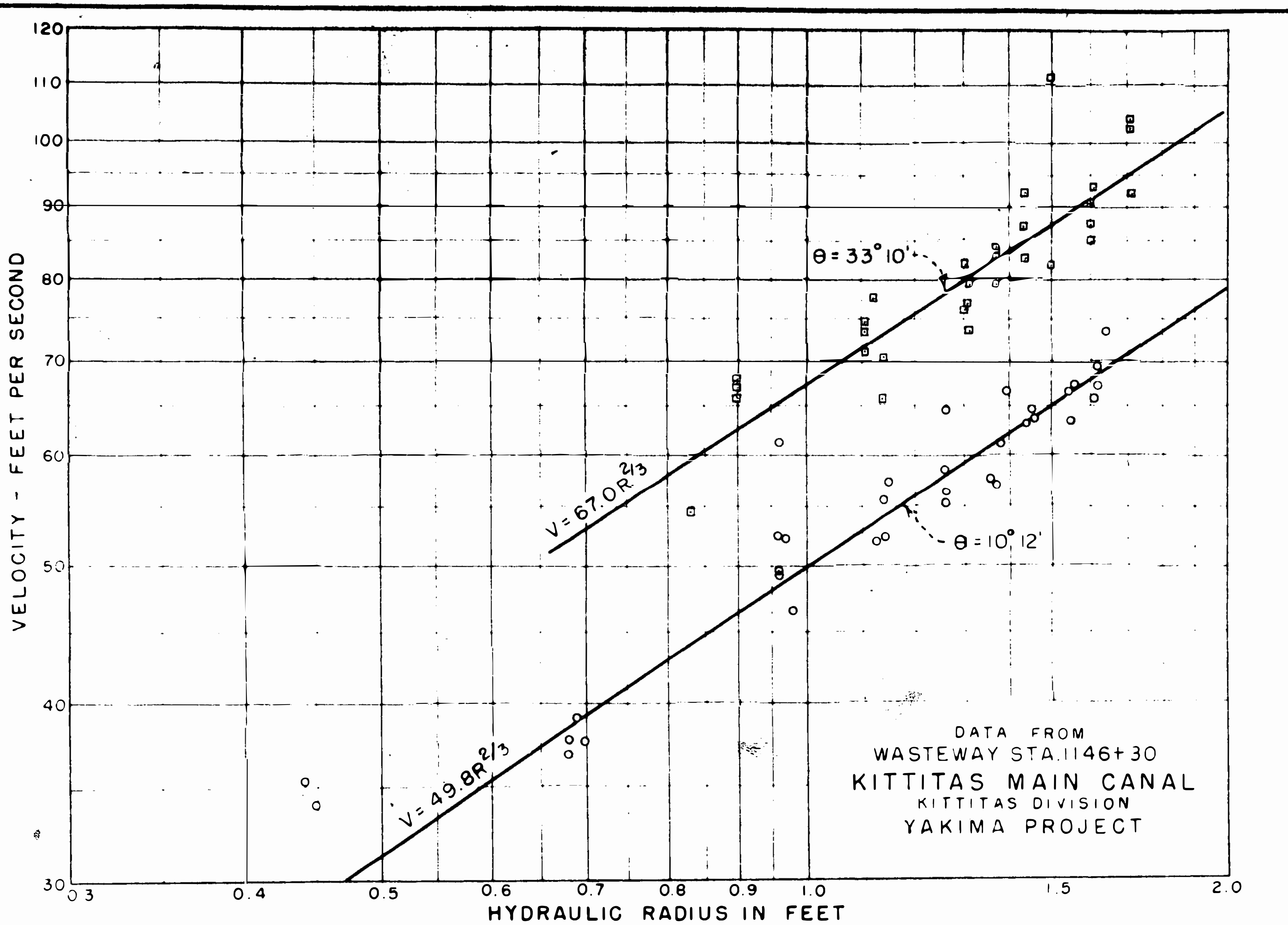
$$V = 97\, R^{0.52} (\sin \theta)^{0.4}$$

This relation was established by model tests made in a wooden chute 0.82 feet wide. The depth varied from 0.048 to 0.161 feet and the hydraulic radius from 0.043 to 0.116 feet. Experiments reported by Ehrenberger on the Ruetz wasteway in Austria show that the velocity varies with $R^{0.53}$. The bottom width of this wasteway was 8.2 feet. The depth for the flows varied from 0.10 to 0.74 feet and the hydraulic radius from 0.097 to 0.640 feet. This wasteway had a wooden lining. Data from this same wasteway reported by Schoklitsch give depths from 0.31 to 0.94 feet and hydraulic radii from 0.29 to 0.79 feet. They showed no consistent relationship between V and R. The experiments made by Steward in 1913 do not show a consistent relationship to exist between velocity and hydraulic radius. The experiments on the Kittitas wasteway covered depths from 0.5 to 2.9 feet and hydraulic radii from 0.5 to 1.7 feet. The data on velocity and hydraulic radius for these tests have been plotted on logarithmic paper and a straight line drawn through the points pertaining to each slope (figure 2). The equations of those lines are:

TABLE 4

COMPILATION OF EARLIER CHUTE MEASUREMENTS

	Discharge Q Second-Feet	Depth d Feet	Hydraulic Radius Feet	Measured Velocity V_1 Ft./Sec.	$\frac{Q}{AV}$ Percent Water
1. Ehrenberger's Model	0.353	0.057	0.050	9.61	79.0
Chute I – Wood	0.706	0.090	0.074	11.94	79.0
Width = 0.82 foot	1.09	0.123	0.094	13.29	80.7
Sin θ = 0.153	1.57	0.161	0.116	14.53	80.1
2. Ehrenberger's Model	0.353	0.054	0.048	10.24	77.0
Chute II – Wood	0.706	0.087	0.072	13.06	75.0
Width = 0.82 foot	1.09	0.120	0.093	14.70	75.0
Sin θ = 0.202	1.57	0.156	0.113	16.04	75.8
3. Ehrenberger's Model	0.353	0.051	0.045	11.48	72.9
Chute III – Wood	0.706	0.082	0.068	14.47	71.6
Width = 0.82 foot	1.09	0.115	0.090	16.31	70.4
Sin θ = 0.305	1.57	0.151	0.111	17.55	70.7
4. Ehrenberger's Model	0.353	0.048	0.043	13.22	67.5
Chute IV – Wood	0.706	0.079	0.066	16.80	64.4
Width = 0.82 foot	1.09	0.112	0.088	18.73	63.1
Sin θ = 0.444	1.57	0.148	0.109	20.18	63.5
5. Ehrenberger's Model	0.353	0.052	0.047	15.78	51.3
Chute V – Wood	0.706	0.085	0.071	19.46	51.2
Width = 0.82 foot	1.09	0.118	0.092	21.85	51.0
Sin θ = 0.606	1.57	0.156	0.113	23.62	51.3
6, 7, & 8. Rusts Wasteway	17.7	0.10	0.097	23.6	64
Trapezoidal – Wood	28.3	0.16	0.157	32.2	44
Bottom width = 8.2 feet	120.0	0.49	0.446	56.1	39
Side slopes = 1.5 on 1					
Sin θ = 0.606	27.9		0.210	35.5	41
(Adjusted values of d,	36.0		0.272	40.8	38
and V as given by	52.3		0.361	47.2	37
Ehrenberger)	129.2		0.512	57.0	40
	32.8	0.26	0.249	39.6	37
	56.6	0.38	0.348	48.2	37
	62.5	0.39	0.364	47.9	37
	70.3	0.45	0.407	51.2	38
	151.9	0.74	0.640	62.3	43
9. Rusts Wasteway – Wood	36	0.31	0.29	68.6	20
Data from Schoklitsch:	52	0.36	0.33	65.9	25
	56	0.46	0.42	53.5	27
Stauverlandung und	98	0.45	0.41	70.2	39
Kolkabwehr	132	0.84	0.72	70.2	25
	159	0.94	0.79	70.2	27
	191	—	—	70.2	64
10. Dago					
Sin θ = 0.246	49.1	0.64	0.46	33.1	64
b ... = 3.28 feet	26.1	0.43	0.34	28.2	66
11. Benkok					
Sin θ = 0.602	211.9	2.20	0.94	77.1	38
b ... = 3.28 feet	102.4	1.21	0.70	67.2	38
12. Kallnitz – Trapezoidal:					
Sin θ ...... = 0.408	166.0	1.23	0.92	68.6	—
Bottom width=6.56 feet	134.2	1.15	0.88	63.0	—
13. Fargo Drop – Wood					
Sin θ = 0.124	95.0	0.57	0.48	32.3	86
b ... = 6.0 feet					
14. Mora Wasteway – Concrete					
Sin θ = 0.081	27.5	0.32	0.28	22.0	78
b ... = 5.0 feet					
15. Valley Mound Chute – Concrete					
Sin θ = 0.156	22.4	0.27	0.22	26.3	63
b ... = 5 feet					
16. Arena Chute – Concrete					
Section 1: Sin θ = 0.202	23.26	0.24	0.22	20.4	79
b ... = 6 ft.					
17. Arena Chute – Concrete					
Section 2: Sin θ = 0.151	23.26	0.22	0.21	19.6	90
b ... = 6 ft.					
18. Arena Chute – Concrete					
Sin θ = 0.206	50.40	0.32	0.29	29.4	89
b ... = 6 feet					
19. Lizard Chute No. 1 –	0.44	0.04	0.04	4.97	73
Concrete	2.04	0.11	0.10	9.33	66
Sin θ = 0.082	2.80	0.12	0.11	10.9	71
b ... = 3 feet	5.72	0.17	0.16	14.3	72
	7.97	0.24	0.21	14.2	78
	16.42	0.36	0.29	19.2	79
20. Lizard Chute No. 2 –	0.44	0.05	0.05	6.9	42
Concrete	2.04	0.10	0.09	7.8	87
Sin θ = 0.194	2.80	0.10	0.10	11.1	85
b ... = 3 feet	5.72	0.16	0.14	19.8	60
	7.97	0.21	0.18	16.0	80
	16.42	0.31	0.26	23.8	78
21. Kittitas Wasteway –					
Concrete					
Sin θ = 0.547	231	0.80	0.67	52.2	69
b ... = 8 feet	484	1.3	0.98	66.0	70.5
(Measurements made down-stream from chute)					
22. Hammerhill Flume – Metal					
Canadian Pacific Ry.					
Alberta, Canada	61.0	—	0.573	27.5	85
Sin θ = 0.057	26.5	—	0.433	18.6	88
b ... = 5.10 feet					
23. Dalroy Flume – Metal					
Canadian Pacific Ry.					
Alberta, Canada	59.2	—	0.993	15.2	54
Sin θ = 0.032	151.4	—	1.311	17.6	76
b ... = 10.2 feet					
24. Lateral C-11 Flume – Wood					
Canadian Pacific Ry.					
Alberta, Canada					
Sin θ = 0.052	1.24	—	0.107	9.82	99
b ... = 0.9 foot					
25. Secondary Canal – Wood					
Canadian Pacific Ry.					
Alberta, Canada	6.16	—	0.155	9.25	95
Sin θ = 0.025					
b ... = 4.18 feet					
26. South Canal Chute					
Milepost 2 – Concrete	382	1.15	0.98	40.24	87
Uncompahgre Project	465	1.30	1.07	38.17	99
Sin θ = 0.275					
Trapezoidal					
Bottom width=8.84 feet					
27. South Canal Chute					
Milepost 2 – Concrete					
Uncompahgre Project	267	1.06	0.87	28.13	103
Section 2	400	1.39	1.09	31.93	102
Sin θ = 0.070	463	1.53	1.17	32.58	104
Trapezoidal					
Bottom width=8.47 feet					


VELOCITY - FEET PER SECOND
120
110
100
90
80
70
60
50
40
30
HYDRAULIC RADIUS IN FEET
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.5
2.0
θ = 33° 10'
V = 67.0 R^2/3
θ = 10° 12'
V = 49.8 R^2/3
DATA FROM
WASTEWAY STA.1146+30
KITTITAS MAIN CANAL
KITTITAS DIVISION
YAKIMA PROJECT

FIGURE

$$V = 49.8\, R^{2/3} \text{ where } \theta = 10^\circ\ 12' \qquad (1)$$

$$V = 67.0\, R^{2/3} \text{ where } \theta = 33^\circ\ 10' \qquad (2)$$

It might be said that the exponent of R increases as R is increased if Ehrenberger's formula, the data from Ruetz wasteway, and the data from Kittitas wasteway are considered. However, the data are too meager to place a great deal of weight upon this relationship without further experimentation. Since the experiments on the Kittitas wasteway include only two slopes, it is not considered advisable to determine a relation such as Ehrenberger's between V and sin θ for R constant. However, if we assume the velocity to be an exponential function of the hydraulic radius and compute the exponent using only the two values of sin θ and include this function in a general formula, we have

$$V = 81.0\, R^{2/3} (\sin \theta)^{0.266}$$

By comparing this with Ehrenberger's formula it appears that as the hydraulic radius increases, the exponent of R increases and the exponent of sin θ decreases. This statement should not be considered as final because of the small amount of data upon which to base a conclusion. The fact that this exponent of R agrees with the exponent of R in Manning's formula suggested that "n" be computed for uniform flow in steep chutes, the loss of head per unit length of flow is expressed by sin θ, where θ is the angle of inclination of the bottom with respect to the horizontal. Thus Manning's formula for steep slopes becomes

$$V = \frac{1.486}{n} R^{2/3} (\sin \theta)^{1/2} \qquad (3)$$

Computing "n" using equations (1), (2), and (3) we find:

$n = 0.0126$ ($\theta = 10^\circ - 12'$)
$n = 0.0164$ ($\theta = 33^\circ - 10'$)

This would indicate that the value of "n" increases with the slope but this conclusion is not logical since the value of "n" is assumed to depend upon the roughness of the channel. The value of "n" for the 10° 12' slope is what might be expected but the "n" for 33° 10' slope is high for the type of material in the channel. Hence, we may assume that Manning's formula is not correct for steep chutes. Here again more data should be considered before making a positive statement.

24. Air content of flow in chutes. Ehrenberger also developed formulas for determining the water portion, μ, in a unit volume of white water. These are:

$$\mu = 0.42\, R^{-0.05} (\sin \theta)^{-0.26} \quad \text{for } \sin \theta < 0.476$$

and

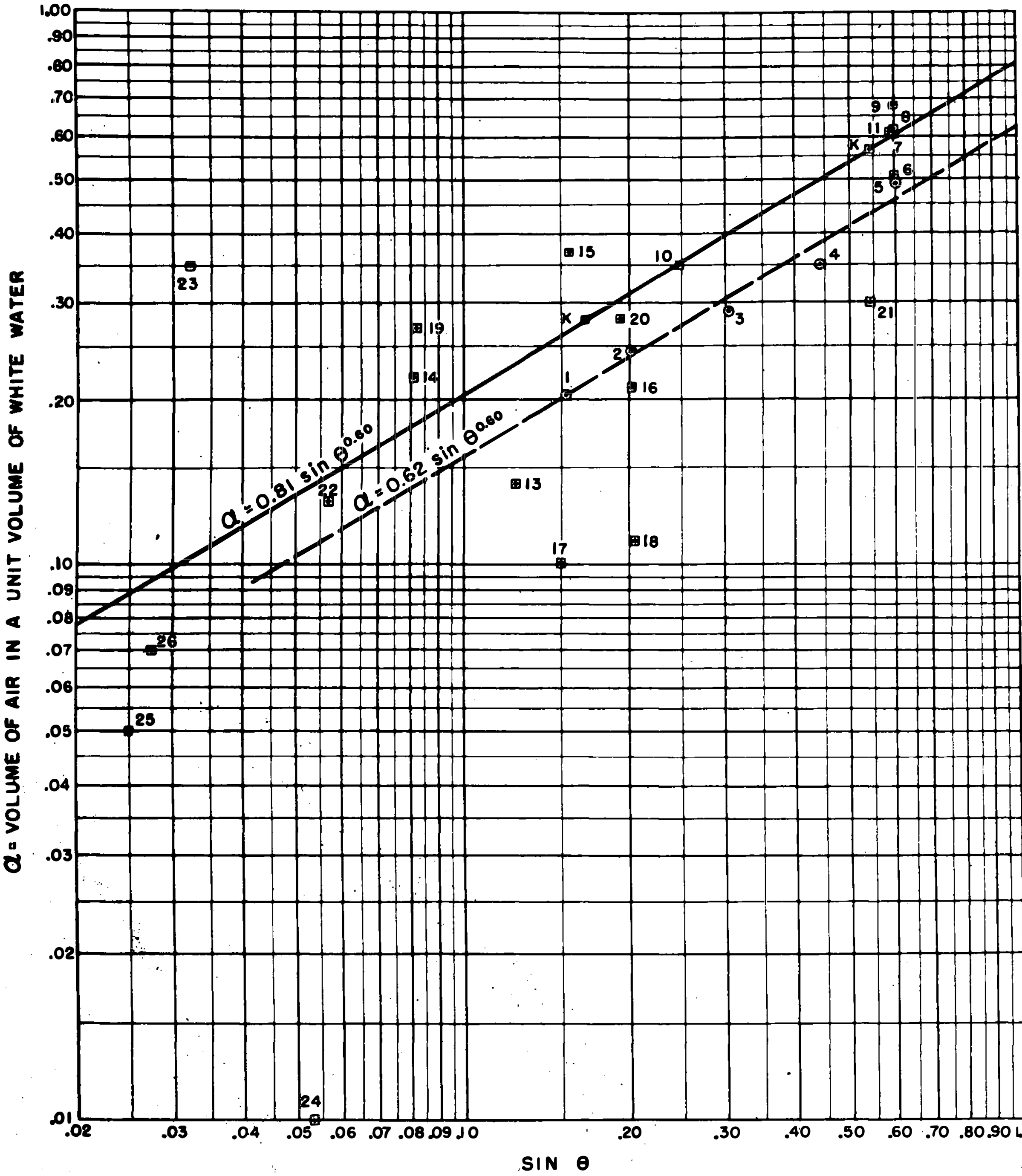
$$\mu = 0.30\, R^{-0.05} (\sin \theta)^{-0.74} \quad \text{for } \sin \theta > 0.476$$

These formulas are based on tests made on five different slopes ranging from $\theta = 8^\circ 49'$ to $\theta = 37^\circ 18'$ and hydraulic radii ranging from 0.043 to 0.116 feet. From the formulas it appears that with equal wall roughness, the slope is the most important factor, and the hydraulic radius, and hence the depth, are only minor factors. A comparison of the velocities and air content observed in the Kittitas wasteway and corresponding values calculated by Ehrenberger's formulas are given in Table 5. Although the observed and calculated values agree to a certain extent, there is not a consistent relationship. However, when the data are considered collectively for each slope, there is better agreement. The mean air content for each slope of the Kittitas wasteway and the data from table 4 was plotted on logarithmic paper (figure 3). Two parallel lines may be drawn through these points. The equations of these lines are

$$\alpha = 0.81 \sin \theta^{0.6}$$
$$\alpha = 0.62 \sin \theta^{0.6}$$

where α is the volume of entrained air in a unit volume of aerated water. The numbers appearing in the figure correspond to the numbers given the data in table 4. Two lines were drawn because the points representing data from the model chutes did not appear to be closely associated with those from prototype structures. The upper line may be said to represent values from prototype tests, except for the flatter slopes where the points are badly scattered.

25. General discussion of chute data. The flow of water in open channels with high gradients is a moot subject. Difficulties encountered in securing data from such conditions of flow cause the results to be subject to considerable variation. Lack of suitable equipment and structures of sufficient size have retarded progress toward an understanding of the conditions prevailing. Concerted search of literature supplemented by field measurements show that water flowing at high velocity in an open channel does entrain air and the velocities are lower than previously computed or assumed. This statement of course applies only to the type of structures studied. To what extent the conditions may be extrapolated can only be determined by further research. In the experiments on the Kittitas wasteway, the indications were that with the given conditions, a terminal velocity existed. Furthermore, there is no question but that a very large amount of air was entrained. With a flow of 1,005 second-feet on a slope.



θ = Angle of inclination of chute measured from the horizontal.

RELATION OF AIR CONTENT IN FLOW TO SLOPE OF CHUTE

Comparison of Observed Velocity And Air Content with Those Calculated by Ehrenberger's Formulas

SLOPE 10° - 12'
Sin $\theta = 0.177$

Discharge Second-feet	Observed Mean Hydraulic Radius ft.	Observed Mean Velocity ft./sec.	Calculated Velocity ft./sec.	Observed Mean Air content Percent	Calculated Air Content Percent
89	0.45	34.7	32.0	35.0	31.4
193	0.69	37.9	40.0	21.3	32.9
362	0.96	53.3	47.5	31.0	34.0
401	0.97	49.4	47.8	18.5	34.1
491	1.14	54.3	52.0	26.5	34.5
587	1.26	58.7	54.7	27.0	34.9
719	1.38	60.7	57.4	27.0	35.2
777	1.45	63.7	58.9	31.3	35.3
922	1.55	66.0	61.0	29.5	35.5
1005	1.62	69.0	62.4	32.0	35.7

SLOPE 33° - 10'
Sin $\theta = 0.547$

Discharge Second-feet	Observed Mean Hydraulic Radius ft.	Observed Velocity ft./sec. (Mean)	Calculated Velocity ft./sec.	Observed Mean Air Content Percent	Calculated Air Content Percent
193	0.90	62.6	72.2	64.0	52
362	1.17	70.0	82.6	58.0	53
401	1.12	75.9	80.8	56.0	53
491	1.30	77.4	87.3	57.6	54
587	1.37	82.0	89.8	55.7	54
719	1.43	87.1	91.7	52.7	54
777	1.51	96.6	94.4	56.0	54
922	1.61	89.1	97.6	50.8	54
1005	1.71	99.0	100.7	53.0	54

of 10° 12', a maximum mean velocity of 69 feet per second and an air content of 32 percent by volume was found. In a similar manner, on a slope of 33° 10' with a flow of 922 second-feet, a maximum mean velocity of 89 feet per second and an air content of 51 percent was determined. Indications were that stable flow conditions had been reached in each case. The velocity increased with the two-thirds power of the hydraulic radius for values of R between 0.5 and 1.7 feet. For a given discharge with constant flow conditions (R constant) the velocity varied for the two slopes tested as

$$V = K \sin \theta^{0.277}$$

where θ is the angle of inclination of the channel bottom with the horizontal, and K is a constant. Comparing this with earlier experiments, it seems that the exponent of sin θ may decrease as the hydraulic radius increases. The air content in a unit volume of water-air mixture appeared to be dependent on the slope of the channel, hence hydraulic radius and velocity being only minor factors. The relation as determined from the two slopes is

$$\alpha = 0.81 \sin \theta^{0.6}$$

This relation, of course, is tentative since the data from the 33° 10' slope may have been influenced by the fact that the section was preceded by the flatter slope.

26. Mechanics of air-water mixing. The mechanics by which the air enters the water is not known. Personal observations and existing data point to certain factors that influence the air entrainment by the water:

(1) Roughness of the sides and bottom of the channel.
(2) Slope of the channel.
(3) Depth of flow.
(4) Velocity of the flow.
(5) Area of the water surface in contact with the air.
(6) Width of the channel.
(7) Pressure in the flow.

Turbulence in the flow, regardless of the factors that create this condition, is without doubt, of prime importance in mixing and retaining the air in the flow. It may be that a solution to the entire problem may best be obtained from a better understanding of the mechanics of air-water mixture. Theoretical consideration has been given to the development of a means of determining the terminal velocity for accelerating flow. This work is in progress and definite conclusions have not been drawn. Practically all of the data collected to date are applicable to flow in channels. Only one instance can be found where the velocity has been measured at the toe of an overfall dam; those on Madden Dam. No water surface measurements are available, hence the air content of the jet cannot be calculated. To what extent the laws of flow in chutes applies to the flow on the face of a dam have not as yet been determined, principally because of insufficient data. Observation of photographs taken of numerous overfall dams seem to indicate that the jets overflowing structures of this type do not contain air in the quantities observed in narrower channels. This may be because there is not sufficient length of face on the dam to establish constant flow conditions. It may also be due to some relationship between depth and width of the jet to the air content. The entrance conditions may also be an important consideration. Roughness of the channel must not be overlooked as a prime factor contributing to retardation of the flow. For instance an extreme example is a cascade in a mountain stream. Here sizable quantities of flow have been observed to travel down a boulder-strewn bed on a slope of near 45° without attaining any great velocity even after flowing some distance. A terminal velocity apparently has been reached in this instance and the channel bed is the governing factor. Visual observations of water falls supplemented by slow-motion pictures show that the jet disintegrates rapidly after leaving the brink and assumes a very white, turbulent appearance. Here, of course, the flow is completely surrounded by atmospheric pressure. The only force holding the jet together is surface tension and in the case of large jets accompanied by a high degree of turbulence this force is relatively small. Consequently the pressure in the flow is probably very close to atmospheric and there is merely an interchange of position of particles of water and air. Whether or not a terminal velocity exists somewhere below the brink has not been determined but it is reasonable to assume that it does. The internal pressure may have some bearing upon the air mixture in high velocity flow in steep channels particularly where the flow traverses a vertical curve.

27. Application of data to Shasta spillway. In the case of the spillway for Shasta Dam present conjectures are that at the maximum discharge the jet may be of such proportions that the entrainment of air with its consequent effect on the depth and velocity of flow may not be of major importance. However, at some lower discharge, the conditions may be conducive to entrainment of air in large quantities. If the results of the experiments on Kittitas wasteway may be considered to be applicable to the conditions that will prevail in Shasta spillway, the air content, as calculated from the formula $\alpha = 0.81 \sin \theta^{0.6}$, will be 70 percent of the flow by volume, considering of course that the spillway is of sufficient length for uniform flow conditions to be established. This may or may not be the case. The velocities, as calculated from the formula $V = 81 R^{2/3} (\sin \theta)^{0.266}$ deduced from the same experiments, will be:

Depth	Discharge per foot of spillway second-feet	Velocity feet/sec.
0.5	3.6	48
1.0	23.0	76
2.0	144.0	120
3.0	427.0	158
3.5	643.0	175

Again, it is emphasized that these velocities will prevail only if uniform flow conditions are established on the face of the spillway and that data from narrow channels may be extrapolated to include overfall dams.

28. Conclusions. Only the most significant results have been noted. Adequate explanation and formulation must await further investigation and analysis. A great deal of further work must be done before the problem can be explained quantitatively and in particular a study of the surface of flow exposed to the air should be made by means of an ultra-speed motion picture camera in order to better understand the mechanics of the air-water mixing process. A satisfactory means of measuring high velocities in flow has been developed which should assist in additional study of the problem. With some changes in equipment and technique and a closer calibration of the method, it should be possible to determine the maximum and average velocities existing in the flow. The ultimate solution of the hydraulic principles involved in high velocity flow may be found in new formulas that do or do not contain the factors generally used. For instance, it may be that the accepted value of the hydraulic radius is not entirely correct but should possibly include the side of the perimeter that separates the water and atmosphere. The relationship between the component parts of the formulas might be shown by some means other than exponential equations. No definite statements can be made at the present time because of the difficulty of establishing arguments for such, but the problem should be recognized to exist and not be overlooked in the design of structures. It is hoped that interest may be stimulated in the engineering profession to the extent that additional data and analyses may be added to the small store now available. Some means of studying the problem of self-aeration of flowing water is being sought in the laboratory. To date, the aerated flow closely resembling observations made in prototype structures has been produced by artificially roughening the channel. This means of producing such flow greatly retards the velocity and no correction for this factor has been determined. Laboratory work is also being done by Dr. L. G. Straub of the University of Minnesota and data from those studies will be available through a cooperative exchange of data sponsored by the Special Committee on Hydraulic Research of the American Society of Civil Engineers.

29. Acknowledgements. All experimental work and the preparation of this memorandum was under the direct supervision of J. E. Warnock. The velocity measuring equipment was developed through the combined efforts of J. E. Warnock, E. F. Wilsey, and C. W. Thomas. Valuable suggestions in addition to the loan of the oscillograph were made by R. E. Glover of the technical section. E. F. Wilsey assisted in the conduct of the tests on the Kittitas wasteway and in the analysis of the results. He also added materially to an understanding of the subject by translating the relevant articles from foreign literature. The electrodes were installed in the Kittitas wasteway under the direction of J. S. Moore, Superintendent, Yakima project. The current-meter measurements for the tests were made by F. A. Jenne, Hydrographer, Yakima project. Efficient control of the flow, as well as other assistance very valuable to the success of the field measurements, was accomplished by W. W. Russell, manager, and H. T. White, watermaster, both of Kittitas Reclamation District. J. C. Stevens, consulting engineer, Portland, Oregon, visited the laboratory while the velocity-measuring equipment was being developed and spent some time on the ground while the field tests were being conducted. On these occasions, he offered valuable suggestions and advice. W. F. Durand has suggested a mathematical aid to be used in solving for a terminal velocity in accelerated flow.

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ABSTRACT OF CORRESPONDENCE

9-21-34	From E. W. Lane to W. M. Borland regarding velocities on face of Grand Coulee model. An outline of initial tests to determine friction on the face of an overfall dam is given.
7-25-35	From E. W. Lane to W. M. Borland regarding air drag on water flowing down the chute at Montrose laboratory.
8-2-35	Memorandum from W. M. Borland and C. W. Thomas to E. W. Lane. Subject: Tests along South Canal Chute at laboratory to determine amount of air flowing above water surface. Outline of proposed tests and estimate of cost.
2-26-38	From Chief Engineer to Superintendent of Yakima Project, regarding velocity measurements in Kittitas Wasteway. Resume of problem is given and outline of proposed tests.
3-5-38	From Superintendent, Yakima Project to Chief Engineer regarding velocity measurements in Kittitas Wasteway. Best time to conduct tests and limitations of irrigation system outlined.
3-17-38	Memorandum from J. E. Warnock to Chief Designing Engineer. Report of progress and request for travel to Kittitas.
3-28-38	From Acting Chief Engineer to Superintendent Yakima Project fixing date of start of tests and preliminary instructions for preparation for tests.
3-30-38	From Superintendent Yakima Project to Chief Engineer regarding effect of demand for irrigation water on Kittitas Wasteway tests.

4-4-38 From Acting Chief Engineer to Superintendent Yakima Project transmitting details for installation of test equipment. Gives outline of tests and procedure to be followed.

6-27-38 Memorandum from J. E. Warnock to Chief Designing Engineer relating to design of Shasta spillway stilling pool. Contains resumé of findings from study of high velocity flow.

7-7-38 From J. C. Stevens to Chief Engineer proposing an exchange of data on the subject of "Simultaneous Flow of Liquids and Gases" through the special committee on hydraulic research of the A.S.C.E.

7-16-38 From Acting Chief Engineer to J. C. Stevens, Chairman of Committee, stating that the Bureau will cooperate in a program of data exchange.