Turbine Discharge Metering at the Safe Harbor Hydroelectric Development

By J. M. MOUSSON,[1] BALTIMORE, MD.

This paper discusses the suitability, calibration, and reliability of certain piezometer systems installed in low-head units of high capacity. An account is also given of a research to determine and develop a suitable type of flow-meter to be operated by the differential pressure from these piezometer systems for continuous integration, indication, and graphic recording of unit and plant discharges. The type of equipment installed is presented in detail, as well as its adaptation as an automatic guide to operation, resulting in appreciable benefits through higher operating efficiencies.

Introduction

Although continuous automatic accounting of unit discharge is not new, several recent improvements and developments have entirely changed the aspect of desirability for apparatus of this kind, as many of the shortcomings of earlier installations, limiting their usefulness, have been successfully overcome.

While, in some plants, automatic water accounting has been carried out for years, the necessary equipment has often been regarded as a luxury, particularly, as its sole purpose was usually confined to collecting runoff data at the project site to augment records of existing gaging stations or, perhaps, replace those of stations rendered inoperative in a project area due to construction of a particular plant. Since the accuracy of river gaging is essentially not very high, and decidedly lower than that required for turbine-discharge measurements for acceptance tests, it has been standard practice to keep unit- and powerhouse-draft records by means of computations based on power output. At the same time, however, it has been generally recognized that the installation of input-measuring apparatus would be highly desirable, if and when unit-discharge and station-totalizing equipment of sufficient accuracy and within economical reach were available to serve as a yardstick for plant operation, both as to proper and efficient loading of the units and to detect troubles affecting their efficiencies.

To illustrate the difficulty of the solution to this problem, it may be mentioned that, while equipment of this kind was contemplated at Safe Harbor at the outset of construction in 1930, as at that time already certain provisions had to be incorporated in the substructure, on the generator-room floor, in the conduit system, and in the control room, nevertheless, the various investigations and development work required a substantial amount of time and it was not until late in 1938 that suitable equipment was finally installed.

1—INVESTIGATIONS PURSUED

The various investigations carried out dealt not only with the exploration of the principle to be employed, but also with the possible consistency, sensitivity, and suitability of various apparatus. In the first place, it had to be established that the index method, based on differential piezometer deflection, is of sufficient accuracy as a basis of continuous water measurements.

Piezometer Installation

In each of the substructures of the six main units comprising the initial development, there were installed three piezometers of the Winter-Kennedy type[2] in the turbine scroll and two piezometers of the Peck type[3] on one of the stay vanes of the speed ring, Fig. 1. While one of the Winter-Kennedy taps was placed in the high-pressure low-velocity region, the two other taps were located radially opposite thereto at the speed ring in the low-pressure high-velocity region, one just above the speed ring and the other tapped in the crown of the speed ring.

The Peck piezometer locations are shown in Fig. 2, the impact tap in the nose and the low-pressure tap in the flank of the stay vane. In the first four main units to be installed, the Peck impact tap was located at the nose tip. On the fifth main unit it was placed at a slight angle to the longitudinal axis of the stay vane, $^3/_4$ in. from the nose tip, and on the sixth unit to be installed at a still larger angle, that is, 45 deg and $2^1/_{16}$ in. from the stay-vane tip. At the same time, some shift in upstream direction of the Peck low-pressure tap was also made on the latter two units.

In addition, two auxiliary piezometer openings were located at

[2] "Improved Type of Flow Meter," by I. A. Winter, Proc. American Society of Civil Engineers, vol. 59, part 1, 1933, pp. 565–584.

[3] "Two Methods of Measuring Water to Hydraulic Turbines," *Power*, vol. 77, March, 1933, pp. 126–127.

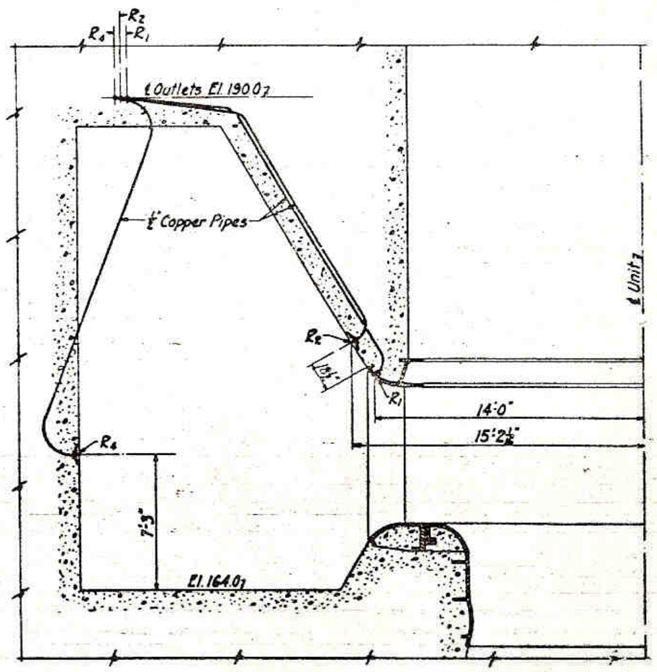

Fig. 1 Winter-Kennedy Piezometer-System Installation at Main Units
(Taps R_1, R_2, and R_4.)

[1] Hydraulic Engineer, Safe Harbor Power Corporation. Mem. A.S.M.E.

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the downstream nose of one of the intake piers of each main unit for possible use should pumping with the units ever be resorted to for peak storage requirements during low flow. Both service units were provided with two piezometers of the Winter-Kennedy type. To prevent air pockets, all piping leading to the individual piezometer openings was placed with a continuous slope and copper piping was used to prevent corrosion. In the pipe tunnel beneath the generator-room floor, a piezometer board with vertical glass tubes was installed at each unit where the deflections could be measured in feet of water.

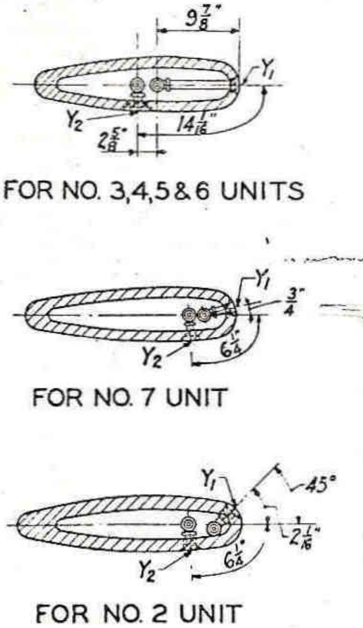

FIG. 2 LOCATION OF PECK PIEZOMETERS ON MAIN-UNIT SPEED-RING STAY VANES
(Taps Y_1 and Y_2.)

After placing each unit in service, it was essential, as a first step, to determine which combination of two piezometers would prove most consistent. This was done by plotting the differential pressure of any two taps against that of any one of the other possible pairs. From Fig. 3, it may be noted that the three Winter-Kennedy taps and the Peck impact tap showed a markedly better consistency than the Peck low-pressure tap Y_2, the latter being responsible for the erratic behavior in three of the plots. On the other five main units, the results were similar with the exception that even the Peck impact tap, located closer to the nose or at the very nose tip of the stay vane, was considerably less steady. For all main units, the Winter-Kennedy taps showed a high degree of consistency.

This result should not be interpreted as a general weakness of the Peck type of system. Investigating the origin of this erratic behavior, that is, through analysis of the results with the various Peck tap locations, as shown in Fig. 2, it was found that the cause for instability, particularly of the low-pressure tap, was rather in the design of the stay vanes than in the type of piezometer system. The Safe Harbor stay vanes are comparatively short and have a straight longitudinal axis. Since, on the one hand, the low-pressure tap was erratic in all units, irrespective of the shift upstream, and, on the other hand, the consistency and magnitude of deflection of the impact tap increased decidedly by the shift away from the nose tip, it could be concluded that the stay vanes of the speed ring were not pointed head on into the flow but at a considerable angle, causing a region of local disturbance on one side of the stay vanes, with the unstable region extending almost to the very tip of the vane. In the light of these results and, in view of the experience obtained elsewhere with piezometers of the Peck type, it would appear that a considerable improvement in stay-vane design is yet to be accomplished by lengthening, better streamlining, and curving these vanes. It is noteworthy

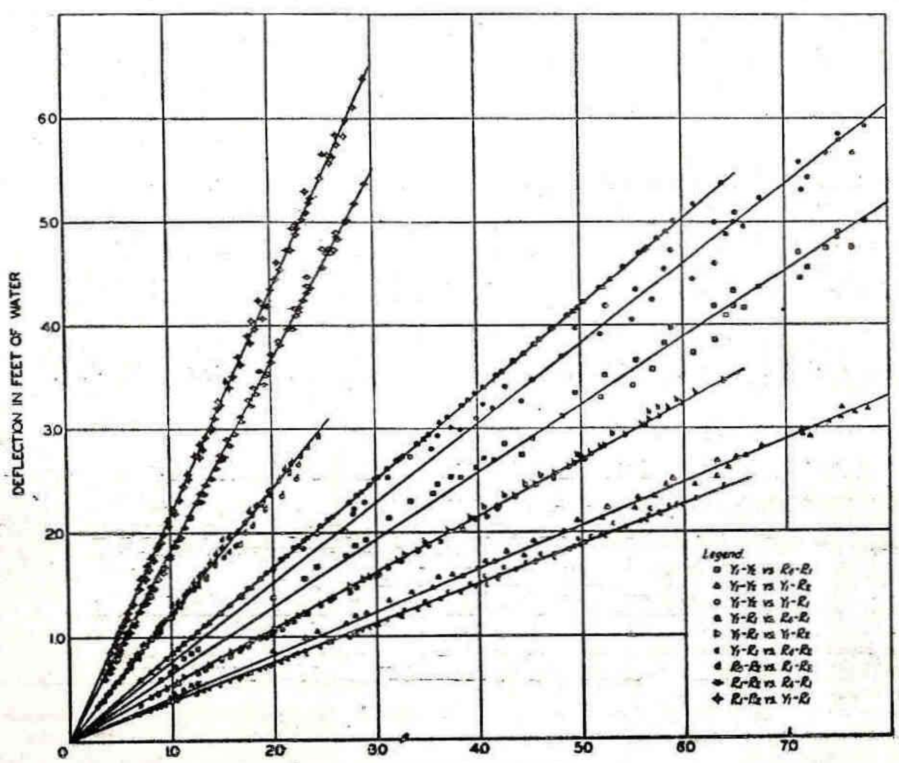

FIG. 3 ANALYSIS OF PIEZOMETER DEFLECTIONS OBTAINED AT NO. 2 UNIT

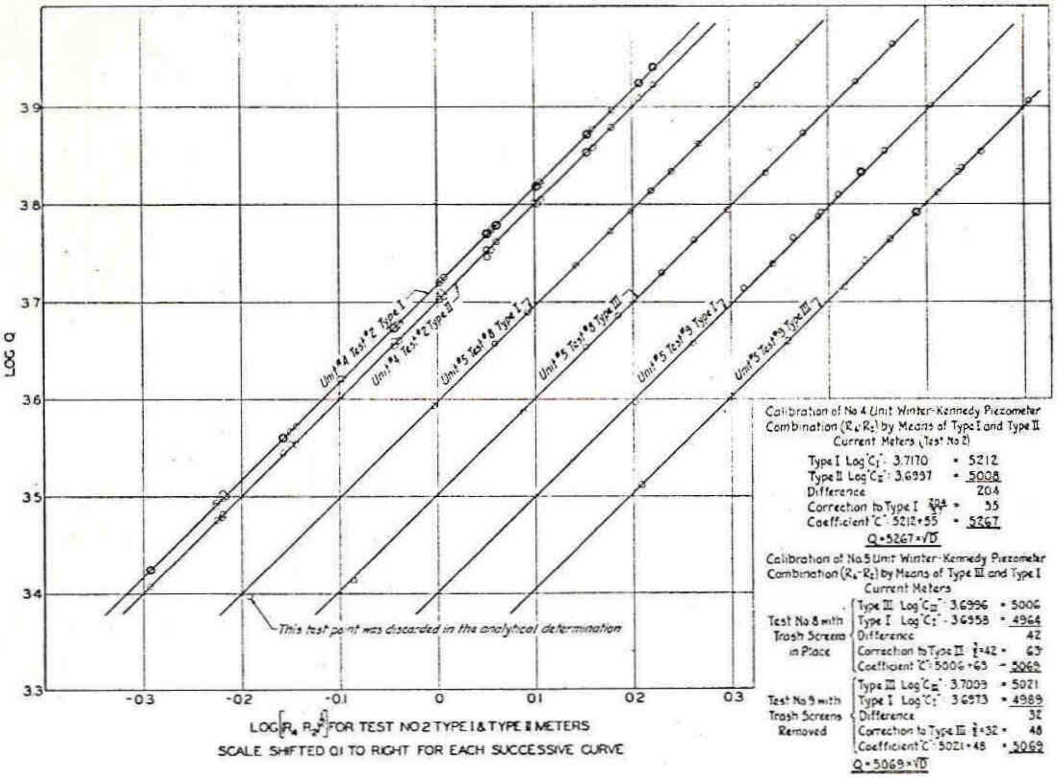

FIG. 4 CALIBRATION OF PIEZOMETER PAIR (R_4-R_2) AT NOS. 4 AND 5 UNITS BY MEANS OF TWO-TYPE CURRENT-METER METHOD

that, in more recent installations, some improvements in this direction already have been made.

While the piezometers were used initially simply as a relative index to determine the proper relation between turbine-blade and guide-vane positions under various operating heads for the Kaplan main units and served as a basis for the cam designs controlling the gate-blade relation, these piezometers were calibrated for absolute-discharge measurements in course of the acceptance tests by means of the two-type current-meter method.[4] The results obtained for the piezometer pair (R_4-R_2) (refer to Fig. 1) of the Winter-Kennedy system of two main units are shown in Fig. 4. These curves relate piezometer deflection and discharge in accordance with the fundamental equation

$$Q = C \times D^a$$

where Q is the discharge measured in cubic feet per second and D the differential piezometer pressure in feet of water. The slope of the curves and their intercept at zero corresponding to the exponent a and coefficient C, respectively, were determined analytically, based on the method of least squares.

Of the six main units, three were tested by means of current meters.[4] The piezometers of the other units were calibrated indirectly by assuming their peak efficiencies to be identical with those of other units of the same design and manufacture actually tested. This procedure was also followed for the two identical Francis-type service units in testing one of them by means of current meters and assuming the peak efficiencies of both to be alike.

It is recognized that such a procedure is not absolutely correct because identical units have not necessarily identical peak efficiencies. However, based on experience available, it is believed that the error thus introduced will not exceed 1 per cent for any one unit and that the average for the entire station should be even closer, because the actual efficiencies of these units might be higher or lower. The calibrations of the piezometer pair (R_4-R_2) of the Winter-Kennedy systems on the six main and the two service units are given in Table 1.

TABLE 1 CALIBRATION OF PIEZOMETER PAIR (R_4-R_2) OF WINTER-KENNEDY SYSTEMS

Main unit no.	Coefficient C	Departure from average, per cent	Calibration procedure
2	5107	−0.80	Current meters
3	5090	−1.13	Based on No. 5 unit
4	5267	+2.30	Current meters
5	5070	−1.52	Current meters
6	5185	+0.72	Based on No. 4 unit
7	5170	+0.43	Based on No. 5 unit
Average	5148		
Service unit No.			
41	330.8	−0.86	Based on No. 42 unit
42	336.6	+0.86	Current meters
Average	333.7		

Recognizing the fact that piezometers are very sensitive and greatly affected by local disturbances, due to irregularities of the water passage, as well as due to minute changes in the shape of the piezometer opening, the differences in the coefficients are relatively small.[5] The variation in the exponent a of the equation ($Q = C \times D^a$) was also very small, varying between 0.500 ± 0.005, so that for all practical purposes the square root was found to be of sufficient accuracy.

To guard against unexpected trouble in the future, which would render one or the other piezometer unreliable or useless, all taps were calibrated during these tests. For instance, Fig. 5 shows the calibration of No. 2 unit Peck impact tap Y_1 and Winter-Kennedy low-pressure tap (R_2) combination (Y_1-R_2).

The calibrations of the piezometers also permitted arriving at some conclusion regarding the degree of consistency and relative precision of these systems, Table 2. The consistency or average

[4] "Water Gaging for Low-Head Units of High Capacity," by J. M. Mousson, Trans. A.S.M.E., vol. 57, 1935, pp. 303–316.

[5] "Piezometer Investigation," by C. M. Allen and L. J. Hooper, Trans. A.S.M.E., vol. 54, 1932, pp. 1–11.

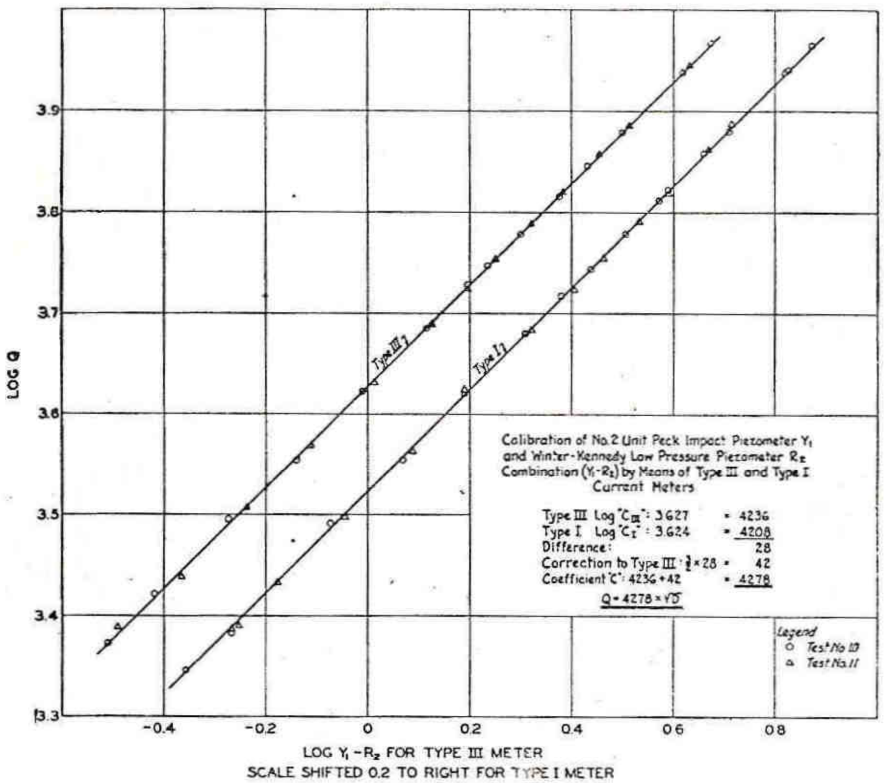

FIG. 5 CALIBRATION OF PIEZOMETER PAIR (Y_1-R_2) AT NO. 2 UNIT BY MEANS OF TWO-TYPE CURRENT-METER METHOD

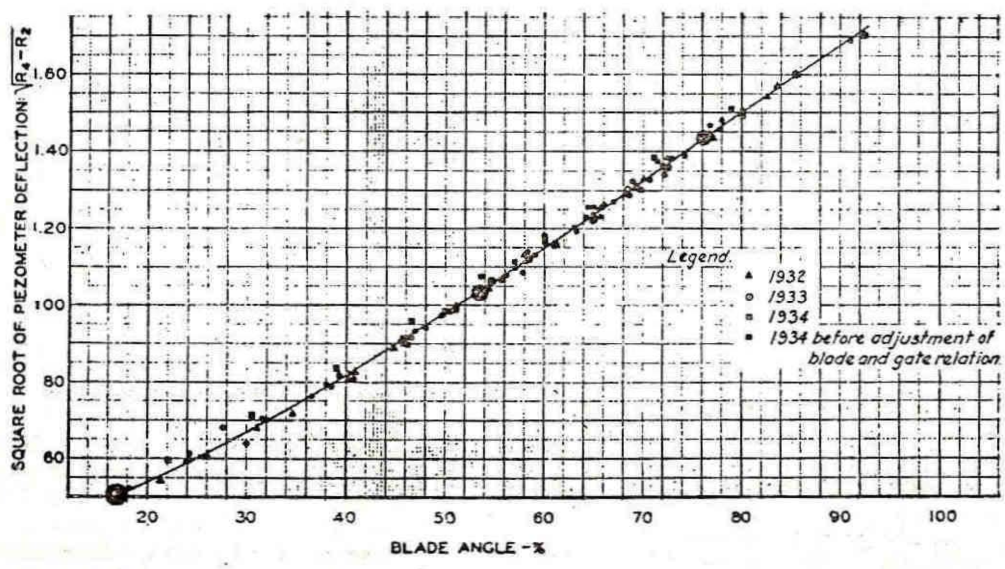

FIG. 6 CHECK ON CONSISTENCY OF PIEZOMETERS USING TURBINE-RUNNER BLADE OPENING AS A PARAMETER.

departure of one test point was determined analytically to ±0.25 per cent for the measurements with the type I current meter, shown in Fig. 4. The mean departure of one measurement was ±0.34 per cent. The mean departure of all measurements was ±0.06 per cent and the relative precision ±0.04 per cent. Considering that these values include not only the errors of the piezometer system but also those of the current-meter measurements, it is believed that the accuracy of the systems is fully adequate as a basis for continuous-flow measurements.

As a next step it was essential to see whether or not the piezometers would maintain their calibrations over a period of years. The results for one unit and one pair of piezometers of the Winter-Kennedy system are shown in Fig. 6, using the runner-blade angle of the Kaplan units as a parameter. In this instance a somewhat wider dispersion of the test points as compared with that in Figs. 4 or 5, is to be expected as the measure of blade angle is not very accurate due to the inevitable lag in the blade-operating mechanism. The results indicate, however, that during the period of observation no change in calibration had taken place. Of particular interest are the test points obtained in 1934, prior to proper adjustment of the blade-gate relation which for some reason had become slightly incoordinated.

TABLE 2 DETERMINATION OF CONSISTENCY AND RELATIVE PRECISION OF PIEZOMETER PAIR (R_4-R_2); CALIBRATION OF NO. 4 UNIT

Test Run	Turbine Discharge for Type I Current Meter Q_1 c.f.s.	Square Root of Piezometer Deflection $\sqrt{R_4-R_2}$	$\frac{Q}{\sqrt{R_4-R_2}}$	Departures δ	Departures Per Cent	δ^2
1	7518	1.448	5192	−20	0.38	400
2	5946	1.140	5216	+ 4	0.08	16
3	4752	.917	5182	−30	0.58	900
4	4768	.915	5211	− 1	0.02	1
5	3687	.708	5208	− 4	0.08	16
6	3735	.718	5202	−10	0.19	100
7	3182	.604	5268	+56	1.07	3136
8	3145	.605	5198	−14	0.27	196
9	3163	.608	5202	−10	0.19	100
10	5245	1.006	5214	+ 2	0.04	4
11	6594	1.268	5200	−12	0.23	144
12	6571	1.262	5207	− 5	0.10	25
13	8729	1.664	5246	+34	0.65	1156
14	8697	1.666	5220	+ 8	0.15	64
15	8415	1.613	5217	+ 5	0.10	25
16	8401	1.612	5212	0	0.00	0
17	7875	1.510	5215	+ 3	0.06	9
18	7444	1.424	5228	+16	0.31	256
19	7426	1.427	5204	− 8	0.15	64
20	6611	1.278	5173	−39	0.75	1521
21	6651	1.276	5212	0	0.00	0
22	5987	1.153	5193	−19	0.36	361
23	5994	1.155	5190	−22	0.42	484
24	5887	1.127	5224	+12	0.23	144
25	5858	1.127	5198	−14	0.27	196
26	5289	1.011	5231	+19	0.36	361
27	5301	1.015	5223	+11	0.21	121
28	4726	.906	5216	+ 4	0.08	16
29	4712	.906	5201	−11	0.21	121
30	4174	.797	5237	+25	0.48	625
31	4173	.801	5210	− 2	0.04	4
32	3632	.697	5211	− 1	0.02	1
33	3634	.697	5214	+ 2	0.04	4
34	3115	.595	5235	+23	0.44	529
35	3091	.595	5195	−17	0.33	289
36	2657	.510	5210	− 2	0.04	4
37	2664	.510	5224	+12	0.23	144
			Avg =5212		Avg =0.25	$\Sigma\delta^2$ =11537

Results

Consistency or average departure of one measurement = ±0.25%

Mean departure of one measurement = $\pm\sqrt{\Sigma\delta^2/(n-1)} = \pm\sqrt{11537/36} = \pm\sqrt{320.472}$ = ±17.90 = ±0.34%

Mean departure of all measurements = $\pm\sqrt{\Sigma\delta^2/n(n-1)} = \pm\sqrt{11537/(37\times36)} = \pm\sqrt{8.661}$ = ±2.94 = ±0.06%

Relative Precision of all measurements = 0.674 x 0.06% = ± 0.040%

This may be regarded as one example demonstrating the degree of sensitivity of piezometers and how useful they may be to detect improper operating conditions.

Flowmeter Investigation

During 1934 and 1935, three types of flowmeters, each employing a different principle, were investigated in detail to determine which type would meet the rigid requirements or could be further developed to a satisfactory stage. Aside from a minimum amount of maintenance desired, the chief requirements stipulated were a high degree of accuracy and sensitivity over the useful range and the possibility of totalizing the unit flow automatically for the entire station, as well as metering characteristics permitting short duration tests on each unit to determine its efficiency. The basic principles employed by these types of meters were as follows:

For the first type of meter the differential pressure of two piezometer taps served to establish flow in a system, the intake being the high-pressure tap and the exit the low-pressure tap, the rate of flow through this system varying with the differential pressure or discharge through the turbine. The meter consists of a drum about 10 in. diam and 5 in. long with the axis of the drum or cylinder in a horizontal position. A vertical partition divides the drum into two half-cylindrical chambers. This partition supports the hollow central core of the drum. If the drum were split open its cross section would be similar to a wheel with two spokes. In the central hollow core of the drum, there is located a knife-edge bearing or a ball bearing to allow the drum to swing back and forth. The two drum chambers are interconnected through an orifice located near the lower end of the partition, that is, near the drum periphery.

By utilizing the flow through the system to displace mercury from one half-cylindrical drum chamber into the other through the orifice, there results a rotational movement of the drum around its own axis. Water displaced by the mercury in the second drum chamber is discharged through the low-pressure tap. When reaching a certain predetermined limit of tilting, a four-way cock operated by a mercury switch is turned 90 deg, changing the feed from the high-pressure tap to the other drum chamber and also connecting the low-pressure tap to the opposite chamber, thus reversing the flow of mercury and, accordingly, the direction of rotation of the drum. In continuous operation, a cyclic rotational drum movement is obtained similar to a pendulum motion; and the larger the differential pressure, the shorter the time required for each cycle. A counter, operated by the limit mercoid switches mounted on either side of the drum, records the number of drum swings and can be calibrated to serve as a flow integrator through the turbine.

The second type of meter employed the differential-piezometer pressure to lower or raise a float or dome also through displacement of mercury, the dead weight of the float being balanced by a counterweight supported by a cable fed over a pulley. By means of gears, the motion of the pulley shaft may be utilized for instantaneous-flow indication. The integration of flow is accomplished through a clock-operated disk driving a small wheel attached to the cable. The cable movement changes the position of the small wheel and places it at a certain distance from the disk center. While at a high rate of flow, the small wheel is placed close to the disk periphery and, therefore, operating under a high gear ratio, it is placed in the disk center at zero position of the meter and, consequently, does not rotate at all. The small wheel driven by the disk in turn operates an integrating counter. At the same time, a graphic record of the unit discharge can be obtained by means of a pen recording the cable movement or position on a drum making 1 revolution per 24 hr.

The third meter type employed a radically different principle. It is based on the fact that the centrifugal force exerted by a flyball system has the same relation to the rate of rotation that the differential pressure has to the rate of flow. The essential parts of this instrument are a tilting mercury manometer and a motor integrator carrying a flyball system, so arranged that the centrifugal force due to rotation of the integrator is opposed to the force of the tilting manometer, Fig. 7. A mercury switch operated by the beam of the tilting manometer controls the motor speed, maintaining a balance between the centrifugal force of the motor integrator and the piezometer-differential force acting upon the tilting manometer. Since the force due to the piezometer differential varies with the square of the flow being measured and the centrifugal force of the integrator also varies with the square of the integrator speed, the two square laws accordingly cancel, thus leaving a direct relation between flow and integrator speed. A counter geared to the motor integrator shows revolutions in terms of flow.

While the first type of flowmeter referred to was found to be extremely accurate even for very low differential pressures, that is, low turbine discharges, its main disadvantage lay in necessitating a continuous flow through the piezometer piping system. For the measurement of gas, steam, filtered water or any refined fluid, there would be no danger from plugging up the piping, but with silt-laden river water, such as carried by the Susquehanna River, there was great danger of rendering the entire piezometer piping system useless, even with frequent flushing by compressed air or filtered water. At the same time, this apparatus did not lend itself particularly to totalizing, because a like periodicity of the drum motion on different units would not correspond to equal unit discharges, due to the difference in the piezometer calibrations. Theoretically, it could be compensated for by introducing different gear ratios for the individual counters or by changing the size or location of the orifice connecting the two drum chambers or even through adjusting the amplitude of the cyclic rotational drum movement. In view of the various disadvantages and complications, this type of meter, though accurate, could not be given any further consideration.

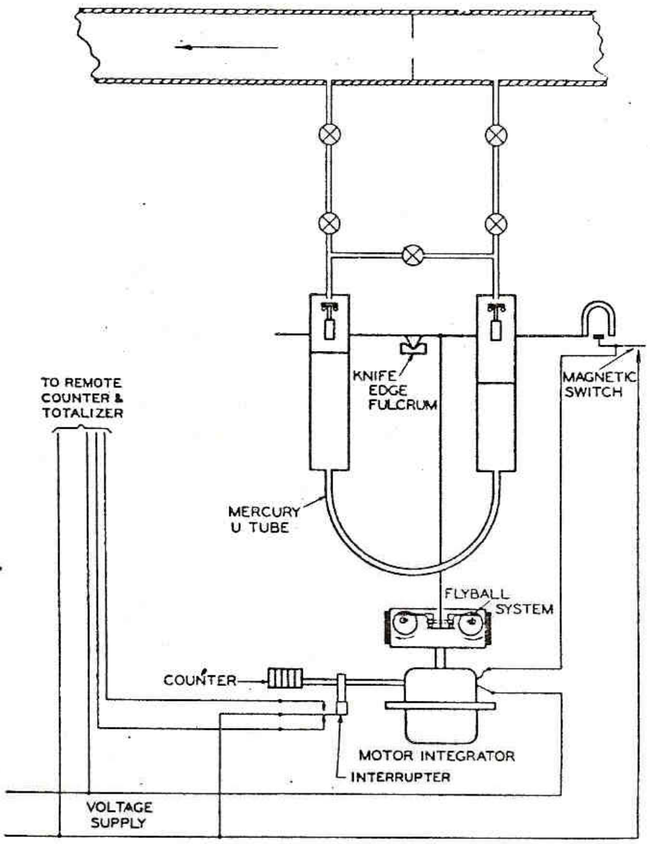

Fig. 7 Diagrammatic Sketch of Type 3 Flowmeter
(By courtesy of the Leeds & Northrup Company.)

Two flowmeters of the second type were purchased and installed temporarily on separate units in the pipe tunnel beneath the generator-room floor. Prior to shipment, these meters were calibrated by the manufacturer for the respective piezometer systems. As a first step, hourly readings of the meters were compared with analytically determined unit discharges based on output. As expected, the flowmeters showed consistently larger unit discharges, the discrepancy being more the greater the fluctuation in loads carried by the units. With the units operating on hand control and blocked to generate at a constant output, there was close agreement between metered and analytical discharges. These results may be attributed to the concave shape of the unit-efficiency curves.

Next, these flowmeters were used to make turbine-efficiency tests of 5- and 10-min duration, the flowmeters being read every 15 sec and the watt-hour-meter-disk revolutions and the time in seconds being recorded by a chronograph. On each unit, the test points thus obtained spread considerably over a band about 3 per cent in terms of efficiency. This discovery led to analysis of the instrument errors by making standard water-column tests. Three major sources of errors were revealed. A first error was traced to the eccentricity of the integrating disk. This error was not constant but had a periodic sinusoidal characteristic completing the cycle in $^1/_2$ hr, corresponding to the time required for 1 revolution of the disk. While for one of the flowmeters the amplitude of this sinusoidal-error curve varied between +0.63 and −0.38 per cent, the other flowmeter showed disk-error variations between −0.82 and +1.39 per cent. The second error, which could not be controlled, was the variable frequency of the station-service system from which the clock driving the integrating disk obtained its power supply. Since the frequency varied about 1 per cent, it was sufficient to make the disk error inconsistent with time, by causing a phase shift in the disk-error curves.

The third source of error was due to the lap of the counter gears and the weight of the rotating countersweep hand, its weight tending to accelerate the motion in the downstroke and retard it in the upward swing. This phenomenon superimposed another error of periodic characteristic upon the first error referred to. To make matters more complicated, the frequency of the second periodic error was not constant but varied with the discharge, being a function of the speed of the countersweep hand and, therefore, decreasing with increasing discharge.

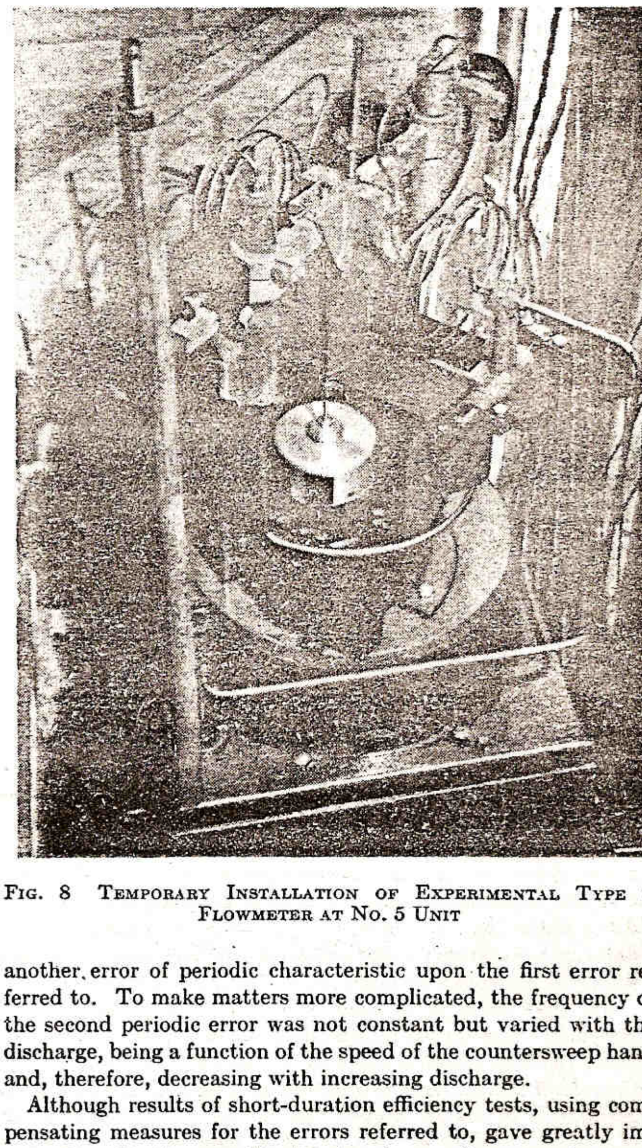

Fig. 8 Temporary Installation of Experimental Type 3 Flowmeter at No. 5 Unit

Although results of short-duration efficiency tests, using compensating measures for the errors referred to, gave greatly improved results, it was realized that such procedures were too complicated to be adopted as a routine measure on all units, because the effort involved, in analyzing instrument errors for meters to

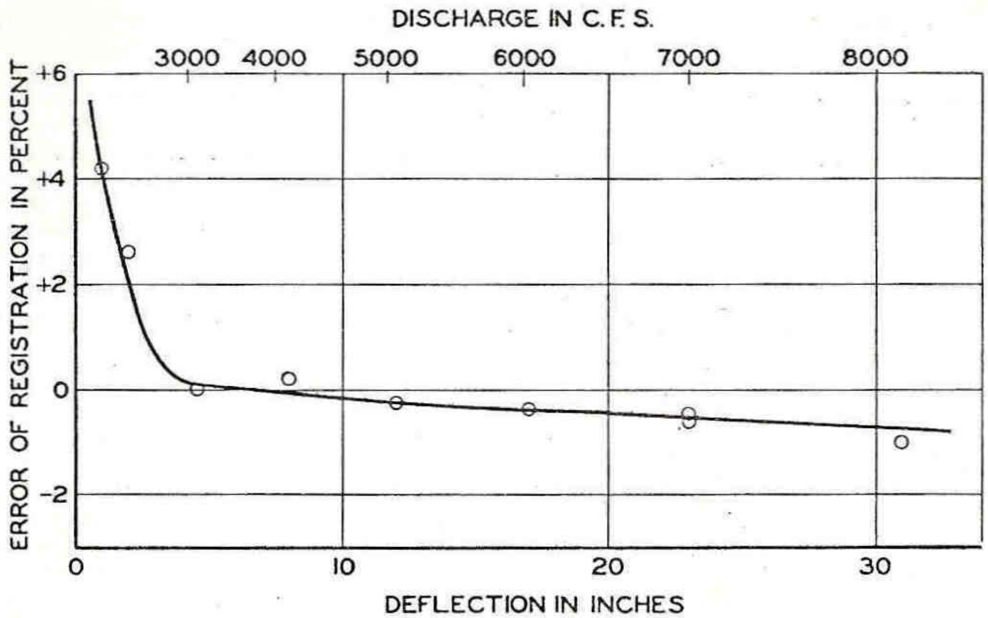

FIG. 9 ERROR CURVE OF EXPERIMENTAL TYPE 3 FLOWMETER

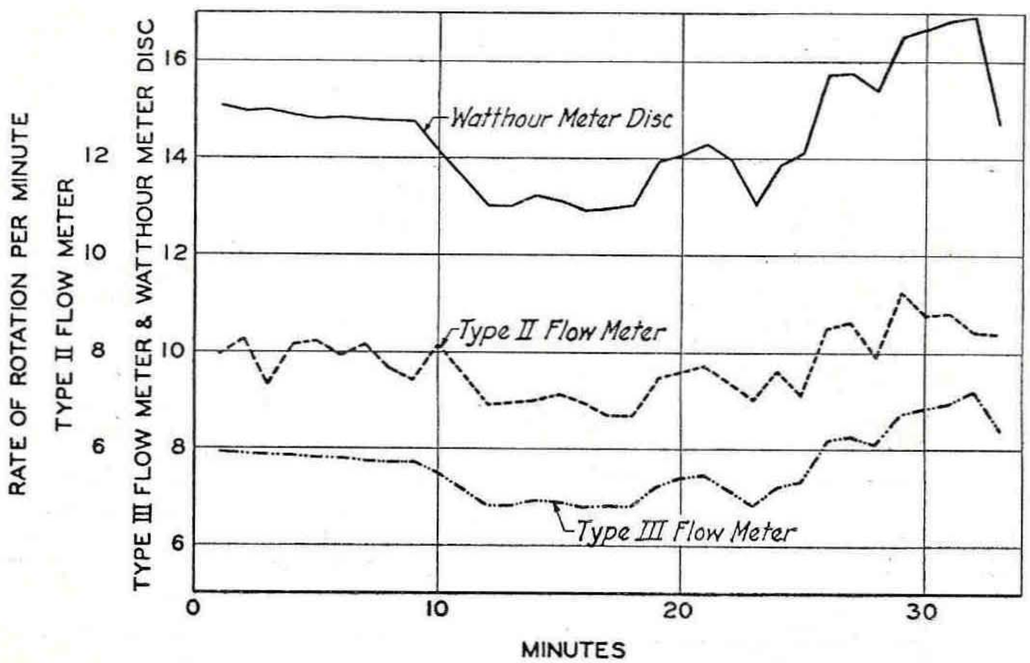

FIG. 10 SENSITIVITIES OF TYPES 2 AND 3 FLOWMETERS

be installed on all units and the use of difficult and complicated compensating procedures for each meter, was far too great in comparison with the accuracy of the results obtained.

An experimental flowmeter of the third type was installed temporarily on one of the units, Fig. 8, and operated in parallel with one of the meters of the second type. Hourly readings on both meters were compared with each other as well as with discharge computations based on power output. The two flowmeters agreed within 0.5 per cent in average, the third type of meter being closer to the analytically determined discharge.

Short-duration efficiency tests on the third type of meter showed a very small spread of test points and a very good agreement with the results of the turbine acceptance tests. The execution of these tests could be simplified considerably by being able to record the flowmeter countershaft revolutions, Fig. 7, by means of electrical impulses on the chart of a recorder simultaneously with the revolutions of the watthour-meter disk and second impulses. The watthour-meter-disk revolutions were obtained by means of a photoelectric-cell arrangement, a small electric bulb being placed on one side of the disk and the photoelectric cell on the opposite side. The beam of light causing the impulses fell through the balancing hole in the watthour-meter disk. The second impulses were obtained also by means of a photoelectric-cell arrangement mounted on the master clock for frequency control of the system, the beam of light being cut by the pendulum.

Next, the meter errors of the third type of flowmeter were analyzed by means of the standard water-column tests. As may be seen, the error curve as shown in Fig. 9 had the typical shape of a rotational integrating device. While the test points were rather consistent, nevertheless it was concluded that further improvement of the meter should be carried out to flatten and lengthen the horizontal leg of the error curve and improve its accuracy to such a degree that even analytical compensating measures would not be required for short-duration efficiency measurements on the turbines.

Additional tests were carried out to determine the responsiveness and sensitivity of the second and third types of flowmeters with varying load on the generating unit. The results, shown in Fig. 10, demonstrate the consistency of the third type of flowmeter, as it follows the watthour-disk-revolution indications consistently in contrast to those of the second type.

In view of the fact that the totalizing with the third type of meter was a simple electrical problem and well-established principle, it was decided to use the third type of flowmeter for the Safe Harbor installation, provided satisfactory improvements were made by the manufacturer in the error characteristics.

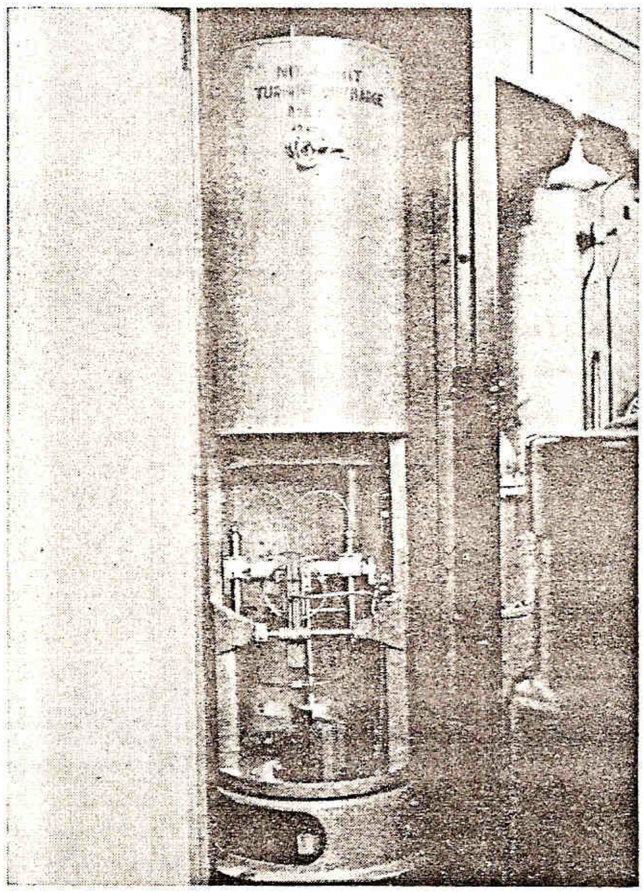

Fig. 11 Typical Flowmeter Installation

2—FLOWMETER EQUIPMENT INSTALLED AT SAFE HARBOR

During 1936 and 1937, various studies were made on remote unit-discharge-totalizing equipment. The manufacturer's attention was drawn also to the possibility of using this type of equipment as part of unit- and station-efficiency indicating-and-recording apparatus. By 1938, the plans for such an installation had crystallized to a point where it was felt safe to proceed with the installation of the flowmeter equipment for all units, as well as the flow-totalizing apparatus for the entire station.

The flowmeters selected were installed in cabinets originally provided on the generator-room floor, located adjacent to and forming an integral part of the gage boards of each unit, Fig. 11. This installation comprised eight flowmeters, one for each of the six main units and one each for the two service units. On all units the flowmeters were connected to the Winter-Kennedy piezometer pair (R_4-R_2) and calibrated, based on the data given in Table 1.

It should be noted that the error characteristics of these meters had been materially improved, so that no correction of any sort had to be applied over the entire range of turbine discharge actually used. The improvement in the error characteristics can best be realized by comparing the check calibrations of three flowmeters after installation, Fig. 12, with the results obtained with the experimental flowmeter in 1934, which is shown in Fig. 9.

Another desirable advantage of these meters is that the checking or recalibration is greatly simplified by calibrated weights to be hung on one arm of the tilting mercury manometer, thus eliminating the use of standard water columns. As demonstrated by the data plotted in Fig. 12, the results obtained by each method are, for all practical purposes, identical.

The power supply for the flowmeter motor integrators was obtained from the 120-v 60-cycle station-service system at outlets

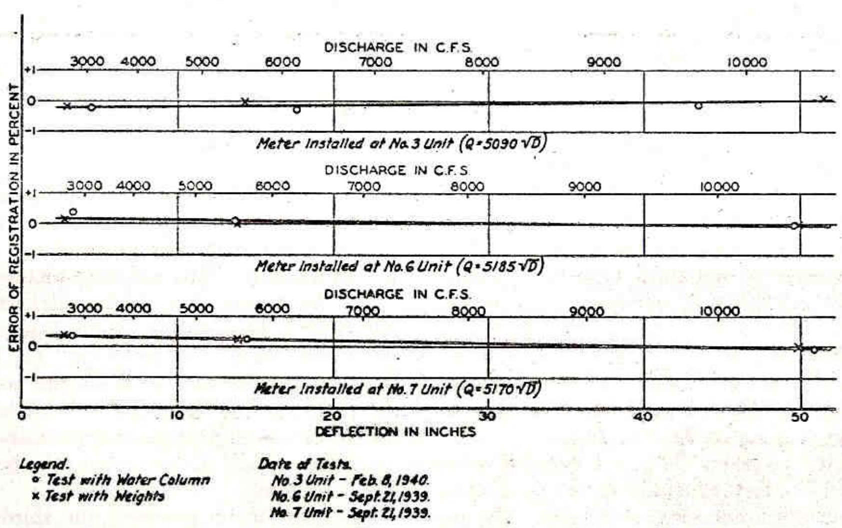

Fig. 12 Check Calibrations of Three Type 3 Flowmeters After Installation

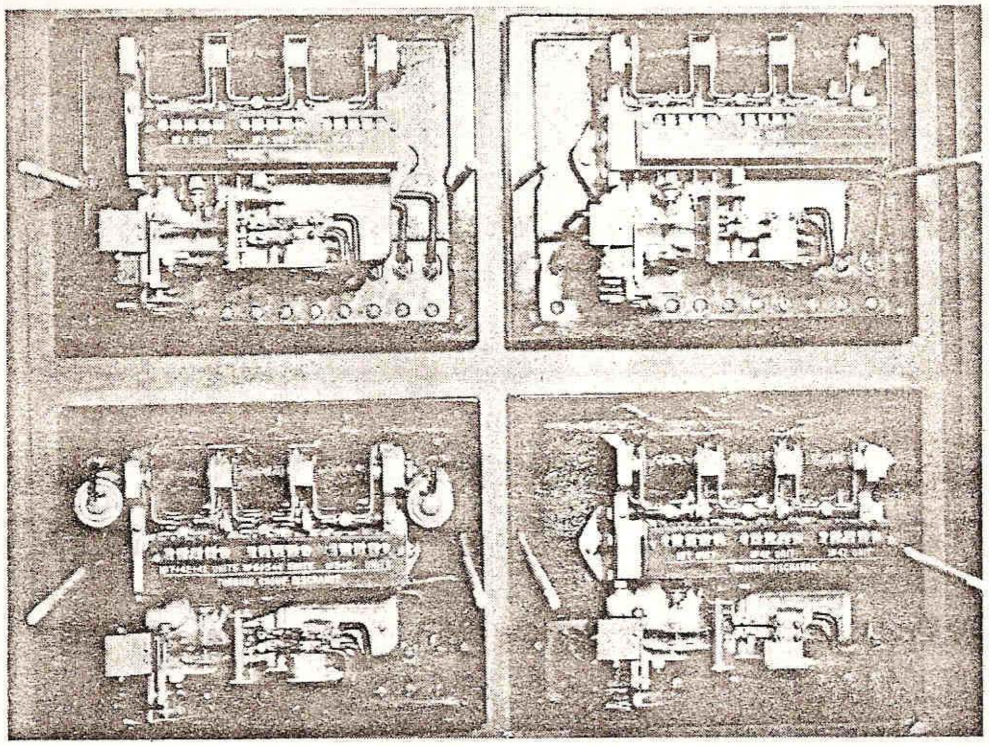

FIG. 13 DISCHARGE TOTALIZING RELAYS

available at each unit gage board. The totalizing apparatus was installed on a panel of the relay board in the control room, Fig. 13. Its principal parts consist of four impulse totalizing relays. Three of these serve as unit-discharge totalizers for a group of three turbines each and one as master totalizer for the entire station, giving the sum total of the three unit totalizing relays. The spare position on the first totalizing relay will be used for the flowmeter at No. 1 unit, now being installed. While the input-output ratio of the unit totalizing relays is 5:3, the master totalizer has a ratio of 3:1. Since each impulse sent out by the interrupter on the countershaft of the individual flowmeters represents 20,000 cu ft, each impulse received by the station total discharge counter from the master totalizing relay corresponds to 100,000 cu ft. The station-total counter is mounted below the totalizing relays on the same panel, Fig. 14. Individual unit discharges can be read on the individual impulse counters of the unit totalizing relays. Mechanical counters were provided on all flowmeters in order to facilitate the checking of impulse transmission and relay operation, as well as for rechecking the calibrations of the flowmeters themselves.

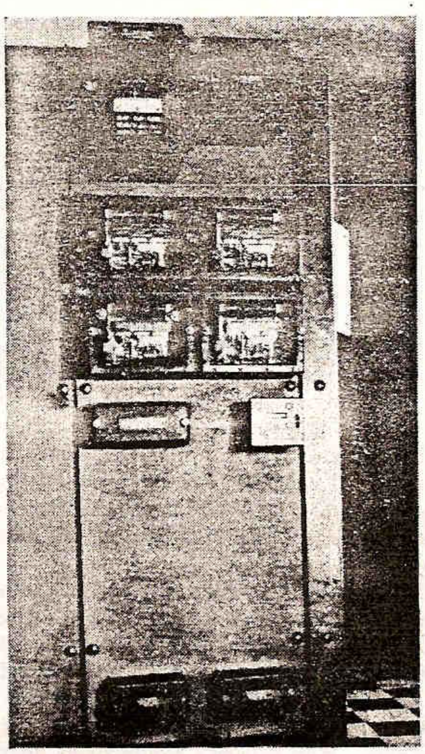

FIG. 14 TOTALIZING RELAYS AND STATION TOTAL DISCHARGE COUNTER INSTALLED ON RELAY BOARD IN CONTROL ROOM

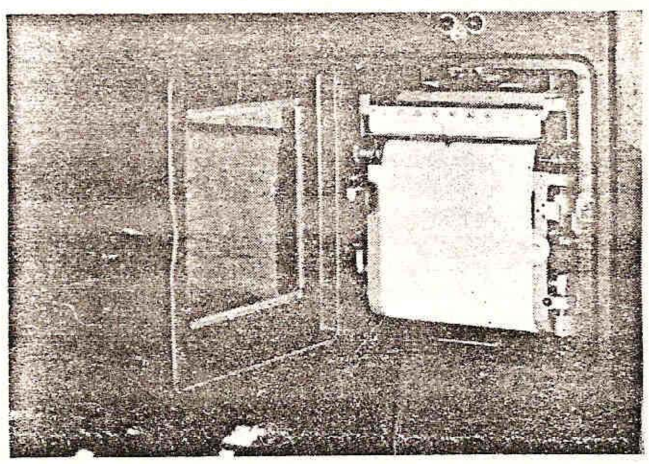

FIG. 15 STATION TOTAL DISCHARGE INDICATOR AND RECORDER INSTALLED ON INSTRUMENT BOARD IN CONTROL ROOM

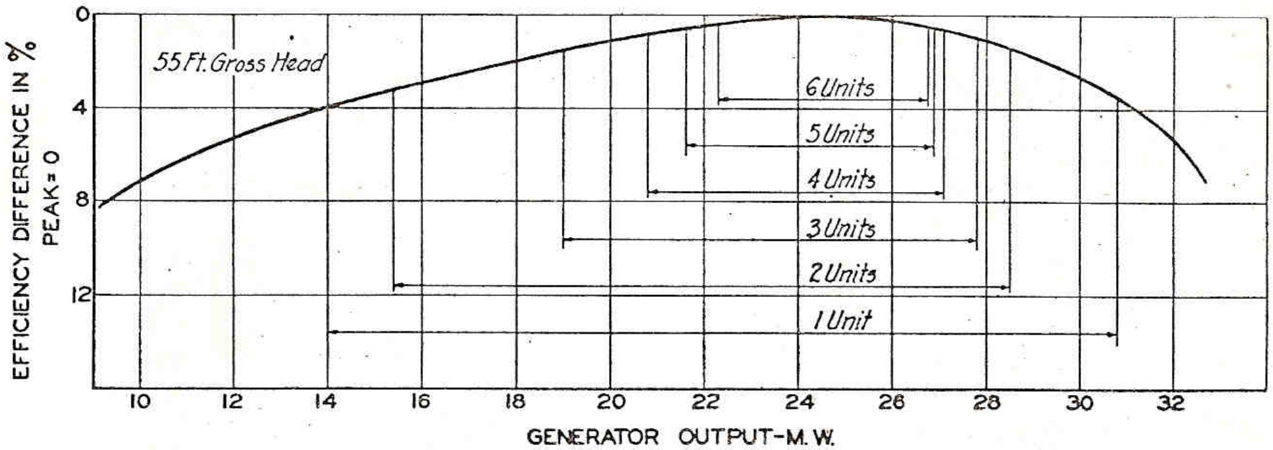

Fig. 16 Typical Loading Schedule for Safe Harbor Main Units

A total station discharge graphic recorder and discharge indicator, combined in one instrument, was installed on the instrument panel located opposite the totalizing-relay panel, Fig. 15. The upper range limit of the graphic recorder and the indicator was chosen as 80,000 cfs, representing the approximate maximum station draft of the Safe Harbor development for a number of years in the future.

3—BENEFITS OBTAINED THROUGH FLOWMETER INSTALLATION

During 1939, various investigations were made based on the data obtained by the flowmeter installation. The operators were required to read the individual unit discharges and the station-total draft every hour on the hour, together with the unit and station integrating watthour meters, as well as forebay and tailwater indications. The operators, however, were still charged with computing the individual unit and total-station drafts based on power output, as had been standard practice. It was felt that a long-term comparison was essential to obtain the proper basis for continuous-flow records at Safe Harbor, the transition period furnishing the ratio between computed and automatically recorded station drafts under the various seasonal loading schedules. Once sufficient data have been accumulated, it is expected that the operators will be relieved altogether from computing the discharge based on output.

The data obtained by the operators were also used to investigate unit and station operating efficiencies. An investigation of this kind was all the more essential, as during approximately 290 days of the year the available river flow at Safe Harbor is less than the station draft required with all six main and two service units installed operating at maximum capacity. After placing the seventh main unit in service, which is now under construction, the corresponding period will increase to 305 days. It was interesting to note that the availability of an input yardstick had a decidedly stimulating effect on the operating personnel. While, during the first month of flowmeter operation, that is, January, 1939, the ratio of actual loss in generation to expected loss was greater than unity on all but 8 days, this ratio did not exceed unity during 18 days in May, 1939, under similar river-flow conditions and loading schedules. It has been estimated that an improvement of this magnitude is responsible for an increase in generation of at least 0.3 per cent, or approximately 1,700,000 kwhr per year with the present installation of six main units and 1,900,000 kwhr per year with the seventh main unit placed in service, so that the flowmeter installation will pay for itself in a very short time.

With a close continuous check on unit operating efficiencies available, it was also possible to keep the losses due to trash on the intake screens appreciably below those which must have been prevailing during previous years. Prior to the installation of the flowmeters, the screen losses were determined from time to time by measuring the screen head loss. Now, as soon as any of the units show a drop in operating efficiency, as indicated by the hourly readings, the screen losses are determined independently. After cleaning the racks, the operating efficiency invariably increases to the expected level. Although it is difficult to estimate the increase in station economy due to this means of obtaining an earlier indication of the loss in efficiency due to plugging up of the screens, nevertheless, it is believed that the benefits thus derived are substantial.

Since the availability of the particular type of flowmeters permitted short-duration turbine-efficiency tests to be carried out by one man, therefore justifying itself as a routine measure, it was also possible to investigate in detail the efficiency characteristics of each main turbine over the entire range of operating heads. Such a procedure was particularly desirable as these turbines are of the Kaplan type, requiring an adjustment of the cam controlling the gate-blade relation for the various operating heads, the operators being required to change to a new cam setting after each 1 ft of change in head. While these compensating devices on all main units were originally designed and calibrated, based on a minimum of information due to the costly testing procedures even with the use of the index method with piezometers, the flowmeters available made it possible to check and recalibrate these compensating devices with a large amount of detailed information obtained with a minimum of effort. The scope of the work involved can best be realized by mentioning that, although five of the six main units were of identical design, nevertheless, the characteristic of each unit was found to be sufficiently different from the others to warrant individual cams, consequently requiring individual calibration of the cam-adjustment device for variation in head. The results of this investigation reflected favorably upon the operating efficiencies of the individual units and the station as a whole.

As a next step, a detailed study was undertaken to determine the magnitude and duration of avoidable inefficient operation in percentage of total operating time. From the ideal loading schedule for the main units, as shown in Fig. 16, and valid for a gross head of 55 ft, it is apparent that the band of permissible load variations of each unit decreases with increasing number of units on the line. With capacity requirements above the most efficient station operating range with all available units operating, all individual unit loadings are increased by equal amounts up to the point of maximum capacity.

By analyzing the chart of the total station discharge recorder, Fig. 15, in the light of the operator's log, it was noted that considerable periods elapsed between the time of placing units on or off the line and the ideal loading schedule. The losses thus sustained, though by no means excessive, when compared with some other stations were nevertheless appreciable, amounting to about 10 per cent of the total operating time on the average.[6,7] It was realized that there was considerable room for improvement provided proper means were available for giving instantaneous warning when reapportioning of load to individual units is required. It is obvious that in this connection some thought was again given to efficiency-indicating-and-recording apparatus, but another and far simpler and less expensive solution was discovered.

4—INSTALLATION OF LOAD-LIMIT LIGHTS

The characteristics of the Kaplan-type main turbines installed at Safe Harbor are such that the most efficient discharge range of these units is, for all practical purposes, independent of the head if the loading schedules, valid for each head similar to that in Fig. 16, are adhered to. Thus the discharge, with one unit operating within the permissible load range, varies between 4000 and 8200 cfs irrespective of the head, and the discharge ranges with any given number of units operating are also constant, i.e., independent of the head for all practical purposes. In view of these characteristics and taking proper account of station-service unit draft requirements, it was possible to provide for an automatic and instantaneous load-limit indicating apparatus as an integral part of the total station discharge indicator and recorder, shown in Fig. 15.

TABLE 3 DISCHARGE LIMIT SETTING FOR LOAD LIMIT LIGHTS

Discharge range, no.	Discharge-range setting, cfs	Main units to be operated, no.
1	0– 4000	0
2	4000– 8200	1
3	8200–14900	2
4	14900–21400	3
5	21400–27500	4
6	27500–33900	5
7	33900–40800	6
8	40800–48000	7

Essentially, this device consists of a contact-making cam arrangement controlling two warning lights, one located on the operator's desk and the other on the instrument board above the station total discharge recorder. For each load range between two discharge limits, Table 3, there is available one contact-making cam assembly independently adjustable as to what part of the total-discharge range it will control. A control switch is provided with one position for each discharge range, that is, number of units to be operated, connected so as to keep the light extinguished when set for the number of units to be in operation for best efficiency, as long as the discharge is in the corresponding range. If the discharge crosses the limits of this range, the lights will be lighted from the contact assembly of the adjacent range either until the switch has been reset to the number of units, corresponding to this new range, or the discharge has returned within the range. With the control switch being kept set correctly, that is, corresponding to the number of units in operation for best efficiency in each discharge range, the illumination of the lights will indicate inefficient operation.

It may be noted that eight discharge ranges have been provided, the reason being that the seventh main unit is now being installed and that an indication is also desirable when the station as a whole, with all seven main units operating, has reached the upper limit of the range of most efficient operation.

In addition, the scope of the total discharge station indicator and recording instrument will be increased by means of adding a load-operating-range scale, each division of this scale corresponding to the permissible range of discharge for a certain number of units in operation as shown in Table 3. By means of this improvement, it will be possible to observe at a glance how many units should be in operation at any time. When reaching a load limit as indicated by the warning lights and observing the shape of the discharge curve plotted by the station-discharge recorder, it also will be immediately apparent whether an upper or lower limit has been reached, requiring one unit to be put on or off the line, respectively.

To keep a definite record of inefficient operation, the station total discharge recorder is also to be equipped with an additional pen element operating simultaneously with the load-limit lights. This added provision will also enable the operators to ascertain the duration of the period of inefficient operation prior to noticing the lighted load-limit lamps, so that the allowable 10-min interval of borderline operation is not exceeded. Some inefficient operating time is necessarily unavoidable and, for the present and some time past, we have felt that a 10-min period of allowable inefficient operating time is reasonable.

The installation of this load-limit light apparatus is now in progress and it is expected that, due to its availability, avoidable inefficient operation will be reduced to a negligible amount, resulting in an additional and substantial increase in operating efficiency and station output.

[6] "How We Raise Hydro Efficiencies," by E. B. Strowger, *Electrical World*, vol. 103, April 14, 1934, pp. 535–538.

[7] "Waterwheel Testing and Operating Records of Plant Discharges," Proceedings National Electric Light Association, vol. 85, 1928, pp. 872–904.