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DISCHARGE MEASUREMENTS USING RADIOISOTOPES IN HIGH-HEAD TURBINES AND PUMPS AT FLATIRON POWER AND PUMPING PLANT, COLORADO–BIG THOMPSON PROJECT

December 1968

Office of Chief Engineer
Bureau of Reclamation
Denver, Colorado

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General Report No. 40 same as Chemical Engineering Branch Report No. ChE 83 and Hydraulics Branch Report No. HYD-587.

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RADIOISOTOPE AND RADIATION
APPLICATIONS (TID-4500)

General Report No. 40

DISCHARGE MEASUREMENTS USING RADIOISOTOPES IN HIGH-HEAD TURBINES AND PUMPS AT FLATIRON POWER AND PUMPING PLANT COLORADO-BIG THOMPSON PROJECT

by
J. C. Schuster and R. L. Hansen

December 1968

CHEMICAL ENGINEERING
AND
HYDRAULICS BRANCHES
DIVISION OF RESEARCH

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION
Office of Chief Engineer . Denver, Colorado

ABSTRACT

Techniques and equipment are being developed to improve methods for measuring flow rate in high-head turbines and pumps. A series of discharge measurements was begun in 1967, at Flatiron Powerplant near Loveland, Colo, to evaluate techniques and equipment developed in preliminary investigations of the use of radioactive material. Measurements were made on a 6000-ft-long, 6-ft-dia penstock and on a 6000-ft-long, 8-ft-dia pump discharge line. Thirty-five injections of radioactive Bromine-82 were made in the penstock, and 12 injections were made in the pumpline. Ninety-three discharge values were computed for penstock flows and 29 for pumpline flows. Mixing lengths ranged from 47 to 755 diameters; discharge ranged from about 130 to 300 cfs. The measurements gave good information on lengths of pipe required for natural turbulence to mix pipe flow and tracer and for additional mixing caused by a pump. Discharge measurements on the turbine and pump were not as precise as desired but were encouraging.

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IDENTIFIERS--/ Colorado-Big Thompson Proj/ Flatiron Pwrplt, Colo/ Atomic Energy Commission/ Colorado/ radioactive counting

FOREWORD

This report, a product of the Research Division, is issued as part of a contract between the U.S. Atomic Energy Commission and the Bureau of Reclamation. The work was cooperatively done by the Hydraulics and Chemical Engineering Branches directed by H. M. Martin and L. O. Timblin, Jr.

The research was materially assisted by the work of G. A. Teter, U. J. Palde, R. A. Dodge, R. B. Dexter, and L. D. Klein, all of the Research Division; C. P. Buyalski, Regional Office, Sacramento, California; and the personnel operating and maintaining Flatiron Power and Pumping Plant under the supervision of Messrs. G. R. Highley and L. Willits.

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SYNOPSIS

A series of discharge measurements was conducted on a 6,000-foot-long (1,830 m), 6-foot-diameter (1.8 m) penstock and a 6,000-foot-long, 8-foot-diameter (2.4 m) pump line of the Flatiron Power and Pumping Plant near Loveland, Colorado (Figures 5 and 22).

Thirty-five separate injections of radioactive Bromine-82 were made in the turbine test series. Ninety-three discharge values were computed from these injections because multiple samples were obtained from each injection. Injections were made at 0.1 and 0.4 of the pipe radius from the pipe wall and at the centerline. These positions were selected to show the effect of the radial location of single-point injection upon mixing length. Measurements were made in pipeline lengths of about 47, 311, and 645 diameters (D) to show the results of mixing the tracer and pipe flow for lengths well above and well below the anticipated minimum mixing length. Sampling locations were installed at the draft tube, at the inlet of the turbine, and in the penstock at 311 and 47 diameters from the injection. The locations at the turbine were to explore any unique effects of the turbine upon mixing or other aspects of the measurement. The sampling locations on the penstock were made essentially at the pipe wall (0.04 of the radius) and at the centerline to determine the degree of mixing. Flow measurements with radioisotopes were compared with flow determinations by a carefully performed pitot tube traverse made completely across two diameters. Also, results were compared with flow measurements as indicated by use of the calibrated flowmeter taps at the turbine. The flowmeter indicated discharges ranged from about 2 to 6 percent less than the discharges measured by the pitometer. No corrections were made for the difference in indication because of the longer time required to perform a pitometer measurement with respect to the time for the radioisotope method. Repeatability of the measurements was of first concern and the spiral case flowmeter gave an independent measure of discharge and indication of the steadiness of the flow.

Specialized equipment for these tests includes injection and sampling probes which could be located at various positions in the penstock diameter. Simplified pressure reducers based upon hydraulic studies were developed for sampling the high-pressure penstocks. Samples were taken at pressures of 350 psi (24.5 kg/cm^2) and 475 psi (33.3 kg/cm^2). Injections of tracer were made into the pipe through four configurations of holes in the injector tips at pressures ranging from about 295 psi (20.7 kg/cm^2) to 950 psi (66.5 kg/cm^2). These studies were made to explore the possibility of using high-pressure injection to reduce mixing length.

A second series of measurements was made on the pump-turbine unit of the Flatiron Power and Pumping Plant. The unit was operated as a pump to evaluate procedures and techniques used in the radioisotope method applied to pump flows. Twelve separate injections of BR-82 were made in this test series. Twenty-seven discharge values were computed from these injections as samples were taken from three places in the pipeline flow. Injections were made in the pump flow at a distance of 6 inches (15 cm) from wall of the inlet elbow upstream from the pump. Another injection point was located about 8 inches (20 cm) from the pipe wall downstream from the pump and a butterfly valve. A sampling and counting system containing two tubes for sample withdrawal was located 1,300 feet (164 D) downstream from the pump.

A second counting and sampling system withdrawing a sample through the sidewall of a valve was located 6,044 feet (755 D) downstream from the pump. A calibrated spiral case flowmeter was selected for the discharge comparison. The injection and counting equipment for this measurement series was similar to that used for the turbine tests.

In general, the discharge measurements on both the turbine and pump were not as precise as desired but were encouraging, Table A.

Table A

SUMMARY OF DISCHARGE MEASUREMENTS

Measurement length	No. of measurements	Average discharge, cfs Flowmeter	Average discharge, cfs Radioisotope	Deviation percent
		Turbine		
46.5 D				
Center sample	12	127.0	131.5	+3.5
Side sample	12	127.0	94.8	-25.4
310.8 D				
Center sample	23	126.7	130.7	+3.2
Side sample	23	126.7	131.3	+3.7
645 D				
Side sample	12	127.2	128.7	+1.2
		Pump		
164 D				
.07 R sample	11	287.6	281.3	-2.2
.57 R sample	11	287.6	282.3	-1.8
755 D				
Side sample	5	288.2	289.9	+0.6

A series of discharge measurements for the turbine made by varying the configuration of the holes in the injection tip and the injection pressure did not show a significant effect on the mixing. Discharges computed for a mixing length of 46.5 diameters selected to more readily distinguish the change in mixing, differed from the flowmeter by +10 to a -30 percent. An average value for 12 measurements at the side and 12 at the center of the penstock appear in Table A, and the discharges for individual measurements in Table 4.

Twenty-three measurements were made using 310.8 diameters for mixing. Samples were withdrawn from the center of the flow and near the sidewall. The deviations for the average discharge values from the flowmeter and radioisotope method were +3.2 percent for the center and +3.7 percent for the side, Table A. The individual measurements, flowmeter and radioisotope, differed by -5 percent to +10 percent, Table 2.

For a mixing length of 645 diameters of the penstock, the average deviation of 12 discharges indicated by the flowmeter and radioisotope method was +1.2 percent, Table A. The deviations for individual measurements ranged from -1.8 percent to +4.8 percent, Table 5.

Two mixing lengths, 164 diameters and 755 diameters, were used in the 8-foot pumpline. At 164 diameters, the deviation for 11 discharge measurements was -2.2 percent for a side sampling and -1.8 percent for a center sampling. Of the 11 measurements, the first 6 measurements by radioisotopes averaged about 5 percent lower than the flowmeter. These measurements are believed to be in error and lower the average discharge of the 11 radioisotope measurements, Table 6. The five remaining measurements gave values about 2.1 percent higher than the flowmeter-indicated discharge.

For a mixing length of 755 diameters the flowmeter and radioisotope indication of the pump discharge differed by +0.6 percent for 5 measurements, Table A and Table 7.

The tests gave good information on lengths of pipe required for natural turbulence to mix the pipe flow and tracer injected at the pipe centerline, radiation measurement procedures, and injection and sampling techniques. These studies showed that injections at a selected point between the center and side of the penstock did not produce a significant reduction in the mixing length. The scale and intensity of the turbulence for mixing of the tracer and pipe flow was increased by the pump. The mixing in a length of 164 and 755 diameters in the 8-foot pump line appeared to be satisfactory for a tracer injection near the pipe sidewall into water flow at a velocity of about 6 feet per second (1.8 mps). A 310-diameter mixing length for a centerline injection into water flowing about 4.5 feet per second (1.4 mps) apparently did not result in satisfactory mixing produced by the natural turbulence of the penstock. Some of the discharges computed from the samples taken at the draft tube of the turbine were obviously in error and the measurements had a greater variation than desirable. Investigation using a fluorometer showed that a significant amount of recirculation of water from the tailrace into the draft tube was occurring for the less than maximum discharge used in the measurements. The recirculation caused excessive dilution of the sample being extracted from the draft tube and thus an error in the discharge measurements.

INTRODUCTION

The Atomic Energy Commission (AEC) and Bureau of Reclamation (USBR) are cooperating in the research and development of a radioisotope system for an improved method of measuring discharge in high-head turbines and pumps. The purpose of the program is to establish the feasibility and develop procedures for making precision discharge measurements safely, quickly, and with a minimum of personnel and equipment.

The program is being accomplished in several major divisions of work. These include program coordination and evaluation, outside contracts, literature searches, hydraulics, radioisotopes, and systems development. Under program coordination and evaluation, a report, "Potential Economic Benefits From Use of Radioisotopes in Flow Measurements Through High-Head Turbines and Pumps," by E. Barbour, was written for the AEC to show the possible gains accruing from an accurate easy-to-apply method of discharge measurement, Appendix 1. Under contract, H. G. Richter of the Research Triangle Institute, North Carolina, was unsuccessful in developing a radio-release procedure for measuring the necessary concentrations of tracer ions at the nanogram per milliliter (ppb) level or the microgram per milliliter (ppm) level, Appendix 2.

The program was divided into five phases to cover about 5 years of work. Phases I and II were completed by September 30, 1966. The results, summarized briefly below, were covered in a previous report.1/

In Phases I and II, an extensive search of foreign and domestic literature produced about 300 references related to the measurement of flow using radioisotopes and chemical tracers and on radioisotopes suitable for making pipeline discharge measurements. An annotated bibliography was included as a part of a report on contract work done by Colorado State University, Fort Collins, Colorado. Theoretical studies were made to define and evaluate the hydraulic parameters that affect and control mixing of the tracer with the flowing water. A 36-inch-diameter pipeline 825 feet long was used to study the mixing and distribution of fluorescent dye in flows ranging from 8 cfs to 62 cfs. The measurements resulted in approximately 1,000 analog records of dye concentrations in the pipeline for mixing lengths of from 27 to 184 pipe diameters.1/2/ In a separate testing environment in the Hydraulics Branch, USBR, an 8-inch-diameter transparent plastic pipeline about 85 feet long was used to measure the mixing of a sodium chloride solution in pipe flow for eight mixing distances ranging from 12 to 110 pipe diameters. A conductivity probe and electronic circuitry were developed to measure the concentration and the

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1/Numbers designate references at end of report text.

distribution of the salt solution in cross sections of the pipe. The experimental phases included the investigation of tracer injection and sampling techniques and the establishment of basic requirements for accuracy of the equipment. The studies resulted in the development of equations for estimating diffusion coefficients and pipeline lengths required for tracer water mixing.

These equations are $K/\nu = 0.0118 \sqrt{f}\, R_e$ for computing the diffusion coefficient K, and $L/d = 9.25/\sqrt{f}$ for computing the mixing distance L.3/ For example, if f = 0.02 (Darcy-Weisbach) and d = 6 feet, then L is about 390 feet (about 65 pipe diameters).

Radioisotope calibration, counting, and sampling procedures were applied to a sample tank designed and fabricated in the laboratory. The check of procedures included the evaluation of the total error that might result from each operation. The maximum probable error expected at this stage of the program was ± 0.73 percent based on the results of preliminary tests. Improved methods were developed for radioisotope dilution and volume measurement. A mobile nuclear laboratory was designed, purchased, and assembled using USBR funds. The mobile laboratory is used for performing field tests using radioisotopes in ground-water tracer studies and flow measurement in open channels and closed conduits.

Field tests were performed during August 1966 in a 320-foot-long, 10-foot-diameter, high-head turbine penstock of Flaming Gorge Dam near Vernal, Utah, to field evaluate procedures and equipment. Samples of tagged water were withdrawn from the penstock both upstream and downstream of the turbine for discharge measurements. The planned objectives of the Flaming Gorge Dam turbine discharge measurements were achieved. Much was learned about the injection, sampling, and general procedures necessary for making radioisotopes discharge measurements in a high-head installation. The difference between the discharges computed by the radioisotope method and that measured by the flowmeter gave indirect indication that good mixing did not occur in flows of about 1,400 cfs (design maximum 1,530 cfs) in a pipeline length of about 30 diameters for a single jet of isotope introduced at 0.3 of the radius from the pipe wall. The flow, between the injection and sampling locations, did not have turbulence of sufficient scale and intensity to produce good mixing in a length of about 320 feet for the injection method.

Studies by other investigators using a 50-point injection manifold at about 0.38 of the pipe radius from the wall indicated that a nearly uniform concentration of tracer could be obtained in about 20 diameters of 6-inch-diameter straight pipe.4/ The penstock at Flaming Gorge contained one 70° and one 80° bend in the 30 diameters of mixing length and a manifold could not be installed for tracer injection.

Measurements at Flaming Gorge were the conclusion of planned work for Phase II. Phase III of the joint program reported in the following pages was started in April 1967 to include a series of discharge measurements at a selected powerplant. Flatiron Power and Pumping Plant in the Colorado-Big Thompson Project, Colorado, was chosen for the study. A cooperative agreement was made between the Chief Engineer's Office and the Office of the Regional Director, Denver, and South Platte River Projects Office, near Loveland, Colorado, to perform the measurements using a turbine and pump at Flatiron.

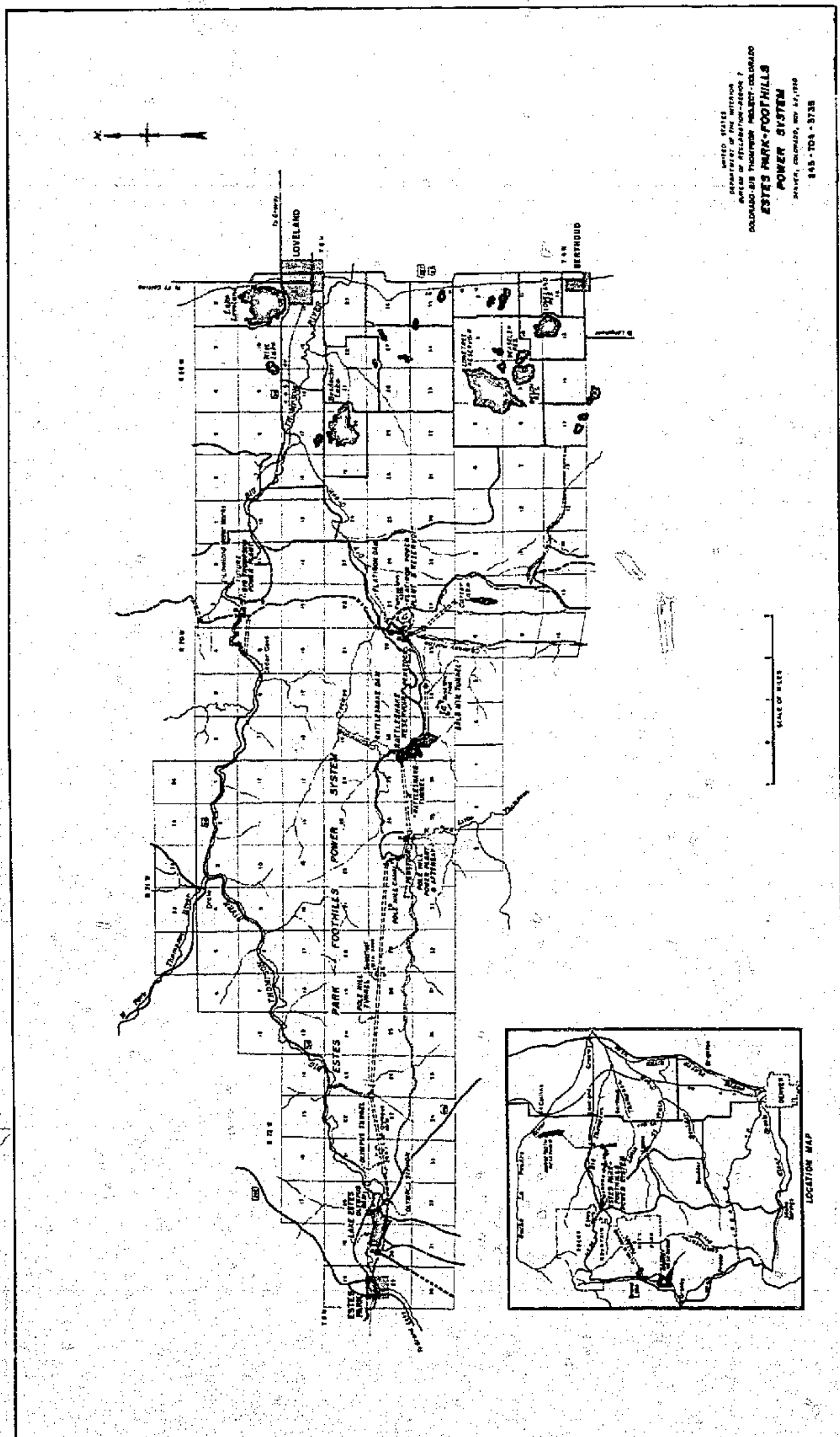
COLORADO-BIG THOMPSON PROJECT

General Description

The Colorado-Big Thompson Project (Figure 1) was designed to divert annually 310,000 acre-feet of surplus waters of the Upper Colorado River watershed to the eastern slope at a maximum rate of 550 second-feet. Surplus waters collected and stored on the western slope are pumped by two pumping plants, Willow Creek and Granby, to the level of Grand Lake then flow by gravity through Alva B. Adams Tunnel to the eastern slope.

Green Mountain Dam, Reservoir, and Powerplant below the project collection system on the western slope provide for replacement storage, and are operated to facilitate unrestricted development and growth of western slope areas dependent on the Upper Colorado River watershed.

Figure 1


ESTES PARK-FOOTHILLS POWER SYSTEM
LOVELAND
BERTHOUD
ESTES PARK FOOTHILLS POWER SYSTEM
LOCATION MAP

Power is developed in four powerplants on the eastern slope in the 2,800-foot fall from the east portal of the Alva B. Adams Tunnel to the foothills just above the irrigated areas of the project. Marys Lake, Estes, Pole Hill, and Flatiron Powerplants include seven conventional generating units and one reversible pump-turbine unit which operates from pumped storage part of the time.

Construction of one additional unit, the Big Thompson Powerplant, was completed in 1959 for seasonal power production. Provision was made for connection of this powerplant to the Flatiron Switchyard for utilization of its seasonal power production in the project system.

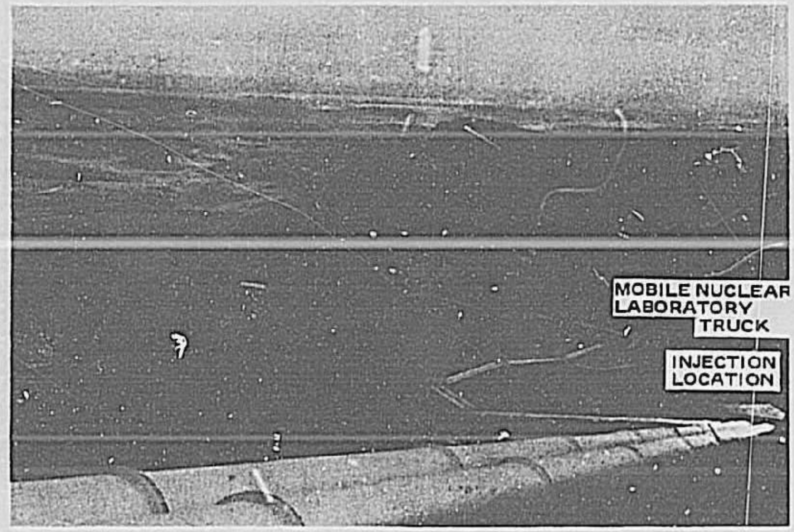
In general, the Colorado-Big Thompson Project utilizes the western slope of the Continental Divide for the collection, storage, and replacement area of the project, and the eastern slope down to the foothills east of the Continental Divide for collection, diversion, and power production. Eastward in Colorado is the major distribution and service area of the project. The powerplants of the Colorado-Big Thompson Project are interconnected and are all controlled from the Upper Platte System dispatching office located near the Flatiron Power and Pumping Plant.

Flatiron Power and Pumping Plant

Flatiron Power and Pumping Plant is located about 14.5 miles east of Estes Park and 4 miles south of the Big Thompson River, Figure 1. The plant develops power from regulated flows in the 1,110-foot fall from Rattlesnake (renamed Pinewood) Reservoir to Flatiron afterbay for peaking purposes. Water flows from Rattlesnake Reservoir through the Bald Mountain pressure tunnel to a 50-foot-diameter, 81-foot-high surge tank near the outlet of the tunnel. Water flows from the location of the tank through a wye transition to the penstock valve house. The valve house, located approximately 5,780 feet southwest of the powerplant, is 1,060 feet higher in elevation. Two 84-inch butterfly valves control flow into the two penstocks, Figures 2A and 3, leading to the powerplant, Figure 2B.

There are two main generators with a total capacity of 63,000 kilowatts in the powerplant, Figure 4. These generators are each driven at 514 revolutions per minute by a Francis-type turbine rated at 48,000 horsepower at 1,055 feet for flows up to about 480 cfs. The pump-turbine unit is rated at 13,000 horsepower to pump 370 cfs at 240 feet at a speed of 300 revolutions per minute, Figure 4. As a turbine the unit develops 12,000 horsepower at a head of 290 feet to produce 8,500 kilowatts from the motor-generator.

Figure 2



A. Flatiron Powerplant Penstocks - Butterfly valve house was about 300 feet behind the camera and Flatiron Powerplant (arrow) at the afterbay reservoir in the distance. Photo P245-D-60413NA

B. Flatiron Power and Pumping Plant and channel to afterbay reservoir. Photo P245-700-1502

PENSTOCKS AND POWERPLANT AT FLATIRON

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

Figure 3
COLORADO-BIG THOMPSON PROJECT

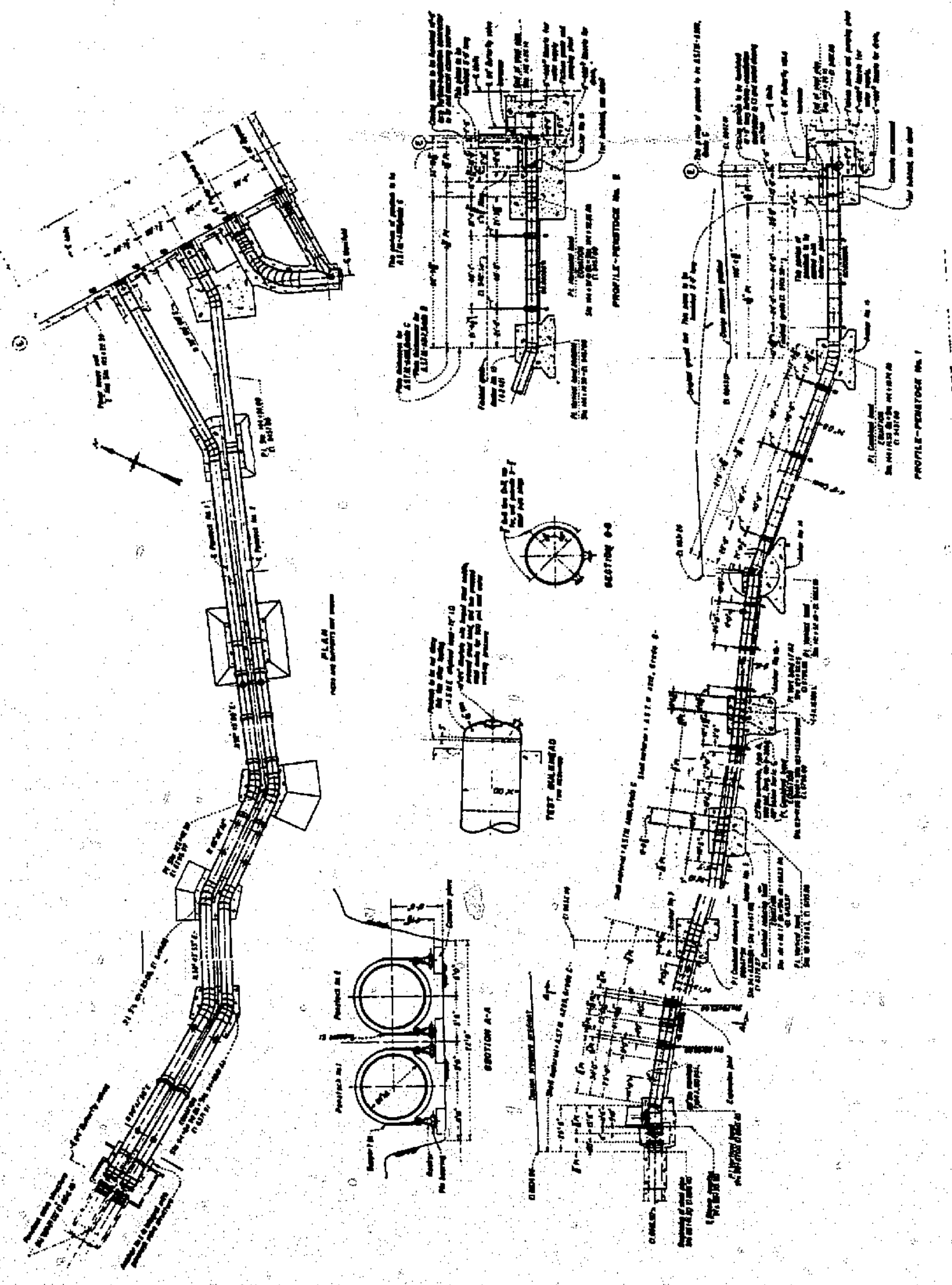
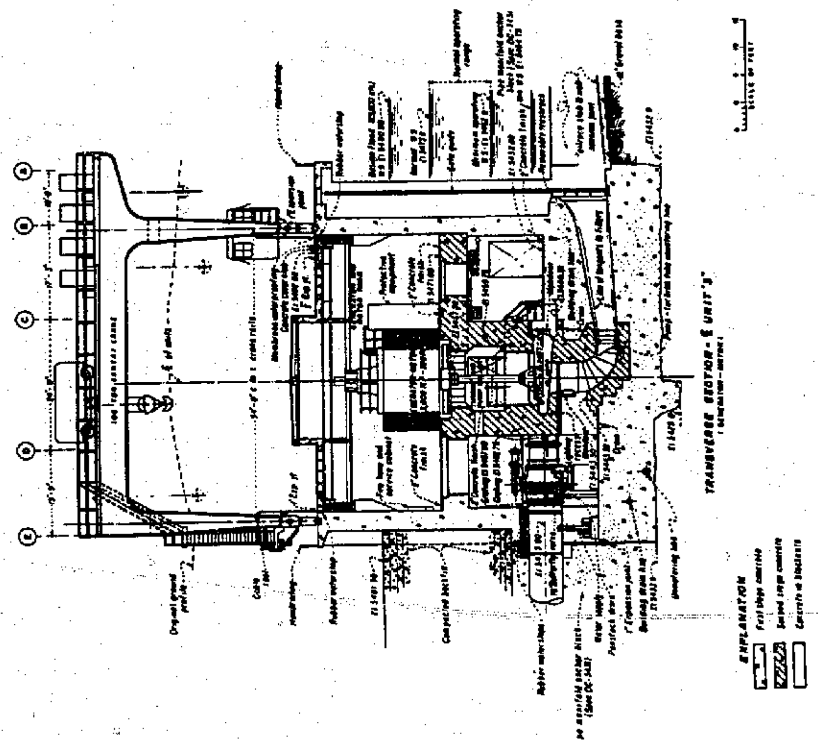
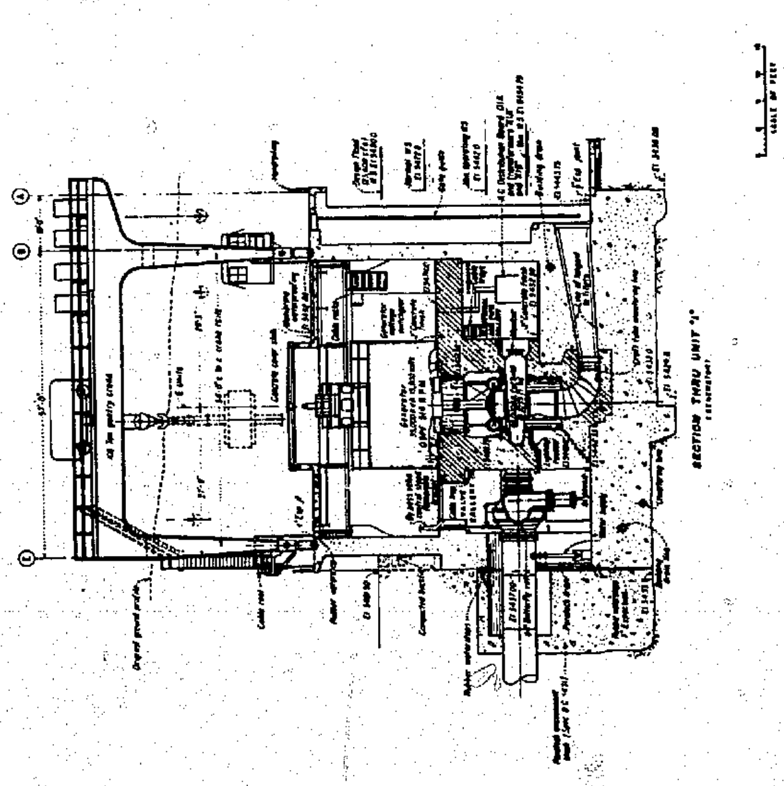


Figure 4





The Flatiron pump-turbine operating as a pump, delivers water from Flatiron afterbay through Carter Lake pressure conduit and tunnel into Carter Lake Reservoir.

Generating Unit 2 and the pump-turbine Unit 3 were used for discharge measurements using radioisotopes.

DISCHARGE MEASUREMENTS - TURBINE UNIT 2

Preparations for Measurements

Penstock

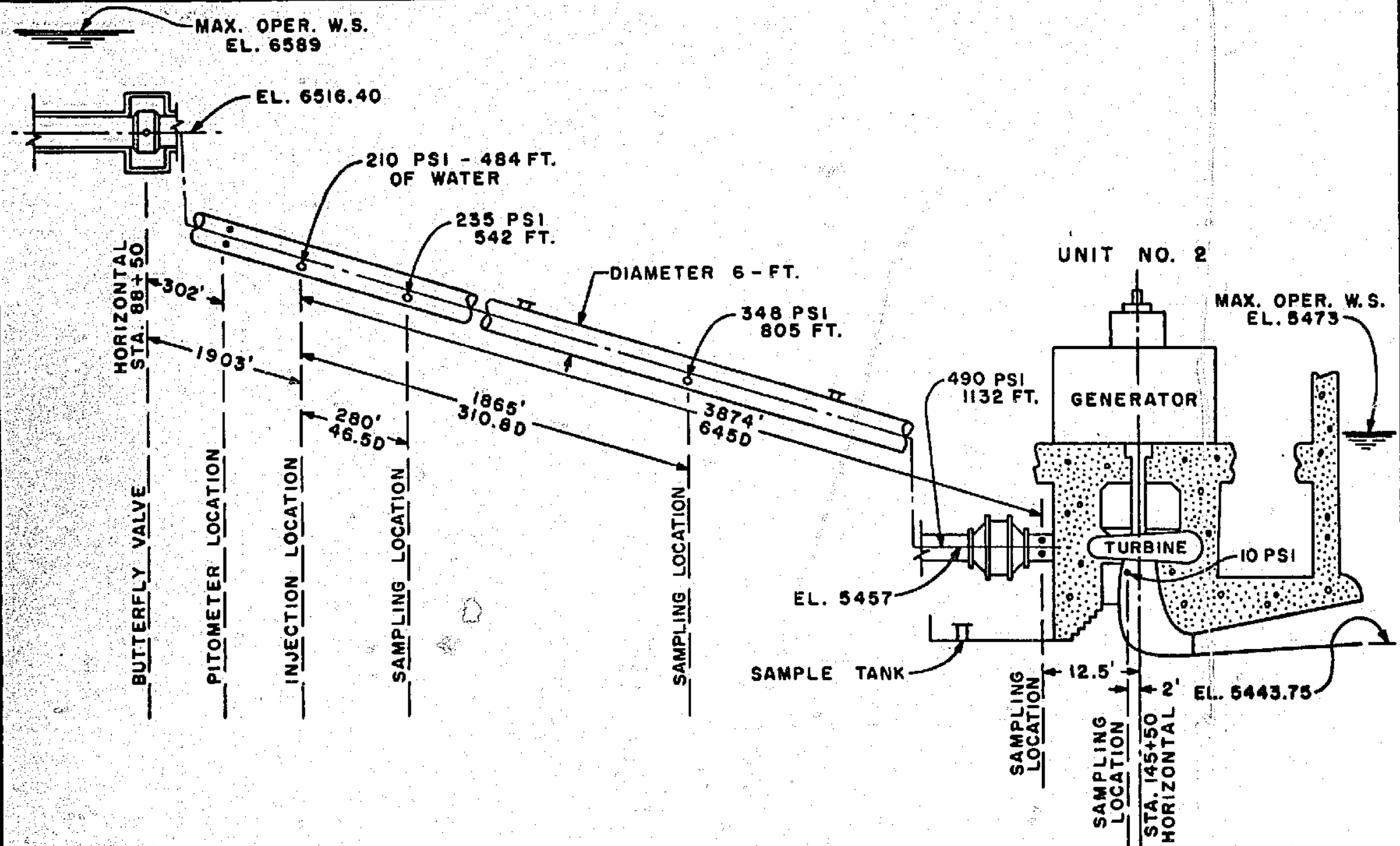
Flatiron Power and Pumping Plant was chosen for the discharge measurements because of the relatively long penstocks, Figures 2 and 3. Turbine Unit 2 of the powerplant was selected because acceptance tests made in 1954 provided a discharge rating of the flowmeter (Winter-Kennedy taps) on this unit.5/ The penstock, ranging from 7 to 6 feet inside diameter, is exposed for most of its length on the hillside above the powerplant.

Manways, having a diameter of 20 inches, were provided for access to the pipe interior at intervals of about 275 feet (46 pipe diameters). The manways were located on the top of the penstock and at a clockwise angle of 135° when an observer looks in the direction of flow. For ease of installation and handling of radioisotope injection and sampling equipment, the manways near the bottom of the penstock cross section were used for the discharge measurements.

Study of the penstock profile and alinement showed that a good measurement section began at a distance of about 1,900 feet and ended 3,700 feet downstream from the butterfly valve at the entrance to the penstock, Figure 5. This section was straight when viewed in plan except for one 32°, 15-foot radius elbow upstream of the last 228 feet of pipe. The pipe had three small changes in slope in the test section, the largest of which had an angle of about 9° 20', Figure 3. Thus, in this particular reach of pipe, a mixing length of about 311 diameters of essentially straight pipe was available for discharge measurements. The minimum length computed from the mixing length equation was 390 feet or about 65 pipe diameters. Thus, the 311 diameters were nearly five times as long as computed from the equation. The test reach, therefore, provided test lengths both longer and shorter than the computed minimum.

Radioisotope Injection System

A mechanical system was designed to provide for either injection of the radioisotope or sampling the tracer-water mixture at points between the wall and the centerline of the penstock. The supports for the injection and sampling tubes were attached to manway covers replacing the covers provided during the construction of the penstock. The replacement manway covers were provided with a fairing plug to reduce the flow disturbance caused by the manway, Figure 6.

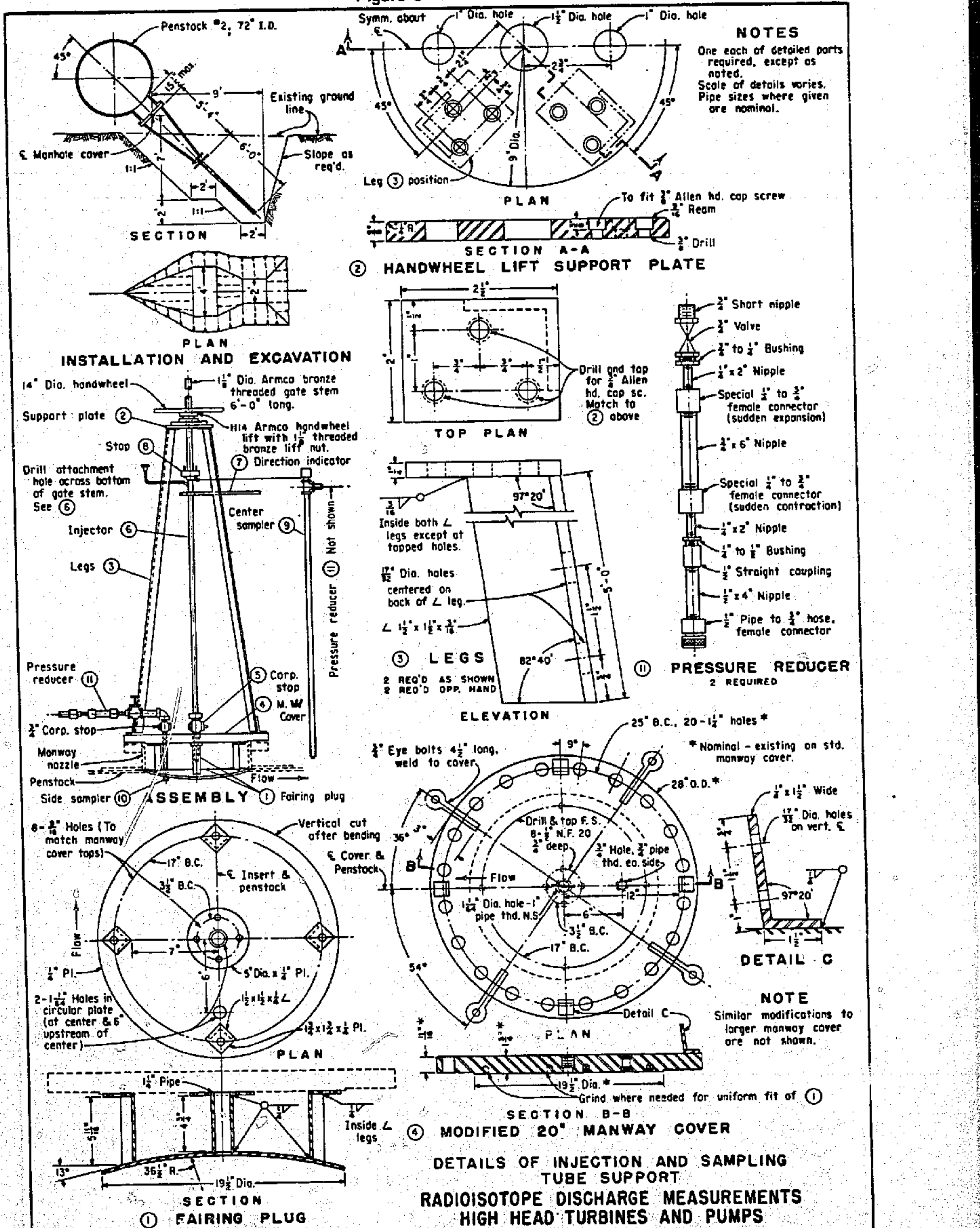


GENERAL ARRANGEMENT OF PENSTOCK AND TURBINE UNIT NO. 2
FLATIRON POWER AND PUMPING PLANT

RADIOISOTOPE DISCHARGE MEASUREMENTS HIGH HEAD TURBINES AND PUMPS

Figure 5

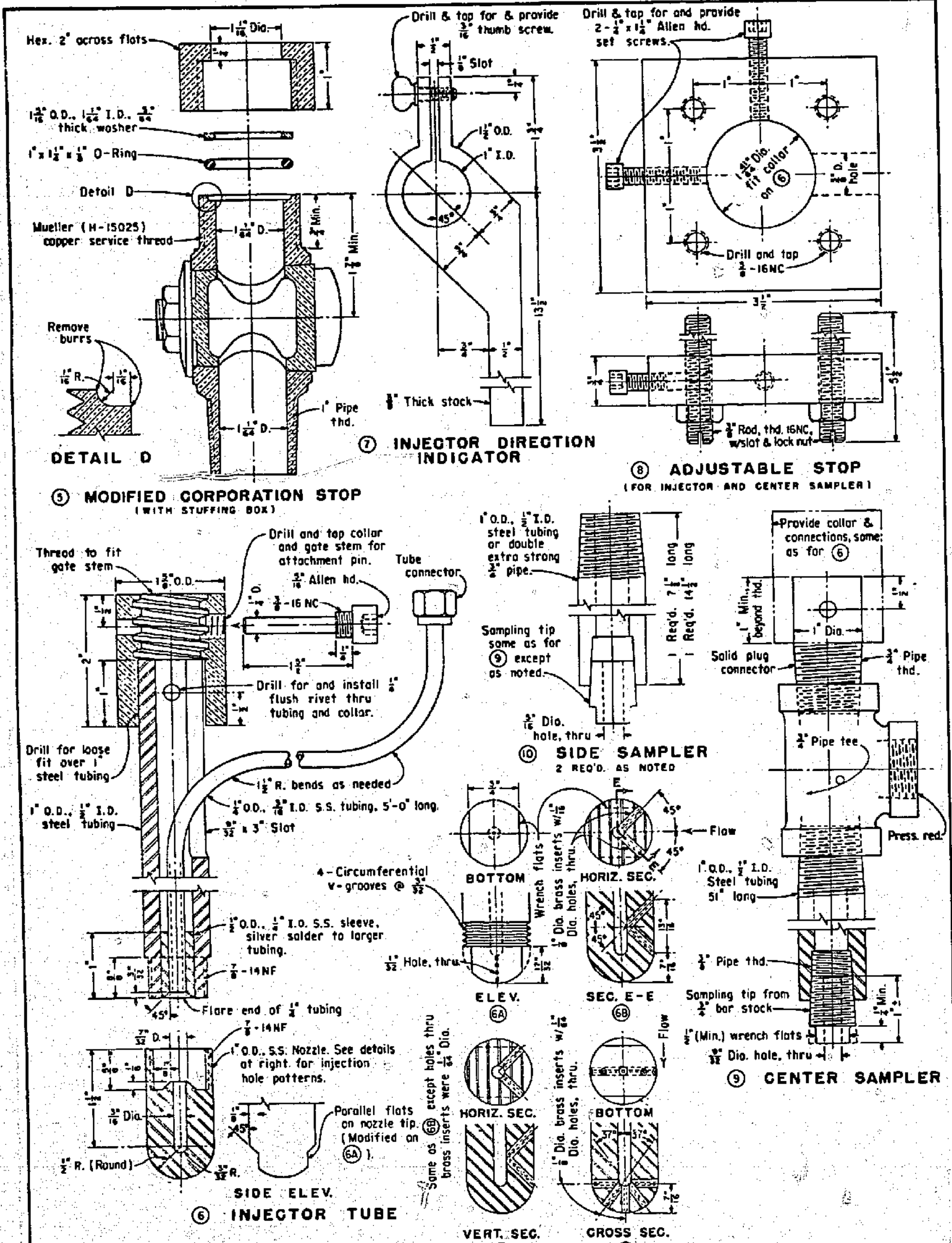
Figure 6


NOTES
One each of detailed parts required, except as noted.
Scale of details varies.
Pipe sizes where given are nominal.
Penstock #2, 72" I.D.
Existing ground line
Monhole cover
Slope as req'd.
SECTION
PLAN
INSTALLATION AND EXCAVATION
Symm. about ℄
1" Dia. hole
1½" Dia. hole
1" Dia. hole
Leg ③ position
PLAN
To fit ⅜" Allen hd. cap screw
Ream
Drill
SECTION A-A
② HANDWHEEL LIFT SUPPORT PLATE
TOP PLAN
Drill and tap for ⅜" Allen hd. cap sc. Match to ② above
Inside both ∠ legs except at tapped holes.
Dia. holes centered on back of ∠ leg.
③ LEGS
2 REQ'D AS SHOWN
2 REQ'D OPP. HAND
ELEVATION
¾" Short nipple
¾" Valve
¾" to ½" Bushing
½"x2" Nipple
Special ½" to ¾" female connector (sudden expansion)
¾"x6" Nipple
Special ¼" to ¾" female connector (sudden contraction)
¼"x2" Nipple
¼" to ½" Bushing
½" Straight coupling
½"x4" Nipple
½" Pipe to ¾" hose, female connector
⑪ PRESSURE REDUCER
2 REQUIRED
14" Dia. handwheel
1½" Dia. Armco bronze threaded gate stem 6'-0" long.
Support plate ②
H14 Armco handwheel lift with 1½" threaded bronze lift nut.
Stop ⑧
⑦ Direction indicator
Drill attachment hole across bottom of gate stem. See ⑥
Center sampler ⑨
Injector ⑥
Legs ③
Pressure reducer ⑪ Not shown
Pressure reducer ⑪
⑤ Corp. stop
④ M.W. Cover
¾" Corp. stop
Manway nozzle
Penstock
Flow
Side sampler ⑩
ASSEMBLY
① Fairing plug
Vertical cut after bending
℄ Insert & penstock
17" B.C.
3½" B.C.
Flow
¼" Pl.
2-1 Holes in circular plate (at center & 6" upstream of center)
5" Dia. x ¼" Pl.
PLAN
1½" Pipe
Inside ∠ legs
36½" R.
19½" Dia.
SECTION
① FAIRING PLUG
25" B.C., 20-1½" holes *
* Nominal - existing on std. manway cover.
¾" Eye bolts 4½" long, weld to cover
28" O.D. *
Drill & tap F.S. 8-½" N.F. 20 ¾" deep
¾" Hole, ¾" pipe thd. ea. side
℄ Cover & Penstock
Flow
1-1 Dia. hole-1" pipe thd. N.S.
3½" B.C.
17" B.C.
Detail C
PLAN
19½" Dia. *
Grind where needed for uniform fit of ①
SECTION B-B
④ MODIFIED 20" MANWAY COVER
¼" x 1½" Wide
Dia. holes on vert. ℄
DETAIL C
NOTE
Similar modifications to larger manway cover are not shown.
DETAILS OF INJECTION AND SAMPLING TUBE SUPPORT
RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH HEAD TURBINES AND PUMPS

The position of the injector and sampler in the pipe was controlled by a 1-1/8-inch-diameter threaded bronze stem. The stem passed through a handwheel and bronze nut that were supported on the manway cover by four legs made from 1-1/2- by 1-1/2- by 3/16-inch steel angles. One end of each steel leg was bolted to the handwheel baseplate and the other end bolted to a bracket welded on the manway cover, Figure 6. The threaded stem provided a positive means of positioning the injection or sampling tube in the flow. The stem and handwheel were required to push the 1-inch-diameter tubes into the penstock against a force of 165 to 275 pounds caused by the penstock pressure.

The injector tube was made of 1-inch OD by 1/2-inch ID steel tubing, Figure 6. A 1/4-inch OD, 5-foot length of stainless steel tubing was placed inside the injector to carry radioisotope from the supply to the pipeline. The stainless steel tubing was flared and fitted into a plug at the discharge end of the injector. This 45° flare matched the cone machined into the injection tube tip. A machine thread connection was used to attach the tip to the probe, Figure 7. Thus, the radioisotope injection path was continuous and did not contain places that could trap the tracer. A single hole of 1/16-inch- or 1/32-inch-diameter at the discharge end of the tip was used for isotope injection in the majority of the discharge measurements. Multiple hole configurations of both 1/32- and 1/64-inch-diameter

Figure 7



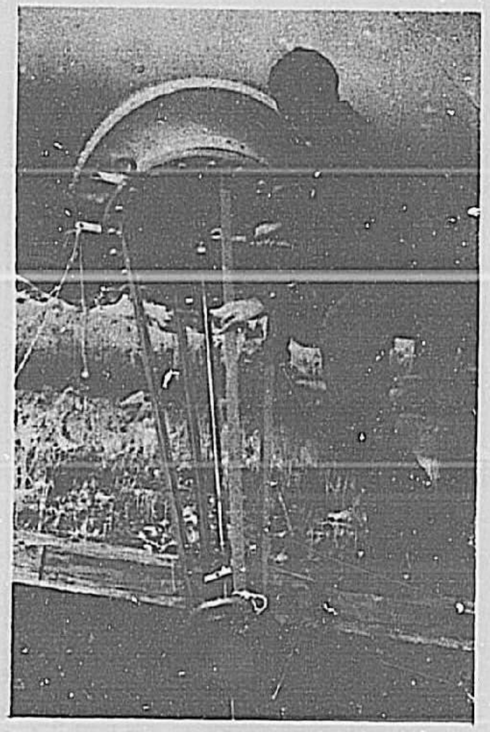
DETAILS OF INJECTION AND SAMPLING TUBES

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH HEAD TURBINES AND PUMPS

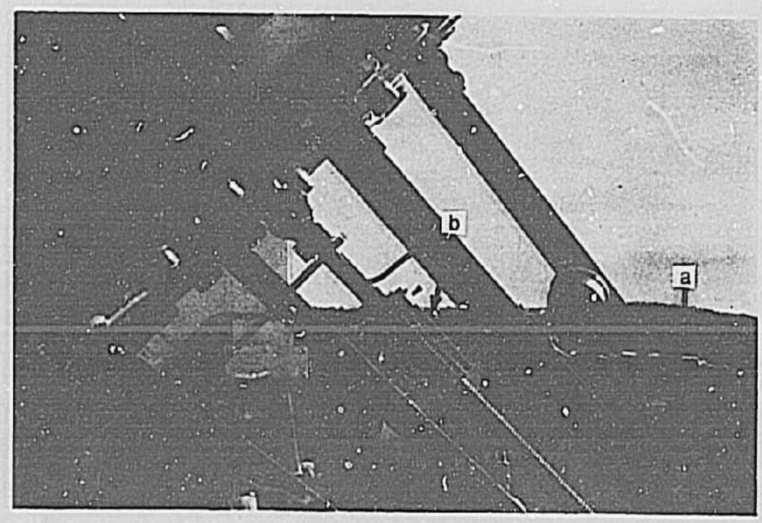
holes were used for additional measurements to determine the effect of increased injection pressure on the mixing of the tracer and pipe flow, Figure 7.

The injector was inserted into the penstock through a corporation stop (a form of plug valve) that had been modified for an "O" ring seal, Figure 7. A hexagonal nut drilled to fit the probe and threaded to fit the stop was used to pressure the "O" ring around the tube and prevent water leakage from the penstock. The tube was placed in the corporation stop to nearly touch the closed plug. The stuffing box was then sealed by the nut, and the stop was opened to the penstock pressure, Figure 8A. By turning the handwheel the injector then could be pushed into the penstock, Figure 8B. A hole was excavated in the ground adjacent to the penstock for clearance of the threaded stem when the stem was retracted to withdraw the probe, Figure 6. To prevent accidential withdrawal of the injector while the corporation stop was open, a bracket with four adjustable screws was added to the stem-probe coupling, Figures 6 and 8B. The screw lengths (b), Figure 8B, were adjusted to touch the underside of the handwheel support plate after the injection or sampling tube was inserted into the outer end of the closed corporation stop.

Figure 8



A. Injection tube installed in preparation for insertion into penstock. Photo P245-D-60424



B. Injection tube inserted into penstock and connected to radioisotope supply tube (a) check valve (b) safety stop. Photo P245-D-60419NA

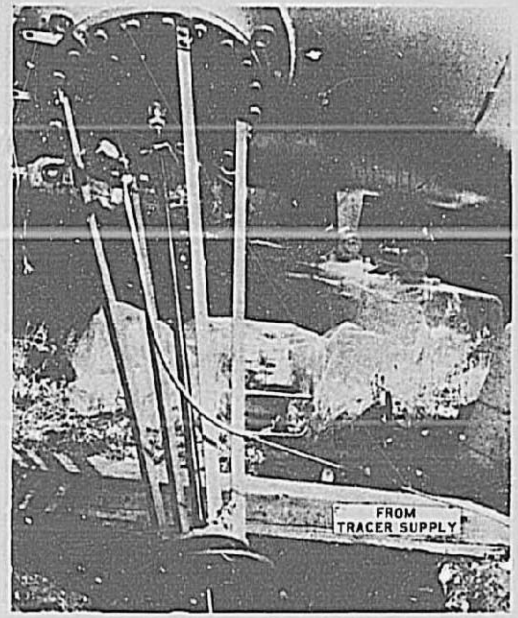
RADIOISOTOPE INJECTION TUBE AND SUPPORT

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

The radioisotope solution was forced into the penstock by a pump- or pulse-type system. The diaphragm-type pump operated at 203 strokes per minute from a 110-volt, 60-cycle supply of a portable engine-generator. The capacity of the pump was 9,000 milliliters per hour at 0 psi (maximum) and would pump 5,600 ml per hour at 5,000 psi. Flow rates through the pump were varied by changing the length of stroke of the piston driving the diaphragm.

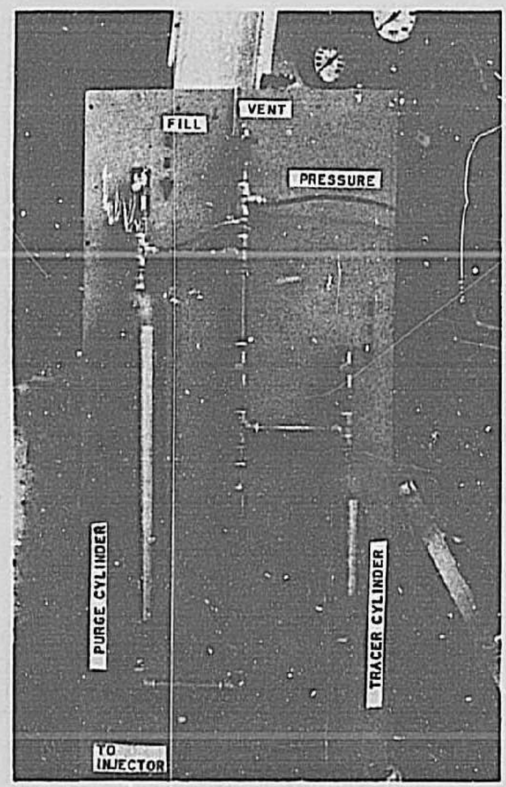
The pulse system was constructed of 1,800-psi sample cylinders and 3,000-psi piping and valves, Figures 9A and B. A 1-liter cylinder was used to hold the radiotracer before injection into the penstock. A 3.78 liter cylinder was used to hold water to purge the tracer cylinder after injection. The pipe was arranged to apply pressure from a 2,000-psi nitrogen bottle to the tracer cylinder and then to the water purge for rinsing, Figure 9B. Flexible and rigid stainless steel tubing carried the tracer solution and then the water to the injector. A check valve to prevent waterflow from the penstock to the injection system was installed in the injection line, Figures 8B and 9A. A pressure gage on the injection line near the check valve measured the penstock pressure and was used as an indicator for setting the pressure regulator on the nitrogen tank. The rate of injection of the tracer could be changed by increasing the differential pressure between the nitrogen supply and the penstock. Cold-weather protection was required during the late November and

Figure 9



A. Injection tube inserted in penstock and connected to radioisotope supply system.
Photo P245-D-60425NA

C. Protection of equipment from freezing.
Photo P245-D-62878



B. Radioisotope system for pulse injection using compressed nitrogen or air (valves in position for filling cylinders)
Photo P245-D-60420

INJECTION TUBE AND PULSE INJECTION SYSTEM
AT PENSTOCK

RADIOISOTOPES DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

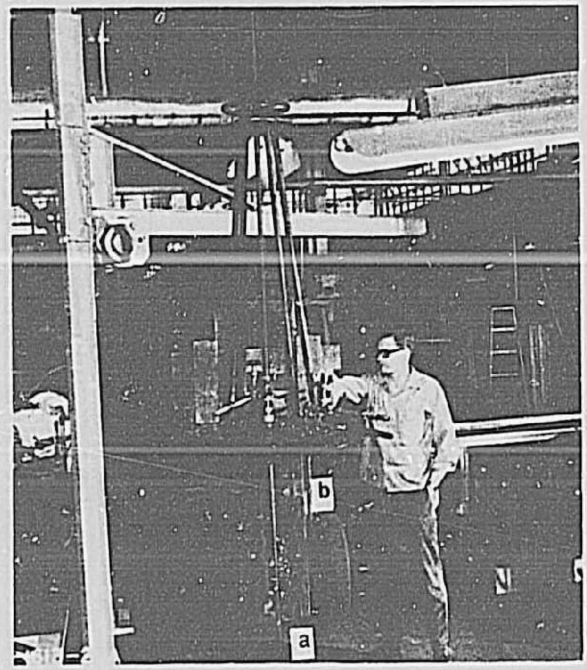
December test series, Figure 9C. Water temperature in the penstock was 39° F and sufficient heat was available to prevent freezing of the valves under the insulating covers over the manway. Heat from burning charcoal was used to prevent freezing of the injection system.

Radioisotope Sampling System

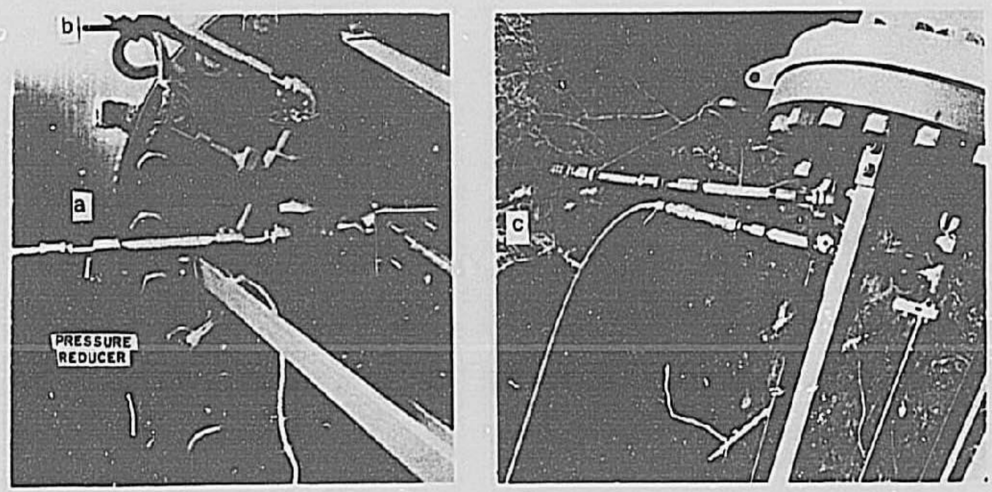
Two tubes were made for sampling the tracer-water mixture. A movable sampler similar in design and supported in the same manner as the injector was made to sample the flow between the pipe wall and centerline. A shorter tube threaded to the manway cover and projecting about 1-1/2 inches (0.04 of the pipe radius) into the pipe flow was made to sample at a fixed position near the pipe wall, Figures 6, 7, and 10.

The "sample tank" technique was used in the Flatiron discharge measurements for counting the tracer-water mixture taken from the penstock (see section, Method of Computing Discharge - Total Count). The flow rate through the sample tanks, Figures 15A and 16B, used in these measurements was 20 to 25 gallons per minute (gpm). To conserve weight and increase portability, the tanks were constructed from 12- and 20-gage stainless steel. These tanks could not stand extreme pressure without deformation of the ends. Therefore, a simple pressure reducing system was devised to provide a 20-gpm flow for a pressure drop ranging from about 1,100 feet down to 0 (atmospheric pressure).

Figure 10



A. Shop assembly of movable and fixed sampling tubes on manway in shop (movable tube extends near floor (a), fixed tube (b) to right). Photo PX-D-62906



B. Sampling system installed on penstock - (a) sampling line from movable tube (b) sampling line from fixed tube (c) rubber hoses to sample tanks
Photos 245-D-60415 and 245-D-60416

PENSTOCK SAMPLING SYSTEM FOR RADIOISOTOPE-WATER MIXTURE

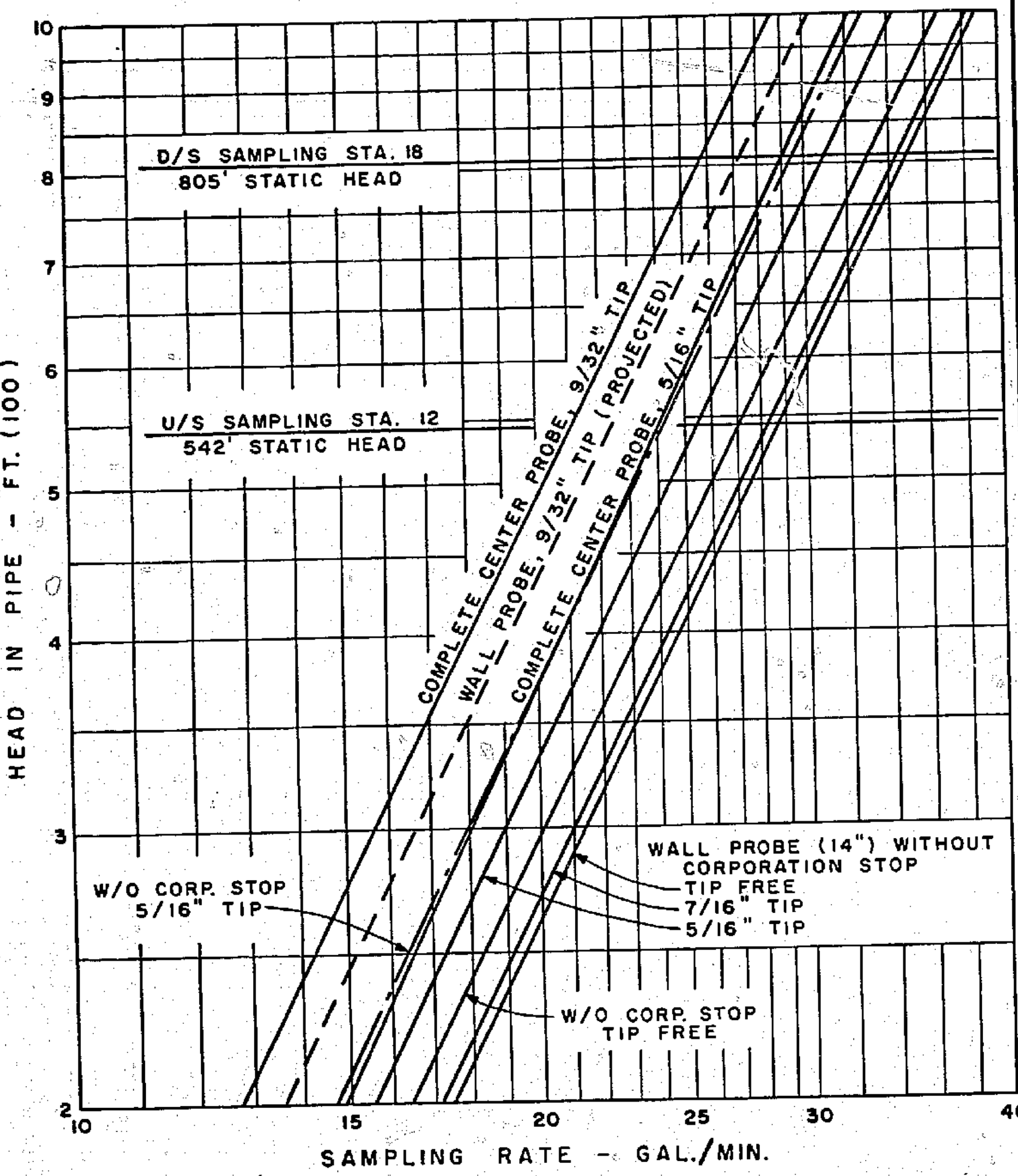
RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

The pressure reducer had no moving parts and head loss was achieved through the use of sudden enlargements and contractions of the flow. Previous studies of pipeline orifices in the Hydraulic Branch had shown that for maximum effectiveness, the ratios of diameters of the expansions and contractions should be 1.75 to 1 or larger.6/ Standard pipe fittings were selected and assembled to provide changes in flow passage diameter at a ratio of about 2.25 to 1, either increasing or decreasing, Figures 6 and 10. By the use of 1/4-inch and 3/4-inch pipe fittings, the size and weight of the reducer were kept to satisfactory values.

The drop in pressure from the penstock to sample tank was controlled by the sample tube, valves, pressure reducer, and friction in connecting hoses. An orifice insert was installed in the tip of each of the samplers to assist in reducing the pressure, Figure 6. The pressure reducing system was assembled for each sampling probe to allow a flow of 20 to 25 gpm for penstock heads of 540, 805, and about 1,100 feet. Studies in the Hydraulics Branch, using an 8-inch pump producing 600 feet of head, established the characteristics of the pressure reducers, Figure 11.

Two manway covers having 150- and 300-psi ratings were fitted for use in withdrawing the radioisotope-water sample from the penstock. These manway covers could be placed over several combinations of

Figure 11



SAMPLING RATE CURVES FOR PRESSURE REDUCERS

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH HEAD TURBINES AND PUMPS

manways to change the mixing length between injection and sampling. A third sampling system was installed near the turbine in the powerplant, Figures 5 and 12.

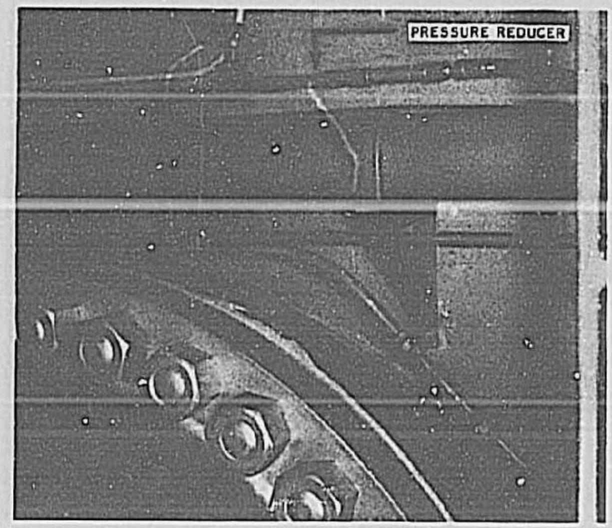
The penstock pressure taps were used to obtain a sample at the inlet to the turbine spiral case, Figure 12A. A four-orifice piezometer ring and piping manifold were available at the turbine inlet. One of the 1/4-inch orifices and the manifold piping were connected through a 3/4-inch globe valve to a sudden enlargement pressure reducer, Figure 12A. By adjusting the 3/4-inch valve, the system could be set to produce a flow of 20 gpm through the sample tank.

An existing 1-inch connection was used to withdraw water from the turbine draft tube, Figure 12B. The draft-tube pressure was not sufficient to force 20 gpm through the sample tank. Therefore, a centrifugal pump was used to obtain the necessary discharge, Figure 12C.

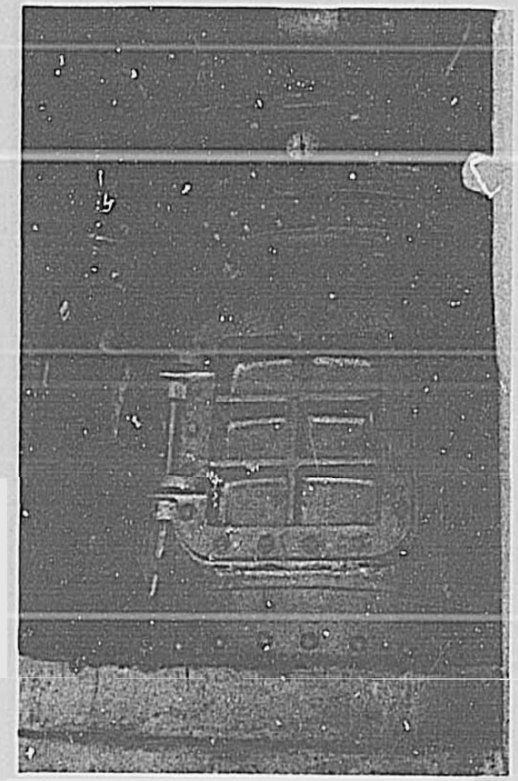
Pitometer and Spiral Case Flowmeter

Pitometer. - Using procedures governed by recommendations in the ASME power test codes, the velocity distribution was measured in the penstock. This velocity distribution was used for an independent computation of the discharge.

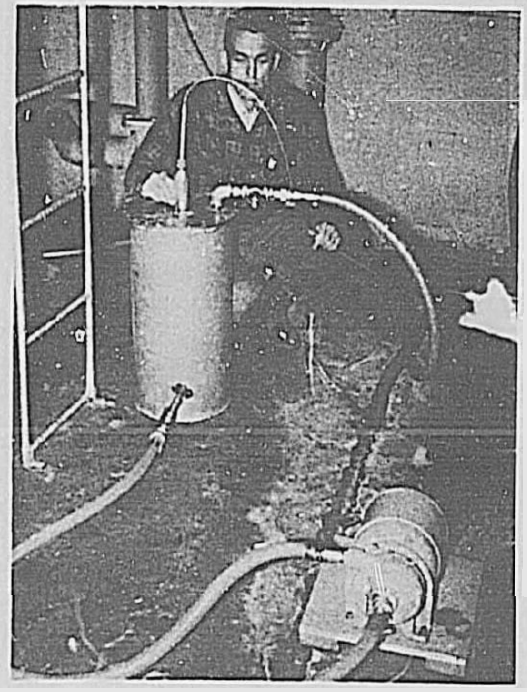
Figure 12



A. Piezometer manifold and pressure reducer at inlet to turbine spiral case. Photo P245-D-62879



B. 1-inch pipe connection at turbine draft tube. Photo P245-D-60418NA



C. Centrifugal pump and sample tank in powerplant near draft tube, scintillation detector in center of tank. Photo P245-D-60417

SAMPLE TANK INSTALLATION AT TURBINE UNIT NO. 2

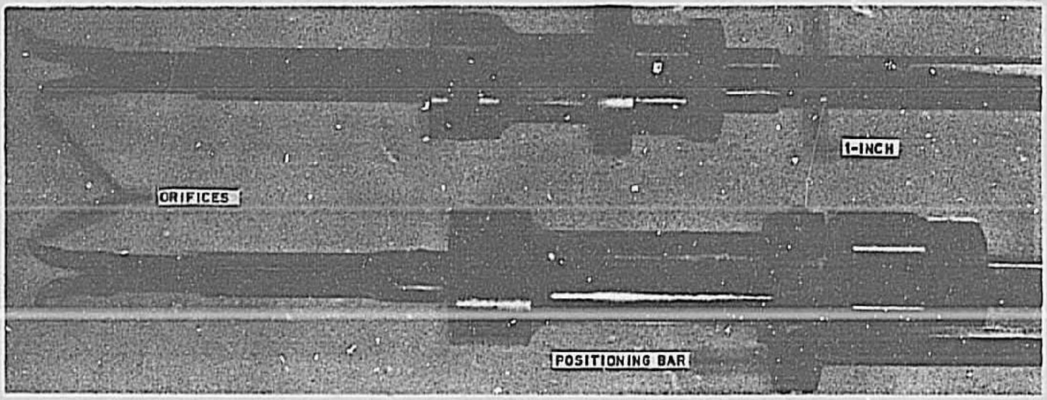
RADIOISOTOPE DISCHARGE MEASUREMENTS HIGH-HEAD TURBINES AND PUMPS

Velocities were measured with a special form of pitot tube, a pitometer containing two orifices, Figure 13A. One of the orifices reacts to the total head (velocity plus pressure) and the other orifice reacts only to a pressure head. A stuffing box threaded to a pipe nipple on the penstock seals the pitometer and allows positioning of the orifices in the penstock.

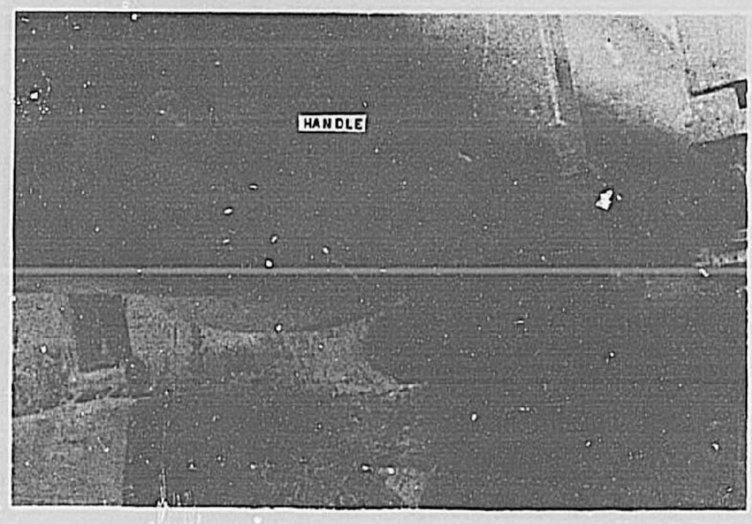
Four access pipes located at 90° intervals on the penstock perimeter were provided during construction for insertion of the pitometer, Figure 13B. Two calibrated pitometers, one 4 feet and the other 7 feet long, were used to traverse from opposite ends of a diameter. The location of the orifices on the radius was set by a premarked brass bar attached to the pitometer stuffing box and to the pitometer, Figure 13A. The position of the orifice on the radius could be accurately repeated, and the pitometer was held in a known location during the velocity measurement. A well-defined velocity distribution was obtained by carefully adjusting the position of the orifices in critical areas of velocity change.

A U-tube manometer of 3/8-inch semirigid plastic tubing was installed adjacent to the penstock to measure the differential head created by pitometer orifices, Figure 13C. The manometer was equipped to provide air pressure to force the water columns into the plastic tubing after air was purged from the connecting lines between the pitometer

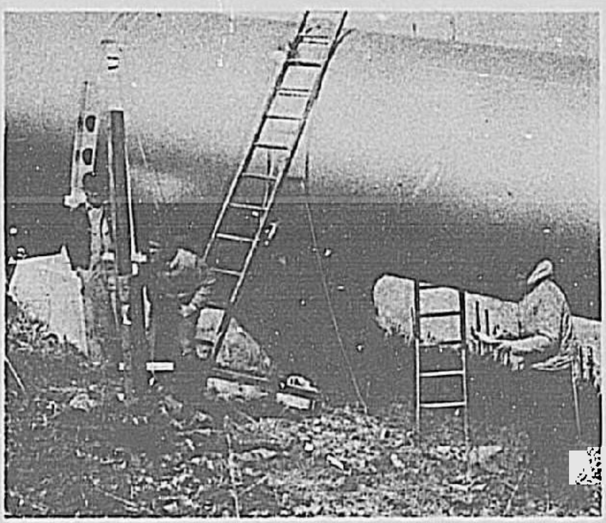
Figure 13



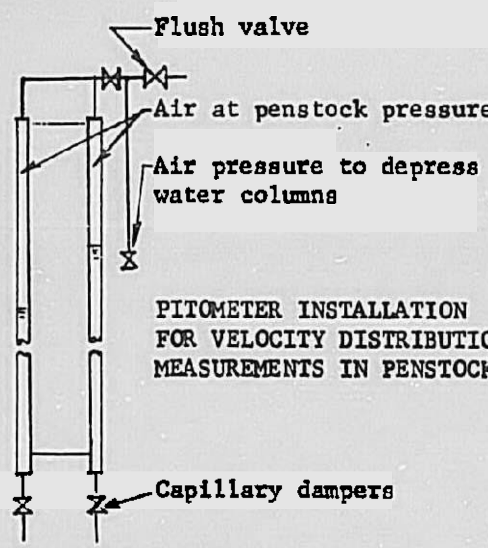
A. Pressure sensing orifices and stuffing box of pitometer
Photo P245-D-62880



B. Pitometer inserted into 6-foot-diameter penstock - Right angled handle used for pushing pitometer into pipe.
Photo P245-D-60412NA



C. Water manometer (see sketch) fastened to support near penstock.
Photo P245-D-60411



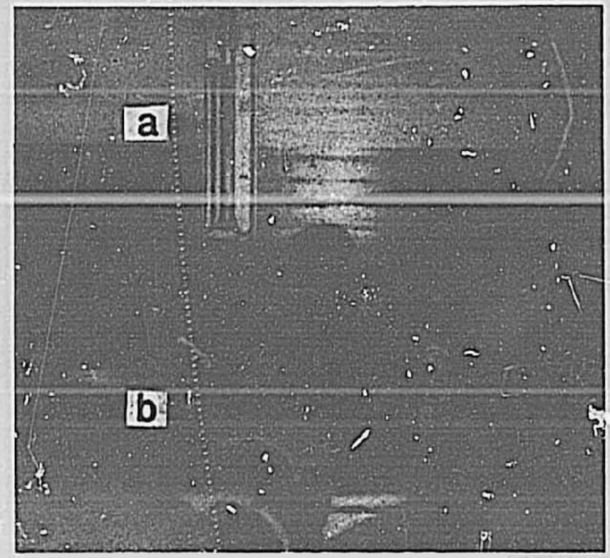
PITOMETER INSTALLATION FOR VELOCITY DISTRIBUTION MEASUREMENTS IN PENSTOCK orifices and manometer. Capillary dampers of 1/16-inch OD tubing in a coil having a length of 94 inches were used to reduce the water level fluctuations in the manometer. A steel tape graduated to 0.01 foot was used to measure the differential head.

Spiral case flowmeter. - An elbow-type flowmeter (Winter-Kennedy taps) was installed on the turbine during construction. A calibration of the flowmeter was performed in 1954 by the salt-velocity method of discharge measurement. Before conducting the radioisotope discharge measurements, the two flowmeter orifices in the turbine were inspected and cleaned to provide the smooth flow surface of the calibration.

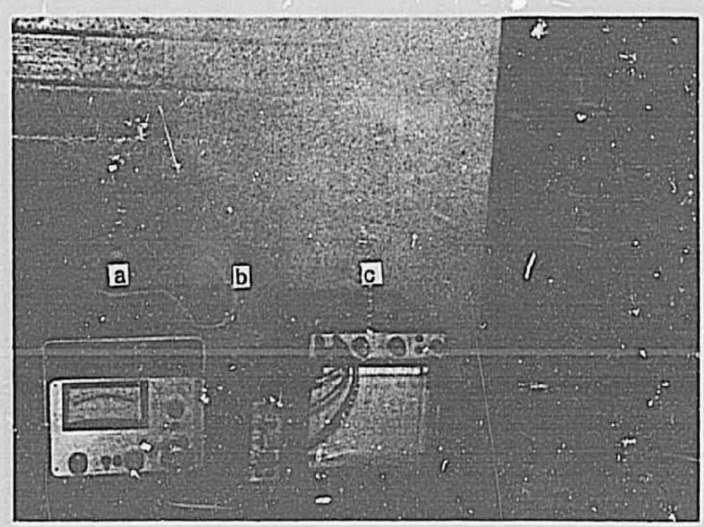
A mercury U-tube manometer was connected across the orifices, Figure 14A. The flowmeter was designed to produce a differential of about 7 inches of mercury for a turbine discharge of 500 cfs. The manometer was purged of air and adjusted for zero reading before each measurement series. Periodic readings of the differential were manually recorded.

A diaphragm pressure transducer was connected across the inlet side of the manometer, Figure 14A. A valved bypass was provided on the transducer to check the system for a balance at zero differential. The transducer, calibrated to measure the differential in feet of water, was connected to an analog recording system, Figure 14B. A

Figure 14



A. Turbine flowmeter differential pressure sensors - (a) mercury manometer, (b) pressure transducer and bypass. Photo P245-D-62881



B. Pressure differential recording system (a) carrier amplifier, (b) filter, (c) recording voltmeter. Photo P245-D-60410NA

MANOMETER AND RECORDER FOR TURBINE FLOWMETER

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

carrier-type amplifier energized the transducer and conditioned the signal through a resistive-capacitive filter for recording by a high-impedance voltmeter. The filter was used to damp the fluctuating pressure signal and provide an averaged record of the differential for determining the discharge.

Turbine Operation

A steady flow through the penstock and turbine was desired for the radioisotope discharge measurements. This could not be maintained in an absolute sense because the penstock and turbine has inherent flow disturbances that cause the discharge to vary up to 6 cfs or more over short periods of time. To minimize the unsteadiness, the forebay reservoir (Rattlesnake) and Flatiron afterbay reservoir were operated in such a way as to maintain a nearly constant head on the turbine. The turbine governor was blocked to provide a constant gate setting. The source of disturbances was thus those of the inlet valve structure, penstock contractions, the turbine, and the draft tube. Operation of the two turbines under blocked load and constant head reduced the flow fluctuations to a minimum for the discharge available for the measurements.

Because of the experimental nature of the radioisotope discharge measurements, the tests were made over periods of 4 to 6 hours. A discharge of 130 cubic-feet per second was selected for this length of test period. The 130-cfs flow could be repeated on several consecutive days, over a period of several weeks. Thus, there was a continuity to the tests and better conditions were maintained for power generation and sale.

Radioisotope Investigations

Selection of Tracer

A part of the research program has been directed toward obtaining data and information to allow confident selection of the best radioactive tracer.1/ After considering a long list of radioactive materials, the number has been reduced to a list of 11 commercially available isotopes having a radiological half-life in the 1- to 9-day range. The reasons for limiting the half-life range from 1 to 9 days are to: (1) have a long enough half-life to allow transport and use of the material at the field site before too much activity is lost by decay; and (2) have a short enough half-life so that the residual radioactivity will soon be gone from the waters being measured and from the apparatus used in the test.

The radiation emission from the tracer must include (γ) rays. Even though the presence of gamma radiation from concentrated solutions at the injection point does present handling problems, the ease of detection of gamma rays at the point of measurement warrants the use of gamma emitting tracers. Any tracer used in flow measurement must be completely water soluble and any loss of tracer caused by adsorption on the exposed surfaces of the conduit must be minimal.

The radioisotope, Gold-198 (Au-198), had been used in all of our flow measurements in canals and pipes. There is indication that gold is strongly adsorbed on surfaces of sand and clay, and probably on concrete. However, when working with the measurement in turbines and pumps, the surfaces of the conduit are usually lined with a protective coating and the contact of the concentrated tracer with these surfaces is minimal, resulting in an insignificant amount of tracer loss.

The use of Au-198 in both laboratory and field phases of the turbine flow measurement program had been satisfactory. Investigations of other isotopes resulted in the selection of Bromine-82 (Br-82) for use in the Flatiron discharge measurements.

Laboratory tests showed that the Br-82 when diluted in a potassium bromide solution did not form deposits on laboratory apparatus. Remnants of the solution could be easily removed from a container by rinsing the container with tap water.

The counting yield (observed count) per unit of radioactivity is approximately three times larger than for Au-198. The greater number of γ-rays per disintegration of Br-82 can be readily used to reduce the amount of injected activity and keep a counting accuracy comparable to Au-198.

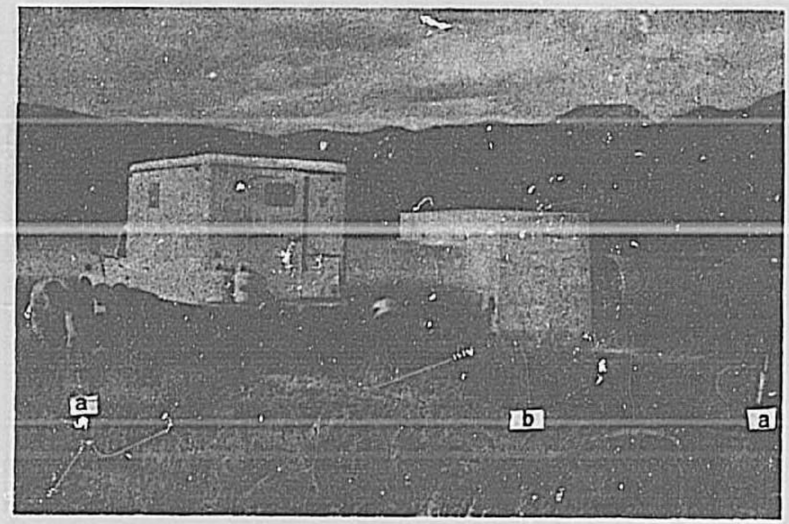
Radioisotope Counting System

The mobile nuclear laboratory, Figures 15A and 16A, was designed specially for performing field tests using radioisotopes in ground-water tracer studies and flow measurement with radioisotopes in open and closed conveyance systems. The laboratory is mounted on a 4-wheel-drive vehicle and is completely self-contained. It is equipped with a regulated power supply to enable the use of standard laboratory instruments in the field.

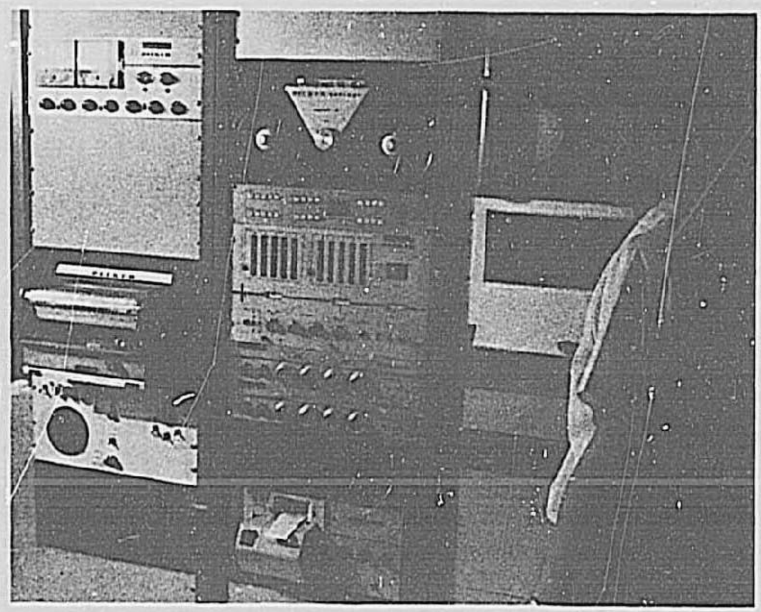
The vehicle provides the capability of performing all field tests with radioisotopes envisioned in the Bureau's program.

An automatic counting system, magnetic tape, and recording system have been installed in the mobile laboratory for use with the turbine flow measurement program, Figure 15B. The system includes: (1) dual-channel scaler (counter), (2) high-voltage power supply, (3) parallel printer, (4) two complete, integral line, scintillation detector assemblies with transistorized preamplifiers, (5) dual-pen potentiometer recorder, and (6) four-channel digital tape recorder.

Figure 15



A. Mobile nuclear laboratory located at Sampling Station 311 pipe diameters downstream from injection station (a) sample tanks (b) sample containers. Photo P245-D-60414NA



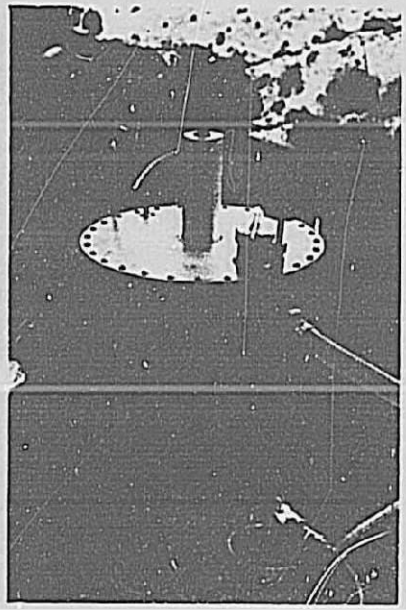
B. Radioisotope counting and recording system installed in mobile laboratory. Photo PX-D-55953NA

MOBILE NUCLEAR LABORATORY

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

Figure 16

A. Mobile laboratory at Sampling Station 47 pipe diameters downstream from injection station. P245-D-62882



B. Sample tank containing detector and connected to penstock sampling system - Small plastic tube at entrance to tank used to collect samples for "integrated" and "dilution" methods of discharge measurement. P245-D-62883

C. Decade scaler and timer for sampling station at inlet to turbine. P245-D-62884

RADIOISOTOPE COUNTING SYSTEMS AT PENSTOCK AND POWERPLANT

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

The dual-channel scaler has two 5-decade fast readout scalers to totalize the detected radiation emissions. The scaler contains neon indicators and buffer storage with a 4-decade electronic timer that has 999 preset positions. The two scalers can be operated in series as a single 10-decade scaler. The instrument can be used manually as a regular scaler with one or two counting channels for preset time or preset count measurements, or as an automatic instrument with the data fed to the recording devices. When the count or time has reached its preset value, the information accumulated by each of the scalers is transferred to a buffer storage and the scalers are reset and restarted, all within 10 microseconds. The information accumulated by the dual-channel scaler is recorded in two ways. The digital data stored in the buffer storage circuits are read out to the parallel entry printer, along with the index number from the 2-decade internal index counter. The printer records these 12 digits of information (2 index, 5 from each scaler) at a maximum repetition rate of 3 printings per second. In addition or alternatively, an analog signal is available from each buffer storage channel for a histogram presentation on a potentiometric recorder.

Input data going to the dual-channel scaler can be simultaneously recorded on tape for playback at another time. This recorder is a high-speed, high-fidelity memory unit designed specifically for research with radioisotope measurement systems. It includes a digital buffer storage to derandomize pulses for reliable recording, a choice of speeds for both recording or playback, a background simulator for net playback (background subtraction) and a very flexible track assignment. The use of this instrument allows the scientist the opportunity to repeat a questionable measurement after the completion of the field tests and will enable him to manipulate the time scale of the data. It is possible to use four detectors at one time when using the instrument.

Refinements in Equipment and Methods

One objective of this research program in high-head turbine flow measurement is to refine methods and equipment to reduce all measurement errors to the absolute minimum. For example, tests in the laboratory have shown that the high-voltage output from the portable scalers for operating the detectors will vary directly with the battery voltage and with ambient temperature. These changes and the resulting error in detector response are insignificant in many field applications but induce an undesirable degree of error in precision measurement of turbine flow rate.

Now in use, as a part of the counting system, is a line-operated, high-voltage power supply. This power supply has two outputs (A and B). Output A is variable from 500 to 1,500 volts. Output B is the same output plus or minus an adjustable percentage to allow two detectors which are closely matched to be operated simultaneously. The temperature stability is 0.002 percent per degree centigrade change in temperature.

With such a power supply, the changes in ambient temperature and the resultant changes in high-voltage output no longer create a measurable error in our detector response. In addition, the entire electronic system is enclosed in the controlled temperature environment of the mobile laboratory where temperature changes are minor.

Timing for the counting system is based on a 60-cycle line frequency. This frequency is subject to significant variations at times. In order to make corrections in the time measurement, the alternating current line frequency is monitored continuously during the test by a crystal-controlled frequency counter.

Two radiation detection probes have been fabricated in our laboratory. Scintillation crystals were used rather than geiger tubes because the crystals have higher sensitivity to gamma radiation. The detectors are thallium activated, sodium iodide crystals, optically bonded to a photomultiplier tube in an integral line assembly. The electrical pulses from the photomultiplier tube are taken through a transistorized preamplifier which is a dual emitter follower configuration providing sufficient current to drive the pulse through the cable to the scaler with a minimum of pulse shape deterioriation or attentuation. The probes are both encased in a 2-inch OD brass tube. The NaI(Tl) crystal in D-II (Denver Office detector number) is 1-1/4 inches diameter by 3/4 inch long. Probe D-III is of similar design but is encased in a 2-7/8-inch-diameter aluminum case. The crystal is 1 inch thick and 1-1/2 inches in diameter.

The scintillation detectors when used in flow measurement are attached to a 50-foot cable and input connectors near the rear door of the mobile laboratory.

Method of Computing Discharge

Dilution. - The radioisotope technique of discharge measurement is directly related to an older principle of measurement, the chemical dilution method. The dilution method of measuring discharges eliminates the need for knowing or determining the area of flow, the velocity of flow, the roughness of the flow boundary, the water stage, the head loss, or any of the other hydraulic quantities encountered when rating by usual methods. In the dilution method, chemical or radioactive tracer detectable by chemical or electronic means, of known concentration C is introduced at a constant rate, q , into a flow, Q, containing natural amounts of tracer, C_o. At a cross section of the flow sufficiently far downstream from the place of injection to assure adequate transverse mixing of the tracer and flow, the concentration is then C_2. From the equation of continuity, where Q is the unknown discharge,

$$QC_o + q_1C_1 = (Q + q_1)C_2 \quad \text{or} \qquad (1)$$

$$Q = q_1 \frac{C_1 - C_2}{C_2 - C_o}$$

if C_o is negligible compared to C_2, C_2 is small compared to C_1 and q_1 is negligible compared to Q

then $$q_1C_1 = QC_2$$

or $$Q = \frac{q_1C_1}{C_2}$$

An inspection of the terms in Equation (1) shows that no knowledge is required of the flow or cross section geometry, the velocity, gradient, or other hydraulic characteristics normally associated with flow measurements. The discharge, Q, in the conduit may be detetermined from the measured concentrations, C_o, C_1, C_2, and the injection rate, q_1.

Integrated sample and total count. - In the integrated sample and total count methods, a measured amount, A, in microcuries (μc) of the radioisotope solution is introduced into the flow in a comparatively short time, producing a pulse of radioactivity in the flowing water.

At the measurement cross section downstream, where the tracer is thoroughly mixed with the flowing water, the concentration of the tracer is determined from the gamma ray emissions detected and counted. However, where C_2 is a constant of concentration in the chemical dilution equation, the concentration of radioactivity in the pulse is variable with time. In this case, considering the conservation of matter,

$$A = Q\int_T C_2\,dt \quad \text{or}$$

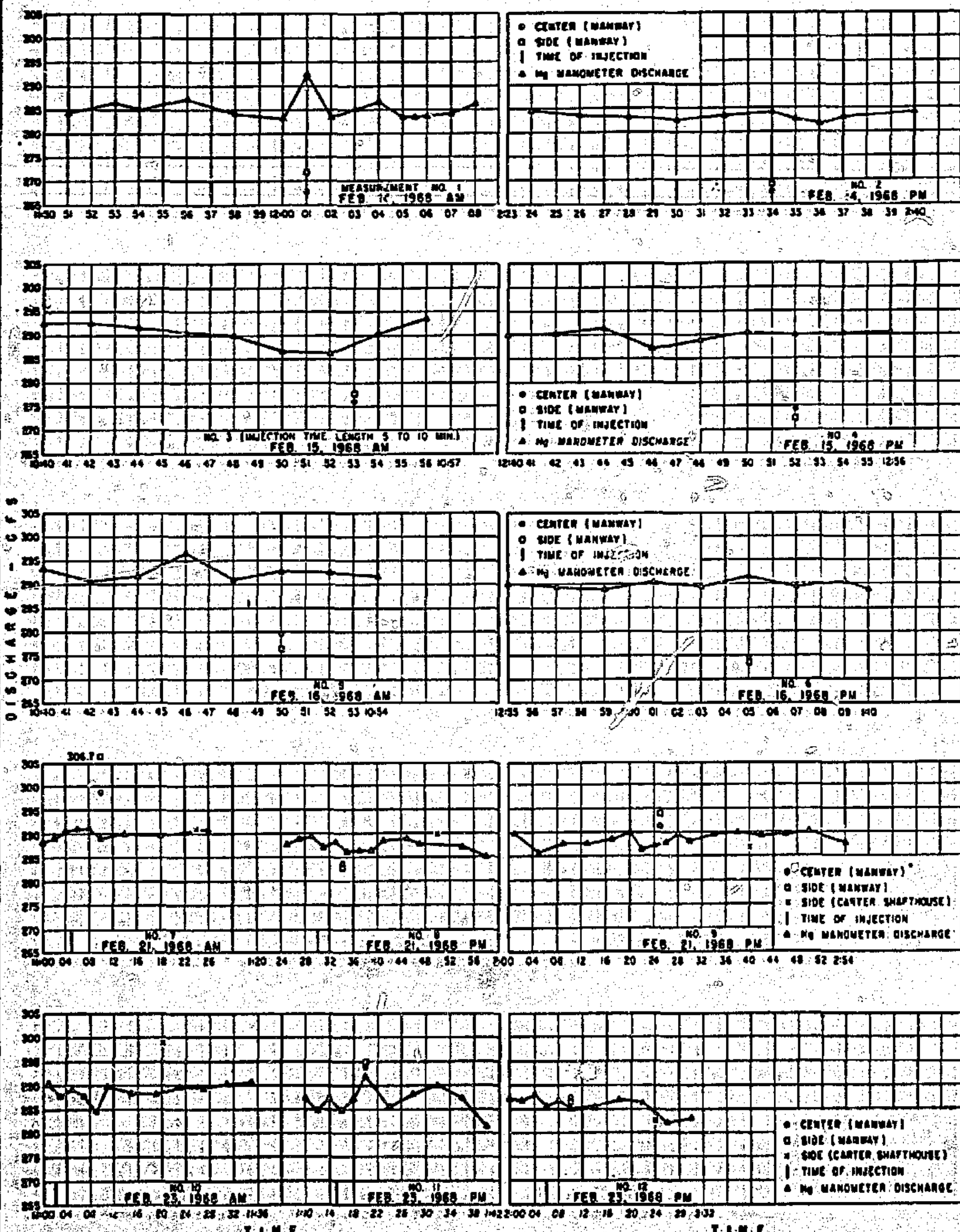
$$Q = \frac{A}{\int_T C_2 dt} \tag{2}$$

where changes in concentration, C_2, are measured with respect to time. If the varying concentration, C_2, is integrated over the time, T , required for the entire tracer cloud to pass, Equation (2) reduces to Equation (3), the equation for the integrated sample method.

$$Q = \frac{A}{\bar{C}T} \left[\frac{\mu c}{(\mu c/\text{cubic foot})\ \text{seconds}}\right] \tag{3}$$

where $\bar{C}$ is the average concentration during time T. It should be noted that again physical quantities to be measured to determine the discharge, Q, do not refer to the conduit shape or the hydraulic characteristics of the flow.

Figure 28



SPIRAL CASE FLOWMETER AND RADIOISOTOPE DISCHARGE COMPARISON

FLATIRON PUMP - TURBINE

RADIOISOTOPE DISCHARGE MEASUREMENTS HIGH HEAD TURBINES AND PUMPS

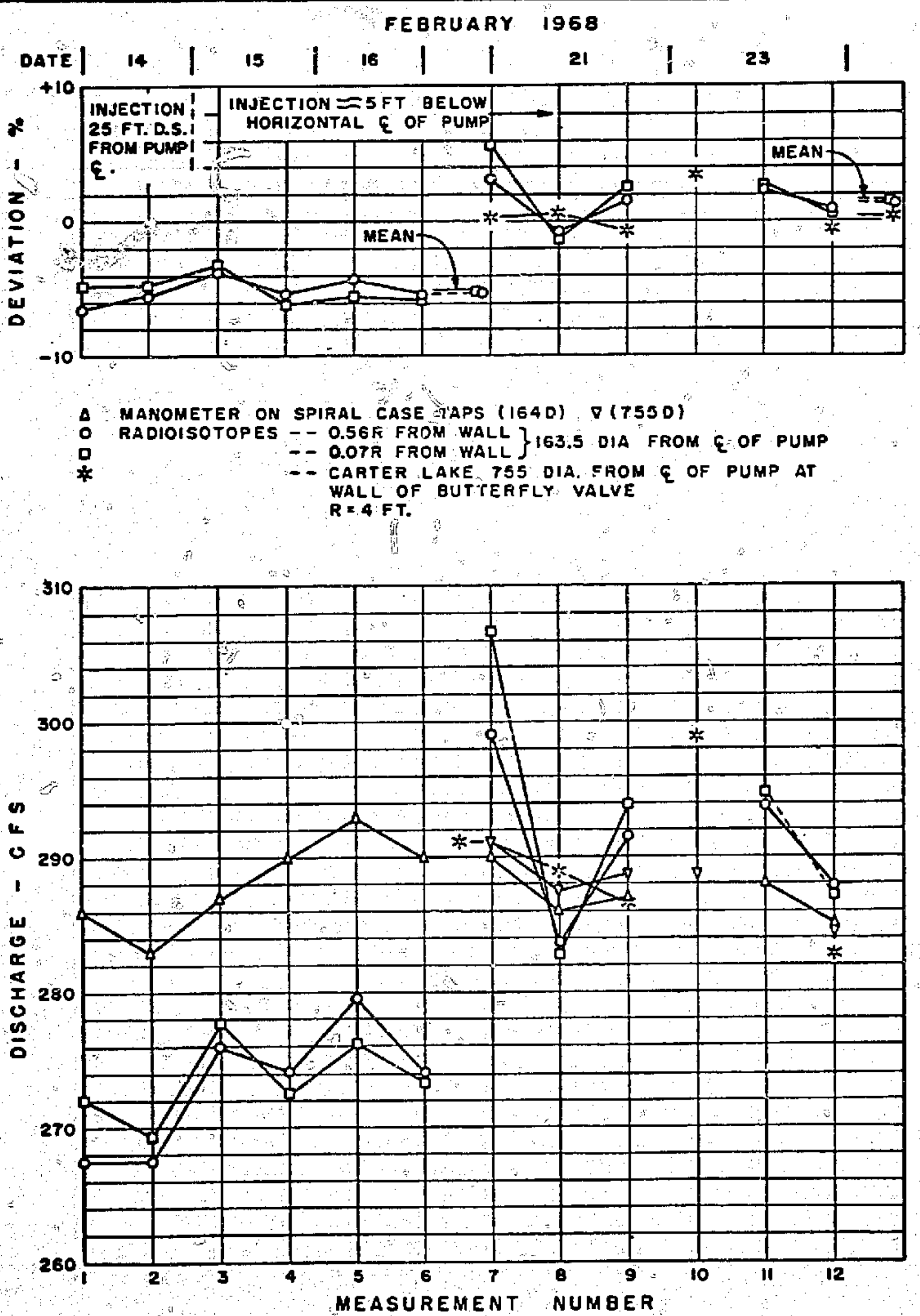
February 14, 1968, Figure 24. The discharges computed from the 0.56R and 0.07R samples (center and side) differed by about 1.5 percent in the first and by 0.6 percent in the second measurement, Figure 29. The four computed discharges differed from the flowmeter by about -5 percent.

Both the hydraulic and radioisotope measurement procedures were reviewed and no definite reason could be found for the underregistration by the tracer method. The following day, February 15, a second series of two injections was made into the elbow of the pump. Relatively close agreement, 0.3 and 0.6 percent differences were computed for the center and side samples but the radioactive measurements were 4 to 6 percent less than the flowmeter.

No apparent advantage was shown for injecting the tracer either upstream or downstream from the pump for the 164-diameter mixing length. The difference in discharges computed from the radioisotopes for the February 14 series was slightly larger than those on February 15. Again, no reason could be found for the 5-percent difference between the flowmeter and radioisotope discharge measurement.

Two more measurements were made on February 16. The tracer was injected in the elbow to take advantage of the lower injection pressure. The difference was again about -5 percent, whereas a

Figure 29



DISCHARGE MEASUREMENTS PUMP – TURBINE
FLATIRON POWER AND PUMPING PLANT

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH HEAD TURBINES AND PUMPS

1.1- and 0.4-percent difference was computed between the center and side samples of the radioisotope method.

With the completion of the series, a critical review was made of all the procedures including the original calibrations of the flow-meter. This review disclosed that the procedures used in the sample tank calibration might be a source of error. The radioactive material, Br-82, used in the measurements is received in a concentrated form. This concentrate is then diluted accurately by volumetric methods to become a base supply for the planned measurements (Tracer Handling Procedures). The diluted solution is kept in a shielded compartment and accurately measured volumes are taken for the discharge measurement and another volume for the calibration of the sample tanks. The dilution and extraction of the solution parts were done at laboratory temperature. Cold weather prevailed during the measurements on the turbine and in the February measurements, Figure 25. Although the calibration solution and pipet were kept warm, the change of temperature from storage to sample tank could have caused a decrease in the volume and possibly concentration of the calibration solution. The decrease in the volume was believed sufficient to produce a low calibration factor F for the tank. To better control the amount of tracer used for calibration of the tank, each amount was proportioned by weight on a precision analytical balance in the laboratory. Over the temperature range encountered during the measurements from less than 32° to 72° F, the specific weight of the tracer solution changed a maximum of 0.2 percent. Each weighed amount of tracer was put in a sealed glass bottle and transferred directly from the bottle to the sample tank. Each bottle was rinsed in the sample tank to assure complete transfer of the calibrating solution.

For a second series of measurements, February 21 and 23, that included the change in tracer handling procedure, a third counting system was placed in the Carter Lake valve shaft, Figure 26. This counting system was installed to take advantage of the 6,044 feet of pipe available for mixing the tracer and water.

Discharge computations from the data of February 21 showed that excellent agreement was obtained between the spiral case flowmeter and the radioisotope measurement from the valve shaft sample, Table 7 and Figures 28 and 29. The discharges computed from the samples taken at 164 diameters for the first measurement did not agree well with the flowmeter. The discharge computed for the center was 3.05 percent larger than the flowmeter discharge and the side 5.76 percent larger. The difference of 2.7 percent between the two was greater than encountered in the February 14-16 series.

The second measurement on February 21 again showed good agreement between the counting system at 755 diameters and the flowmeter.

Table 7

Flatiron Pump-Turbine
Radioisotope and Spiral Case Flowmeter
Discharge Measurements (755 diameters)

Carter Lake Valve Shaft Sample

Measurement No.	February 1968	Differential manometer, inches Hg	Flowmeter discharge, cfs	Isotope discharge, cfs	ΔQ, cfs	Deviation, percent
7	21	4.85	290.9	291.25	+0.35	+0.12
8		4.74	287.5	289.89	+2.39	+0.83
9		4.81	289.7	286.85	-2.85	-0.98
10	23	4.78	288.7	298.72	+10.02	+3.47
12		4.63	284.4	282.83	-1.57	-0.55

The discharges computed from the two systems at 164 diameters differed by less than 0.3 percent but the average was 1.0 percent less than the flowmeter.

A wider variation was found on the third measurement of February 21 for the 164 D sampling station, Figure 28. The radioisotope method center sample showed a discharge 1.77 percent greater than the flowmeter and the side sample 2.58 percent greater. The flowmeter discharge measurement differed by less than 1 percent from the valve shaft measurement.

The measurements were continued on February 23. An equipment failure in the mobile nuclear laboratory caused the loss of a measurement at the 164 D sampling station. A measurement was obtained at the valve shaft, but the discharge value differed by nearly 3.5 percent from the flowmeter. In the second measurement of February 23, a communications failure caused the loss of the valve shaft measurement. The discharges computed from samples at 164 diameters were in very close agreement, about 0.3 percent, but differed from the flowmeter by about 2.5 percent. The third and last measurement of the series showed good agreement of discharges computed from the three radioisotope samples and flowmeter. About 0.1 percent separated the discharges computed from the two samples from 164 D measuring location, Figures 28 and 29. Both of the discharge values were less than

1 percent larger than indicated by the flowmeter. Calculation of the discharge from the radioisotope count at the valve shaft gave a value of about 0.6 percent less than the flowmeter.

The series of discharge measurements on the pump-turbine unit at Flatiron indicated that satisfactory mixing can be obtained in the 8-foot-diameter pipe in a length of about 1,300 feet (164 D).

The repeatability of the discharge measurements was fair for the radioisotope method. The variance between the discharge indications of the selected standard (spiral case flowmeter) and the radioisotope method, ranging from 0.1 to nearly 7 percent, was too great. The discharge measurements showed that very precise control was required in the procedures used in the injection, sampling, and counting of the radioactivity. The series also showed that extreme care must be maintained in measuring the flow by the flowmeter. The pump and the turbine do not have an unvarying flow and the flowmeter discharge must be determined at the time of the radioisotope measurement.

CONCLUSIONS

In general, the computed discharges for the turbine had a variation greater than desirable, Figure 20. Mixing of the tracer and penstock flow was believed to be adequate in the 645 diameters of penstock.

The large variation in the computed discharges when compared to the spiral case flowmeter was attributed to anomalies in the radioisotope techniques of sampling and/or counting. The exact causes of the variations could not be determined but procedures for preparing the radioisotope for use in the sample tank were modified to improve the tank calibration.

The quality of mixing of the tracer and water in the penstock was indicated to be unsatisfactory in 310 diameters of the 6-foot pipe. At a velocity of 4.5 feet per second (Reynolds Number of 2.6×10^6), the natural turbulence of the flow apparently did not produce satisfactory mixing. Studies of the radioisotope counting and sampling should continue to determine the amount of variation caused by the mixing and by the radioisotope procedures.

The series of discharge measurements on the pump-turbine unit indicated that satisfactory mixing was produced in the 8-foot-diameter pipe in a length of 164 diameters. The repeatability of the radioisotope discharge measurements was fair, 0.3 to 2 percent. The discharge measurements require very precise control of procedures used in injection, sampling, and counting of the radioactivity. Because of the unsteadiness of the pump flow, extreme care must be maintained in measuring the flow by the spiral case flowmeter.

Error analysis of the variables in the radioisotope and spiral case flowmeter discharge measurements should be continued to better define the variations within the methods. Because of the unsteady flow in both the pump and turbine, confidence limits must be established for the flow measurements. Should the precision of the radioisotope measurement be shown greater than for the spiral case flowmeter consideration can be given to performing salt-velocity measurements coincident with the radioisotope measurements.

FUTURE MEASUREMENTS

Continuing phases of the program will include modification of equipment and revision of techniques.

The refinements of techniques and equipment will be applied to field measurements at Flatiron Power and Pumping Plant. Discharge measurements will be made to obtain statistical information on the maximum probable error in discharge to be expected from the radioisotope method.

The experiments will include the effects of injection and sampling techniques on the tracer velocity, total count, dilution, and integrated sample methods of radioisotope counting. Emphasis will be placed on measurement repeatability and accuracy with variations in the injection technique and geometrical relationship of the radiation monitoring apparatus to the hydraulic system.

Investigations will include the velocity method of measuring the travel time of the water-tracer mixture between two cross sections of the pipeline. Discharge measurements will be made to establish the accuracy of the velocity method relative to those cited in the preceding paragraph. The investigation is included because the principles of the method are simple and the method may be particularly applicable to certain configurations of penstocks in powerplants.

Studies to devise a simple way of increasing the mixing of the tracer and pipe flow will continue. These studies would result in achieving complete mixing in shorter pipe lengths. The shorter mixing length is important if radioisotope tracer methods are to be applied to existing pumps and turbines that have less than 100 diameters of conduit length.

The use of tritiated water as a tracer is proposed for use with the integrated sample method. This method requires retention of the sample for laboratory analysis with the liquid scintillation counter. The process of liquid scintillation sample preparation will be carefully investigated to evaluate the reproducibility of results. The use of tritium will provide the advantages of: (1) easier handling procedures for the tracer in the field, (2) the elimination of critical measurements at the field site, and (3) allow the stocking of large amounts of tritium for immediate use without significant losses caused by radioactivity decay.

The above tests are proposed for the summer months of 1968 and will be scheduled over a period of 3 to 5 months. It is estimated that the tests will involve about 6 weeks of field activity.

Technical Direction

The proposed program will be a coordinated effort in the Division of Research between the Hydraulics and Chemical Engineering Branches. The work will be under the technical direction of H. M. Martin, Chief, Hydraulics Branch, and L. O. Timblin, Jr., Chief, Chemical Engineering Branch. Working on the project will be two physical scientists and two hydraulic engineers, all having experience in water measurement procedures and in the application of radioisotopes to flow measurements. The scientists and engineers will be assisted as required by technical personnel from the Research Division. The work will be performed at the Bureau of Reclamation, Denver, Colorado, and at the Flatiron Power and Pumping Plant near Loveland, Colorado.

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APPENDIX 1

POTENTIAL ECONOMIC BENEFITS FROM THE USE OF RADIOISOTOPES IN FLOW MEASUREMENTS THROUGH HIGH-HEAD TURBINES AND PUMPS

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November 1967

FOREWORD

This report was prepared at the request of the Research Division with close support and direction provided by staff of the Chemical Engineering and Hydraulics Branches of that Division. The intent is to present a "broad-brush" study which identifies the economic potentials of the use of radioisotopes in measuring high-pressure waterflows through hydraulic turbines and pumps. There is general agreement that a need exists for a highly accurate, simple, and inexpensive means for measuring flows. No doubt other promising alternative measuring devices not employing radioisotopes may warrant further consideration; the emphasis here, however, is on a particular program item now under active study.

The main question to which this report is addressed is not whether the radioisotope method will prove technically successful--this is the purpose of the current research effort--but rather what are reasonable expectations of the benefits to be gained if this potential new tool successfully meets its goals. The report indicates that the possible economic gains from application to the Bureau of Reclamation program are attractive. This would logically apply not only to the use of radioisotopes but to other approaches if the same objectives were served.

The preparation of the manuscript rested mainly on the author. Special acknowledgment is due for the contributions made by Messrs. Robert L. Hansen, Chemical Engineering Branch and Jack C. Schuster, Hydraulics Branch. Valuable assistance on the estimates of the costs of acceptance tests was provided by Mr. George H. Johnson, Hydraulic Machinery Branch. Numerous others cooperated in the study including members of the Hydraulic Machinery and Technical Engineering Analysis Branches of the Division of Design, Division of Power Operations, and Division of Irrigation Operations.

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CONTENTS--Continued

SUMMARY

The Bureau of Reclamation and Atomic Energy Commission are cooperating in research to determine the feasibility of using radioisotopes for measuring waterflows through high-pressure turbines and pumps to meet a well-established need for a method which is highly accurate, simple, and inexpensive to apply. Achievement of this goal would provide an improved tool not now available. The possibilities for realizing economic gains from such a development were studied using the Bureau of Reclamation's program as a basis for analysis, although there would be opportunities for broader application both nationally and internationally.

A brief appraisal of alternative methods now used in gaging high-pressure waterflows indicated that the pressure-time (Gibson) and the salt-velocity methods are in predominant use by the Bureau, with the former favored but applicable to turbines only. A projection of field application procedures and hardware requirements suggests that substantial savings in testing expenses over these two methods could accrue to the use of radioisotopes. This excludes expected reductions in shutdown periods not specifically evaluated but of possible importance. Of the three measurements normally required to make acceptance tests of efficiency--pressure head, electrical, and water discharge--the latter is the most difficult, costly, and least accurate.

The new method's advantages of simplicity, low cost, and high precision could encourage routine and more widespread testing. For existing facilities, the availability of additional data of greater accuracy over a wide range of operating conditions and for more than one unit of a multiple-unit installation could prove valuable in refining operating criteria. Better information permitting greater selectivity and control of individual units at a given site, or geographically separated installations, could permit fuller utilization of design machine capabilities and the institution of more timely maintenance programs. Turbines and pumps may thus be made to run closer to top efficiencies so that average efficiency levels attained over a period of time could be somewhat higher.

An analysis was made to determine to what extent the radioisotope method would be applicable to Bureau turbines and pumps constructed and under construction, and the monetary benefits that might be associated with small increases in efficiency of 1 percent or less. Offsets against benefits which would need to be considered are the additional costs of testing and possible incremental costs of repairs to bring the unit back up to design capability. Added repair costs could be minimal as the effect may simply optimize the timing of regular maintenance programs.

The analysis developed value data for selected powerplants and pumping plants covering a range of sizes. Bureau-wide it was found that of the 11,600,000 kw in total powerplant capacity constructed or under construction, 3,000,000 kw were considered amenable to radioisotope flow measurements. Making these machines operate on the average 1/2 percent closer to their built-in efficiency potentials could yield capacity and energy valued at $250,000 annually, which would have a present worth of over $2,000,000 for 10 years.

For pumping plants, reduced costs of the radioisotope method may permit beneficial application to installations as small as 5,000 hp; normally, field testing is economically practicable for only much larger sizes. Of the total 1,700,000 hp constructed or under construction, radioisotope flow tests may be applicable to over 1,000,000 hp. The potential gain is considered greater for pumps because of greater difficulties in testing. Thus an average annual yield of 1 percent more of machine efficiency the 1,000,000 hp in pumps could result in a saving in pumping energy worth $150,000 which would have a present worth of $1,300,000 for 10 years.

The successful development of a waterflow measurement method which is highly reliable and has a probable inaccuracy of ± .75 percent could have beneficial effects on the industry producing turbines and pumps. Stricter standards that are enforceable could result in elevating levels of machine efficiency specified and ultimately obtained. Under ideal conditions, accuracy of existing methods is considered relatively high; nevertheless, because true rates of flow are not known and field conditions vary, there are questions concerning accuracy of particular tests and whether some methods test consistently higher or lower than others. Penalty clauses now included in invitations to bid provide good examples of the value of fractional efficiency losses in the event the manufacturer fails to meet specified standards. Value curves developed for a wide range of plant sizes demonstrate the economic importance of increases in efficiency of 1/4, 1/2, and 1 percent. The resulting benefits from gains in efficiency are sensitive to installed capacity as it requires a full 1 percent increase of efficiency and a minimum of about 5,000 kw in a turbine and about 4,000 hp in a pump to produce an annual benefit of some $1,000. At the other end of the scale only a 1/2 percent increase in efficiency for a 1,000,000 kw turbine or 750,000 hp pump could be worth $100,000 during the first full year of operation.

Limitations of the radioisotope method involve problems of achieving complete mixing of the solution in a relatively short distance and potential health hazards and public acceptance. The first has restricted the number of installations subject to measurement and means that a more costly multiple-point injection system may need to be used where less than 100 diameters in length of pipe are available. The second limitation is nontechnical involving following proper safeguards and public education.

POTENTIAL ECONOMIC BENEFITS FROM THE USE OF RADIOISOTOPES IN FLOW MEASUREMENTS THROUGH HIGH-HEAD TURBINES AND PUMPS

Introduction

In the water-resource conscious world of today, making the best use of limited supplies is a challenge of high order. The ability to accurately measure waterflow is obviously vital to this process. Hydraulic flow must be precisely known before the highest level of efficiency can be demanded from machines transforming the work potential of falling water into mechanical and electrical energy or, the reverse, from energy-consuming machines which lift water to where it can be beneficially used. The vexing problems of making exact measurements have a long history--for it was over 300 years ago that Galileo marveled that his discoveries on the movements of astonishingly distant heavenly bodies met with less difficulty than investigating flowing water before his very eyes. Though much progress has since been made, there is still a continuing and growing need for a simple, cheap, and accurate way to gage large waterflows. This is especially true in attempts to measure discharges in closed conduits under pressure to determine whether turbines and pumps are delivering the kind of performance for which they were designed or which is possible under current technology.

The purpose of this report is to provide insight on the possible economic gains resulting from a measurement method utilizing radioactive tracers. Active research in this field is well underway in the Bureau of Reclamation's Engineering and Research Center at Denver with the expressed objective of developing a rapid, accurate, and inexpensive method of using radioisotopes to measure the rate of flow of water through high-pressure hydroelectric generating facilities and pump systems. The program is being conducted and financed in cooperation with the Atomic Energy Commission as a part of the United States' worldwide program to harness the atom for peaceful and constructive uses.

This study is based upon the potential application of radioisotopes to the Bureau of Reclamation's program of building and operating multiple-purpose water development projects. The size and number of turbines and pumps included in that program are illustrated by the 58 hydroelectric powerplants constructed and under construction having a total capacity of 11.6 million kilowatts, and the 96 major pumping plants over 1,000 horsepower having a total capacity of 1.7 million horsepower. Power revenues from operations in fiscal year 1966 amounted to over $100 million. Possible gains from an improved flow measurement method are, of course, not limited to the Bureau's program. From a demonstration of potential usefulness at that program level, however, it would naturally follow that a multiplication of the effects would stem from a broader application encompassing other Federal facilities, state and municipal works, privately owned features, and finally water resource developments of other countries.

This study will first survey the various alternative methods available for water discharge measurements in high-pressure conduits, with emphasis placed on Bureau practices. The second section describes the radioisotope approach and specific goals, including a projection of field application procedures and hardware requirements. A cost analysis follows comparing relative magnitude of expenses involved in acceptance tests for turbines and pumps to determine machine efficiency levels. Possible benefits on Bureau-operating projects from the widespread and frequent use of radioisotopes are then generalized. And finally, potential gains from application to new facilities are considered.

Alternative Methods of Discharge Measurements

Accurate measurements of flow through hydraulic machinery are essential in design and construction and finally in actual operations. Together with measurements of pressure head and electrical output or input--depending upon whether it is a turbine or pump--the basis for testing machine efficiency is thus established. It is universally agreed that the accurate measurement of waterflow is the most difficult and complex aspect of this rating process. The finding of efficiency is of vital interest to both the purchaser and the seller, as it determines not only whether technical guarantees have been met but has industrywide ramifications on the quality of machines produced. In Bureau projects provisions are made for the assessment of stiff financial penalties against contractors for failure to meet efficiency specifications as effects may extend over the lives of the hydro facilities normally designed for at least 100 years and which must show financial feasibility in 50 years. Most of the efficiency tests for Bureau facilities are conducted as a part of formal acceptance tests after the completion of installation.

The universal interest in testing-machine efficiency resulted in international codification of procedures and methods. It appears most recently in published form as the "International Code for the Field Acceptance Tests of Hydraulic Turbines," 1963, by the International Electrotechnical Commission and recommended for publication by 19 participating countries including the United States and the Union of Soviet Socialist Republics. In establishing standards for efficiency tests, methods identified in that publication which are pertinent to the problem of accurate flow measurements in high-pressure conduits are (1) pressure-time (Gibson), (2) salt-velocity, (3) dilution, (4) current meter, and (5) pitot tube. The use of radioisotopes as presently conceived fits under the third category, the dilution method.

A choice of the method selected depends upon the particular installation--physical arrangements of intake works, penstocks, manifolds, and turbines differ and can present difficulties in test equipment location and installation. Heads can vary over 1,000 feet, discharges over 3,000 cubic feet per second and pressure conduits 20 feet or more in diameter. In Bureau acceptance tests preference is given to the pressure-time (Gibson) method for determining waterflows through turbines. The salt-velocity method is used for turbines where there may be a question of validity of results from the Gibson approach and almost exclusively on pumps since the Gibson test is not applicable to pumps. Brief descriptions of the various methods available for use in acceptance tests are presented in the following paragraphs.

Pressure-time (Gibson) Method.--This method, patented by N. R. Gibson, was devised to measure flows through a closed conduit or penstock controlled by a valve, turbine, or regulating device located at the downstream end. Pressure variations are measured between two pressure taps located along a pipe section preferably 25 feet or more in length. The variations are determined over a measured period of time during which the valve or regulating device is closed. Changes in pressure are automatically recorded on the chart of a recording device such as the Gibson apparatus which photographs on a revolving film drum the movement caused by the pressure change of the top surface of a column of mercury in a U-tube manometer. Equipment requirements are modest, do not require installation inside the pipe, and the recording apparatus can conveniently be carried by one man. Use of the Gibson method requires specially trained personnel and in Bureau projects is now accomplished on an outside contract basis. Since the recent expiration of the patent, development work is in progress to improve the recording of pressure-time diagrams.

Salt-velocity Method.--The salt-velocity method developed by Professor C. M. Allen and Mr. E. A. Taylor is based on the fact that salt in solution increases the electrical conductivity of water and that a "slug" of brine flowing through a conduit travels at the same velocity as the water and does not lose its identity. A quantity of salt solution is forced into the stream under pressure through quick-acting pop valves. After mixing in the stream, usually with the assistance of a turbulator located inside the pipe immediately below the point of introduction, two or more sets of electrodes located downstream detect the passage of the slug of brine. The average flow velocity is calculated by measuring the speed of the solution as it moves between the electrodes in the pipe section whose interior dimensions and characteristics have been carefully determined. The Code specifies that the first set of electrodes should be at least 4 diameters from the injection valves and the second set of electrodes at least the same distance downstream from the first set. The equipment is relatively large and complex; the injection facilities used by the Bureau, for example, weigh over a ton. The requirements for internal placement of the multiple-injection valves, turbulator, and electrode detectors make this method expensive. Bureau personnel and equipment are used for project tests.

Dilution Method.--This method consists of introducing a known concentrated solution of a tracer at a steady measured rate into the main flow of water. The tracer may be a solution of salt or dye. Through chemical or fluorescence analysis the concentration of the flowing water with the added chemical is measured at a point far enough downstream to ensure thorough mixing. No internal measurements of the pipe are required nor is it necessary to know the exact distance traveled. The total flow is measured directly by identifying the amount of flowing water "tagged" by the tracer. Only small amounts of dye are required. Presently available instruments cannot measure solution concentrations to a high degree of accuracy.

Primary disadvantages of the dilution method are achieving complete mixing, the requirement for long lengths of pipe, and obtaining precise measurements of tracer concentration in the diluted downstream flows. Recent work in this field has revealed indications of dye concentration decreases due possibly to chemical reaction with elements in the flowing water. The advantages are that simple injection and detecting facilities may be utilized and that no internal pipe measurements are necessary. The application of radioisotopes falls under the dilution method, but greater accuracy is anticipated as the radioactive tracers can be more easily detected and counted.

Pitot Tubes.--The method involves making observations of velocity heads through the use of a tube having a short right-angled bend placed vertically in the flow with the bent part or sensing end pointed in the direction of the flow. Average velocity is determined by measuring a sufficient number of points in a known cross-sectional area of the conduit. The average velocity multiplied by the cross-section area determines the discharge. Reinforced pitometers have been successfully used in pipes up to 5 feet in diameter with flow velocities of 5 to 20 feet per second. By probing from access points on both sides of the pipe, flows in even larger pipes can be measured. The principal disadvantages are that it is time consuming and relatively large forces push on the tube when flow velocities are high making it difficult to position and secure the instrument. The resulting instability causes inaccuracies. Pitot tube openings are usually small so that sediment and trash can plug the tubes. Flows must be steady for a sustained period to insure proper readings.

Current Meters.--In this method a number of individual current meters are properly placed in open or closed conduits to register individual water velocities. The meters must be accurately mounted and arranged with their axis parallel to the conduit in order to measure the velocity distribution through a cross section in a manner similar to the pitot tube. Several configurations of propeller-type meters are available but their initial cost plus the costs of placement calibration, maintenance, and data analysis make this method relatively expensive. Accessibility for installation of the meters and anchorage assemblies is also a problem. The current meter method is used in Europe but has not been extensively adopted in the United States.

Accuracy of Flow Measurements in Determining Efficiencies.--The accuracy of flow measurements of the various methods can be high under ideal conditions employing trained personnel and using properly selected, installed, and maintained equipment. The International Code for field acceptance tests presents as a guide the following ratings of probable inaccuracies in the determination of flow.

Method	Probable inaccuracy
Pressure-time (Gibson)	± 1.0 percent
Salt-velocity	± 1.0 percent
Dilution in penstocks	± 1.5 percent
Pitot tube	± 1.5 percent
Current meter	± 1.5 percent

To identify overall probable inaccuracies in testing machine efficiency, the possible errors in measurements of pressure head and electrical output must also be considered. Normally these two measurements are not considered difficult and result in probable inaccuracies of ± 1 percent or less. When all factors are combined the overall determination of efficiency is considered subject to a probable inaccuracy of ± 2 percent or more depending upon the method and success of the waterflow measurement.

There are differences in opinion among scientists on which of the flow measurement methods performs best and is most accurate. Considering physical variations of installations, no doubt all methods will continue to enjoy some degree of use. As true rates of waterflow under field conditions are not actually known, it would appear that more widespread comparative field testing would prove enlightening. Though limited in amount, information available from comparative studies indicates variations among and within the various methods employed. A classic example is the Finlarig comparative tests1/ where

1/Hutton, S. P., and G. B. Murdock, "Comparative Flow-Measurement Tests at Finlarig Power Station," Parts 1 and 2, Water Power, October, November 1962.

it was concluded that each flow measurement method tested was obviously consistent and gave clearly defined smooth curves; however, even when carefully carried out various methods can give differences of several percent. Also that it would be unwise to draw general conclusions as to which methods are likely to read high or low until similar comparative tests are made for many different installations under controlled conditions.

The development of a simple and inexpensive method, permitting repeated and widespread testing with a minimum of disruption of operations, could provide a ready means for evaluating performance. Basic accuracy is of course dependent upon the degree of inherent error in the measuring system; however, the ease with which a suitable number of samples over a wide range of conditions may be obtained with the radioisotope method could reduce the statistical error among the number of observations. The degree of precision to which modern scintillometers have been developed may substantially enhance the basic accuracy of the measured data. The development of an improved method would provide a tool not only useful in itself but also as a check on the performance of other approaches. The application of radioisotopes holds promise in this regard.

A passing notation is made of a different approach to testing efficiency used in some European countries which is referred to as the thermodynamic method which incidentally was also tested in the Finlarig study. It is considered to be particularly suited to heads of about 500 feet or more. Determinations of efficiency are made directly by measuring temperature differentials of flows through the turbine. Hydraulic losses have the effect of slightly raising the temperature of the fluid. Pressure and temperature measurements combined with the knowledge of certain thermodynamic properties of the liquid enable the direct determination of hydraulic efficiency. The mechanical losses must also be evaluated. Probable inaccuracies are considered comparable to the more accurate procedures discussed previously.

The Radioisotope Method

As mentioned before, the utilization of radioactive tracers for the purposes of waterflow measurement is a variation of the dilution method. Instead of the conventional uses of salt or dye, the degree of dilution is obtained by counting the gamma (or beta) ray emission of radioisotopes with Geiger counters or scintillation counters. This application of nuclear technology should add greater precision to the dilution approach because of the presence of highly detectable tracer materials, even though very small quantities are employed. As shown graphically in Exhibit 1, the injection and sampling system now under development would add simplicity and economy to water-measurement techniques.

RADIOISOTOPE METHOD FOR MEASURING HIGH-HEAD FLOWS

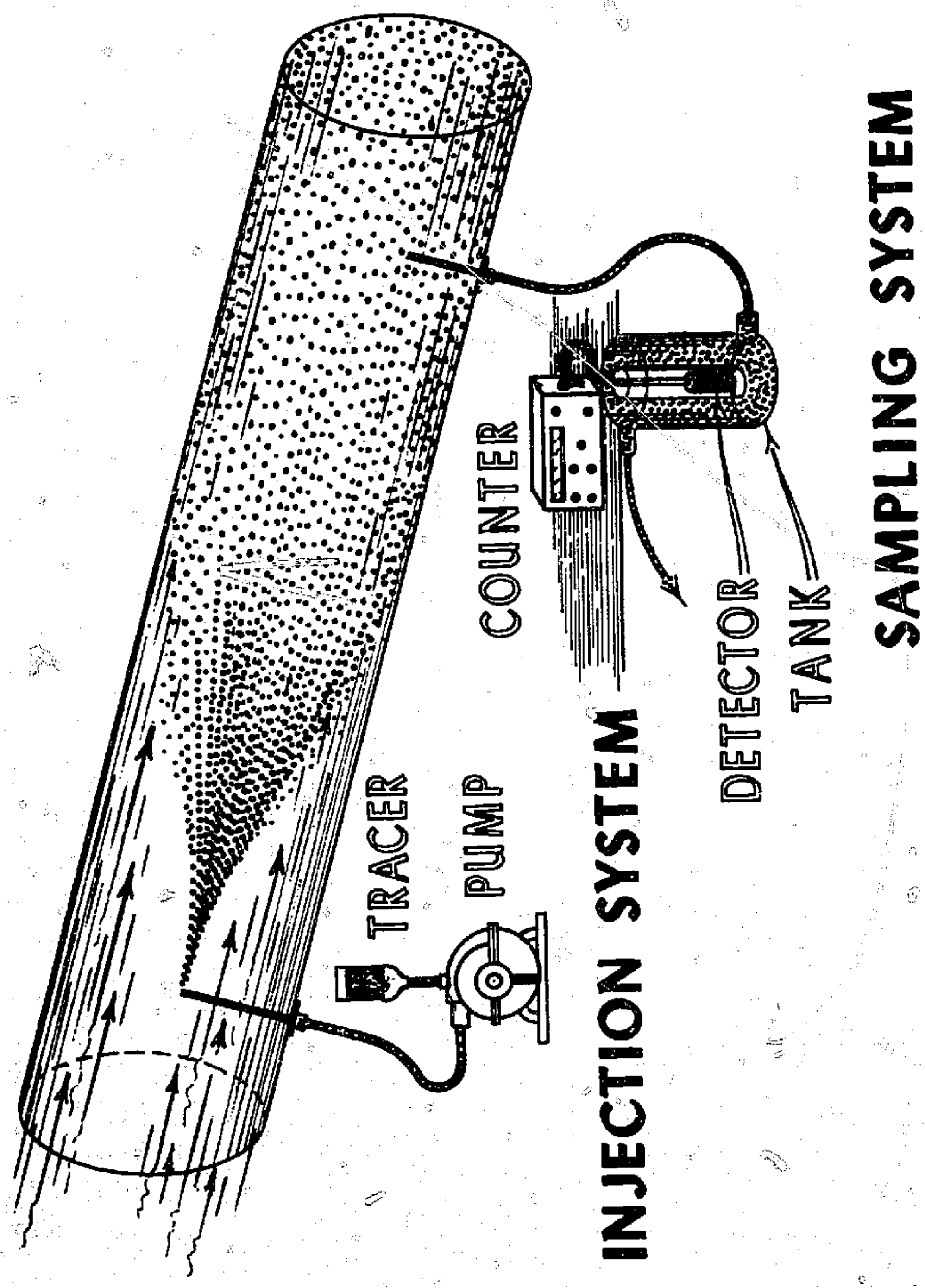


EXHIBIT 1

Three different approaches to the measurement of radioisotope concentrations offer opportunities for improvements in accuracy. These are the conventional dilution approach, the total count method, and the integrated sample method. In the first, a radioisotope solution of a known concentration is injected at a steady rate and the concentration is counted downstream. Unlike the dilution approach where the absolute quantity injected need not be known, the total count method requires that the radioactivity be completely quantified since the solution is injected as a pulse. A downstream detector and recorder sums up the radioisotope emissions during the passage of the pulse. The integrated sample method is a variation of the total count approach where individual samples are continuously withdrawn from the flow for a period starting shortly before injection and continuing for a short time after the tracer has passed the point of sampling.

As with other materials used in the dilution approach, achieving complete and thorough mixing of the radioactive material is a critical factor in the outcome of the measurements. The distance required between the points of injection and measurement can determine the type of injection equipment required and whether it is feasible to attempt an application of radioisotopes. Where adequate mixing can be assured, the radioisotope method should work equally well on turbines and pumps. By taking advantage of the turbulence produced by passage through pumps, some opportunities are present for accelerating the mixing process.

Hardware Requirements.--The amount of radioisotope solution needed for a particular test is small (1 - 10 liters) so that the injection equipment can be relatively simple and compact. Depending on the method used in detection, two types of injection systems are used. One is for application at a constant measured rate and the other for pulse injection of a measured quantity rapidly under high pressure. The feed pump for constant rate injection would weigh about 80 pounds and would be capable of producing a steady discharge (milliliters per hour) at pressures up to 5,000 psi. The pulse injection apparatus would consist of pressure cylinders and valves mounted on a single portable rack and would be charged by compressed air or nitrogen. The total weight of the pulse injection apparatus would approximate 150 pounds and could be installed by one man. Average initial cost for either of these systems would be about $1,000.

The equipment items discussed in the preceding paragraph are pressure generating facilities exterior to the pipe. These would be used in connection with a single-point injection system where the solution is introduced into a tube, about three-fourths inches in diameter, thrust through a watertight seal to the centerline of the flow. Present indications are that single-point injections can be employed at installations where 100 or more pipe diameters in length are available for mixing the tracer in flowing water.

When less than 100 pipe diameters in accessible pipe length are available, a multiple-point injection system will more likely be required which would make introduction of radioisotopes more complex and time consuming. However, simpler techniques such as very high-pressure injection are under study. Although on a smaller scale, because of the relatively smaller amount of solution required, a multiple-injection system for radioisotopes would be quite comparable to the corresponding salt-velocity system. Provision must be made for initial dispersion of the tracer at a number of discharge points through the cross section of the pipe. Although initial costs are greater, the important disadvantages of the multiple-point injections are the requirements for installation inside the pipe and the possible disruption in operations. The relative costs of the single- and multiple-injection systems are analyzed in the next section.

Counting and recording instruments must be highly accurate and reliable for precision measurement of radioactive concentrations. Investigations disclose that these instruments should be 60-cycle, line-operated because portable battery-operated sources of power are subject to irregular performance. A list of counting and recording instruments would include a high- and low-voltage power supply source, electronic scaler, analog recorder, digital printout, and radiation detector. Initial cost of these facilities, all presently available, would be about $10,000 and with proper care should have a service life of some 10 years. The instruments are relatively small and compact and can be easily transported and installed at the field site by one man.

Accuracy.--One of the goals of the research program on the use of radioisotopes is to improve the precision of waterflow measurements in addition to the objectives of quick and simple application at low cost. Under ideal conditions, probable inaccuracies of the best methods now being used are indicated to be $\pm$ 1 percent. Development of the radioisotope method is directed toward achieving a probable inaccuracy of $\pm$ 3/4 of 1 percent. As discussed later, small percentage gains in accuracy in the field of hydraulic flow measurement may result in important financial and economic benefits.

Limitations.--Two important limitations to radioisotope application are accomplishing complete mixing of the radioactive solutions in the pipeline and licensing requirements because of possible health hazards in handling and the release of radioactivity to the environment.

The problems of mixing the tracer in the pipe flow can limit applicability and increase the complexity of the facilities required. The breakover point in mixing distance required is anticipated to be 100 diameters in pipe length. More elaborate mixing devices, longer shutdown periods, and increased expense would be required with the shorter distance unless present efforts to develop other techniques are successful. When the length of accessible pipe falls below about 25 diameters it is not expected that the radioisotope method can be successfully applied. (This condition also poses problems for the salt-velocity method.) With regard to pumps, there is the possibility of injecting the tracer materials in the intake which could facilitate mixing from the additional turbulence and reduce the length of pipe required.

A Federal license is required to handle the radioactive material, to insure proper radiation shielding while shipping and handling. The release of radioactive solutions to public water supplies requires the formal approval of local, state, and in most cases Federal authorities. When domestic and municipal uses are involved, some difficulties in securing permission may be encountered. When properly informed of the safeguards undertaken, objections from private or public bodies are expected to be reduced to a minimum. The tracers now being used are Gold-198 with a radioactive half life of 2.7 days and Bromine 82 with a radioactive half life of 1.5 days. The maximum concentration released to the flow would be only a small fraction of the rigid standards controlling the amounts of radioactivity permitted for human consumption. As with other radioactive materials, such as those now directly injected in the human body for medical diagnosis, public acceptance of the use of radioisotopes for waterflow measurement purposes is keyed to the success of educational programs and good public relation practices.

Current Status of Radioisotope Studies.--The last decade has seen an increased use of radioisotopes for flow measurement in both open and closed conduits. Generally, however, flow measurement in pipe has been confined to small-diameter low-pressure water, oil, and other lines.

Previous studies by the U.S. Geological Survey in cooperation with the Atomic Energy Commission and the Tennessee Valley Authority have shown the radioisotope method promising with large low-head turbines and with a possible inaccuracy of about ± 1 percent.2/ Considerable work has been done in the United Kingdom on perfecting radioisotope techniques for measurement in pipe using both dilution- and velocity-type techniques. Recent investigations on flows in small-diameter pipes indicate probable inaccuracies well within ± 0.5 percent can be obtained consistently.3/

2/Frederick, Bernard J., "Measurement of Turbine Discharge with Radioisotopes," October 1964, USGS Report TEI-855.
3/Clayton, C. G., et al, United Kingdom Atomic Energy Authority, Report No. SM84/39, 1967.

The Bureau's study is exploring an area of measurement of very large flows in closed conduits under high heads using the shortest possible length of pipe without sacrificing a high degree of precision and the economy and convenience associated with radioisotope flow determinations. Problems of injection, mixing, and sample collection and measurement are compounded by the large flows and heads. Current field studies at Flatiron Powerplant, Colorado, are pointed toward field testing of equipment and procedures, establishing reliability, identifying areas for further improvement, and studying tracer mixing. The results to date are approaching the goal of probable inaccuracy of less than ± 0.75 percent. Field tests of the method have proven successful and additional measurements are planned for a pumping unit at the Flatiron Plant in order to gain comparable data on the application to pumps. Laboratory and field studies are continuing in order to further perfect equipment and field procedures, and to further define the limitations of length of pipe imposed by mixing requirements.

Cost Analysis

An important objective of the radioisotope approach is to achieve simplicity and economy in application. This accomplishment would meet an expressed need and could encourage more frequent testing of turbine or pump capabilities, especially on operating projects. Insofar as new facilities are concerned, the amount of cost involved in water discharge measurements is not as an important factor in determining whether acceptance tests of new facilities will be made, since testing is a prerequisite to contract completion and represents a small fraction of the initial investment required. However a significant reduction in the cost or complexity of making accurate flow measurements could influence the present practice of testing at random only one machine of a multiple-unit installation. As discussed subsequently, possible minor variations of efficiency among units (a fraction of 1 percent), and identification of optimum operating characteristics peculiar to specific units over a range of heads could justify testing more than one unit if the associated costs, inconveniences, and shutdown time were reduced to a minimum.

An analysis was made to provide the relative order of magnitude of total costs incurred for formal acceptance tests of efficiency and the proportions associated with the more difficult waterflow measurement phase. For comparative purposes estimates were predicted for the radioisotope method based on best information available assuming a routine application. The two conventional methods selected for comparison are the ones now in predominant use by the Bureau in testing high-head turbines and pumps, the pressure-time (Gibson) and the salt-velocity methods. As indicated previously where physical conditions permit, the Gibson method is favored for turbines; the salt-velocity method is used for all pumps and for some turbines.

Because each test must be engineered to fit the particular installation involved, the estimated costs shown for the two methods in Table 1 must be considered approximate.

Table 1. Comparison of typical costs of formal acceptance tests for a single turbine-generator unit using the pressure-time and the salt-velocity methods of flow measurement

Item	Pressure-time (Gibson)	Salt-velocity
Water discharge measurements	$ 9,000	$ 7,700
Pressure head measurements	700	700
Electrical measurements	2,500	2,500
Brochure and report preparation	2,800	2,800
Test supervision	1,600	1,600
	$16,600	$15,300

It is apparent from the estimates that the major portion--about one-half of the totals--is for measuring discharges with the balance common to all acceptance tests regardless of method used in determining flow. It is noted that all costs of the salt-velocity application are for Bureau labor, materials, and supplies and include minor depreciation expenses on about $5,000 of reusable equipment. In the Gibson estimate about $6,000 is included for outside contractor fees. Inasmuch as the Gibson patent rights have expired, consideration is being given the Bureau to develop necessary equipment to conduct its own pressure-time tests. Hardware requirements are considerably less than those necessary for the salt-velocity method and it is expected that at some future time costs for the pressure-time approach can be reduced.

The estimates of the potential costs for the radioisotope method assume that a small cadre of technicians would be trained in handling the required radioactive tracers and the counting and recording instruments. One trained and experienced technician would be available in each region and would secure the necessary field assistance from operating personnel, preferably located at the site. All instrumentation and special equipment would be centralized at one location in the region and be designed for maximum portability and rapid installation. Two estimates were prepared, one reflecting the use of a single-point injection system where the penstock or discharge line has the equivalence of 100 pipe diameters in length accessible for testing and the other requiring multiple-point injection which would have much wider application where as little as 25 pipe diameters in length are available. A summary of significant elements of cost for radioisotope water measurements is presented in Table 2; other costs in a formal acceptance test would be the same as previously listed.

Table 2. Predicted costs for radioisotope method for waterflow measurement

Item	Single-point injection	Multiple-point injection
Labor	$ 700	$1,100
Transportation and travel expenses	200	200
Radioisotope	300	300
Engineering design and fabrication of fittings and pipe	300	1,500
Depreciation of equipment	300	300
	$1,800	$3,400

As indicated in the preceding table, the single-point injection routine would require minimum labor and hardware costs. It is expected that a major share of the labor costs will be for local operating personnel, as it is expected that the regional technician would direct and assist installation of equipment on the first day, perform the radioisotope injections and measurements the second day, and reduce the data and remove the equipment on the third day. By use of automatic recording instruments the tests can be conducted with a minimum of time and effort. The multiple-point injection system would require dewatering, design and installation of a more elaborate injection assembly, and consequently additional expense in labor and material.

An important factor bearing on the appraisal of costs not recognized in the preceding estimates is the relative shutdown time required under the various test procedures. This can be a crucial item for turbines and pumps in continuous operation. Interruption of operations is not as important in formal acceptance tests, because internal inspection of water passages and vital parts of the machinery is a required procedure.

An array of methods according to the length of shutdown period would rate the salt-velocity as the most demanding because of its elaborate injection, mixing, and detection devices that must be placed inside the conduit. The pressure-time (Gibson), pitot, and radioisotope methods would require significantly less time. In this regard, a significant advantage would accrue to the single-injection radioisotope procedure, as shutdown can be greatly minimized and possibly altogether eliminated if advance provisions were made for the relatively inexpensive taps and fittings permitting access to the pipe under pressure. Multiple injection of radioisotopes would be more time consuming but still would require less time than the salt-velocity method.

The photographic comparison presented in Exhibit 2 provides perspective on the relative size of the facilities required for application of the salt-velocity method and the radioisotope method. It is noted that only those instruments necessary for the radioisotope test have been blocked out on the instrument panel of the mobile nuclear laboratory. The especially equipped truck is used for performing field tests using radioisotopes in ground-water studies, open-channel flows, as well as in studies of flows in high-pressure conduits.

Routine checks of efficiency could involve considerably less cost than the totals shown for a complete and formally documented acceptance tests. The costs of brochure and report preparation and test supervision shown in Table 2 could be reduced substantially and, in those instances where there is a lack of information on efficiency and less accurate data are useful, the expense of the electrical measurements can be materially decreased by using the instruments normally available in recording day-to-day operations. These reductions together with the possibility of reducing conventional water measurement costs by three-fourths to one-half with a minimum of shutdown time should make the benefits from accurate flow measurements from using radioisotopes within reach of many operating hydroelectric and pump projects having a wide range of installed capacities. Since the costs appear attractive, the next step is to analyze the possibilities for widespread use from both an economic and physical viewpoint in order to get some insight on potential benefits from radioisotope application to operating and new projects.

Application to Operating Projects

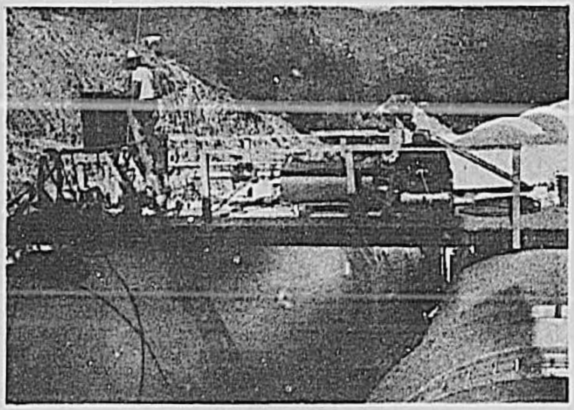
One of the most promising opportunities for use of the radioisotope method of flow measurement lies in the potential widespread application to existing projects. The provision of highly accurate and readily available discharge data on flows in high-pressure conduits over the whole spectrum of operating conditions could result in better utilization of existing machine capabilities. Substantial benefits could result from the use of a new measuring tool not now available by capitalizing on small increases in the overall average efficiencies of turbine-generators and pumps operated over a period of time, and from better control of available water supplies.

Powerplants.--Often the only precise information on the performance of a particular turbine-generating unit is the results of the efficiency test made at the time of acceptance on completion of the facility. Inasmuch as acceptance tests are oriented toward determining that warranties have been met, optimum operating criteria are assumed and tests are not scheduled until the design head is reached. (Under some relatively rare circumstances, such as occurred at Glen Canyon Dam, the design head might not occur until after the supplier's guarantee on efficiency has lapsed.) Day-to-day and month-to-month operations over

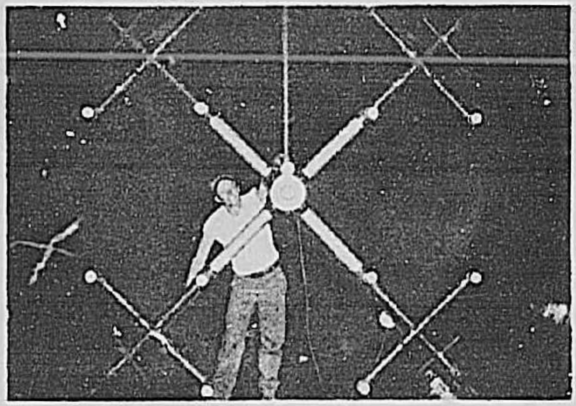
EXHIBIT 2

Comparison of equipment for salt velocity and prospective radioisotope methods for high-pressure flow measurements.

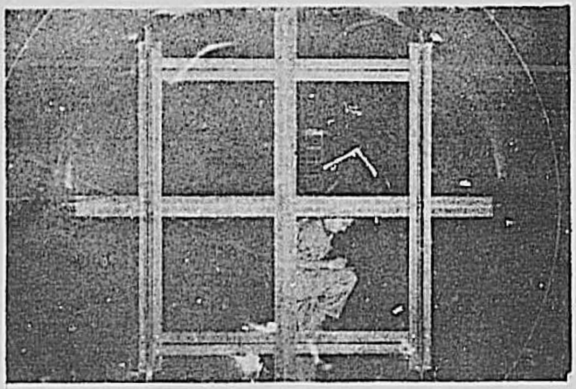
SALT VELOCITY--Injection Equipment



Brine Injection Station Photo P416-D-56696NA

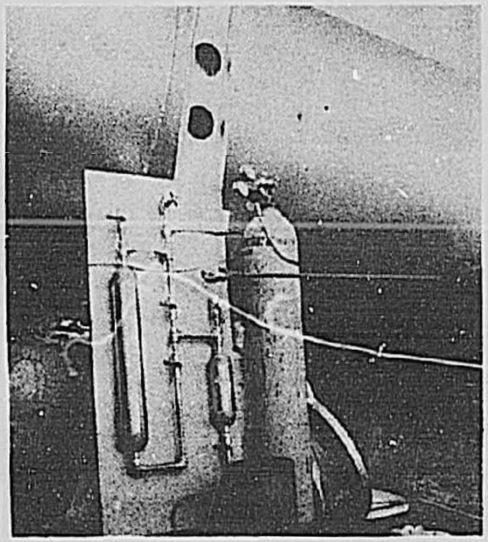


Multiple-Point Injector Photo P416-D-56702NA



Turbulator Photo 416-D-56705NA

RADIOISOTOPES--Injection Equipment



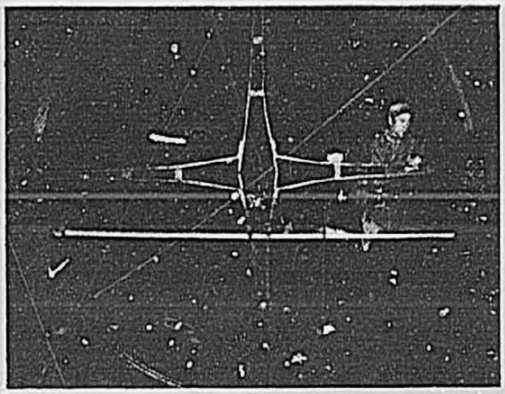
Radioisotope Injection Station--single-point injector. Small volume of radioactive solution (< 1 Liter) is pulse injected into the flow using nitrogen or compressed air. Photo P416-D-60358NA

EXHIBIT 2--Continued

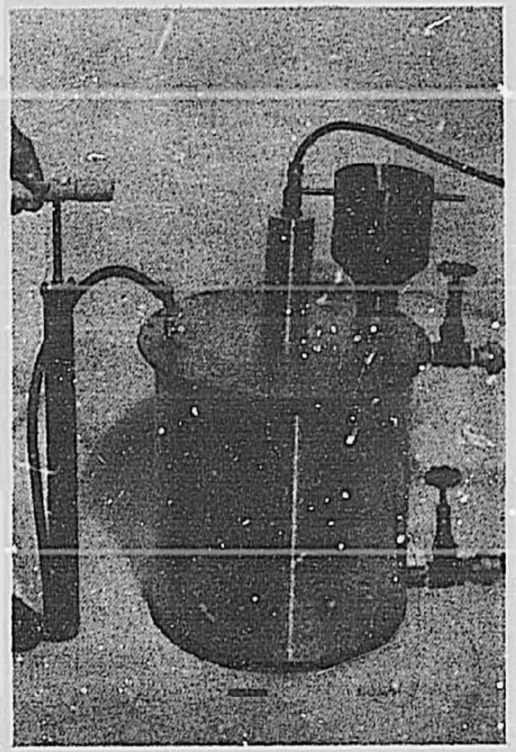
Comparison of equipment for salt velocity and prospective radioisotope methods for high-pressure flow measurements.

RADIOISOTOPES--Detection & Recording Equipment

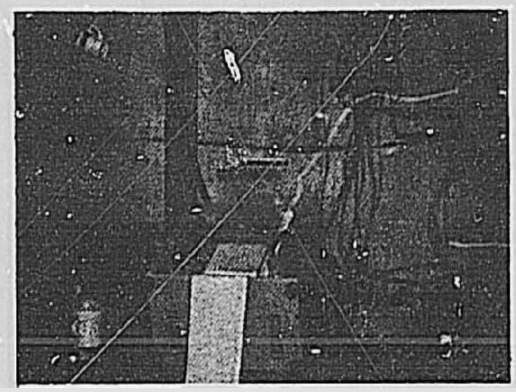
SALT VELOCITY--Detection & Recording Equipment



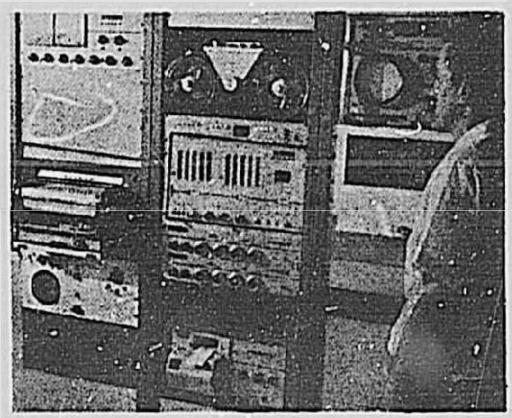
Electrode No. 1 (2 required) Photo P416-D-56706NA



Flow Sampling Tank and Nuclear Detector
Photo PX-D-55948NA



Two-Channel Direct Writing Recorder
Photo P416-D-56699NA



Nuclear Counting Equipment in Mobile Laboratory--Instruments necessary for flow measurement inside bordered area. Photo PX-D-55953NA the hydrologic cycle seldom equal the ideal design parameters, and consequently there is a need for accurate performance ratings over a broad range of conditions.

In those projects where efficiency tests have been completed and flowmeters installed and calibrated, performance characteristics can be extrapolated with accuracy within some reasonable margin of the test point. When operating heads depart significantly from the design head, less accurate calculations and approximations on relative efficiency of the turbine-generators must be relied upon. Furthermore, many of the older projects do not have the benefit of calibrated flowmeters.

The time lapse between the initial installation, at which time tests are made, and current operations can also adversely affect performance due to wear and tear on the machines. Physical inspection and measurement of wearing parts of the turbine and available flow indicators can indicate possible losses in efficiency but it is questionable whether reduction of a few percentage points can be detected in this manner. Thus the timing of repairs necessary for restoration to initial efficiency levels may not be at optimum intervals. An improved and convenient method such as radioisotopes may offer would facilitate inspection.

Using available information, performance curves for powerplants are normally prepared for each installation covering the full range of operating conditions and become the basis for selecting specific units needed to meet certain demands. In many systems power generation is greatly influenced by water releases for other purposes. Where there is a choice of making the necessary water releases through two or more geographically separated installations or individual units within an installation, the logical selection would, of course, be to utilize the best machine available to get the most kilowatt-hours out of a given quantity of water. On the other hand, when electric energy is the primary purposes for releases of water the most efficient plant--if it can be identified--would be called upon to produce the required power with a minimum of water to avoid unnecessary waste. Power contracts may specify the amounts to be delivered under certain water supply situations, especially during dry periods. In these circumstances, there are distinct advantages in being able to predict turbine performance within a small percentage of error under conditions which may widely differ from those existing at the time acceptance tests were conducted.

The availability of an accurate and inexpensive means to measure flow discharges could permit the institution of a program calling for periodic and routine testing of efficiency so that the performance characteristics of individual turbine-generators could be precisely known. Then, not only could greater use be made of the best power units, but also maintenance programs could be more timely scheduled as accurate basic data would be at hand to analyze the tradeoff between the incremental expense of making necessary repairs and adjustments, and potential gains in power revenues. Optimization of maintenance programs could mean an average increase in costs from scheduling repairs at more frequent intervals; on the other hand, it is possible that precise efficiency data may show that economies can be gained by lengthening the interval.

Before estimates of potential benefits can be reduced to dollars and cents, the extent to which the radioisotope can be applied to powerplants in the Bureau's program must first be determined. The current list of 58 powerplants constructed or under construction having a total capacity of 11.6 million kw was screened to make this determination. As mentioned earlier, the length and accessibility of high-pressure penstocks are important factors in answering the question of applicability. This limitation resulted in the elimination of a number of concrete dams having short penstocks. It is noteworthy that among the larger plants excluded were Hoover and the Grand Coulee developments, as current research efforts suggest that the radioisotope method cannot be expected to perform with accuracy for these projects.

A total of 21 powerplants having a combined installed capacity of 3 million kw were delineated as having a reasonable chance for successful application of radioactive tracers. A further inspection disclosed the relative influence of the penstock length requirement of 100 diameters by identifying those plants susceptible to the use of the simple and less costly single-injection system. Although it was found that only one-third of the installed capacity subject to radioisotope application fell in this preferred category, two-thirds of the total number of plants were covered. This finding has its favorable side as a large number of the smaller units were included which could better afford the less expensive single-injection approach. The category requiring the more expensive and complex multiple-injection assemblies encompassed larger plants such as Glen Canyon, Shasta, Yellowtail, and Hungry Horse which, of course, could more readily absorb the greater expense involved but might still be disadvantaged due to shutdown requirements.

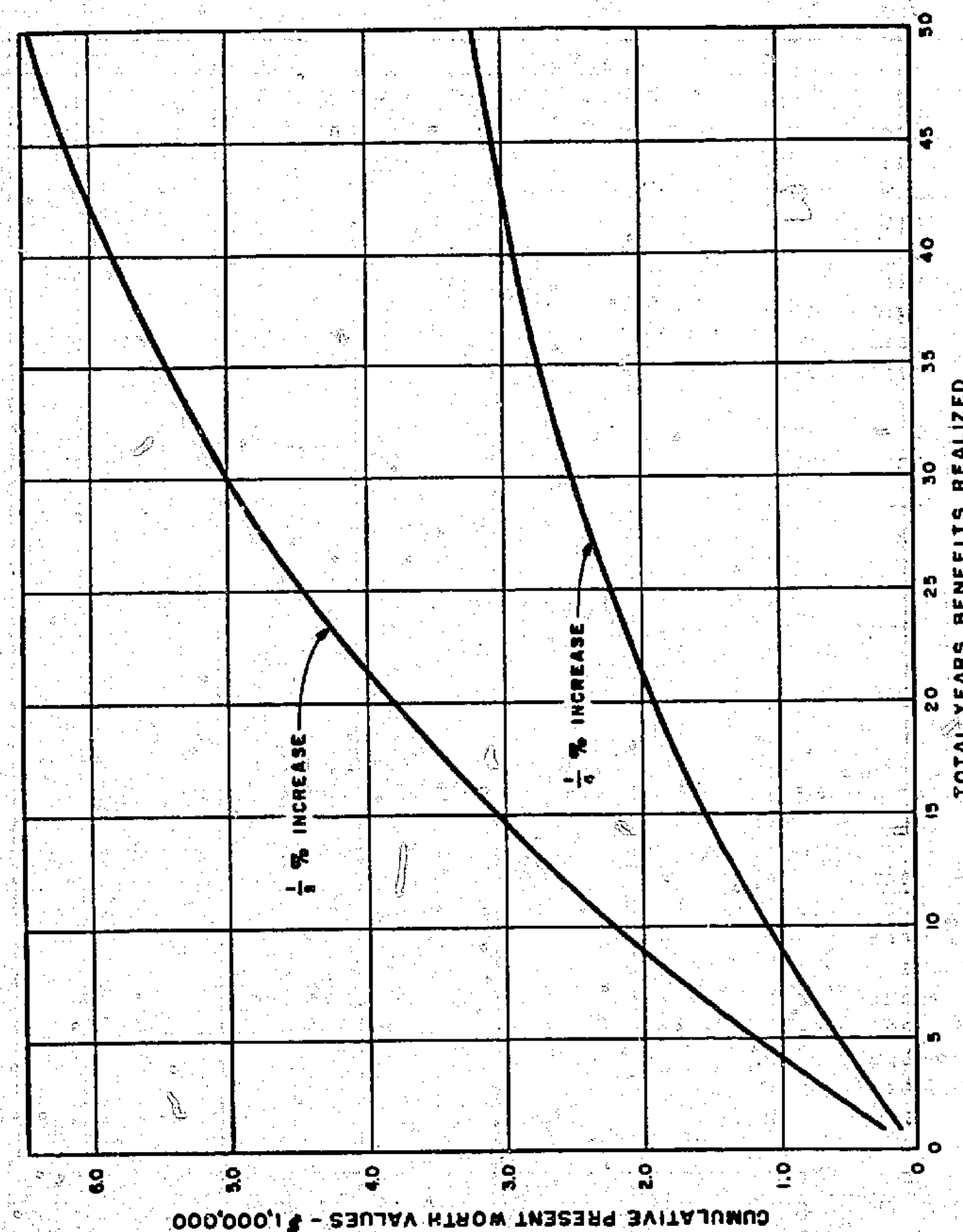
Several value curves were developed to test the hypothesis that a small fraction of an increase in efficiencies for turbine-generators can produce substantial economic benefits. Since large Federal investments have already been committed, any incremental cost would be restricted to additional testing, modifications of machines over and above that now incurred, or refinements in operating techniques. It is noted that an increase of 1 percent in the rated efficiency of a turbine means more than a 1 percent gain in the overall effect on power production (or consumption in terms of a pump). For example, a gain of rated efficiency from 90 to 91 percent means an overall gain in productivity of 1/90, which equals 1.11 percent. The value determinations in this report reflect the overall effect on electric power production (or consumption in the case of pumps).

As presented in Exhibit 3, separate curves were computed for possible increases in machine efficiencies of one-fourth and one-half percent covering the 3 million kw in the Bureau's program subject to the radioisotope flow measurement method. The amounts shown on the left scale are values at the time improvements are first made reflecting "present worth" using the current Federal interest rate for water resource developments of 3-1/4 percent. The bottom scale indicates the number of years benefits might accrue. Thus from the curves it can be readily determined how much one is willing to pay today for increased machine efficiency that would last a specific period of time; for example, a one-half percent increase in overall efficiency lasting 10 years would have a present value of $2.2 million. For the first year at the same increase in efficiency the value would be about one-fourth of a million dollars.

These values are based on generalized assumptions regarding plant factor and power rates per kwhr. These factors would actually vary among major river basins as well as individual projects. The use of rates representing power revenues introduces some conservatism in the study, for in many instances, the rates are below average market prices. If potential benefits were measured in terms of alternative costs at other than Federal financing in accordance with present evaluation procedures, values would tend to be higher. It is believed that the averages used which reflect a 50 percent plant factor and a 4-mill-per-kwhr rate are reasonable. The relationships, however, are linear and adjustments up or down for either plant factor or rate can be easily approximated. It is noted that reductions in plant factor are normally attended with an increase in the value of energy per kwhr because of use as peaking.

Appraisals were also made of the potential gains from individual plants with the evaluation criteria tailored to meet the particular project. Each powerplant is operated as part of basinwide systems, consequently average conditions within each basin were postulated. The value of power as reflected in power revenues can vary significantly from the Pacific Northwest where firm power rates at comparable load factors may yield 4 mills or less as compared to up to 6 mills in the Colorado River Storage Project. Missouri River Basin Project and Central Valley Project fall in between these points. Sales of nonfirm, secondary, and pumping energy have the effect of reducing the average returns.

EXHIBIT 3



POTENTIAL BENEFITS FROM FRACTIONAL INCREASES IN MACHINE EFFICIENCIES FROM 3 MILLION KW OF INSTALLED POWERPLANTS CONSIDERED SUBJECT TO RADIOISOTOPE WATER FLOW MEASUREMENTS

The following tabulation illustrates the potential economic gains for selected projects having a wide range of installed capacities, and assuming 1 percent increase in efficiency. It was considered that an increase of 1 percent was possible on individual plant basis, but that the fractional increases previously presented were more appropriate as an overall average gain covering all powerplants susceptible to radioisotope flow measurements. The smallest installation shown is for one unit of the Flatiron Powerplant of the Colorado-Big Thompson Project to provide an idea of the relative magnitude of gain for smaller units. Values for still smaller units can be approximated on a straight proportionate basis. Potential gains presented for selected years are cumulative and reflect present worth at the current interest rate of 3-1/4 percent.

Table 3. Present worth of potential gains from a 1 percent increase in turbine-generator efficiency for selected plants

Powerplant	Region	Capacity (mw)	Possible increases in values				
			1 year ($1,000)	5 years ($1,000)	10 years ($1,000)	25 years ($1,000)	50 years ($1,000)
Glen Canyon	4	900	$210	$990	$1,820	$3,670	$5,320
Hungry Horse	1	285	23	110	200	400	580
Yellowtail	6	250	34	160	290	580	850
Trinity	2	100	19	90	170	330	480
Flatiron No. 1	7	31.5	6	30	55	110	160

Pumping Plants.--The general approach in determining potential benefits from the operation of high-pressure pumps closer to maximum capabilities through better discharge measurements is similar to that used to evaluate powerplants. Frequent availability of good information on relative efficiencies would provide greater discretion in selecting the best units for baseload operations, more timely maintenance programs so that year-to-year outputs consistently score higher on the efficiency curve, and better control and regulation of water supplies. The most obvious gains would be potential savings in pumping energy.

An analysis of the application of the radioisotope method to pumps pointed up two important variations from conditions encountered when considering powerplants. First it was noted that there was a preponderance of relatively small pumps and consequently a greater sensitivity to the expense of testing; and, secondly, there was a greater potential in realizing several percentage points in efficiency because of a general lack in testing and the greater incidence of wear-inducing sediment in water pumped.

In Bureau operations, formal acceptance testing in the field has been limited only to the larger pumps with the salt-velocity method being used almost exclusively. In the recent past, five actual tests have been conducted at project sites. Shop tests normally form the basis for acceptance for smaller plants (up to 2,500 hp). The expense; the requirements of access to discharge lines for internal placement of the elaborate injection, mixing, and detecting equipment; and the shutdown requirements all combine to limit the number of tests run using the salt-velocity method.

Flow measurements by use of pitot tubes may prove to be an attractive alternative method for application to small installations; however, technical problems of obtaining precise results as yet have not been overcome. At present that method has occasional field use, primarily in connection with comparative studies in problem areas where several methods are employed.

In appraising the extent of radioisotope applicability, the current list of Bureau pumping plants, 1,000 hp or larger, either constructed or under construction was examined. In the screening process it became apparent that physical criteria had to be supplemented by economic considerations because potential gains from a 1,000-hp installation would justify only a small additional dollar expenditure. As a result, a minimum plant size of 5,000 hp was selected as the break-even point where potential gains from a small increase in machine efficiency approximated the anticipated cost of a flow test using radioisotopes. The smaller plants have two factors which tend to offset size; one is that there should be a greater opportunity to pick up several percentage points in efficiency; and two, the average cost for energy is higher as often local sources of power must be relied upon.

It is recognized that a pump installation normally consists of a number of individual units each of which could have a separate discharge line requiring individual testing. It is expected, however, that the added costs of testing more than one unit at the same site and time would be small; especially where several units manifold into a single discharge line necessitating only one setup and where the single injection of radioisotope material is permissible.

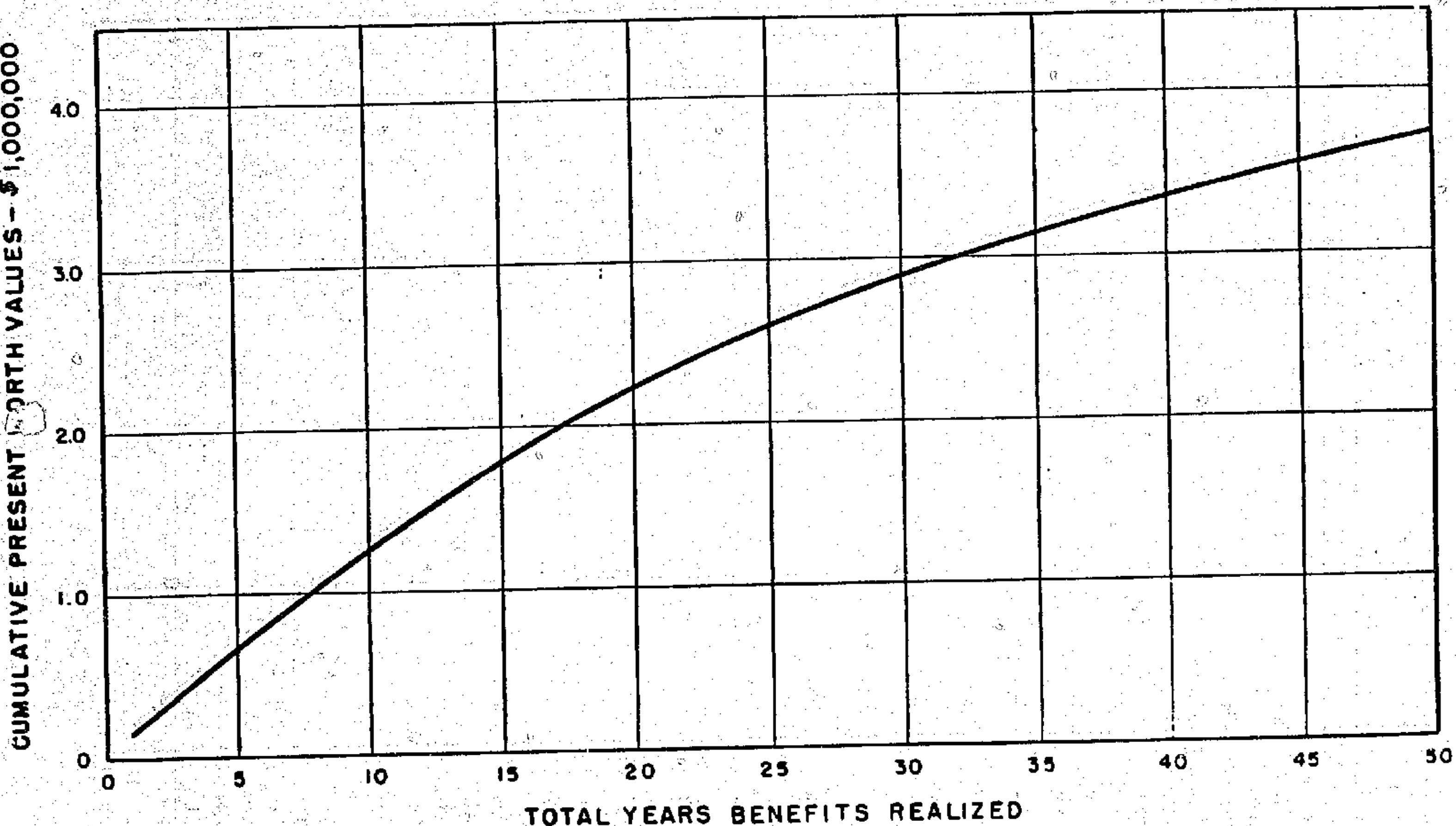
Inspection of published statistical data as of 1966 disclosed that of the total rated horsepower of 1.7 million in 96 pumping plants, 1.3 million hp in 13 plants met the physical and economic conditions of applicability for radioisotope testing. The importance of large units was conspicuous by the fact that 4 of the 13 plants ranged in size from 135,000 to 460,000 hp, and 9 plants were in the 5,000- to 14,000-hp range. All but 2 of the plants were considered amenable to the application of the less expensive single-injection system. These 2 plants were over 200,000 hp in size and could well afford the extra cost. As mentioned previously, due to the possibility that the pump impellers can be used as mixers for the radioisotope solution, the single-injection system could have an even more widespread application.

Economic indicators were developed on relative magnitude of values resulting from possible reductions in energy requirements for the 1,300,000 hp susceptible to radioisotope water measurement techniques. A value curve representing 1 percent potential increase in efficiency was plotted using power values comparable to those assumed for powerplants. Federal pumping power rates were not used in computing the monetary benefits as these are considered to be artificially low. This is due to the large influence of low, partially subsidized irrigation pump rates which result from present policy and legislative history to encourage irrigation. Furthermore, any power released by reduced pumping should find a ready commercial market.

As with powerplants, variations in power values and plant factors occur from one regional area to another and required generalizing and weighting in the selection of averages used. Precise and detailed statistical analyses are not considered necessary for the purposes of this study as the emphasis is to develop value indicators and trends. However, some mention of the wide variations encountered in plant factors and power values may be of interest. The lowest plant factor was under 15 percent and represented the pumping cycle of a reversible pump-turbine facility. Pumping during irrigation seasons only, produced factors of about 30 percent depending upon climatological conditions; year-round pumping for regulation or supplying municipal and industrial needs increased annual operations to up to 90 percent of the time. The capability to avoid pumping during daily or seasonal electrical peaking hours and location in areas of "cheap" power resulted in values as low as 3 mills. On the other hand, where pump operations are located in areas of higher electrical fuel costs or where local sources must be relied upon, power would have almost twice that value--one was as high as 7-1/2 mills.

Exhibit 4 presents a value curve showing the potential benefits from improving operations on 1.3 million hp in pumps subject to radioisotope measurements. The curve assumes a power value of 4-1/2 mills and a plant factor of 40 percent, which represent averages from weighting the most significant factors. By operating 1 percent closer to actual machine capabilities, benefits realized could amount to $150,000 for the first year and accumulate to almost $1,300,000 in 10 years. The largest installation included is the San Luis Pumping Plant rated at 460,000 hp. All of the San Luis units are reversible and have a total generating capability of 424,000 kw. This pump-generator plant, as well as one other, is included in both the powerplant and pumping plant studies as separate waterflow measurements are necessary for testing efficiencies in each of the pumping and generating cycles.

EXHIBIT 4



POTENTIAL BENEFITS FROM 1% INCREASE IN MACHINE EFFICIENCIES FROM 1,300,000 H.P. OF INSTALLED PUMPS CONSIDERED SUBJECT TO RADIOISOTOPE WATER FLOW MEASUREMENTS

The possible variations in evaluating criteria for efficiency gains strongly indicate that case-by-case analyses would need to be made to determine first the degree of testing expenses involved and secondly in the event that repairs are necessary just how much added cost will be incurred. As discussed previously, the effect on costs of repair would more than likely be in changes in the timing of maintenance programs. To provide some illumination on the amount of added cost a 1 percent average increase in efficiency could support, selected plants were studied individually and the results are summarized in the next table. The apparent poor correlation in size and benefits is due to the wide variations in plant factors and values of electric energy.

Table 4. Present worth of potential gains from a 1 percent increase in pump efficiency for selected plants

Plant	Region	Capacity hp	Time periods--in $1,000				
			1 year	5 years	10 years	25 years	50 years
Grand Coulee	1	390,000	30	140	260	520	750
Tracy	2	135,000	39	180	340	670	980
Flatiron1/	7	13,000	1.3	6	11	22	32
Canadian River Pump No. 2	5	5,000	1.9	9	17	34	49

1/Pump-generator used primarily as pump.

Water Control.--It naturally follows that the ability to accurately measure discharges through high-pressure turbines and pumps not only produces benefits in terms of energy gained or saved but also advantages in the management of water supplies. Releases through powerplants are normally into open river channels and are difficult to gage precisely. The ability to calculate flows within a small margin of the true flows would mean better administration of water rights and improved accounting of supplies released to various water users. This would make a contribution toward the elimination of waste and may mean greater availability for project use.

Pump discharges into open channels are difficult to measure within a percentage or two of actual flows. Through a periodic determination of efficiencies pumps can be maintained to operate closer to their designed capabilities so that full output can be relied upon during those critical dry periods when maximum capacities are taxed. Timely water applications can make substantial differences in irrigated crop yields. Water put to municipal and industrial use can have even a higher value. Greater amounts of M&I supplies are expected to be delivered through high-head pumps over longer distances. In view of project repayment requirements and equitable distribution of supplies, accurate metering of M&I water is to the best interest of all parties involved.

A number of variables are involved in reducing the benefits from improved water management to a hard dollar estimate. There are many links in the chain beginning from the storage and diversion of riverflows to the final delivery to the water user. Water losses in the form of evaporation, transportation, and on-farm application all play major roles in the control and distribution of water. Nevertheless the provision of an accurate measuring tool such as that anticipated by the use of radioisotopes in high-pressure conduits can make a contribution to better management and use of valuable water supplies.

Application to New Facilities

Preceding sections indicated that the radioisotope method for determining hydraulic flow in high-pressure conduits has potential application to a significant percentage of projects constructed or under construction by the Bureau. The availability of a highly precise method which can measure discharges from turbines and pumps within an expected probable inaccuracy of ± 3/4 of 1 percent could encourage the production of more efficient machines for inclusion in future projects. It is generally agreed that in any industry where it is difficult to establish rigid specifications or standards and which lack a precise gage for checking acceptability within these criteria, there may be opportunities for product improvement not yet exploited. A method which can accurately determine whether design standards are met and which is agreeable to both the seller and the buyer can encourage competition and result in the upgrading of the product. A highly accurate method for measuring discharges through turbines and pumps--an expressed goal of the radioisotope research program--could make some contribution to expectations of securing machinery having small but economically significant gains in efficiency.

An indication of the value of a fraction of a percent of machine efficiency is provided by a review of standard penalty clauses included in invitations to bid. Provisions for financial adjustments are thus made in the event that the supplier fails to meet the warranted efficiencies operating under the specified design conditions. Several examples are provided for various sizes of powerplants and pumping plants. As noted in the following summary table, the amount of penalty is a direct function of the size, percentage of time the plant is expected to operate, and power values. Penalties are usually shown separately for losses in energy and capacity and are specified to the nearest 1/100 of 1 percent. For purposes of presentation, the penalties have been converted to the equivalence of a 1 percent loss.

Table 5. Selected examples of penalty clauses for losses in efficiency included in invitations to bid

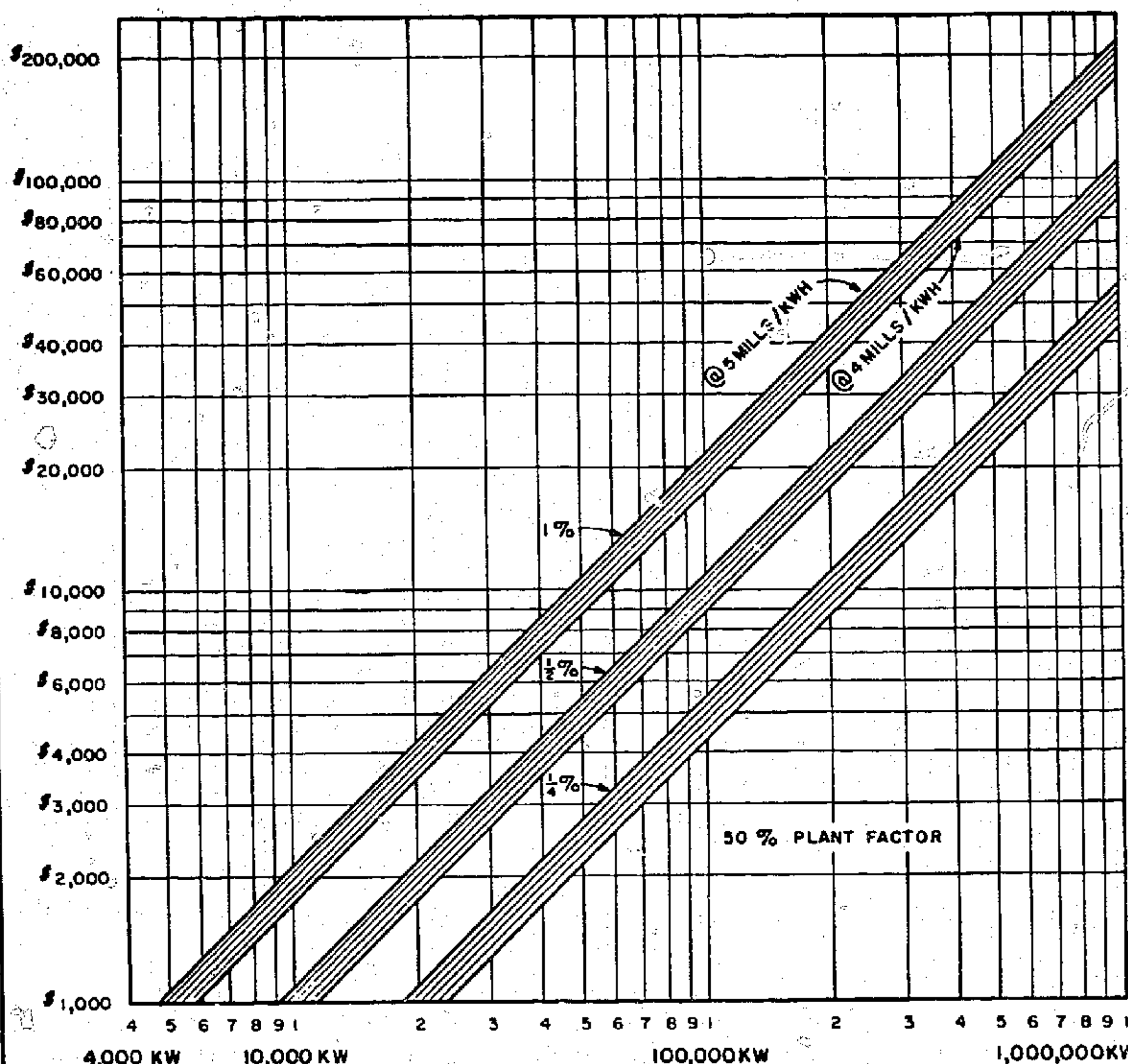
Plant	Total capacity	Penalty for 1 percent efficiency loss	
		Energy	Capacity
Glen Canyon Powerplant	900,000 kw	$670,000	$1,070,000
Judge Francis Carr Powerplant	134,000 kw	157,000*	*
Dos Amigos Pumping Plant	240,000 hp	92,500	95,000
Flatiron Pumping Plant	13,000 hp	12,500	12,500

*Combined value representing a loss in both components.

The possibility for realizing benefits from increased efficiencies in new powerplants is perhaps not as great as those for pumping installations. A good many of the best hydroelectric damsites have been developed and a large share of those remaining represent large concrete structures with relatively short penstocks and consequently are not good prospects for the use of radioisotopes. On the other hand, as water supply needs expand and greater distances are involved in bringing water supplies to points of service, it is expected that more and more pumping plants of major size and higher lifts will be necessary. Thus, there are greater prospects in the area of pump developments for the realization of improvements in efficiencies by virtue of having a simple, inexpensive and accurate method of measuring discharges under high pressure.

To provide a general guide on potential increases in electrical production or savings in energy, several value curves were developed to represent a wide range of plant sizes of from 1,000 to 1,000,000 kw. These general indicators are useful for both powerplants and pumping plants. Pumping plants normally referred to in terms of horsepower can be easily converted to its electrical equivalent (1 hp equals .746 kw). The curves cover increases in efficiency of 1/4, 1/2, and 1 percent and a band to show values at 4 and 5 mills per kwhr assuming an overall plant factor of 50 percent. As demonstrated in Exhibit 5 the benefits, read on the left scale, are sensitive to installed capacity as it requires a 1 percent gain in efficiency and a minimum of 5,000 kw to produce an annual benefit of about $1,000.

EXHIBIT 5



POTENTIAL BENEFITS FROM SMALL INCREASES IN EFFICIENCY FOR FIRST YEAR OF OPERATION FOR TURBINES AND PUMPS SIZED FROM 4,000 KW TO 1,000,000 KW

APPENDIX 2

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September 12, 1967

DEVELOPMENT OF A RADIO-RELEASE TECHNIQUE FOR MEASUREMENT OF HIGH-HEAD TURBINE AND PUMP DISCHARGE

Final Report

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U. S. Department of the Interior
Bureau of Reclamation
under
Contract No. 14-06-D-6015
RTI No. NU-294

ABSTRACT

In order to make use of the salt-dilution method for measuring volume flow-rates in high-head turbines, a more sensitive analytical technique for measuring the concentration of tracer ion is required. The radio-release method of analysis in principle has the requisite sensitivity. However, in a series of experiments using the following ions as tracers, no satisfactory procedure was developed for tracer concentrations at the ppm level

fluoride	bromate	thiourea
iodide	nitrite	chlorate
dichromate	nitrate	hydrogen peroxide
peroxydisulfate	hydroxylamine	bisulfite
hypochlorite	hydrazine	hyposulfite
hypobromite	urea	hypophosphite

No further experiments are recommended.

INTRODUCTION

There is no simple satisfactory method for measuring the volume-flow of water in high-head turbines. Many physical and chemical techniques have been investigated, but all have one or more disadvantages. One of these techniques is the salt-dilution method, first proposed for other purposes many years ago(1). Its principal disadvantage is its lack of sensitivity at the flow-rates encountered in high-head turbines. A modification of this salt-dilution method was proposed, in the form of radio-release analysis, in an attempt to overcome the lack of sensitivity. This is a report of the work carried out to develop a radio-release modification of the salt-dilution method of measuring high-head turbine discharge.

The salt-dilution method of measuring volume flow of a fluid depends fundamentally on an accounting of the quantity of material introduced as a tracer. Assuming no loss of tracer during the course of the experiment, the mass of tracer passing the sampling point must equal the mass of tracer introduced. In terms of concentrations, if the tracer of concentration C_1 is introduced at a continuous rate q into a fluid flowing at flow-rate Q, then at a point downstream where the tracer has become homogeneously mixed with the bulk fluid, the concentration of the tracer is C_2. And, since the mass of tracer (per unit time) must be accounted for,

$$qC_1 = QC_2 \quad .$$

Now q, C_1 and C_2 are measurable quantities, therefore Q, the unknown volume-flow rate of fluid can be calculated.

The arithmetic of the salt-dilution method is very simple and can be made to include those situations where some of the tracer occurs naturally in the bulk fluid or where all of the tracer is introduced instantaneously. The elegance of the method is apparent when it is realized that the technique eliminates the need for knowing the velocity of flow, cross-sectional area, roughness of boundaries, or the path of the fluid. Further, the tracer may be any material or physical quantity which can be measured quantitatively before introduction and at the sampling point.

The only restriction on the method is that the tracer be homogeneously distributed throughout the bulk fluid at the sampling point. This sometimes causes difficulty, especially in pipes, where laminar flow characteristics prevent complete tracer mixing until many pipe-diameters after the introduction point. Proper sampling points can, however, be found by experimentation.

Another factor, which may act as a restriction, is that the tracer be measurable at the sampling point to as great an accuracy as the purpose of the experiment requires. Indeed, this factor becomes limiting when large flow rates are involved. To illustrate this point, assume a chemical tracer of concentration, C_1, of 0.1 g/ml is introduced at a constant rate, q, of 100 ml/sec into a stream flowing at rate Q of 10 m^3/sec. These are reasonable values for a typical experiment. The concentration of the tracer at the sampling point, C_2, is computed to be 10^{-6} g/ml, or 1 ppm. Although chemical and analytical techniques can measure concentrations much smaller than 1 ppm, the procedures are laborious and they must be carried out by experienced analysts. 1 ppm can be considered the level below which simple conventional analytical procedures do not exist.

To measure larger flow rates by the salt-dilution method, it is necessary to either increase C_1 or q, or measure smaller values of C_2 by a better technique than is presently available. It is not possible to increase C_1 and q by very much, however, and it would not be desirable in any event, because of the quantity of tracer involved. With the values chosen above, 600 grams of tracer are introduced each minute. In a 30 minute experiment 40 pounds of tracer dissolved in about 50 gallons of water would have been used. The only alternative is to develop a better analytical procedure.

One of the early attempts to measure smaller values of the tracer at the sampling point made use of the sensitive methods of detecting radioactivity. If a radioactive material were used as tracer, it should be easy to measure more than a 10^5-fold dilution of tracer--as is done in the above illustration. It is indeed possible to do this, but other factors then enter the experiment: availability of suitable radioactive species, logistics of heavy shielded containers, difficulties of working by remote control, but most important, the possibility of contaminating equipment and water supplies.

Gold-198 has most of the desirable characteristics of a radioactive tracer for flow measurements and has been used in many experiments. It would be desirable to avoid entirely the introduction of radioactivity into water supplies, yet take advantage of the sensitive methods for detecting radioactive isotope. The radio-release method of analysis was developed for this purpose. It is, basically, another analytical technique for measuring low concentrations of non-radioactive ions in aqueous solutions, but it employs the sensitivity of radio-activity detecting techniques.

RADIO-RELEASE ANALYSIS

In radio-release analysis procedures, the ion in low concentration is caused to react with a radioactive species in such a manner that radioactive ions replace the non-radioactive ions in solution. If the reaction is stoichiometric, then a measure of the resulting radioactivity of the solution is a measure of the concentration of the original non-radioactive ions. Since radioactivity is easy to detect, its detection provides a basis for measuring very low concentrations of materials in aqueous solution.

An example will make the technique clear. Dichromate ion in acidic solution oxidizes silver metal producing soluble silver and chromic ions:

$$Cr_2O_7^{=} + 6Ag + 14H^+ \longrightarrow 6Ag^+ + 2Cr^{+++} + 7H_2O \quad .$$

If the silver metal is radioactive, then the silver ions in solution are also radioactive. Since the reaction is stoichiometric, measuring the radioactive silver in solution allows one to calculate the required concentration of dichromate ion originally in solution to produce the measured silver concentration[2].

Other radio-release procedures have been described for dissolved oxygen[3], vanadate ion[4], SO_2[5], iodide[6] and other ions[7]. Unfortunately, the reaction of dichromate ion with silver metal is slow and one hour is required for completion. This is not suitable for routine analysis of samples. However, it appeared that the principle of radio-release analysis should be explored for the reactions which would make feasible the use of the salt-dilution method for measuring flow-rate in high-head turbines. Therefore, a series of experiments was begun.

EXPERIMENTAL PROGRAM

First, the characteristics of the tracer substance were defined. The tracer must be

1. A stable oxidizing or reducing agent,
2. Relatively non-toxic,
3. Harmless to turbine machinery,
4. Inexpensive, and
5. Very soluble in cold water.

These criteria, in addition to those imposed by the conditions of the radio-release principle and available radio-isotopes limit the choice of tracer.

Characteristics of the radioisotope to be used include

1. Chemical properties, i.e., it must be an oxidizable or reducible species.
2. Radiations--it must emit a gamma ray of sufficient energy that it can be counted conveniently in solutions.
3. Half life--it should have a half-life longer than one week, but not so long that high specific activities would be difficult to obtain.

Emphasis on oxidizing and reducing agents stem from the nature of radio release procedures: radioactive species must replace non-radioactive ions in solution, and the resulting solution must be separable for counting purposes from the bulk of the radioactive member of the procedure. Simply, this means a phase change must occur during the radio-release reaction. This almost limits the possibilities to oxidation-reduction reactions. Although, in principle, precipitation or solubilization reactions might be considered, when the details of solubility and solubility products were examined, no feasible system was discovered.

The radioactive species which met the criteria are

Ta^{182}

I^{131}

Ag^{110m}

Zr^{95}

Cr^{51}

The tracers which met the criteria are

fluoride	bromate	thiourea
iodide	nitrite	chlorate
dichromate	nitrate	hydrogen peroxide
peroxydisulfate	hydroxylamine	bisulfite
hypochlorite	hydrazine	hyposulfite
hypobromite	urea	hypophosphite

The experimental procedure was straightforward. A column of the radioactive isotope was prepared in one of several ways, and a solution of the tracer at the parts-per-million level was slowly passed through. Effluent from the column was placed on a scintillation crystal and counted.

TANTALUM-FLUORIDE ION

Although fluoride ion does not meet the criterion of a tracer substance being an oxidizing or reducing agent its special reaction with tantalum metal singled it out for early attention. Tantalum metal is noted for its inertness to most chemical reagents. The reaction which seemed to have promise for radio-release analysis, however, is that between tantalum, nitric acid, and hydrofluoric acid. Nitric-hydrofluoric acid mixtures are one of the few solvents for tantalum metal. Tantalum is insoluble in nitric acid of any concentration at any temperature. The fluoride ion is necessary to form a very soluble complex fluo-tantalate ion. The hope was that even small concentration of fluoride ion in nitric acid would dissolve proportionate quantities of tantalum.

Tantalum metal was irradiated and small pieces were packed in a small polyethylene column. Nitric acid solutions of various concentrations, including the concentrated reagent, containing 1-10 ppm F^- were passed slowly (0.5 ml/min) through the column without success. Various mixtures of nitric acid, sulfuric acid, and phosphoric acid, with fluoride ion, were also passed through without any perceptible tantalum being dissolved. Iodate ion is reported[8] to oxidize niobium (which is similar to tantalum) in acid solutions so various concentrations of sodium iodate were tried with the fluoride--again without success.

Higher concentrations of fluoride dissolve the metal rapidly, but it must be concluded that at the part-per-million level, fluoride does not attack tantalum metal in any concentration of nitric acid.

REACTIONS WITH I-131

Whereas most radio release reactions occur between a soluble ion, the tracer, and a solid member of the reaction, the radioactive material, it is not necessary that this be the arrangement. It is only necessary that the radioactive species formed in the reaction be separable from the bulk of the isotope. The reactions of the various valence states of iodine can be used to advantage. Only the element is soluble in organic solvents and can thus be extracted from the bulk of an aqueous solution containing the other valence atates.

Both peroxydisulfate and dichromate ions are capable of oxidizing iodide ion to iodine:

$$S_2O_8^{=} + 2I^- \longrightarrow 2SO_4^{=} + I_2$$

$$Cr_2O_7^{=} + 6I^- + 14H^+ \longrightarrow 2Cr^{+++} + 3I_2 + 7H_2O \quad .$$

At the 10 μg/ml level preliminary colorimetric experiments showed that the reactions were slow, but it was not clear whether the oxidation was slow, or the subsequent color-formation reaction was limiting. With iodide ion-I-131, it was soon shown that the oxidation reaction was indeed the slow step.

Reactions with peroxydisulfate ion usually are carried out with silver ion as catalyst. Unfortunately, this specific catalyst cannot be used because of the insolubility of silver iodide. It was soon found that ferrous ion will also catalyze peroxydisulfate reactions and experiments showed that the oxidation of iodide ion might be fast enough to be useful. On going from distilled water to ordinary tap water for the experiments, in order to simulate more closely actual field conditions, other difficulties were encountered: tap water contains enough ferric ion to interfere.

$$2Fe^{+++} + 2I^- \longrightarrow 2Fe^{++} + I_2$$

and peroxydisulfate ion at μg/ml concentrations in tap water rapidly decomposes. Whereas, the ferric ion interference could be handled by complexing agents, the latter difficulty showed the futility of continuing experiments with peroxydisulfate ion as tracer.

No method was found for speeding up the oxidation of iodide ion by dichromate. Chlorate ion has the chemical potential of oxidizing iodide ion, also:

$$ClO_3^- + 6I^- + 6H^+ \longrightarrow 3I_2 + Cl^- + 3H_2O \quad .$$

Preliminary experiments at the 10 μg ClO_3^-/ml concentration, however, produced no iodine within 10 minutes, so the reaction was not pursued.

REACTIONS WITH SILVER-110

The reaction of dichromate ion with silver metal was shown to be slow[2]. In this experimental method, a silver-110 gauze was stirred in a beaker of the dichromate tracer solution until reaction was complete. The thought occurred that the reaction might be accelerated if the dichromate solution could be passed through a column of the finely divided metal.

Silver metal can be so precipitated, but a column of the fine material greatly restricts flow of liquid through it[4]. A better technique seemed to be to precipitate the metal in finely divided form on the surface of an inert substrate. Accordingly, silver ion was adsorbed on a cation resin (Dowex-50) and then the metal was precipitated in situ by an ammoniacal solution of formaldehyde (Tollins reaction).

The column seemed to be very satisfactory, but dichromate solutions of 100 μg/ml failed to oxidize any silver even at pH 2. The idea was not pursued further.

EXPERIMENTS WITH CHROMIUM-51

Chromium appeared to be a metal which showed promise of being a member of a radio-release system. As dichromate ion in acid solution, it is a powerful oxidizing agent, and several common strong oxidizing agents can take chromic ion to chromate ion in either acidic or basic media. Whereas chromium-51 does not have the most ideal nuclear characteristics (only 8-10% of the disintegrations yield a countable X-ray) it still is readily available in high specific activities. Accordingly, many experiments were carried out in attempts to find a good radio-release system for measuring low concentrations of a suitable tracer.

Initially, chromate-51 ions were adsorbed on Dowex-21K, an anion resin. The principle to be used was that while dichromate ion would remain adsorbed on the anion resin, chromic ion, which would be formed by reduction by the tracer ion, would pass through the anion column and be counted in the effluent.

The first experiments to be tried were with hydroxylamine and hydrazine at macroscopic concentrations. The reactions proceeded rapidly. On going to the μg/ml level, however, the appearance of chromic ions in the effluent was restrictively slow, even at pH 2.

The foregoing statement is correct, but does not prove that the chemical reaction is slow. Chromic ions in solution are known[9] to behave peculiarly on ion-exchange resins. It was hoped, however, that at pH 2, these partially hydrolyzed species would be minimized and chromic ion would behave more nearly as a pure cationic species. The possibility therefore existed that the reduction reaction indeed proceeded quickly, but the chromic ions were adsorbed on the anion resin because they assumed poorly characterized hydrolyzed states even at pH 2.

Another problem arose with respect to use of the Dowex-21K column. Radiation decomposition of the organic structure of the resin occurred with resultant leaking of unreduced dichromate ion into the effluent. This had been anticipated and an inorganic ion exchange resin was obtained (HZO-1, BioRad Labs, Richmond, California). HZO-1 behaves as an anion resin at low pH values, but as a cation resin at high values. At pH 1, dichromate ion, Cr-51, was adsorbed on the column and pH 1 solutions of various reducing agents were passed slowly through. Hydrazine, hydroxylamine, nitrite, sulfite, metabisulfite, hyposulfite, hypophosphite, urea, thiourea, and ascorbic acid, all at the μg/ml concentration level, failed to give chromic ions in the column effluent.

Whether the failure to produce chromic ions due to slow reaction of the ions or to adsorption of the released chromic ions by the column is an interesting question, but its solution is not pertinent to the problem at hand. Thiourea at the 10 μg/ml and pH 1.2 reduced dichromate on the column, but even after half an hour of passing solution at less than 0.5 ml/min, the reaction was far from stoichiometric. Less than 5% reaction had occurred. At 1 μg/ml thiourea concentration, no chromic ions could be observed in the column effluent after 2 hours.

The reverse reaction (the oxidation of chromic ion, Cr-51, on a cation column, Dowex-50) was then tried. In principle, chromate or dichromate ions formed from the oxidation should not remain on a cation column. But peroxydisulfate and bromate ions in acid solution, and hypochlorite, hypobromite, and hydrogen peroxide in basic solutions, all at the 10 μg/ml concentration, failed to give radioactive species in the column effluent.

MISCELLANEOUS REACTIONS

Several other potential reactions were tried using macroscopic concentrations of ions and non-radioactive solids to learn whether they would be worth studying at the μg/ml level. Evidence for the reaction was determined either colorimetrically or by simple analytical tests. Following is a list of equations which would describe the reactions

$$Cd + NO_3^- + 2H^+ \longrightarrow Cd^{++} + NO_2^- + H_2O$$

$$3Cd + Cr_2O_7^= + 14H^+ \longrightarrow 2Cr^{+++} + 3Cd^{++} + 7H_2O$$

$$3Zn + Cr_2O_7^= + 14H^+ \longrightarrow 2Cr^{+++} + 3Zn^{++} + 7H_2O$$

$$3Zr + 2Cr_2O_7^= + 28H^+ \longrightarrow 4Cr^{+++} + 3Zr^{++} + 14H_2O \quad .$$

Either no reaction occurred or else, as with zinc and cadmium, the slightly acidic solutions themselves dissolved the metals even in the absence of other oxidizing agents.

SUMMARY AND CONCLUSIONS

Attempts to develop a radio-release procedure for use in measuring very small concentrations of tracer ions were not successful. The goal of the experiments was to be able to measure tracer ion concentrations at the nanogram per milliliter level (ppb). No procedure useful even at the microgram per milliliter level (ppm) was found. From these results it seems as if the radio-release method of analysis, although in principle a very sensitive method, in practice is severely limited by reaction kinetics. Further work on the method cannot be recommended.

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APPENDIX 3

ERROR ANALYSIS OF TOTAL COUNT DISCHARGE MEASUREMENTS

G. A. Teter

Introduction

This study has been made to estimate the probable accuracy of flow measurements made with radioisotopes by the USBR. This analysis considers only those errors due to isotope handling and counting and assumes that the sampling rate is constant and that complete mixing of the tracer and water has been achieved. While the analysis is based on the total count method, the same parameters are generally applicable to the integrated sample and dilution methods. The accuracy using the latter two methods could be improved through the better statistical accuracy obtained from accumulating more counts at the expense of increased time for the measurement. This analysis has been divided into three main groups of development, but all of the resultant errors contribute to the total error of the measurement.

The maximum error (dy) in the determination of some quantity $y = f(x_i)$, is:

$$dy = \sum_{i=1}^{n} \left| \frac{\partial y}{\partial x_i} \right| dx_i \qquad (1)$$

Where x_i is the measured parameter.

Calibration Solution

To make a standard solution for calibration purposes, a small known pipet volume (v) of the stock solution is diluted to some larger-known volume (V_c). Let C_i be the specific activity in μc/ml of the isotope shipment after the initial dilution to make up the stock solution.

Then the specific activity of the calibration solution is:

$$C_c = \frac{vC_i}{V_c} \tag{2}$$

But from equation (1)

$$dC_c = \frac{C_i}{V_c}\,dv + \frac{C_i v}{V_c^2}\,dV_c.* \tag{3}$$

Then the fractional error of the specific activity of the calibration solution is:

$$\frac{dC_c}{C_c} = \frac{dv}{v} + \frac{dV_c}{V_c}\,. \tag{4}$$

Calibration Factor

The calibration factor (F) for a given detector - sampling tank system is determined by mixing a small amount of the calibration

*It can be shown that any absolute error in C_i will not affect the flow measurement provided the calibration solution is made from the stock solution of specific activity C_i.

If a small constant flow (sample) is removed from the main flow during the passage of the tracer wave, the sample will contain a tracer concentration equal to that of the main flow at the time of sampling. The collected sample can be counted continuously ("sample tank" technique) or be collected to form an "integrated sample." The sampling interval must include the entire time of passage of the tracer wave. An excessively long period theoretically will not result in an erroneous discharge, but can result in greater counting errors. To insure that the entire wave is being sampled, one or two samples should be taken prior to t_1 and one or two after t_2.

When using the total count method of flow measurement, the radiation detector is positioned in a sample tank, Figures 15A and 16B, which is continuously sampling the discharge. The total net counts are observed during the time of passage of the tracer through the system. The total count, N , is dependent upon the count rate, R, thus

$$N = \int_T R \, dt = \bar{R}T$$

then

$$\bar{R} = \frac{N}{T} \tag{4}$$

This average count rate, $\bar{R}$, is also directly proportional to the concentration by a simple relationship

$$\overline{R} = F\overline{C} \qquad (5)$$

by equating (4) and (5), we obtain

$$\frac{N}{T} = F\overline{C} \quad \text{or} \quad \overline{C}T = \frac{N}{F} \qquad (6)$$

The proportionality factor, F , is a function of the counting system, the radioactive material used, and the geometry of the detector position. The measurement of F is discussed in another section of this report, Counting System Calibration. By substitution of the equivalent to $\overline{C}T$ into Equation (3),

$$Q = \frac{A}{\overline{C}T} \quad \frac{FA}{N} \frac{\text{(counts/second)}}{(\mu c/\text{cubic foot})} \quad \frac{(\mu c)}{\text{(counts)}} \qquad (7)$$

the equation for the total count method.

Tracer Handling Procedures

The radioactive material used in the tests was received in a concentrated solution. The amount of activity required for a series of field tests is usually in excess of 500 millicuries. The accurate preparation and measurement of each injected amount of radioactivity has been a significant part of our research activity. Due to the presence of a high radiation field around the source, all fluid transfer must be done using remote handling tools. The most convenient method for transfer and measurement of solutions in the field is the use of a remotely operated pipet. However, a remote pipet is not accurate enough for our goals.

To provide better accuracy an apparatus was developed to transfer measured amounts of radioactivity from the original quantity to a separate container for injection. This apparatus, Figure 17, is made up using an automatic buret. The buret is filled and emptied using small pressure bulbs and a long handle to remotely operate the stopcock. Graduations on the glass are disregarded because the true volume of the buret has been measured gravimetrically.

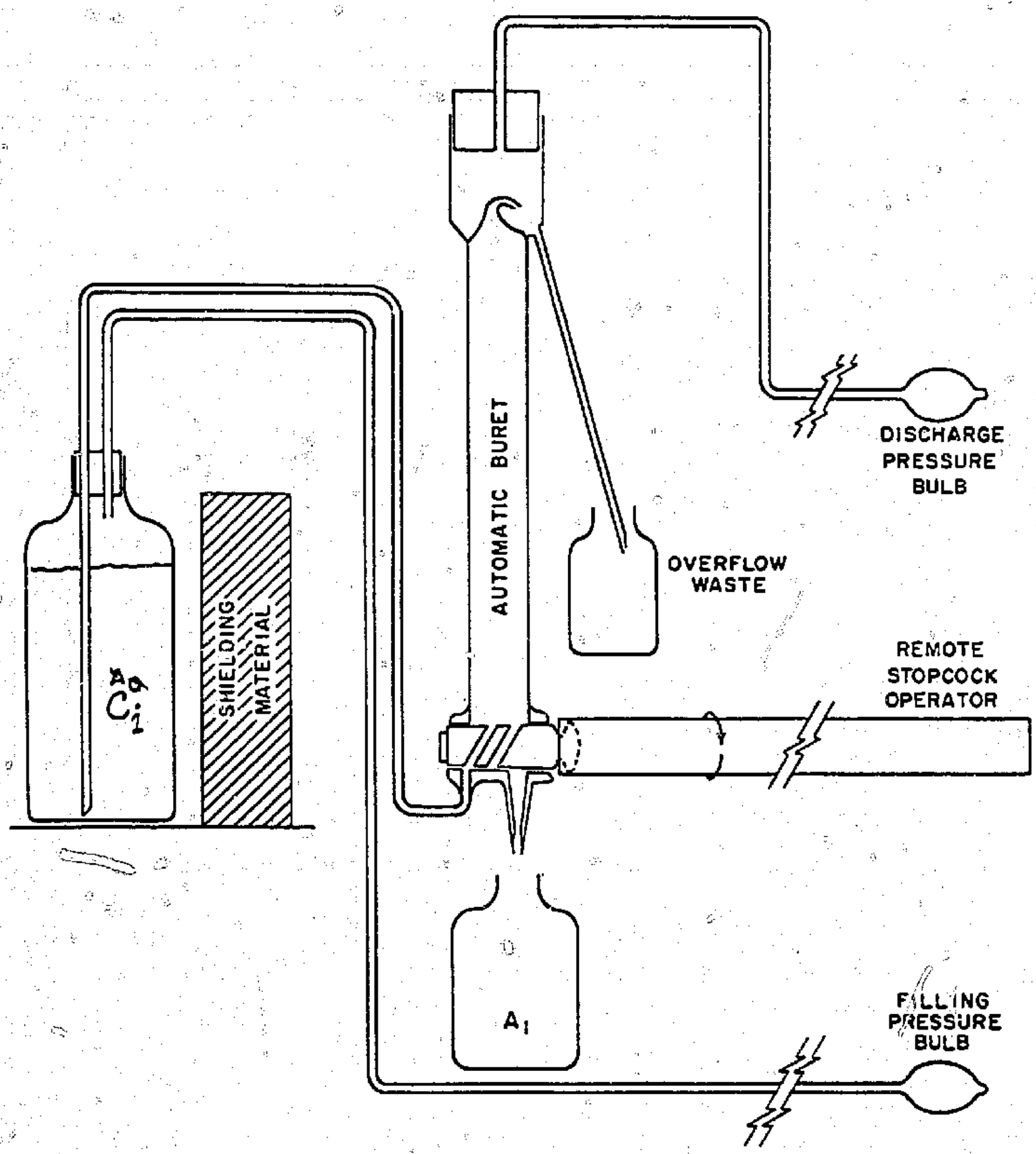
The concentrated radioactive solution, when received at the field site, is diluted to convenient volume (usually 1 liter). This stock solution, C_1, is kept in a shielded compartment while a known fraction of its volume is forced through tubing to the automatic buret. The buret is filled each time to the overflow tip. Any overflow is trapped in a waste container. Injections (A_1, A_2, $\cdots$ A_n) are made up of a predetermined number of buret volumes. The size of the buret can be selected to fit the needs of each individual test series.

Tests of this method of liquid transfer in our laboratory showed that repeated volume measurements can be carried out with an accuracy of plus or minus 0.05 percent.

Counting System Calibration

Procedures. - Experience shows the reported quantity of radioactive material received from suppliers to be widely variable. A previously

Figure 17



AUTOMATIC BURET

APPARATUS FOR ACCURATE DIVISION OF RADIOACTIVE SOLUTIONS.

(NOT DRAWN TO SCALE).

developed method to determine the quantity, using a portable calibration bench was not accurate enough to meet our requirements for field calibration.7/ Therefore, a method has been developed to calibrate the counting systems at the field site using a small volume of the material ordered for that specified test. To eliminate the need for determining the absolute activity of the radioisotope, fractions of the initial dilution are used for the calibration of the counting system. An arbitrary value for the activity can be assigned to the initial dilution of about 1 liter (e.g. 500 millicuries) resulting in a ratio of 0.5 millicurie per milliliter. All quantities to be injected for the discharge measurements and all quantities to be used for calibration of the sample tanks originate from the initial dilution. An absolute error in C_1 will not affect the flow measurement provided that the calibration solution is made from the stock solution. Using this method it is not necessary to know precisely the absolute activity of the isotope injected.

Measurements were performed in the Bureau's Denver Office laboratory to evaluate the procedures for calibrating the sample tank, Figure 16B, and counting systems for radioisotope flow measurements. The measurement system used was the automatic dual-channel scaler-printer, purchased specifically for the flow measurement program, and a scintillation detector with a 1-1/2- by 1-inch NAI(T1) crystal.

Because the volume of the tank must be accurately known for calibration purposes, a series of measurements of the tank volume were made over a water temperature range of 40° to 90° F to determine the variations in volume with temperature. This range of water temperature would include temperatures normally expected in turbine and pump installations. Only a small correction of tank volume is required for temperature variations and the maximum error after correction is plus or minus 0.5 percent.

The response of the photomultiplier tube and solid state preamplifier in the counting system is subject to variation with temperature. To minimize the temperature effect, the sample tank was filled from a flowing source of water and allowed to stabilize until the tank and the scintillation counter had come to a temperature equilibrium.

During the field measurements, the temperature of the water will not vary significantly in the relatively short period of time for the tests. Therefore, it is only necessary to measure the water temperature at the beginning and again at the end of the test period to determine the volume of the tank. The water temperature during the field measurements was very near the temperature of the water when volume measurements were made on the tank in the laboratory. Therefore, no volume corrections for temperature were made in the field because the volume change was considered insignificant.

The background count rate must be determined before any tracer materials are brought near the counting system. The background should be measured to a statistical accuracy of about plus or minus 1 percent. A 1-percent error in the background measurement will result in a negligible error in the gross count after addition of the isotope provided that the gross count rate is large with respect to the background. In practice, the gross count rate in calibrating the tank has been made at least as high as the maximum rate expected during the flow measurement. This rate may range as high as 1,000 cps (counts per second) compared to a measured background count of about 45 cps.

On top of the tank there is a 2-inch pipe cap. The cap is removed and the water level in the tank carefully adjusted to a water level mark for calibration. When the cap is removed a large funnel can be attached over the opening. This funnel is used when adding and mixing isotope in the tank to prevent spills of radioactive material on the outer surface of the tank and to catch bubbles erupting during air mixing.

The tracer is mixed by using a tire pump to bubble air through the tank or an electric mixer was used when power was available. The pump is attached to a valve stem on top of the tank. Air is pumped gently into the tank to rise and escape through the funnel. Vigorous operation of the pump causes air and water to erupt through the funnel and can result in loss of water and tracer from the tank. A loss of tracer results in inaccurate calibration and in contamination of the outer tank surface and the surrounding area with radioactivity.

Tests have shown that the tracer is rapidly dispersed by the bubbling air or by stirring with the mixer. The results of recording the counting rate during mixing show that the greatest dispersion occurs in the first minute of mixing and that nothing can be gained by mixing for more than 5 minutes. Once the count rate in the tank is stabilized it can be assumed that the tracer is well dispersed.

To obtain the final counting yield of the system after the tracer is thoroughly mixed, the funnel is removed and the cap is replaced on the tank. Since the entire γ-ray spectrum is to be counted, care must be exercised to place the counting system at the location of the actual flow measurement. Any change in the location or position of the system may change the extent of γ-ray scatter and thus change the counting yield. The location of the counting system should also be the same when measuring the background rate.

The exact time of the final counting yield must be noted in order to correct the added activity for decay losses. In using materials with a short half-life, this is very important. With Bromine-82 as the tracer, the activity is reduced about 1.9 percent per hour. When calibrating the system to within an accuracy of 1 percent, small inaccuracies in data collection cannot be tolerated.

Following the above procedures the necessary data are obtained to compute a calibration factor for the system. The net count rate of the detector and the concentration of radioactivity in the tank are now known. For the total count method of discharge measurement, the calibration factor, F , is the ratio of the net count rate to the concentration (F = R/C) (count x cubic feet/microcuries x second).

Results. - Calibration procedures developed in the laboratory were duplicated at the field site. The results of a series of six field calibrations made during a 3-day test period are given in Table B. The values obtained for the "F" factors are within the expected range of accuracy. This series of measurements was made on a counting system located inside the Flatiron Powerplant where conditions were good. The radioactivity was transferred to the calibration tank using a constant delivery pipet.

Table B

SAMPLE TANK CALIBRATION FACTORS

Test No.	Date	"F" factor	ΔF	Difference from mean percent
1	12-6-68	379.172	0.019	-0.005
2	12-6-68	381.170	1.969	+0.52
3	12-7-68	380.134	0.943	+0.25
4	12-7-68	379.403	0.212	+0.06
5	12-8-68	377.911	1.280	-0.34
6	12-8-68	377.368	1.723	-0.45

Average = 379.191

In another series of calibrations the sample tank was located outside and the results showed more scatter. It is believed that part of the scatter was caused by the use of the constant delivery pipet when weather conditions made it very difficult to obtain good results. In subsequent studies, a gravimetric measurement of the calibration samples was shown to be superior to the volumetric measurement. The calibration samples were weighed on an analytical balance in the laboratory and transferred to the field site in small vials.

Error Analysis of Radioisotope Procedures

In evaluating the total error involved in making flow measurements with radioisotopes, the error of each operation or function was considered. In order to make the measurement of flow rate with radioisotopes as useful as possible, the error of each operation is reduced to a minimum.

The assessment of accuracy of the radioisotope flow measurement must consider all operations involved in conducting the measurement and their associated errors. In using the total count method of flow measurement the following operations can contribute to the total error: (1) volume measurement errors (5 total), (2) timing errors, (3) counting error during system calibration, and (4) counting error during the discharge measurement.

The accuracy of the five volume measurements are the most difficult to control. The volume of the sample tank was determined gravimetrically in the laboratory using a platform scale. The accuracy of the scale was checked using standard weights. The tank empty and filled with water was weighed several times. The average net weight and water temperature were used to compute the tank volume. A second volume measurement involves the use of a 1-liter volumetric flask. This flask was used for preparation of a standard solution for the counting system calibrations. The dilution and preparation of the solution can be very accurately done under laboratory conditions.

Two transfers of radioactive material were initially made with pipets. One involves the transfer of a small known quantity of solution from the stock solution (C_1) to make the standard solution C_c.

The other involves the transfer of material from the standard solution to the sample tank during the calibration. The pipet glass must be kept very clean and special care must be taken to insure repeatability of the volume transfer.

The fifth volume measurement involves the determination of the quantity of activity to be injected for each flow measurement. This quantity (A_1, A_2, ···, A_n) was measured using an automatic buret, Figure 17. Repeated measurements have been made using the apparatus and technique and an accuracy of ± 0.05 percent has been assigned. Again, the buret glass must be kept extremely clean to assure the delivery of constant volumes.

An accurate stopwatch and a long counting interval (± 1,000 seconds) was used for timing the measurement of the average count rate during calibration of the counting systems. The stopwatch time is used because the variation of the 60-hz line frequency from mobile power supplies can cause significant timing errors.

Statistical accuracy of the counting must be considered in both system calibration and in measurement counting; the more counts accumulated, the greater the accuracy, (% Error = $100/\sqrt{N}$).

Evaluation of the accuracy of the Total Count method is discussed in more detail in Appendix 3 of this report. When all operations in the technique are carried out to the degree of accuracy expected from laboratory measurements, the maximum probable error should be ± 0.50 percent and the maximum possible error ± 0.99 percent. This accuracy, however, seldom occurs because control of field conditions cannot be maintained that well. Bureau experiments show the accuracy of field measurements, based on actual observations, to be in the order of ± 0.97 percent for the maximum probable error and ± 1.73 percent for maximum possible error.

The above accuracies consider only the radioisotope and handling procedures and assume mixing of the tracer with water to be complete and the sampling rate to be constant.

Tracer Injection

The radioactive BR-82 needed for a day's measurements was pipetted into polyethylene bottles in the Denver laboratory. The bottles were taken in a shielded compartment by automobile to the injection station at the penstock of Flatiron Powerplant. The pump or pulse injection system and nitrogen gas bottle were placed near the manway selected for the measurement series. The system was connected to the injection tube and at least one cylinder of water was injected into the penstock to assure proper functioning of the injection system.

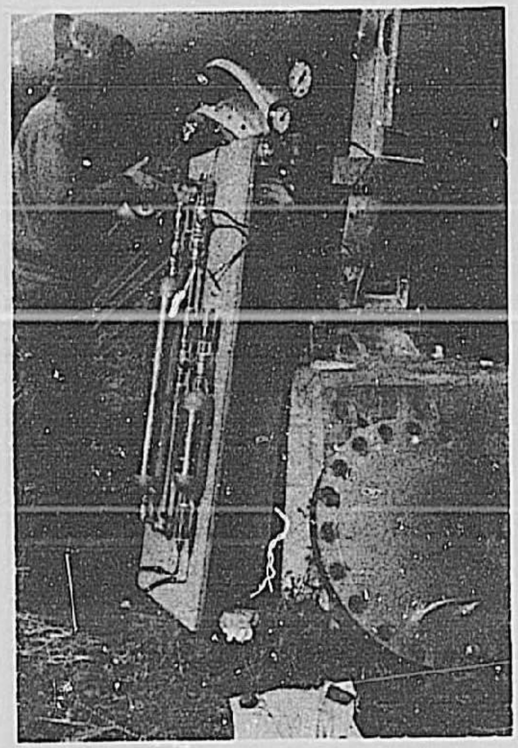
The purge cylinder was filled with water to be used to flush the injection cylinder after completion of the injection, Figures 9B and 18A. A bottle of tracer was then taken from the automobile compartment and poured into the injection cylinder, Figure 18B. The bottle was rinsed and the rinsing was poured into the cylinder followed by additional water to nearly fill the 1-liter cylinder. The added dilution reduced the possibility of retention of the tracer in the injection cylinder.

After the purge and injection cylinders were charged, the vent and filling valves were closed and the regulated pressure from the nitrogen bottle was applied to the system. The valve controlling the outflow from the injection cylinder was operated remotely, Figure 19A. Personnel at each sampling station were signalled by radio to standby immediately before the injection and were then given a 10-second count before the injection time.

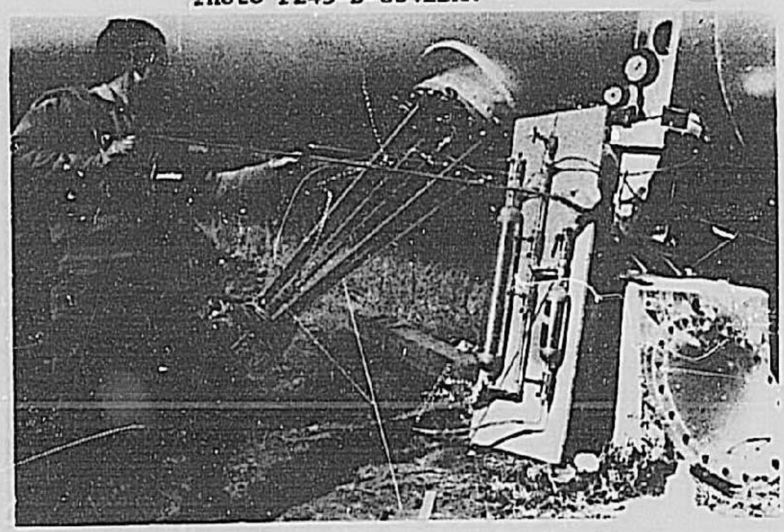
The emptying of the injection cylinder was noted from the noise made by the gas flowing into the penstock through the injection tube. To complete the injection, the gas pressure was diverted to the purge cylinder and water from the cylinder was discharged through the system to the penstock.

Repeated monitoring of the system after the injections showed no appreciable retention of activity. The combined dilution in the

Figure 18



A. Filling purge cylinder before radioisotope is poured into injection cylinder.
Photo P245-D-60423NA

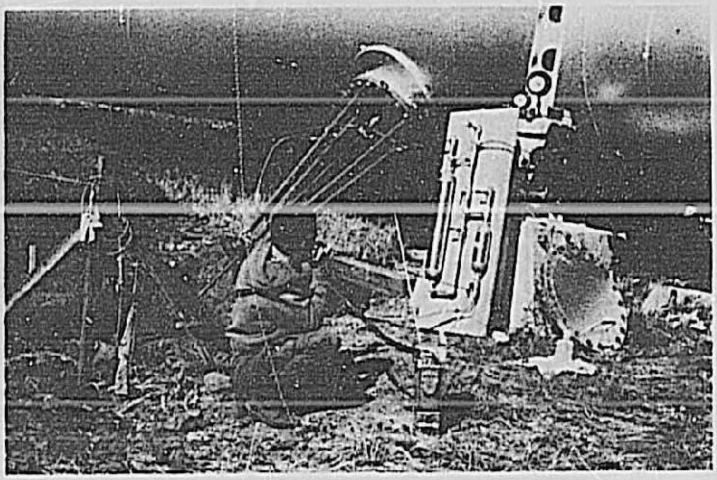


B. Pouring radiotracer into injection cylinder, water is added to cylinder to minimize tracer retention.
Photo P245-D-60422

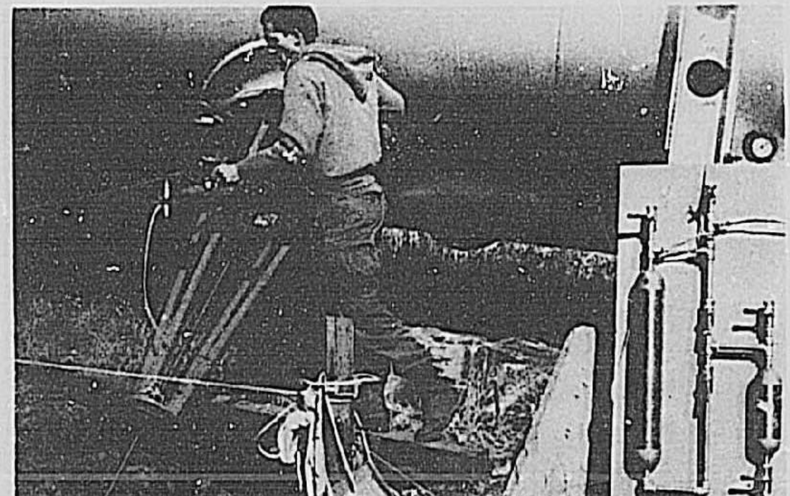
RADIOISOTOPE INJECTION PREPARATIONS

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

Figure 19



A. Pulse system prepared for radioisotope injection into penstock, radio communications were used between injection, sampling, and powerplant stations. Photo P245-D-60426



B. System being monitored after tracer injection. Photo P245-D-60427NA

RADIOISOTOPE INJECTION

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

injection cylinder and the flushing from the purge cylinder satisfactorily cleaned the system.

All of the valves used for discharging water or tracer from the injection system to the penstock were of the "ball" type. These valves provided an unobstructed flow passage when fully opened to prevent retention of radiotracer. All the tubing, pipe, and cylinders in contact with liquid and tracer were made of stainless steel and apparently did not become coated or retain tracer on the surface or in the fittings joining the parts.

On one occasion a minor difficulty was encountered in system operation. The normal procedure of operation was to reduce the pressure on the injection system to atmospheric after the purge cylinder was empty. This was not done after one injection. By having the penstock pressure nearly balanced by the gas pressure, the check valve, Figure 8B, used to prevent return flow from the penstock, could not operate properly. Inspection of the system for the next injection showed the injection cylinder to be nearly full of water. This water, over a period of about 2 hours, had been pumped gradually into the injection cylinder through the check valve by pressure fluctuations in the penstock flow.

Because of the small size of the holes in tips of the injection probes (1/64 inch) precautions were continually taken to exclude foreign particles from the water used for tracer dilution and for flushing. An injection tube was plugged once during the measurements on the pump-turbine but the stoppage occurred after the tracer had entered the pipe. The plug was found to be a particle of rust that came from the piping used to obtain water for the tracer dilution.

Tracer Sampling

The tracer-penstock water was sampled for counting by the "sample tank" technique, Figures 15A and 16B.

Each counting system produced data for computing the discharge by the Total Count method. When samples of the flow were required for a measurement by the "integrated sample" or "dilution" method, a part of the sample flow was withdrawn at the entrance to the tank, Figure 16B. The partial flows were collected in plastic containers placed away from the sample tanks, Figure 15A.

Rubber hoses were connected between the tanks and the pressure reducers on the two sampling tubes inserted in the penstock. The sample tanks were filled with water from the penstock, the counter was placed in the tank, and a background was counted for the tank in the location to be used for the discharge measurement. One of the calibration fractions was added and mixed in the water of the tank. The mixture was counted to provide an inplace calibration of the tank and surroundings. The tanks were located away from the penstock and other radiation sources to prevent an inaccurate count and calibration of the tank.

After completion of the calibration the discharge through the sample tank was regulated to the desired flow of 20 to 25 gpm, and a background count was measured before the arrival of the tracer in the penstock flow. Counting of the tracer sample flowing through the tank was continued until a background level was again obtained. The counting equipment was then prepared for the next injection.

The count data were recorded on printed tape and on magnetic tape in the mobile laboratory as the sample passed through the tank, Figures 15B and 16A. This method provided information for on-site computation of the discharge and for additional analysis in the Denver Office.

The samples collected in the separate containers were transferred to the calibrated sample tank for use in the "integrated sample" and "dilution" methods of measurement. The count obtained from the samples was recorded in the mobile laboratory for later analysis. These additional samples were collected only for the measurements made on the first day of the test series. Handling and counting of the tracer-mixture for the three methods, total count, integrated sample, and dilution, consumed more time than planned in the test series. Therefore, testing of each method was programed for later series of measurements. The simultaneous use of the three methods appeared feasible when time was available for counting the sample necessary for each method. The relative accuracy of each method could also be determined by the use of the single injection needed for the dilution method.

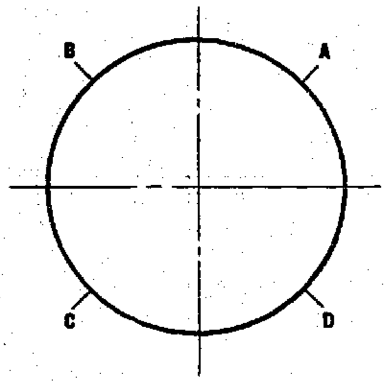
Sampling of the flow in the powerplant was done by the sample tank procedure. Either a pumped flow or pressure flow from the penstock was used to obtain the sample, Figure 12. A portable scaler and timer were installed above the sample tank on the powerplant operating floor, Figure 16C. Both portable and powerplant communications systems were used for radio contact with the injection station.

The "total count" method was used for computing the discharge from the sample at the powerplant. There was no automatic recording feature on the counting system and the count was recorded manually with respect to time, Figure 16C.

Results of Discharge Measurements - Turbine

Pitometer

Velocities in the cross section of the pipe were measured on two diameters 90° apart. These diameters had been accurately measured before the start of the tests.



Diameter in feet

AC	6.958	Vert.	7.013
BD	6.978	Horiz.	6.966

Velocity traverses along
AC and BD

Looking downstream

Each of the diameters, AC and BD, was assigned 11 points at which velocities were measured for computing the discharge. Points of measurement were computed for 0.052, 0.161, 0.292, 0.452, 0.682, and 1.00 of the pipe radius. The centerline velocity thus was a common point for each of the four radii.

The flow velocity (V), at the traverse point was computed from the differential head, (H), measurement read from the U-tube water manometer in the equation

$$V = C\sqrt{2gH}$$

where C = the pitometer velocity coefficient established from a towing tank rating

V = velocity, feet per second

g = acceleration of gravity, feet per second

H = difference in pressure head from pitometer, feet of flowing water

An integration method was used to compute the discharge from the measured velocities. For a cylindrical pipe, there are two convenient ways of performing the integration and they both are based on the equation

$$Q = \int^{A} v dA$$

The incremental area of a pipe is $dA = 2\ r dr = \pi d(r)^2$. The equation becomes

$$Q = \pi \int_{0}^{R^2} v d(r)^2 \quad \text{or} \quad 2\ \pi \int^{R} (vr) dr$$

where r is the radial distance to the point of velocity measurement, v is the velocity, and R is the radius of the pipe. The integrals may be evaluated graphically from a plot of v versus r^2, or vr versus r. The area under the curve is then measured and the result is multiplied by π or 2π.

The second method of integration was chosen for computing the discharge in this study. A computer program was written to perform the integration. For each successive pair of values of vr and r from the test data, points on a segment of a third degree polynomial were calculated using Newton's interpolation formula with central divided difference. A Newton-Cotes integration formula using five successive points on the polynomial was incrementally applied to numerically integrate the area under the curve. The result is the value of the integral,

$$\int_0^R (vr)dr$$

The discharge Q is then obtained by multiplying the integral by 2π. The computer program integrates the velocity traverse and computes a gross discharge (Q_g) for the pipe.

A reduction in the gross discharge was made for the presence of the pitometer rod in the cross section of the flow. The reduction was based on the projected area of the rod in the direction of flow when the orifices were at the center of the pipe. For the cylindrical rod of the pitometer, the area affecting the flow was taken as 1.25 times the projected area of the rod extended to the pipe center. The 4-foot rod could not be extended to the center and the correction was made for the measured projected length. A discharge reduction q was computed from the product of effective area (a) and the average velocity $\overline{V}$ in the pipe. The net discharge is $Q_v = Q_g - a\overline{V}$. The value of $a\overline{V}$ was about 0.28 cfs (cubic feet per second) for the 4-foot and about 0.48 cfs for the 7-foot pitometer.

The discharges measured by the pitometer method are shown in Table 1. For the 4 days on which discharges were measured the flows ranged from a low of 128.9 cfs to a high 135.7 cfs. On the days of radioisotope discharge measurement of the flows ranged from a low of

Table 1

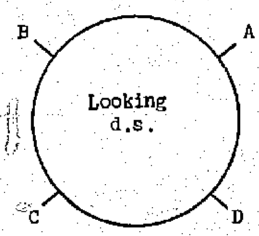
Flatiron Turbine Penstock
Results of
Pitometer Discharge Measurements

Run No. and pitometer rod	Conditions	Date	Discharge	Radius av	$\bar{V}$	Pitometer A/2	q $\left(1.25\,\bar{V}\,\frac{A}{2}\right)$	$Q - q$ Corr. discharge
FLTRN 1A-7'A	Unit No. 2, 22.5 percent open	10-20	129.356 cfs		3.381 fps	0.113 ft^2	0.477	128.88 cfs
FLTRN 4A-7'A	do	10-27	131.518 cfs		3.438	.113	.485	131.03
FLTRN 2A-4'D	do	10-25	131.079 cfs	132.289 cfs	3.427	.063	.270	130.81
FLTRN 3A-4'D	do	10-26	133.203 cfs		3.482	.063	.274	132.93
FLTRN 1B-7'B	do	10-20	130.338 cfs		3.407	.113	.481	129.86
FLTRN 2B-7'B	do	10-25	129.617 cfs	130.336 cfs	3.388	.113	.478	129.14
FLTRN 4B-7'B	do	10-27	131.053 cfs		3.426	.113	.484	130.57
FLTRN 3C-7'B	do	10-26	130.024 cfs		3.399	.113	.480	129.54
FLTRN 4C-4'C	do	10-27	130.316 cfs	130.170 cfs	3.407	.063	.268	130.05
FLTRN 1D-4'D	do	10-20	134.691 cfs		3.521	.063	.277	134.41
FLTRN 3D-4'D	do	10-26	135.350 cfs	135.338 cfs	3.538	.063	.279	135.07
FLTRN 4D-4'D	do	10-27	135.973 cfs		3.554	.063	.280	135.69
			Av = 131.877 cfs		3.456			Av = 131.50 cfs
							Omit 10-20 Av	131.65 cfs

Averages (uncorrected)

Run No.	Date	Traverses	Arith. av
1	10-20	A,B,D	131.462 cfs
2	10-25	A,B	130.348 cfs
3	10-26	A,C,D	132.859 cfs
4	10-27	A,B,C,D	132.215 cfs

7 foot pitometer av Q = 130.318 cfs
4 foot pitometer av Q = 133.435 cfs



A = 38.254 square feet

Mean discharge spiral case
Flow taps 25,26,27, October
125.99 cfs

$$\frac{131.65}{125.99} = 1.045$$

129.1 cfs to a high of 135.7 cfs. Discharges computed from the 4-foot pitometer in quadrant D averaged higher than for the 7-foot pitometer used in the other three quadrants (4-foot, 133.4 cfs and 7-foot, 130.3 cfs). Because of the short distance between the ground and the penstock, the 4-foot piezometer was used primarily at quadrant D. The discharge measured by the 4-foot pitometer at the C quadrant on October 27, resulted in a slightly less discharge, 130.1 cfs, than that (130.6 cfs) from the 7 foot in the B quadrant.

There was no definite confirmation but the pipe quadrant containing the D radius may have had velocities slightly higher than those in the remaining three quadrants. Both pitometers had been rated to the same standard and the discharge comparison (130.1 to 130.6 cfs) indicated the ratings had not changed.

<u>Spiral Case Flowmeter</u>

The mercury manometer connected to the spiral case flowmeter was read at 1/2-hour intervals. The differential was read from a scale marked in increments of inches and fractions equal to 2/100.

Each 1/100 inch of the mercury differential equalled about 1.5 cfs (1.2 percent) in the 125-cfs range of the turbine operation. A continuous graph of the differential was attempted by the pressure transducer and recorder. The recording was only partially successful because of electrical drift problems encountered in the system Good agreement between the manometer and recorder system was obtained in general but there were irregularities caused by high-pressure deformation of the transducer components resulting in a zero drift and calibration shift in the system. Because the manometer was the instrument originally used in the pump rating, the discharges indicated by the mercury differentials were used for comparison to the radioisotope discharge measurements.

These flowmeter discharges ranged from about 2 to 6 percent less than the discharges measured by the pitometer. No corrections were made for the difference because the studies were performed to show the consistency of radioisotope measurement for selected mixing lengths. Repeatability of the measurements was of first concern relative to the mixing of the radiotracer and pipe flow. The spiral case flowmeter and mercury U-tube manometer were read continually and were used to give an independent measure of discharge and to indicate the steadiness of flow in the system.

Radioisotope Discharge Measurements

The results of the measurements by the flowmeter and radioisotope methods show much variation within the method and between methods, Table 2 and Figure 20. Studies of the repeatability of the measurements were made using a pipe length of 311 diameters (October 25 to December 1). Investigations by the Bureau and by others had indicated that lengths of 100 to 200 diameters would be sufficient for satisfactory mixing.

Table 2

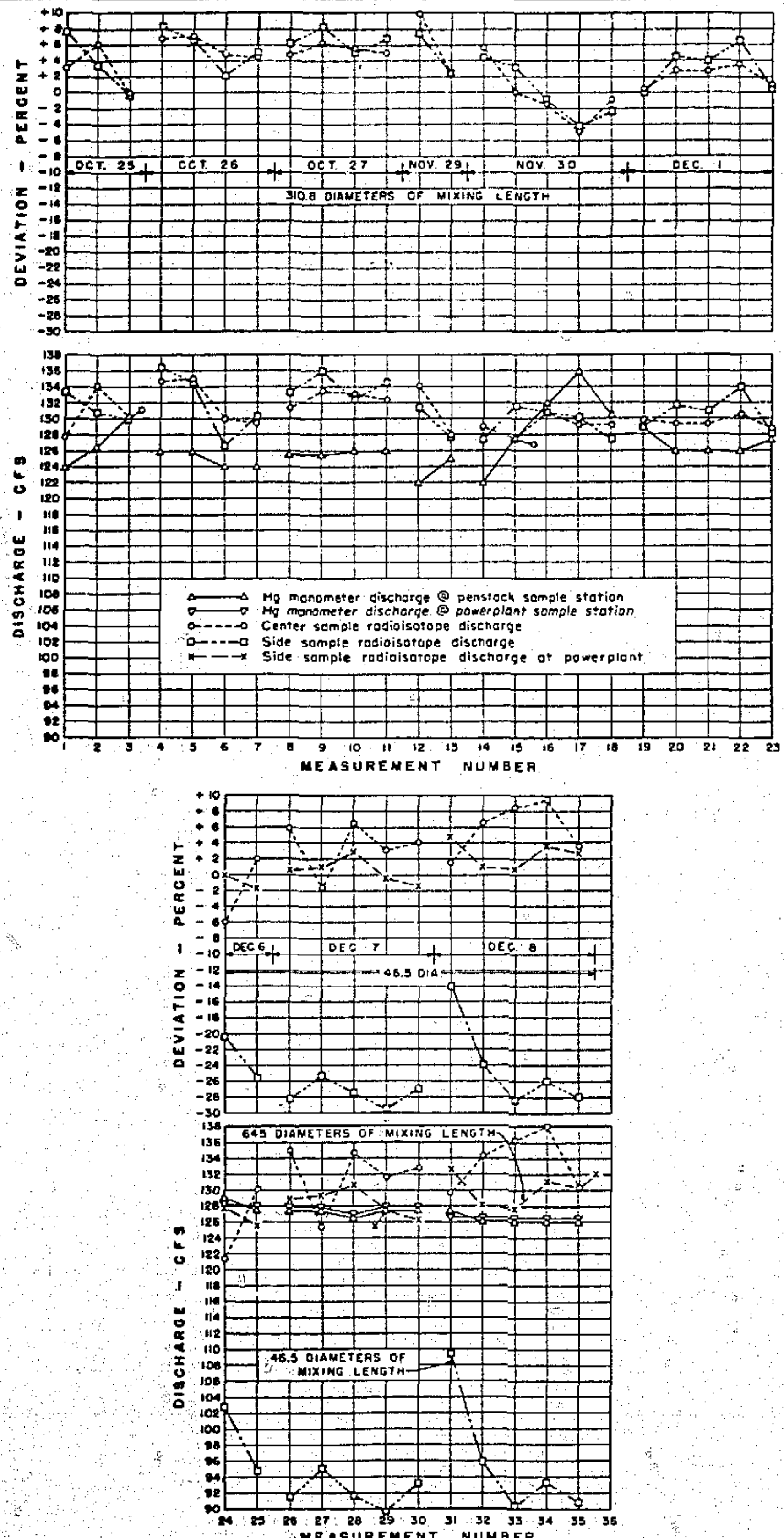
Flatiron Turbine Radioisotope and Spiral Case Flowmeter Discharge Measurements (Mixing length 310.8 diameter)

Month and day, 1967	Measurement No.	Manometer differential, inches	Flowmeter discharge, cfs	Center sample: Radioisotope discharge, cfs	Center sample: ΔQ, cfs	Center sample: Deviation, percent	Side sample: Radioisotope discharge, cfs	Side sample: ΔQ, cfs	Side sample: Deviation, percent	Percent mixing
Oct 25	1	0.44	124	127.73	+3.73	+3.01	133.44	+9.44	+7.61	97.8
	2	0.46	126.5	134.1	+7.60	+6.01	130.81	+4.31	+3.41	98.8
	3	0.49	130.5	130.29	-0.21	-0.16	129.81	-0.69	-0.53	99.8
Oct 26	4	0.46	126	134.63	+8.63	+6.85	136.50	+10.50	+8.33	99.3
	5	0.46	126	134.93	+8.93	+7.09	134.71	+8.71	+6.91	99.9
	6	0.44	124	129.97	+5.97	+4.81	126.63	+2.63	+2.12	98.7
	7	0.44	124	129.41	+5.41	+4.36	130.32	+6.32	+5.10	99.6
Oct 27	8	0.45	125.5	131.34	+5.84	+4.65	133.25	+7.75	+6.18	99.3
	9	0.45	125.5	133.46	+7.96	+6.34	135.98	+10.48	+8.35	99.1
	10	0.46	126	133.00	+7.00	+5.56	132.53	+6.53	+5.18	99.8
	11	0.46	126	132.23	+6.23	+4.94	134.60	+8.60	+6.82	99.1
Nov 29	12	0.43	122	134.14	+12.14	+9.96	131.43	+9.43	+7.74	99.0
	13	0.45	125	127.90	+2.90	+2.32	127.83	+2.83	+2.27	99.9
Nov 30	14	0.43	122	128.85	+6.85	+5.62	127.39	+5.39	+4.42	99.4
	15	0.47	127.5	127.61	+0.11	+0.09	131.65	+4.15	+3.26	98.4
	16	0.50	132	130.07	-1.92	-1.46	130.72	-1.27	-0.97	99.8
	17	0.54	136	129.24	-6.75	-4.96	130.11	-5.88	-4.33	99.7
	18	0.49	130.5	129.21	-1.29	-0.99	127.41	-3.08	-2.36	99.3
Dec 1	19	0.48	129	129.52	+0.52	+0.41	129.25	+0.25	+0.20	99.9
	20	0.46	126	129.28	+3.28	+2.61	131.75	+5.75	+4.56	99.1
	21	0.46	126	129.31	+3.31	+2.63	130.91	+4.91	+3.90	99.4
	22	0.46	126	130.55	+4.55	+3.61	134.08	+8.08	+6.42	98.7
	23	0.47	127.5	128.62	+1.12	+0.88	128.17	+0.67	+0.53	99.8

Water Temperature

October 49° F
November 42° F
December 42° F

Figure 20



DISCHARGE MEASUREMENTS TURBINE UNIT NO. 2

FLATIRON POWER AND PUMPING PLANT

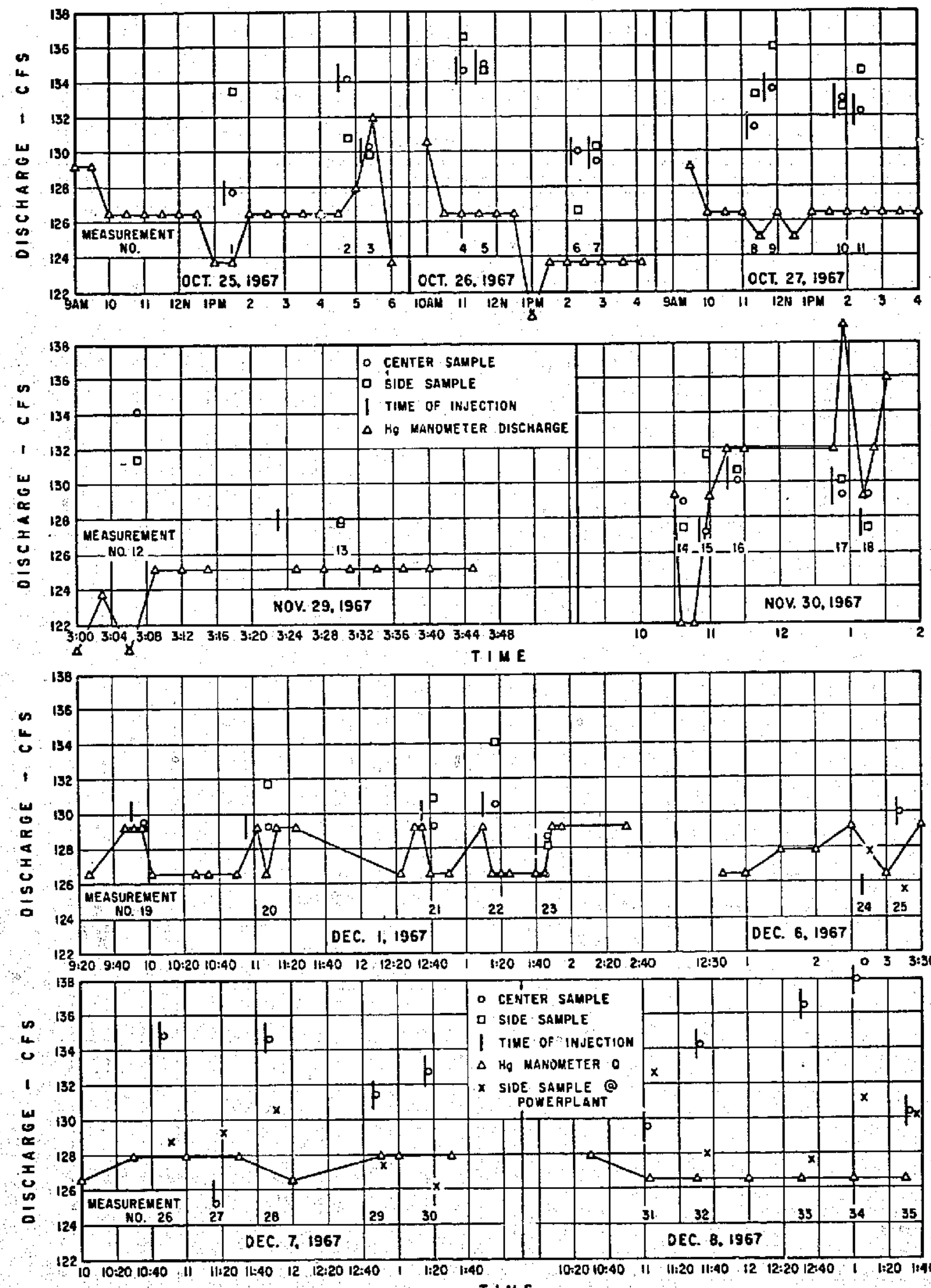
RADIOISOTOPE DISCHARGE MEASUREMENTS HIGH HEAD TURBINES AND PUMPS

Therefore, the repeatability of the method was studied for a mixing length that was considered to be about three times the required minimum.

Discharges indicated by the turbine flowmeter ranged from a low of 122 cfs to a high of 136 cfs during the 6 days of experiments, October 28 to December 1. The radioisotope method indicated flows ranging from 127 to nearly 135 cfs. The maximum and minimum values for each of the methods did not occur at the same time. In particular on October 26, 27, and November 29, low discharges were indicated by the flow meter while high discharges were indicated by the radioisotope method. The unsteadiness of flow in the turbine system and the variation in discharge indication between the center and side samples (0.04 radius from the wall) are shown on Figure 21.

For Measurements 1, 2, and 3, October 25, a centerline injection was made through a 1/32-inch hole in the tip of the injection tube, Figure 7 (Detail 6A). The diaphragm pump was used to force the isotope into the pipe at a constant rate of injection. Samples of the flow were collected to permit a computation of discharge by the total count, dilution, and integrated sample methods. Discharges computed by the integrated sample and dilution methods were unsatisfactory. The unsatisfactory results were caused by not allowing sufficient time during the measurements for proper counting and

Figure 21



SPIRAL CASE FLOWMETER AND RADIOISOTOPE DISCHARGE COMPARISON
FLATIRON TURBINE NO. 2

RADIOISOTOPE DISCHARGE MEASUREMENTS HIGH HEAD TURBINES AND PUMPS

handling the samples for each method. A complete investigation of the integrated sample and dilution techniques was planned for the next phase of the program.

The "total count" measurements were computed from the sample withdrawn through the previously described sample tank. The results (October 25) for Measurements 1 and 2 deviated from the flowmeter by 3 to nearly 8 percent (percent deviation = $\frac{\text{Radioisotope Discharge-Flowmeter Discharge}}{\text{Flowmeter Discharge}}$ x 100). Both of these measurements occurred during an indicated fluctuation in the penstock discharge. Contrary to these variations, Measurement 3 differed by less than 1 percent from the flowmeter for both side and center samples during a substantial fluctuation in the penstock flow. No cause, other than possibly incomplete mixing, could be found for the deviations in the first two measurements and the close agreement in the third for what appeared to be similar conditions of flow in the penstock.

On October 26, discharges were computed by the total count method from samples through the tank. Injections for the four measurements were made at the penstock centerline by gas pressure through an injection tip containing 4-1/16-inch-diameter holes, Figure 7 (Detail 6B). The volume of tracer solution, Br-82 and water, and the injection pressure were controlled to provide an injection time of approximately 1 minute. This injection time produced a counting rate within the range of the counting system. The differences between the discharges computed from the side and center samples were reduced on three of the four measurements, Figure 21, but differed by 2 to 8 percent from the flowmeter indicated discharge. No major changes of discharge were indicated by the flowmeter during the measurements.

On October 27, injections of radioisotope were made by gas pressure through a tip containing a 1/32-inch hole, one from the penstock centerline, two from a point at 0.6 of the radius from the wall, and one from 0.08 radius. Of the four measurements, two were made during indicated fluctuations of penstock flow and two when the flow was apparently steady. Three of the measurements showed about 2 percent variation between the side and center sample and one showed a deviation of less than 1 percent. All four of the measurements (eight computed discharges) were higher than the flowmeter by 4 to 8 percent, Figure 21.

Analysis of the data for the measurement series, October 25 to 27, did not show whether procedures or inadequate mixing caused lack of agreement between methods of discharge measurement and within the radioisotope method. A second series was therefore planned in which procedures for injection, sampling, and counting of the tracer-water mixture would be brought to the best capability of the sampling and injection equipment.

The second series of measurements was performed on November 29 and 30 and December 1, 1967, Figures 20 and 21 and Table 2. A length of 311 diameters was used for mixing the tracer into the pipe flow. Injections of the tracer were made at the centerline of the pipe through the 1/32-inch tip using gas pressure.

Differences in the discharges computed from the radioactivity measurements of the center and side samples ranged from about 0 to 3 percent. Differences between the radioisotope and flowmeter discharges ranged from about -4.3 to 10 percent in the 12 sets of radioisotope discharge measurements; 5 sets of the center and side agreed within less than 1 percent. Three of the five sets of readings were within about 1 percent of the flowmeter indicated discharges, Figure 21. The remaining seven sets differed widely from the desired ± 0.5 percent.

The total radioactivity measurement precision for the November 29 to December 1 measurements was estimated to be within ± 1.5 to 2 percent. The additional errors in the measurements could be caused by inadequate mixing, inadequate sampling, and/or improper comparison with the flowmeter discharge. Five of the measurement sets showed good agreement indicating that a satisfactory tracer-water mixture was obtained. Inadequate mixing was indicated by the unequal discharges computed for the center and side samples from seven of the measurement sets. Of these seven, four sets agreed to within about 1 percent, a larger amount than desirable. Additional sampling points in the cross section could have produced data to allow a better definition of the degree of mixing. The construction of the penstock did not permit the economical installation of more points.

To help evaluate the transverse distribution of the radioisotope, a percent mixing was computed from the relationship

$$\% \text{ mixing} = \frac{1 - (|Q_c - Q_m| + |Q_s - Q_m|)}{2Q_m} \times 100$$

where Q_c and Q_s are discharges measured at the center and side of the penstock and Q_m is the mean discharge.

These computed percentages appear in the last column of Table 2.

The percent mixing equation was used because of the limited number of points in the penstock cross section available for simultaneous sampling. A better method of evaluating the mixing would be to use the coefficient of variance of a number of sampling points.1/3/ A coefficient of variance equal to zero corresponding to a straight line concentration profile would indicate 100 percent or complete mixing.

The sample tanks should not have caused a radioisotope counting error because the flow-through time was rapid, less than 1 minute, for a change of 16 gallons. The tanks were placed about 50 feet from the penstock to prevent a direct count of radiation from the tracer-water mixture in the penstock. A distance of about 50 feet separated the sample tanks.

A measurement of the penstock pressure by a sensitive transducer indicated the flow pressure to be steady in the sampling tube. No instantaneous measure was made of the flow through the hose and sample tank but the penstock pressure measurements indicated a steady flow. Damping of small flow surges that may have occurred between the penstock and the sample tank exit was considered adequate for the expected tracer-water mixture in the penstock. A moderate degree of additional mixing no doubt occurred in the connecting hose and in the tank. Thus, the differences in discharge computed from the center and side sample may have been caused by an inadequate tracer-water mixture in the penstock in the 311-diameter length.

Comparison of discharge as indicated by the isotope with the turbine flowmeter measurement was difficult because of unsteady flow in the penstock. Approximately 2,000 feet of pipe separated the sampling point and the flowmeter at the turbine. To establish the flowmeter discharge to be used for comparison two considerations were made:

(1) the peak arrival time of the tracer at the sampling tank, and (2) the pressure wave travel time between the sample point and flowmeter. The celerity of the pressure wave in the measurement section was about 2,600 feet per second and near the powerplant about 3,700 feet per second. Thus, less than 1 second was required for a pressure wave to travel between the sample tube and the turbine.

The flow time between the penstock and sample tank counter was computed to be about 3.5 seconds and 5 to 7 minutes for the tracer to flow past the sample tube entrance. The flow time between the penstock and tank of 3.5 seconds was considered to be nearly instantaneous with respect to the passage time of the tracer. Thus, the flowmeter discharge was selected from the curve to correspond with the 5- to 7-minute period of the tracer passing the sampling tube, Figure 21.

On November 29, 30 and December 1, an attempt was made to better define the flowmeter discharge. The mercury manometer was read at 4-minute intervals on the 29th, and 15-minute intervals or less on the 30th and December 1st. These readings gave better definition to the discharge but also showed fluctuations as high as 8 cfs. As shown on Figure 21 for November 30, 1967, four of the measurements made that day occurred during an indicated change in the penstock flow.

A correlation was sought between the time of injection and the fluctuations in penstock discharge since there were indications that the injections preceded flow changes. The injection of the tracer and admission of small amounts of nitrogen gas at pressures higher than the penstock pressure caused pressure waves. The quantities of tracer and gas were small and were not expected to have a measurable effect on the flow. Inspection of the data, Figure 21, shows that 15 of the 23 measurements made between October 25 and December 1, 1967, occurred during periods of an indicated change in the flow in the penstock. However, there was no evidence that the injected gas caused the flow change. In addition, the recorder chart from the megawatt meter for the total time of the measurements showed a steady output for the blocked load on the plant.

Discharges computed from the radioactive count taken at the turbine draft tube, Figures 5, 12B, and 12C, were expected to be the most reliable. A mixing length of about 645 diameters of pipe was available between the injection and sampling points. A slight degree of mixing was also expected to occur as the tracer-water mixture flowed through the turbine. It was thus unexpected when the discharges calculated from the draft tube samples were about 23 percent higher than those measured from penstock samples, Table 3.

Table 3

Flatiron Turbine Radioisotope and Spiral
Case Flowmeter Discharge Measurements
(Draft tube samples compared to 310.8-diameter samples)

	Measurement No.	310.8 diameters Center sampling	310.8 diameters Side sampling	Powerplant station Draft tube side sampling	
October 25	1	127.73	133.44	171	)
	2	134.10	130.81	158	) Pump through 1/32 in. opening 10-25
	3	130.29	129.81	162	)
October 26	4	134.63	136.50	173	)
	5	134.93	134.71	167	) Pulse 10-26-67 4-1/16 in. dia. openings
	6	129.97	126.36	159	)
	7	129.41	130.32	155	)
October 27	8	131.34	133.25	158	Pulse 1-1/32 in. opening center)
	9	133.46	135.98	163	-0.6 radius) 10-27
	10	133.00	132.53	16[illegible]	-0.6 radius)
	11	132.23	134.60	159	-0.08 radius from wall)

A dilution of the tracered water was found to be the cause of the larger discharge values. At the discharge used for these measurements (about 130 cfs), water from the afterbay was drawn into the draft tube past the intake to the sample tank, Figure 12B. A diluted tracer-water mixture was then sampled to result in a high computed discharge. This recirculation was disclosed by adding a fluorescent dye to the water at the draft tube exit. A fluorometer attached to the sample pipe registered the presence of dye in less than 1 minute after injection. The sampling point in the draft tube was abandoned and relocated at the inlet to the turbine, Figure 12A.

A third series of discharge measurements was started on December 6, 1967. The measurements were made to determine the effect on mixing of changing the injection pressure and the hole configuration in the injection tube. A mixing length of 46.5 diameters was chosen between the injection and sampling points. Improvements in the mixing could be more readily distinguished in the shorter pipe length if better mixing occurred for some combinations of pressure and tip configurations than for others.

Injections of tracer were made at the penstock centerline and both the pressure and configurations of the tip of the sampling tube were varied on the three test days. Samples of the tracered flow were obtained at the penstock center and at a point 0.04 of the pipe radius from the wall.

Measurements on December 6 and 7 were one series of measurements. A tip for the injection tube contained four 1/64-inch holes drilled to provide a spreading effect of the injected tracer, Figure 7 (Detail 6C). The tip was pointed upstream to increase the interference of the jets and the penstock flow. Pressures of 735, 535, 465, 365, 265, 185, and 70 psi above the 215-psi penstock pressure were used in the set of seven measurements.

Discharge values computed for the center sample differed from flowmeter indications by about -6 percent to a +9.5 percent, Figure 20 and Table 4. The variations between flowmeter and radioisotope methods were irregular, being as close as 2 percent for three measurements. These variations were interpreted to reflect inadequate mixing in the short length between injection and sample.

Discharge values computed for the side sample differed from the flowmeter by a minimum of -20 percent to a maximum of -30 percent. Thus even poorer mixing was indicated at the point of sampling near the wall.

A study of the data for the seven discharges computed for the center samples showed the injection pressure did not significantly effect the mixing. The highest pressure of 735 psi produced the highest pereentage of mixing, 92 percent. The remainder of the measurements indicated mixing percentages ranging from 86 to 81 percent. The

Table 4

Flatiron Turbine Radioisotope and Spiral Case Flowmeter Discharge Measurements (Mixing length 46.5 diameters)

Month and day, 1967	Measurement No.	Manometer differential, inches	Flowmeter discharge, cfs	Net injection pressure, psi	Center sample: Radioisotope discharge, cfs	Center sample: ΔQ, cfs	Center sample: Deviation, percent	Side sample: Radioisotope discharge, cfs	Side sample: ΔQ, cfs	Side sample: Deviation, percent	Percent mixing
Dec 6	24	0.48	129	735	121.31	-7.68	-5.96	102.76	-26.23	-20.34	92
	25	0.47	127.5	535	129.95	+2.45	+1.92	94.77	-32.72	-25.67	84
Dec 7	26	0.47	127.5	465	134.80	+7.30	+5.73	91.44	-36.05	-28.28	82
	27	0.47	127.5	365	125.22	-2.27	-1.79	95.07	-32.42	-25.43	86
	28	0.46	126.5	265	134.65	+8.15	+6.45	91.64	-34.85	-27.56	81
	29	0.47	127.5	185	131.43	+3.93	+3.09	89.69	-37.80	-29.65	81
	30	0.47	127.5	70	132.77	+5.27	+4.14	93.07	-34.42	-27.00	82
Dec 8	31	0.47	127.5	685	129.48	+1.98	+1.55	109.52	-17.97	-14.10	92
	32	0.46	126	610	134.22	+8.22	+6.52	95.74	-30.25	-24.01	83
	33	0.46	126	475	136.51	+10.51	+8.34	90.23	-35.76	-28.38	80
	34	0.46	126	350	137.93	+11.93	+9.48	93.19	-32.80	-26.03	81
	35	0.46	126	175	130.29	+4.29	+3.41	90.75	-35.24	-27.97	79

Water temperature 42° F

size of the four jets of tracer appeared to be too small to produce a substantial effect on the penstock flow for a mixing length of 46.5 diameters.

An additional five measurements to study mixing were made on December 8. A fan-shaped array of five, 1/64-inch holes on the tip perimeter were used to inject the tracer at right angles to the penstock flow, Figure 7 (Detail 6D). Pressures of 685, 610, 475, 350, and 175 psi were used for the injections.

Discharge values computed from the center sample ranged from a +2 percent to a +10 percent, compared to the flowmeter. The side sample varied from a -14 percent to a -28 percent, Figure 20 and Table 4. The center sample showed increased differences to about 10 percent through Measurement 34. Measurement 35 at the lowest injection pressure of 175 psi decreased to a 3-percent difference. Samples from the side of the penstock deviated negatively with decreased pressure with the best mixing of 92 percent indicated for the highest pressure of 685 psi, Measurement 31. Study of the data for these five measurements using the fan-shaped array of holes for injection did not show a definite effect on the mixing.

The discharges computed from both the injection probe tips showed the highest percentage of mixing for the highest pressure. The percent mixing decreased as the pressure was decreased. A possible cause for this relationship would be the presence of the injection tube in the cross section. For higher injection pressures the tracer may be forced out from the tip into the pipe flow. For low injection pressures the tracer may have flowed into the turbulent wake on the downstream side of the tube between the center and side of the penstock. The higher concentration in the wake of the tube may change the injection from a point to a nonuniform line source. The assymetrical and higher concentration flowing downstream to a sampler in the same cross sectional position as the injector could produce the indicated low discharges in Table 4 for the side sampler and near average discharges for the center sampler. Nonuniform distributions caused by injection tubes have been noted in previous studies.1/2/ Tracer premixed with larger volumes of water and injected under high pressure into the penstock could probably produce better mixing in shorter penstock lengths.8/

Included in the December 6 to 8 measurement series were samples of tracered water taken from the piezometer manifold at the turbine inlet, Figure 12A. A mixing length of 645 diameters of pipe was available between the injection and sampling points. The results of these measurements computed by the total count method were in better agreement with the spiral case flowmeter, Table 5 and Figures 20 and 21. Four of the 12 measurements between December 6 and December 8 were within ±1 percent of the flowmeter indicated discharge. Four were within ±2 percent, two within ±3 percent, and two within ±4 percent.

Table 5

Flatiron Turbine Radioisotope and Spiral Case
Flowmeter Discharge Measurements
(Mixing length 645 diameters)

Measurement	Spiral case flowmeter	Radioisotope (turbine inlet)	Deviation, percent
December 6			
24	127.9	127.8	-0.05
25	127.9	125.5	-1.83
December 7			
26	[illegible]	128.8	+0.70
27	127.9	129.3	+1.11
28	126.9	130.6	+2.91
29	127.9	127.4	-0.38
30	127.9	126.2	-1.38
December 8			
31	126.5	132.6	+4.80
32	126.5	128.0	+1.16
33	126.5	127.6	+0.86
34	126.5	131.1	+3.65
35	126.5	130.1	+2.86

Measurements from the flowmeter indicated a relatively steady flow through the turbine. As previously described, the flowmeter differential could be read to about 1/100 inch of mercury or to about 1.5 cfs (1.2 percent of indicated flow). An analysis of the mercury differential readings were made subsequent to this measurement series. The manometer differential was read at 15 second intervals to accumulate 66 to 77 samples for each of 9 discharge measurements. For this population, the standard deviation was 0.036 inch of mercury for an average differential of 2.62 inches. An individual reading would be accurate to ±1/100 inch of mercury about 24 percent of the time, ±2/100 inch about 43 percent, ±3/100 about 57 percent, and ±4/100 about 70 percent of the time. Thus, the discharge could be expected to be within ±1.2 percent, ±2.4 percent, ±3.6 percent, and ±4.8 percent of the calibrated flow 24 percent, 43 percent, 57 percent, and 70 percent of the time, respectively.

The discharge indicated by a differential of about 0.45 inch of mercury in the measurements falls at the low end of the discharge scale. The pressures producing the flowmeter differential may be affected by the flow conditions in the turbine at small discharges. Thus, the accuracy of the flowmeter was difficult to evaluate.

Sample tank calibrations for the 3-day period showed differences in the value of F ranging from 377.37 counts per second to 381.18 cps (about 1 percent). Because of the penstock pressure (about 1,100 feet of water) the flow through the sample tank was considered to be sufficiently steady to produce a satisfactory passage of the tracer sample past the counter.

This series of 12 measurements, using samples from a mixing length (645 D) about six times the suggested minimum length for natural turbulence, showed larger than expected variations and indicated a reappraisal of equipment and procedures were necessary.

The evaluation and modification of procedures and equipment were made before and during a second measurement series performed on a pump-turbine unit of the powerplant. The pump-turbine unit was operated as a pump to test mixing length theory and to evaluate changes in the procedures.

DISCHARGE MEASUREMENTS - PUMP-TURBINE UNIT 3

Preparations for Measurements

Sources of Error

A first step in the appraisal of procedures was a second study of the possible sources of error in the handling and counting of the radioactivity. This study was an extension of the analysis used for the turbine measurements, and published in Reference 1, in the section written by the Bureau of Reclamation.

The results of the second analysis, Appendix 3, showed that the total percentage error to be expected in the discharge measurement Q could be as large as 1.73 percent. The probable error was computed to be in the order of 0.97 percent. Procedure changes in handling the sample tank calibration activity based on the analysis were made in the radioisotope handling and counting techniques during the pump discharge measurements. The procedures for reading the spiral case flowmeter manometer were also modified to increase the number of readings and better define the discharge.

Pump Preparations

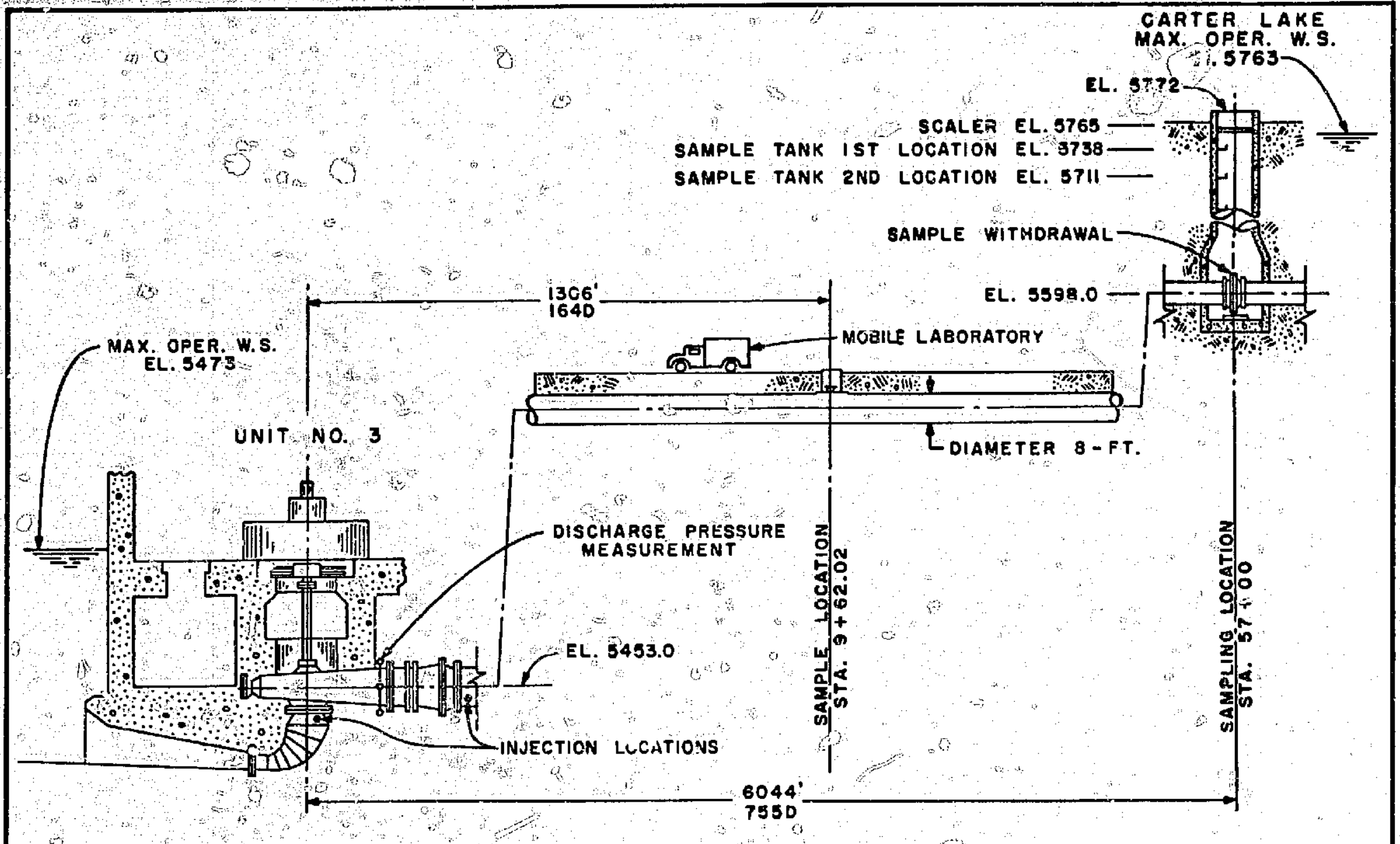
The pump-turbine unit of the Flatiron Power and Pumping Plant was an acceptable installation to experimentally apply the radioisotope method of discharge measurement, Figure 4. The capacity of the unit is about 370 cfs and the water is pumped from the Flatiron afterbay to Carter Lake through an 8-foot-diameter pipeline, Figure 22. The discharge pressure was about 270 feet of water (116 psi). An acceptance test of the unit was performed in 1954 and the spiral case flowmeter was calibrated by the salt-velocity method. The inspection and preparation of the flow surfaces adjacent to the piezometers, immediately before the measurements, assured that the flowmeter calibration curve could be used with confidence for comparison to the radioisotope discharge measurements.9/

Tracer injections were made both upstream and downstream from the pump to determine if the pump caused a measureable increase in the tracer-water mixing. One of the injection locations was in the inlet elbow immediately below the pump runner and the other in a piezometer ring downstream from the pump and butterfly valve, Figures 22, 23, and 24. Pipe fittings and access to the flowing water were available at these two points and it was believed that adequate mixing could be obtained for the tracer and water.

The tracer was injected by the pulse system through a 1/4-inch OD tube containing a plug and 1/64-inch drilled hole, Figure 23C. The 1/64-inch hole was used to increase the injection time and prevent saturation of the counting system. A 1/4-inch standard pipe in the inlet elbow was adapted to the injection tube by a stuffing box. The tube projected 6 inches into the elbow, about 0.2 of the 30-inch radius of the elbow at the injection cross section. The pressure in this section of the elbow was about 5-psi gage.

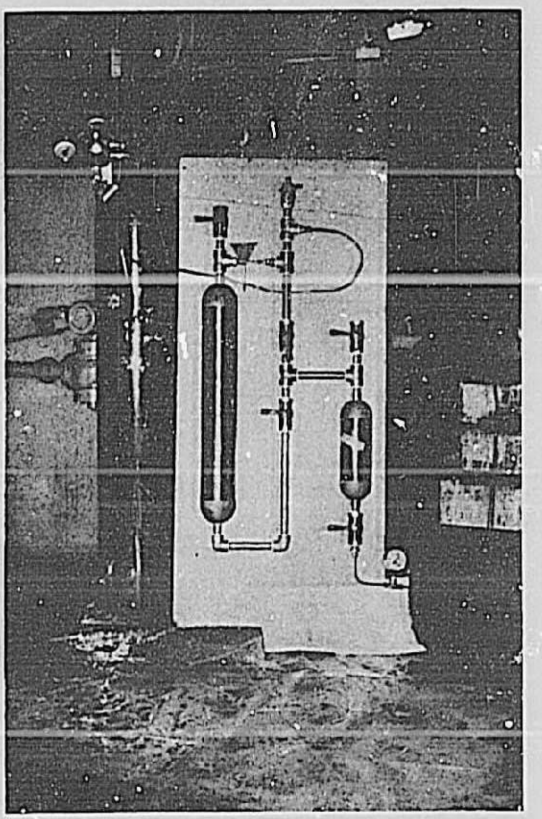
Injections into the pipeline downstream from the pump and valve were made through a 1/4-inch piezometer plug. The plug contained a short pipe nipple and 3/4-inch gate valve on the outside of the pipeline. A stuffing box was made for the 3/4-inch valve and the 1/4-inch injection tube was inserted through the valve and plug into the pipe flow, Figure 24B. An 8-inch length of tube protruded into

Figure 22

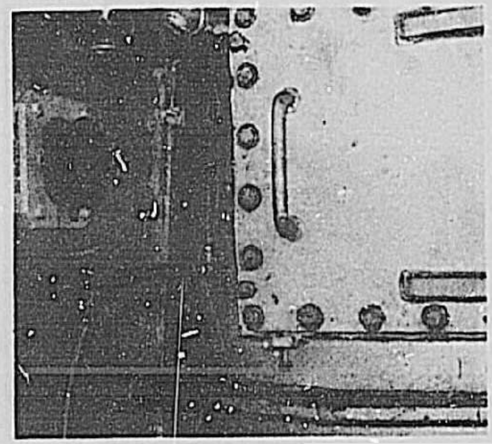


GENERAL ARRANGEMENT OF PIPELINE AND PUMP-TURBINE UNIT NO. 3
FLATIRON POWER AND PUMPING PLANT
RADIOISOTOPE DISCHARGE MEASUREMENTS HIGH HEAD TURBINES AND PUMPS

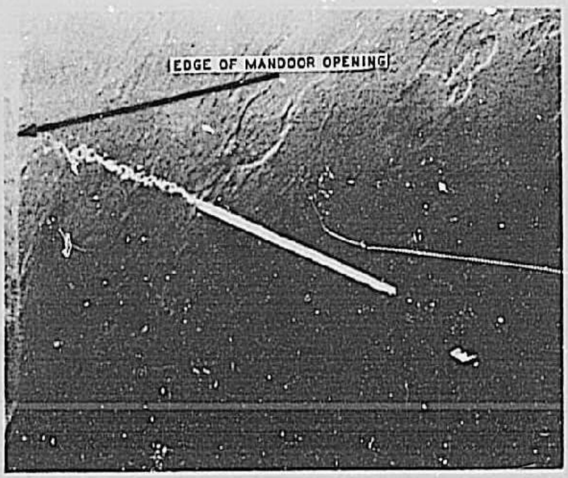
Figure 23



A. Radioisotope system for pulse injection in inlet elbow of pump-turbine. (valves in position for injection) Inlet elbow in right background. Photo P245-D-60437



B. External stuffing box and gate valve for injection tube at inlet elbow. Photo 245-D-60435NA

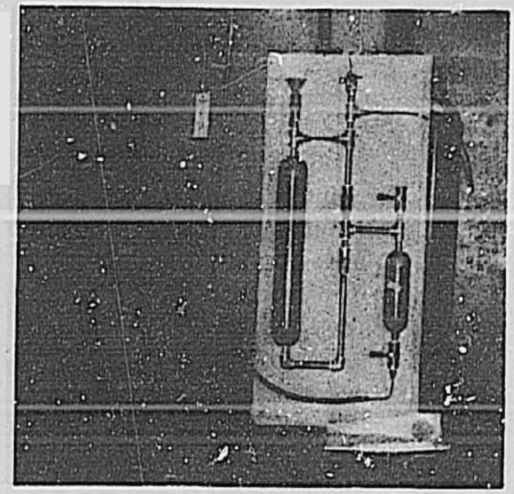


C. Six-inch protrusion of 1/4-inch OD by 1/64-inch ID injection tube into inlet elbow of pump. Photo P245-D-60434

PULSE INJECTION SYSTEM AND INJECTION TUBE
AT PUMP INLET ELBOW

RADIOISOTOPE DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

Figure 24



A. Radioisotope system for pulse injection into pump discharge line, tubing from small cylinder leads to discharge line. Photo P245-D-60436

B. Stuffing box and gate valve attached to 1/4-inch piezometer plug, 1/4-inch OD by 1/64-inch ID. Injection tubes passes through 1/4 orifice of plug, 8 inches into pump discharge line. Photo P245-D-60439NA

PULSE INJECTION SYSTEM AND INJECTION TUBE FOR PUMP DISCHARGE PIPE

RADIOISOTOPE DISCHARGE MEASUREMENTS HIGH-HEAD TURBINES AND PUMPS the flow, a distance of about 0.21 of the pipe radius of 38 inches. The pipe pressure at this cross section was 270 feet of water (116 psi). Consideration was given to an injection through three available piezometers but time, equipment, and the plant structure did not allow the installation of more than one injection tube.

A mixing length of 164 diameters of the 8-foot pipe was used between the pump and first sampling location in the pipeline, Figure 22. A 20-inch manway installed for the pump-turbine acceptance tests by the salt-velocity method was available for installation of the radioisotope sampling system, Figures 25A and B. A manway cover used for the turbine flow measurements was modified and installed on the pumpline. No changes were made on the center sampling tube, Figure 7 (Detail 9), but the side sampler was extended to 19-5/16 inches to pass through the 16-inch nozzle length of the pipeline manway. The extension projected into the flow about 3.3 inches and allowed a sample to be taken at a distance from the wall of about 0.07 of the 48-inch pipe radius. The tube through the center of the manway sampled the flow at a point 0.56 of the pipe radius from the wall. The length of penetration into the flow of 26.9 inches was the maximum obtainable with the sampler designed to reach the center of the 6-foot penstock. The two points of sampling, 0.07R and 0.56R, were believed to be satisfactory to evaluate the relative quality of mixing and whether mixing was assisted by the pump for injections in the inlet elbow.

The mobile nuclear laboratory truck was driven close to the manway outlet of the pipe, Figure 25A. The sample tanks were connected to hoses from the sample tube and separated to prevent radioactive interference between the counters. On-site calibrations of the tanks and counting systems were made two or three times daily to minimize this source of error, Figure 25C.

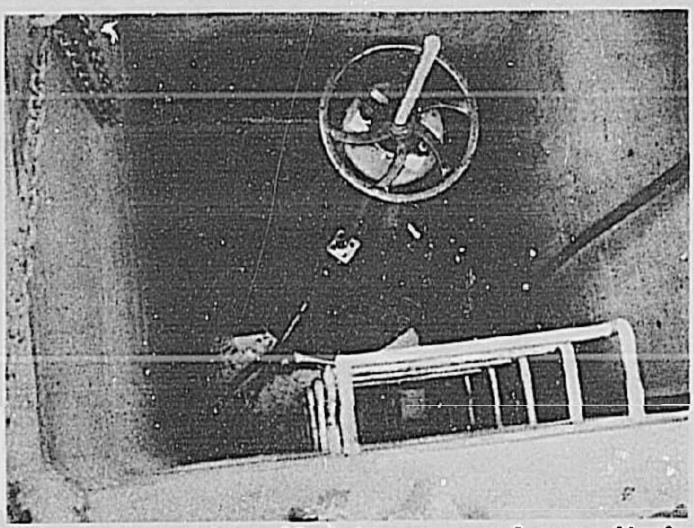
A second sampling station using a decade scaler was placed in a valve shaft, 6,044 feet (755 diameters) from the pump, Figures 22 and 26. A sample of the mixture of tracer and pipe flow was taken from an existing 1/4-inch standard pipe threaded into the wall of the butterfly valve at the base of the shaft. A heavy-duty garden hose was connected between the sample point in the valve and the sample tank. Landings at two elevations of the vertical ladders leading to the bottom of the shaft were used to support the sample tank. For one set of measurements the tank was 136 feet above the valve or about 25 feet below the water surface elevation in Carter Lake. A pump was used to provide the desired flow of about 20 gpm through the tank, Figure 26B.

The location of the sample tank near the top of the shaft was selected because of the available length of cable on the counter and to reduce the amount of climbing necessary during the calibration of the sample tanks.

Figure 25

Arrows mark sample tank locations

A. Mobile nuclear laboratory near manway used for sampling tracer-water mixture. Photo P245-D-60442



B. Sampling equipment installed in manway of pump discharge line. Photo P245-D-60440NA

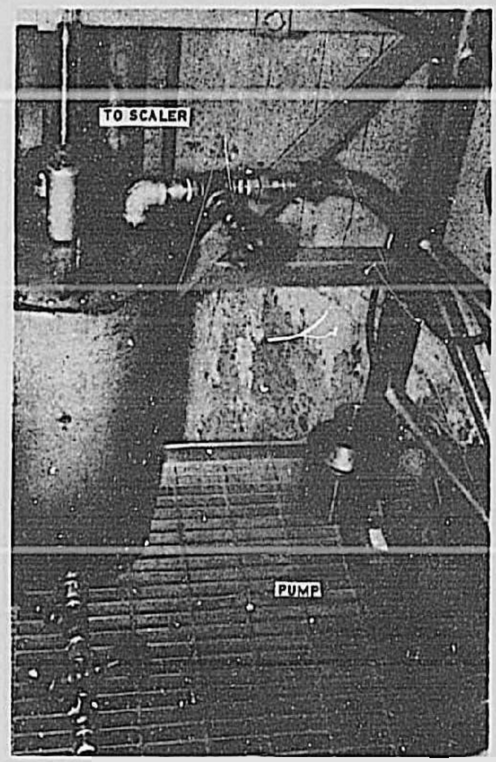
C. Pipeting calibration solution into sample tank. Photo P245-D-60443

D. Using electric mixer for stirring tracer and water. Photo P245-D-60441NA

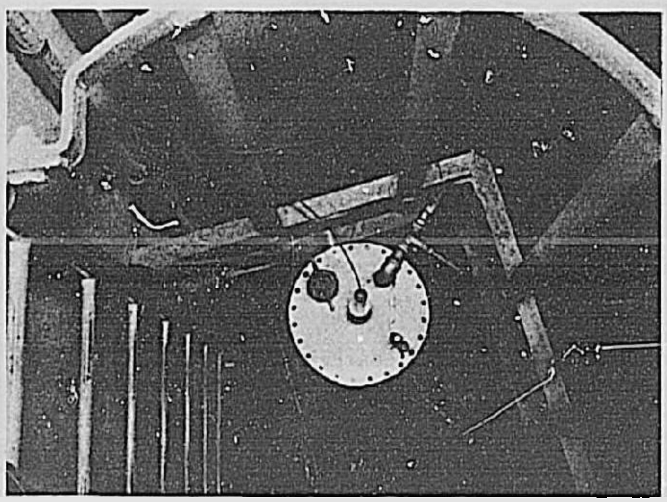
SAMPLING LOCATION 164 PIPE DIAMETER FROM PUMP

Figure 26

A. Decade scaler on operating deck elevation 5765, Carter Lake valve shaft. Photo P245-D-60428NA



B. Sample tank with pumped flow - Tank at elevation 5738, 136 feet above sampling point in body of butterfly valve.
Photo P245-D-60430NA



C. Sample tank with gravity flow - Tank at elevation 5711, 110 feet above sampling point. Carter Lake Reservoir, elevation ranged between 5740 and 5743 feet above sea level. Photo P245-D-60429NA

SAMPLING SYSTEM IN CARTER LAKE VALVE SHAFT

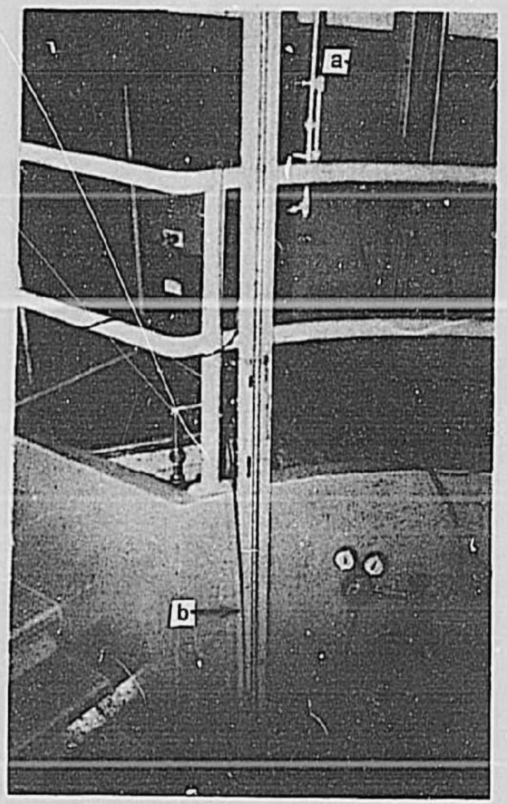
RADIOISOTOPES DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

The tank was relocated on a landing 110 feet above the valve for a second set of measurements. A head of about 52 feet between the lake and landing elevations provided gravity flow through the tank for these measurements, Figure 26C. The elevation of the tank in the shaft was changed to determine whether a higher than expected count rate was produced by tracer flow through the pump located close to the tank, Figure 26B.

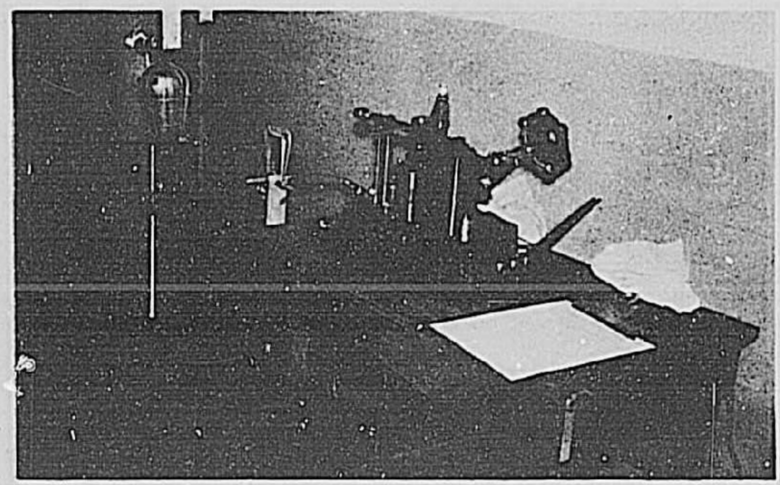
The spiral case flowmeter of the pump was equipped with two manometers. The mercury U-tube used during the measurements of flow through the penstock was transferred to the pump, Figure 27A. An inverted-type water U-tube was also connected to the flow taps to attempt to increase the accuracy of reading the differential. Nitrogen gas pressure was used to force the water columns down into the 9-foot manometer, Figure 27A. For the flows being measured, the flowmeter produced a differential of about 5 inches of mercury or about 5 feet of water. By using capillary dampers, the water columns could be read to about 0.005 foot and the mercury was read to 0.01 inch.

A fluid pressure scale, a beam balance designed to weigh fluid pressure, was connected to the outlet piezometers of the pump, Figures 22 and 27B. The pressure measurements in conjunction with the flowmeter measurements were used to show the steadiness of flow through the pump and to assist in the data analysis.

Figure 27



A. Spiral case flowmeter manometers,
(a) mercury U-tube, (b) inverted-type water U-tube pressured by nitrogen gas. Photo P245-D-60433



B. Fluid pressure scale for weighing in pounds per square inch the pump discharge pressure. Photo P245-D-60432NA

FLOWMETER AND PRESSURE MEASURING EQUIPMENT
UNIT NO. 3 PUMP-TURBINE

RADIOISOTOPES DISCHARGE MEASUREMENTS
HIGH-HEAD TURBINES AND PUMPS

A third check on the operation was the measurement of power input (megawatts) to the pump motor. The power was measured by both the station watt-hour meter and rotating standard watt-hour meters. The time between readings of the meters and the total time of the readings were adjusted to correspond to the time of tracer passage through the pipeline from injection station to sampling stations. The power measurements were not used in the analysis except as an indicator that the motor input was steady throughout the measurement.

Radioisotope Preparations

The radioisotope solutions were prepared and measured as described before in the section on Tracer Handling Procedures for the turbine flow measurements. One important exception was made in the procedure for preparing the calibration solution C_c.

A gravimetric instead of volumetric method was used in measuring the quantity. To better measure the amount of tracer used for the calibration tank, each amount was proportioned by weight on a precision analytical balance in the laboratory. The weighing procedure minimized the effects on the volume measurements caused by temperature changes from laboratory to the field site, from 70° F to below freezing on some days. On the days when cold conditions were encountered, there was suspicion that freezing was causing a separation of the radioactive material from the water used for dilution.

The parts of the tracer solution to be injected for the discharge measurement were not subjected to freezing. These solutions were transferred from the laboratory, to the automobile, and from the automobile to the interior of the powerplant.

Results of Discharge Measurements - Pump

Spiral Case Flowmeter

The water and mercury manometers of the spiral case flowmeter were read at 2-minute intervals while the tracer was traveling in the pipeline between the injection and sampling points. Reading of the manometers started about 10 minutes before injection and continued for about 10 minutes after the tracer passed the sampling point in Carter Lake valve shaft.

Good agreement of discharges was obtained between the water and mercury manometers by using the measured differentials and the calibration published in the report on efficiency tests.9/ Because the calibration had been made with the mercury manometer and no greater accuracy was obtained with the water manometer, discharges for comparison to the radioisotope method were computed from the mercury manometer calibration, Table 6 and Figure 28.

Radioisotope Discharge Measurements

Injections of radioactive tracer were made downstream from the pump and butterfly valve for the first two discharge measurements on

Table 6

Flatiron Pump-Turbine
Radioisotope and Spiral Case Flowmeter
Discharge Measurements (164 diameters)

February 1968	Measurement No.	Differential manometer, inches	Flowmeter discharge, cfs	0.57R Sample: Isotope discharge, cfs	0.57R Sample: ΔQ, cfs	0.57R Sample: Deviation, percent	0.07R Sample: Isotope discharge, cfs	0.07R Sample: ΔQ, cfs	0.07R Sample: Deviation, percent	Percent mixing
14	1	4.72	286	267.57	-18.42	-6.44	271.98	-14.02	-4.90	99.2
	2	4.66	283	267.52	-15.47	-5.47	269.25	-13.75	-4.86	99.7
15	3	4.75	287	276.03	-10.96	-3.82	277.67	-9.33	-3.25	99.7
	4	4.83	290	274.17	-15.83	-5.46	272.40	-17.60	-6.07	99.7
16	5	4.89	292.5	279.45	-13.05	-4.46	276.15	-16.35	-5.59	99.4
	6	4.82	290	274.09	-15.91	-5.49	273.42	-16.58	-5.72	99.9
21	7	4.83	290	298.84	+8.84	+3.05	306.70	+16.70	+5.76	98.7
	8	4.72	286	283.50	-2.50	-0.87	282.74	-3.26	-1.14	99.9
	9	4.73	286.5	291.57	+5.07	+1.77	293.90	+7.40	+2.58	99.6
23	11	4.76	287.5	293.81	+6.31	+2.19	294.78	+7.28	+2.53	99.8
	12	4.69	285	287.49	+2.49	+0.87	287.17	+2.17	+0.76	99.9

Water Temperature 39° F

solution with the water in the sampling tank and measuring the net change in counting rate of the system. The factor can be calculated from the expression:

$$F = \frac{K\ V}{Tn\ v_i\ C_c} \tag{5}$$

where:

V is the sample tank volume

K is the total net count during calibration

T is the time of counting

v_i is the volume of the pipet used for transferring the calibration solution to the tank

n is the number of pipet volumes of solution used

We can then show that the fractional error for F is:

$$\frac{dF}{F} = \frac{dK}{K} + \frac{dT}{T} + \frac{dV}{V} + \frac{dv_i}{v_i} + \frac{dC_c}{C_c} \tag{6}$$

Where the last term is that derived in the preceding section (equation 4).

Flow Measurement

The flow measurement equation is:

$$Q = \frac{FA}{N} \tag{7}$$

where N is the total net count during the discharge measurement

A is v_2C_1 and

v_2 is the volume of stock solution C_1 injected into the flow and is measured by overflow buret.

The fractional error for the flow is:

$$\frac{dQ}{Q} = \frac{dF}{F} + \frac{dv_2}{v_2} + \frac{dN}{N} . \tag{8}$$

Let the operator δ operating on any variable x be the percentage error associated with the variable x. Then substituting equations (4) and (6) into (8), we have

$$\delta Q = \delta K + \delta T + \delta V + \delta v_1 + \delta V_c + \delta v_2 + \delta N + \delta v \tag{9}$$

where δQ is the total percentage error which can occur in the flow Q, assuming that no other factors are involved.

Computation No. 1

The error contributions break down into three categories: counting errors (two terms), timing errors (one term), and volume errors (five terms).

Assume that the counting error is derived from the expected standard deviation of the count (Error = $1/\sqrt{N}$). The worst counting conditions occurring in the field test series were encountered using probe D.O.-5.*. The counts obtained were:

$$N \approx 50{,}000$$
and
$$K \approx 100{,}000$$

Therefore, the errors are:

$$\delta N = \pm 0.45\%$$
and
$$\delta K = \pm 0.32\%$$

The scaler used in the mobile laboratory derives its timebase from the frequency of the a-c power supply. The frequency of the motor-generator on the truck is known to vary. At Flatiron Powerplant, a digital frequency meter was used to monitor the line frequency during calibration and the apparent counting time was corrected.

The mean line frequency of approximately 60 hz was measured to within ±0.2 hz, the limitation of the frequency counter. Thus,

$$\delta T = \frac{0.2\ \text{hz}}{60\ \text{hz}}\ 100 = \pm 0.33\%$$

Of the five volume errors, two of them involve the transfer of solution by the use of an overflow pipet and one by overflow buret. When the glassware has been properly cleaned and dried prior to use, the repeatability of measuring equal volumes as

*USBR detector designation.

established by weighing is ±0.05% of the mean. When the glassware has been improperly cleaned and dried, this error doubles. Thus assume the worst case for each of these transfers to be:

$$\delta v = \delta v_1 = \delta v_2 = \pm 0.1\%$$

The fourth volume measurement involves the use of a volumetric flask to make up the calibration solution. The assumed error here is:

$$\delta V_c = \pm 0.05\%$$

The last volume measurement is that of the sampling tank and is determined by weighing.

$$\delta V = \pm 0.1\%$$

Then the possible total error for a single measurement under the above conditions is:

$$\delta Q = \pm 1.55\%$$

By definition, the probable error (in percent) of some factor y, where y - f(x_i) is:

$$\delta_{pe}(y) = \left[\sum (x_i)^2 \right]^{1/2} \qquad (10)$$

Therefore, the probable error for the above conditions is:

$$\delta_{pe}(Q) = \pm 0.67\%$$

Computation No. 2

An improved technique of calibrating the sample tank was developed and used during the last week of testing on the No. 3 unit at Flatiron. A control setting on the scaler was found whereby the preset time gate could be overridden allowing a longer time interval for counting. The time was measured by a stopwatch and the scaler was stopped manually.

Under these conditions, for the DO-5 system,

$$K \simeq 500{,}000$$

and

$$T \simeq 1{,}000 \text{ sec}$$

and, the errors in these parameters are approximately

$$\delta K = \pm 0.14\%$$

and

$$\delta T = \pm 0.1\%$$

Then, for these conditions

$$\delta Q = \pm 1.14\%$$

and

$$\delta p_e(Q) = \pm 0.52\%$$

Computation No. 3

The above computations are based upon assumed largest errors. Following are the best results that can be expected for the same counting system. First,

$$\delta v = \delta v_1 = \delta v_2 = \delta V_c = \pm 0.05\%$$

while $\delta V = \pm 0.1\%$

If, $K \simeq 500{,}000$

and $N \simeq 50{,}000$,

then $\delta K \simeq \pm 0.14\%$

$\delta N \simeq \pm 0.45\%$

and $\delta T = \pm 0.1\%$

Therefore, the respective errors for Q are:

$$\delta Q = \pm 0.99\%$$

and

$$\delta p_e(Q) = \pm 0.50\%$$

Counter Stability

In the preceding discussions, the counting errors were assumed to be due only to the normal statistical process of counting nuclear events. This assumption presupposes that there are allowed no errors for high-voltage drift, discriminator shifts, noise, etc. Presume now that these effects are presented to an extent which will increase the experimental standard deviation to a value twice that of the expected standard deviation which is:

$$\delta N = \pm 0.9\%$$

and

$$\delta K = \pm 0.28\%$$

This standard deviation has been observed for the counting equipment in the Denver Office mobile laboratory. Using the largest errors described in Computation No. 2 of

$$\delta v = \delta v_i = \delta V = \delta T = \pm 0.1\%$$

and

$$\delta V_c = 0.05$$

the resultant errors are

$$\delta Q = \pm 1.73\%$$

and

$$\delta p_e(Q) = 0.97\%$$

These errors are still less than some of the differences between flowmeter and radioisotope discharges computed in the experimental series at Flatiron Powerplant. Therefore, a more fundamental analysis of the problem is yet needed to explain the results obtained and to suggest methods of improving the technique.