Hydraulic Laboratory Technical Memorandum, PAP-1225

Winter-Kennedy Flow Measurements – Units G24 and G20

Grand Coulee Nathaniel “Nat” Washington Power Plant, WA
Columbia-Pacific Northwest Region

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services
Denver, Colorado

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Introduction

The Hydraulic Investigations and Laboratory Services group was requested by Grand Coulee Powerplant to perform Winter-Kennedy flow measurement testing for units in the Third Powerhouse. This testing was completed in conjunction with field performance (efficiency) and cavitation testing performed by engineers from the Turbines & Pumps and Hydropower Diagnostics & SCADA Groups.

The main objective of the Winter-Kennedy (WK) testing was to determine accurate equations to provide reliable flow measurements from existing WK pressure taps on units G24 and G20. WK is a relative flow measurement method and considered secondary to the ultrasonic flow sensors (Accusonic) currently installed on the penstocks. Having a secondary method to measure discharge is valuable to provide redundancy, is relatively simple and inexpensive to maintain, and is accurate and reliable within certain limitations.

Test Method

Winter-Kennedy Flow Measurement Method

The "Winter-Kennedy" flow measurement method was developed by I.A. Winter and A.M. Kennedy in 1933 (Winter & Kennedy, 1933). It correlates a difference in pressure at a cross section of the scroll case to the volumetric flow rate, or discharge, through the penstock. The pressure difference is measured from taps located at different sides of the conduit, typically one or more at the top and a reference tap at the side (see Figure 1 as an example). Discharge (Q) is correlated to the pressure difference (ΔP) through the relationship shown in Eq. 1 where the coefficient K and exponent n are determined through experimental testing where both Q and ΔP are measured over a range of operating conditions. Both K and n are dependent on the geometry of the conduit and n is typically close to 0.5 (The American Society of Mechanical Engineers, 2011) but both calibration factors are unique to the unit for which they are tested.

$$\boldsymbol{Q = K(\Delta P)^{n}} \qquad \text{Eq. (1)}$$

As with any flow measurement method, the WK method has both benefits and limitations. Benefits include its simplicity and relative low cost. The pressure taps and piping are already in place for all Grand Coulee hydropower units and only require a device for measuring differential pressure. A redundant flow measurement system that can be used reliably when the primary system (Accusonic flow meter in this case) is out of service is very valuable and relatively inexpensive to setup and maintain. Limitations of this method include inaccurate flow estimates at low discharges when the pressure differential reading is small, and variation of pressure readings due to changes to the scroll case, penstock, or pressure taps. Examples of this include modifications to the intake, penstock or scroll case geometry, wear or changes near the pressure taps (e.g., coating failure/repair, welds, grinding, etc.), or any other changes that influence the flow patterns in the conduit that affect pressure readings at the taps (Rau & Eissner, 2014).

Unit G24

Unit G24 is one of the three large units in Grand Coulee's Third Powerhouse. The unit is rated at 805 MW and can operate in a discharge range of less than 15,000 cubic feet per second (cfs) to about 36,000 cfs depending on power needs and reservoir level. G24 has four pressure taps for WK flow measurement; three near the top of the scroll case (labeled A, B, C respectively) and the fourth used as a reference on the side of the scroll case (labeled D). Tap locations and labels are shown in Figure 1 and Figure 2.

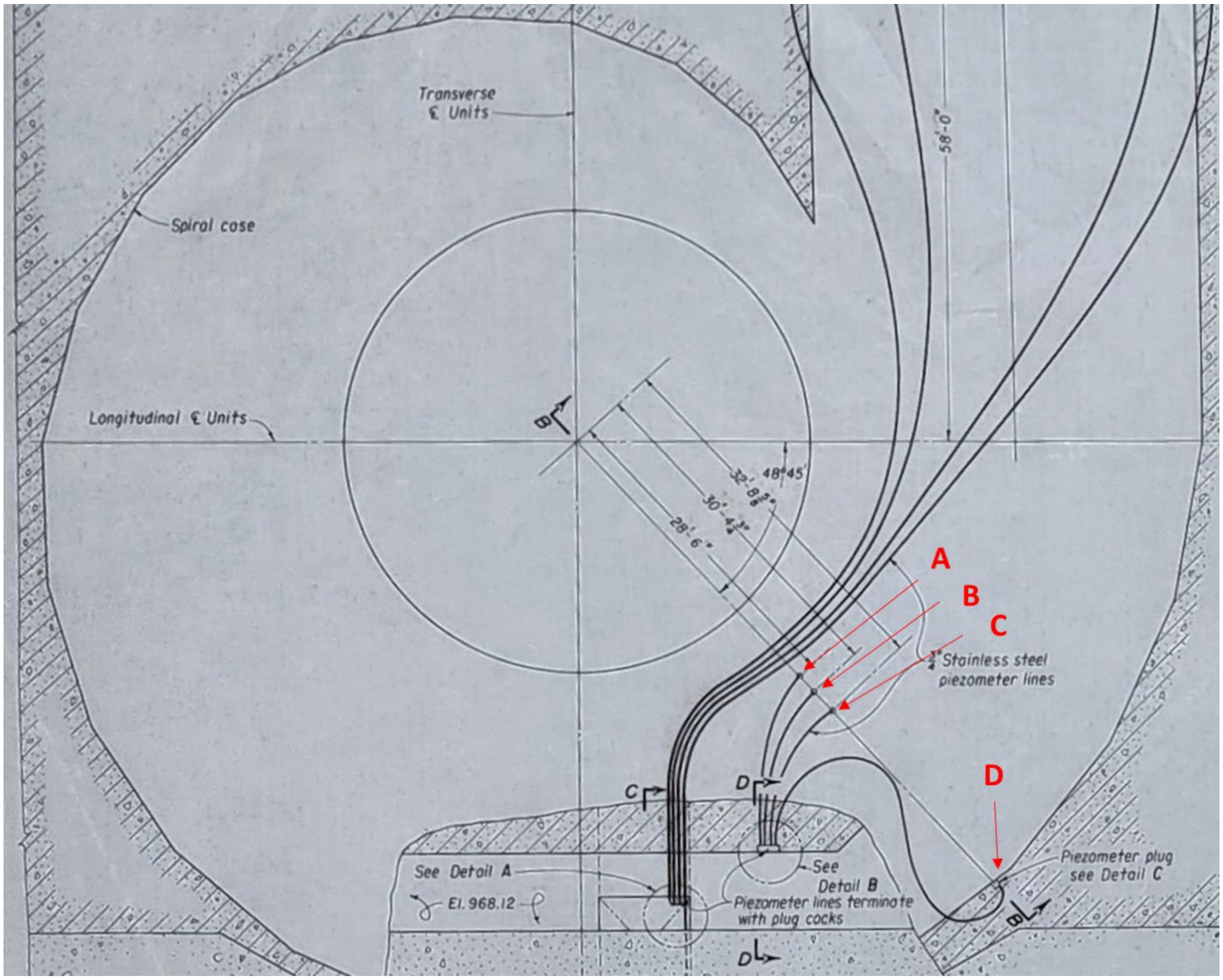


Figure 1. Plan view of WK pressure taps for unit G24 from drawing 1222-D-3686. WK tap locations are shown in red.

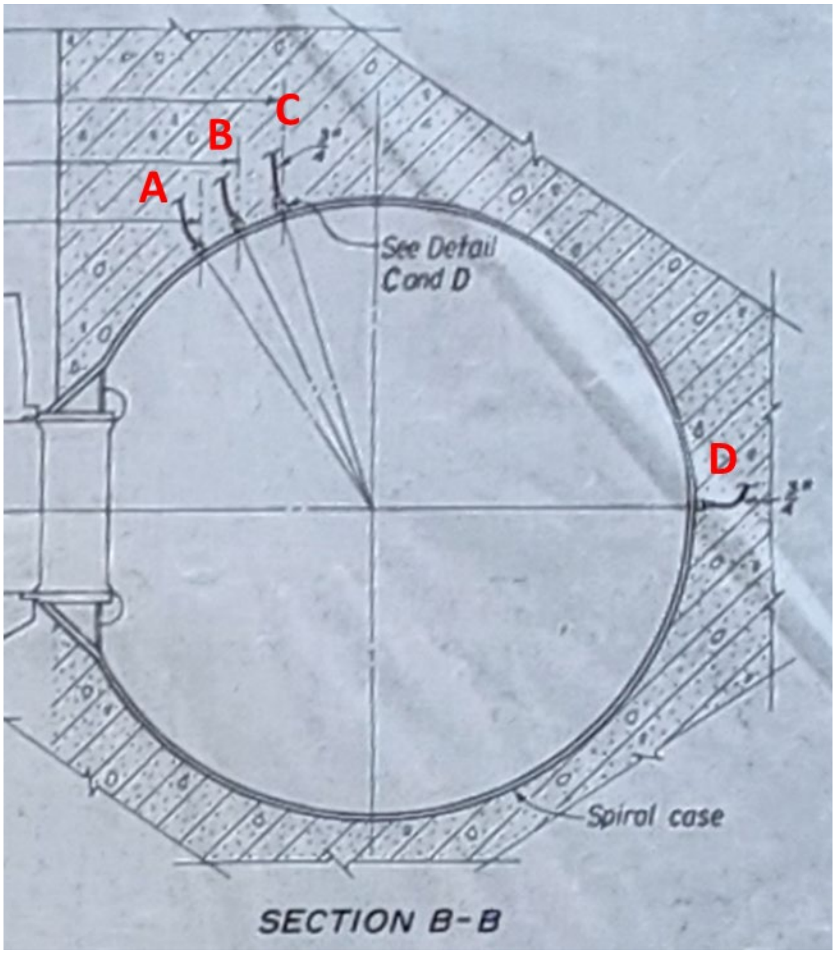


Figure 2. Cross section view of WK pressure taps for unit G24 from drawing 1222-D-3686.

Connection piping for each of the pressure taps is made of ¾-inch stainless steel and terminates at a single location on the main control floor (El. 968.12 ft). A piping manifold was fabricated from ¼-inch stainless steel tubing to connect to the differential pressure sensor and control the tap configuration to be used for measurement with an arrangement of shut off valves (Figure 3). To expedite testing, two additional temporary differential pressure sensors were used to record pressure readings simultaneously. The temporary sensors were placed on the floor and the permanent sensor is mounted to the concrete wall as shown in Figure 3. There are three options for flow measurement depending on the tap configuration. Each measures the pressure difference between a top side tap to the reference tap D on the side of the conduit (A-D, B-D, C-D). There is a unique set of *K* and *n* values for each configuration.

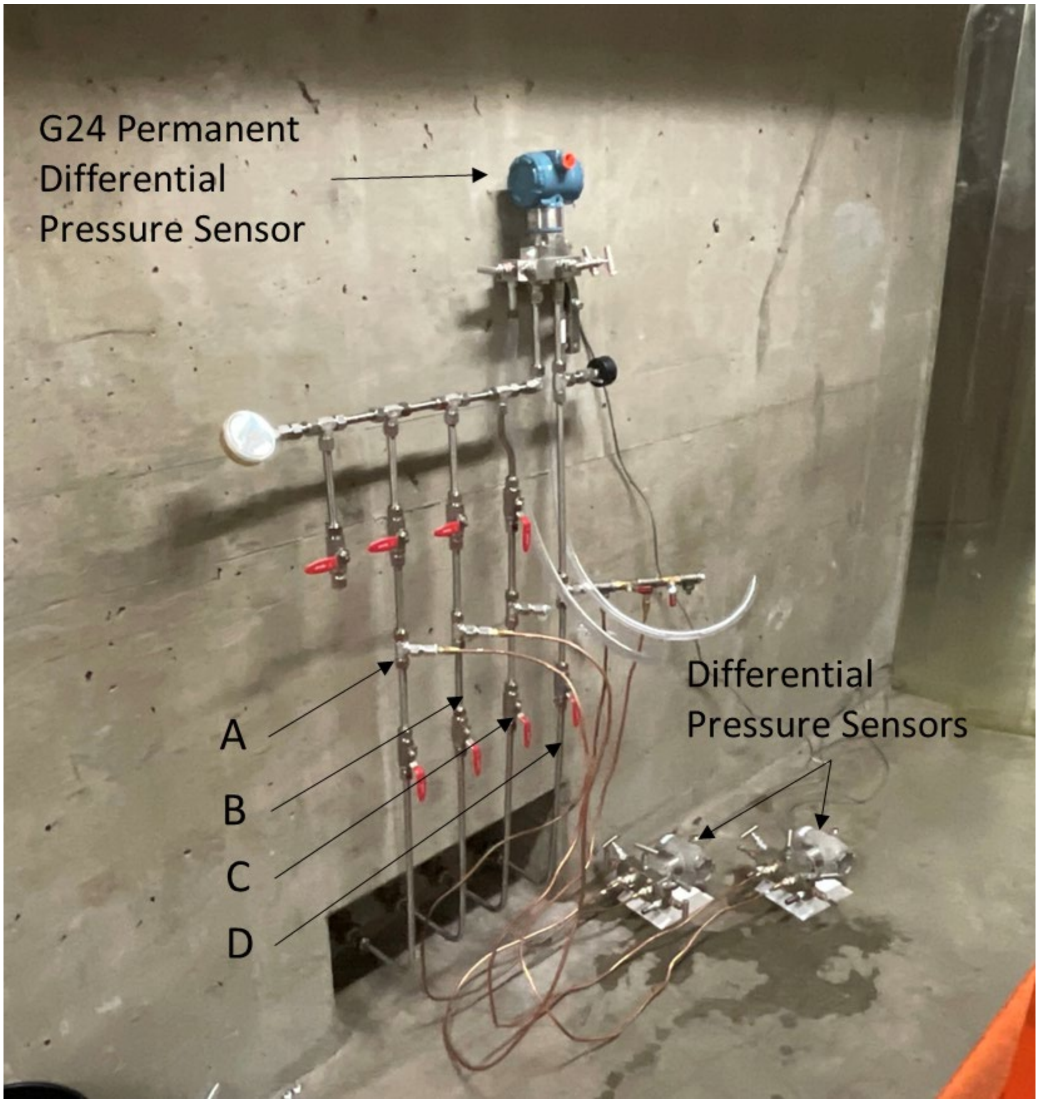
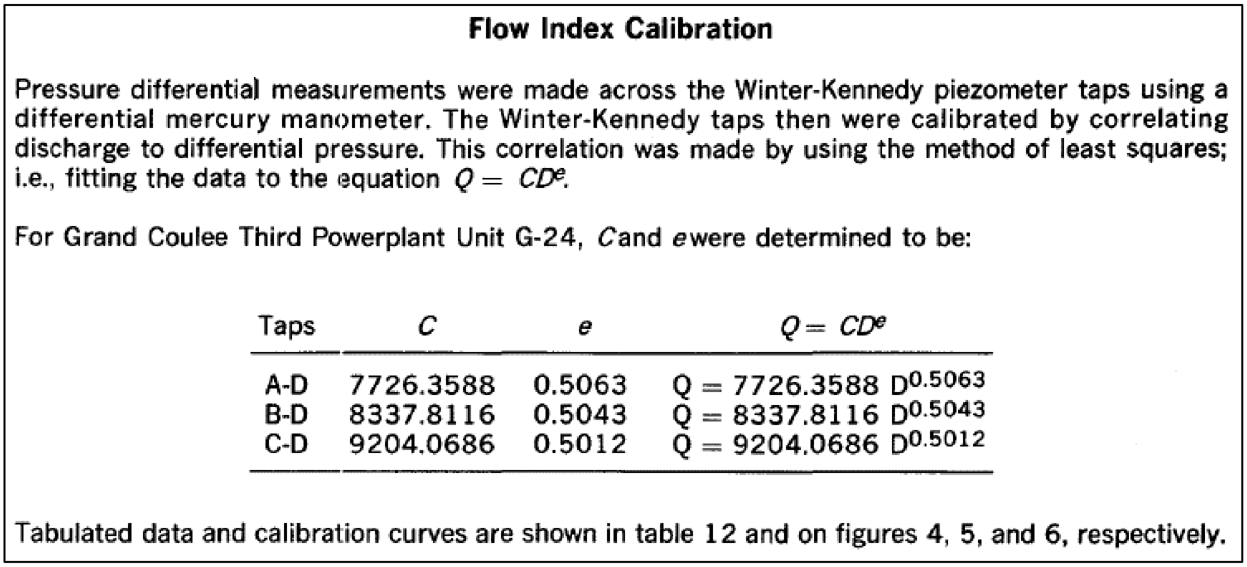


Figure 3. WK pressure tap manifold and differential pressure sensor for unit G24.

In 1983, performance testing established coefficient and exponent values for each WK pressure tap configuration on unit G24 shown in Figure 4 ((Heigel, Lewey, & Favero, 1984). To our knowledge, the WK taps were never used regularly since Accusonic acoustic flow meters were installed in 2003 as the primary method for flow measurement. However, during unit efficiency and cavitation testing performed on G24 by General Electric (GE) in 2017, a discharge comparison was made to the A-D combination of the WK pressure taps. This comparison showed good agreement between the Accusonic and WK flow equation for all flows above 5,000 cfs (Figure 5). The other pressure tap configurations were not tested.



Flow Index Calibration

Pressure differential measurements were made across the Winter-Kennedy piezometer taps using a differential mercury manometer. The Winter-Kennedy taps then were calibrated by correlating discharge to differential pressure. This correlation was made by using the method of least squares; i.e., fitting the data to the equation $Q = CD^e$.

For Grand Coulee Third Powerplant Unit G-24, *C* and *e* were determined to be:

Taps	C	e	$Q = CD^e$
A-D	7726.3588	0.5063	$Q = 7726.3588\ D^{0.5063}$
B-D	8337.8116	0.5043	$Q = 8337.8116\ D^{0.5043}$
C-D	9204.0686	0.5012	$Q = 9204.0686\ D^{0.5012}$

Tabulated data and calibration curves are shown in table 12 and on figures 4, 5, and 6, respectively.

Figure 4. WK coefficient and exponents determined for each configuration from 1983 testing on G24 (Heigel, Lewey, & Favero, 1984).

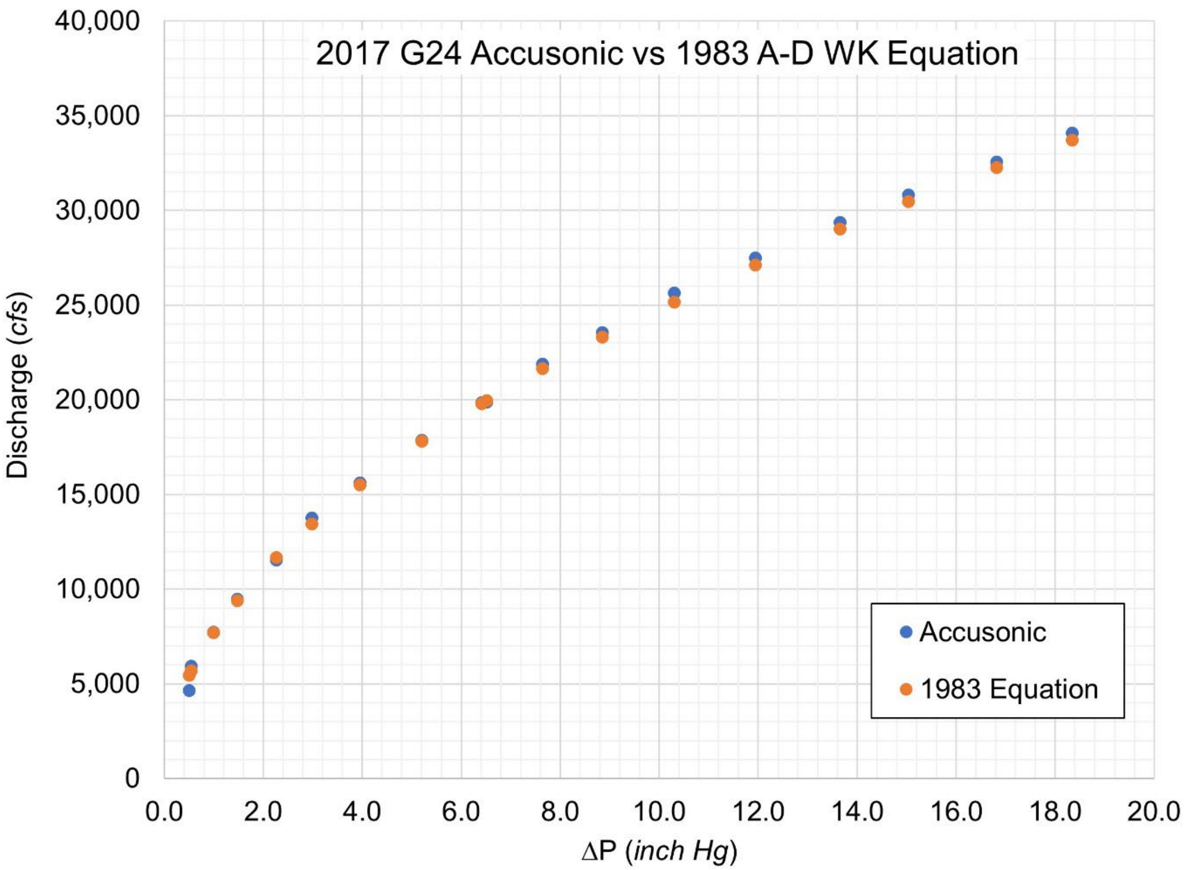


Figure 5. Comparison of GE 2017 testing using the Accusonic flow meter to the 1983 WK flow equation for taps A-D.

Unit G20

Unit G20 is one of the three smaller units in Grand Coulee's Third Powerhouse and is rated at 690 MW and can operate in a discharge range of less than 15,000 cfs to 35,000 cfs depending on power needs and reservoir level. G20 has three pressure taps for WK flow measurement; two near the top of the scroll case (labeled A and B respectively) and the third used as a reference on the side of the scroll case (labeled C). Tap locations and labels are shown in Figure 6 and Figure 7.

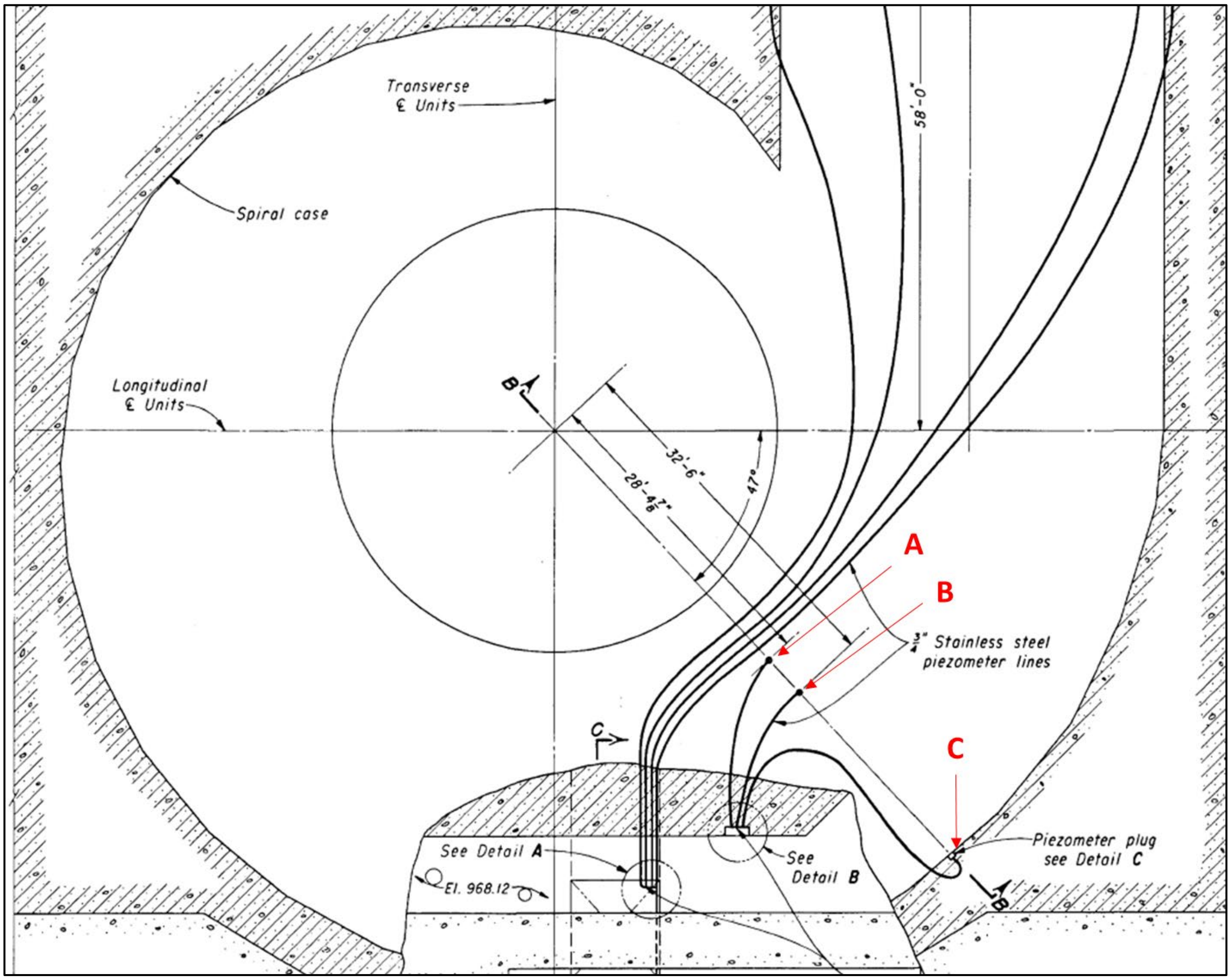


Figure 6. Plan view of WK pressure taps for unit G20 from drawing 1222-D-940.

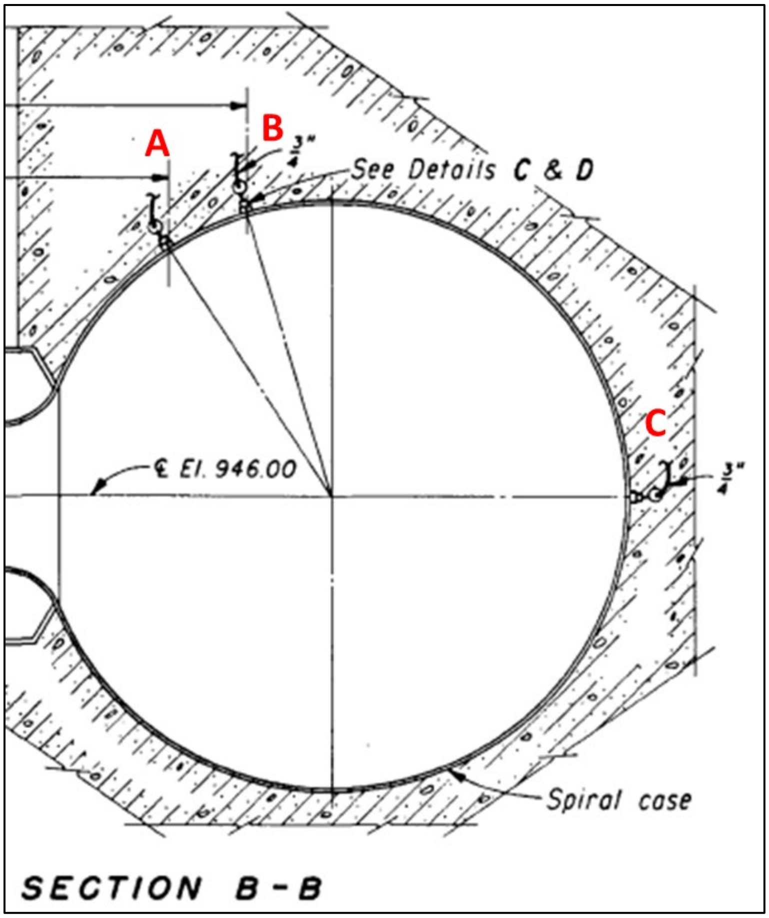


Figure 7. Cross section view of WK pressure taps for unit G20 from drawing 1222-D-940.

Also for G20, connection piping is made of ¾-inch stainless steel and terminates at a single location on the main control floor near the unit (El. 968.12 ft). A manifold was fabricated of ¼-inch stainless steel tubing to connect to the differential pressure sensor and control the tap configuration to be used for measurement with an arrangement of shut off valves (Figure 8). There are two options for flow measurement depending on the tap configuration. Each measures the pressure difference between a top side tap to the reference tap C on the side of the conduit (A-C and B-C). There is a unique set of *K* and *n* values for each configuration.

Documentation of WK original testing and determination of the *K* and *n* values for G20 has not been found. An important goal of this testing was to establish these values for G20 to be used in the future.

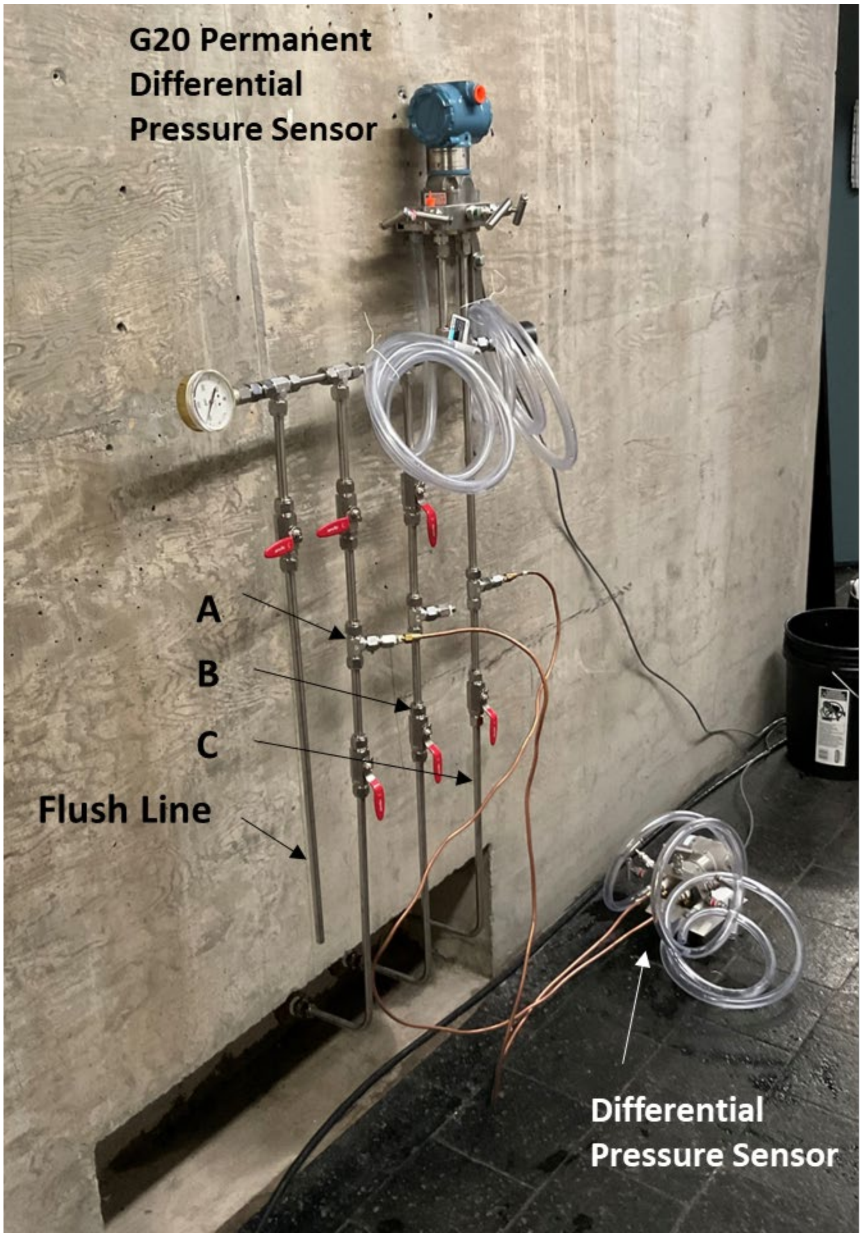


Figure 8. WK pressure tap manifold and differential pressure sensor for unit G20.

Test Setup and Data Acquisition

WK testing was performed simultaneously with unit efficiency and cavitation testing for both G24 and G20. Differential pressure transducers and 8-path Accusonic acoustic flow meters were the primary instruments used as outlined in Table 1. Three independent differential pressure sensors were used to capture pressure readings from all WK tap configurations simultaneously during the test period.

For each test run the discharge and power output were allowed to stabilize and then data were recorded over a 7-minute period. Differential pressure readings were recorded at 1 sample per second and Accusonic flow rate measurements were recorded at the maximum refresh rate of the meter at each unit (about 82 samples per test for G24 and about 292 samples per test for G20). Differences in refresh rate were due to limitations of the Accusonic equipment on each unit.

Table 1. Instrumentation used for WK flow measurement testing for G24 and G20.

GC Unit	Measurement	Instrument	Range	Accuracy	Type	Sample Rate
G24	A-D WK taps	ΔP Sensor (temporary)	0-15 psi	0.1% FS	Rosemount 3051	1 sample / second
	B-D WK taps	ΔP Sensor (temporary)	0-36 psi	0.1% FS	Rosemount 3051	1 sample / second
	C-D WK taps	ΔP Sensor (permanent)	0-36 psi	0.1% FS	Rosemount 3051	1 sample / second
	Penstock Discharge	Acoustic Flow meter	-	1.0%	Accusonic	82 samples / 7 min
G20	B-D WK taps	ΔP Sensor (temporary)	0-15 psi	0.1% FS	Rosemount 3051	1 sample / second
	C-D WK taps	ΔP Sensor (permanent)	0-36 psi	0.1% FS	Rosemount 3051	1 sample / second
	Penstock Discharge	Acoustic Flow meter	-	0.60%	Accusonic	292 samples / 7 min

Differential pressure data were collected from a 4-20mA output signal from the sensor into an Analog to Digital converter and recorded on a laptop computer (Figure 9). A Measurement Computing 1604-HS DAQ hardware device with 16-bit resolution and DasyLab 16.0 software were used to process, scale, and record differential pressure measurements from each WK tap configuration. Each differential pressure sensor was calibrated on site prior to testing to accurately scale the output signals.

Accusonic discharge measurements were recorded by engineers from the Turbines and Pumps Group using AccuFlow software on a laptop computer connected to the Accusonic 8510+. Velocities for each acoustic path were recorded and used with the local area of the penstock in postprocessing to determine the volumetric flow rate.

Figure 9. Data Acquisition setup used for WK testing for units G24 and G20.

Uncertainty Analysis

The uncertainty for each WK pressure tap configuration was estimated for the discharge predicted from the respective WK flow equation (Eq. 1) as determined from field measurements. The approach used to estimate the uncertainty is explained in detail in (Coleman & Steele, 1999). For purposes of this technical memo, a general description is described here.

First, the systematic uncertainty of the coefficient *K* was estimated from uncertainties associated with the differential pressure and Accusonic discharge measurements using Eq. 2. It was assumed that there is no uncertainty associated with the exponent *n*.

$$U_K = \left[\left(\frac{\partial K}{\partial \Delta P}\right)^2 {U_{\Delta P}}^2 + \left(\frac{\partial K}{\partial Q}\right)^2 {U_Q}^2\right]^{1/2} \qquad \text{Eq. 2}$$

Next, the systematic uncertainty of the WK discharge was estimated from the uncertainty associated with *K* established during testing and the differential pressure measurement (Eq. 3). The random uncertainty of the WK discharge was estimated by Eq. 4 for differential pressure measurements, which was then used with the systematic uncertainty in Eq. 5 to determine the total uncertainty of the WK discharge measurement.

$$U_{Q_{wk}} = \left[\left(\frac{\partial Q_{wk}}{\partial K}\right)^2 {U_K}^2 + \left(\frac{\partial Q_{wk}}{\partial \Delta P}\right)^2 {U_{\Delta P}}^2\right]^{1/2} \quad \text{Eq. 3}$$

$$U_{random} = \frac{\frac{t\,(S_d)}{no^{1/2}}}{Avg} \quad \text{Eq. 4}$$

$$U_{total} = \left[{U_{Q_{wk}}}^2 + {U_{random}}^2\right]^{1/2} \quad \text{Eq. 5}$$

Symbols for equations 2 through 5 are defined as:

K = coefficient for WK discharge equation 1 (-)
ΔP = differential pressure measurement (inch Hg)
Q = Accusonic discharge measurement (cfs)
Q_{wk} = Discharge from WK equation 1. (cfs)
t = Student's t coefficient for the 95% confidence level, assumed to be 2 (-)
S_d = standard deviation of measurements recorded over the test period (inch Hg)
no = number of measurements recorded over the test period
Avg = mean of measurements recorded over the test period (inch Hg)

Results and Analysis

Unit G24

Testing was completed for all three WK pressure tap configurations for G24 over a range of operating conditions. The resulting coefficients, exponents, data correlation values, and total uncertainties for each configuration are summarized in Table 2. These *K* and *n* values replace those from 1983 testing and are to be used for future WK flow measurements. These values were adjusted manually to optimize the curve fit visually and produce the highest R^2 result possible for flows greater than 12,000 cfs. R^2 values near 1 show a strong correlation between the Accusonic discharge and differential pressure measurements. The total uncertainties for discharge estimated from the WK equation are near 1% and apply to all flows greater than 12,000 cfs. WK flow estimates below this discharge will provide inaccurate flow results. Uncertainties remain valid assuming there is no change within the penstock, scroll case, or pressure taps that would influence the differential pressure reading.

In postprocessing of the Accusonic velocities for each path, data from Path 4 were removed and not used in the discharge calculation due to a malfunction with its transducer or cabling. This produced a measurement accuracy of 1.0% which is an improvement compared to a result that would have included the bad data from Path 4. Still, this is worse than the typical uncertainty of Accusonic flow meters of 0.5% when all 8 paths function properly.

Table 2. Unit G24 coefficients, exponents, correlations, and uncertainty

Pressure Taps	*K*	*n*	R^2	Uncertainty
A-D	8680.0	0.4760	0.955	1.04%
B-D	9090.0	0.4850	0.955	1.04%
C-D	10,257	0.4790	0.952	1.04%

Discharge and differential pressure readings for G24 testing are shown in Table 3 including notes about air injection at the turbine runner which was an important component for concurrent efficiency and cavitation testing. Test data are also plotted in Figure 10 through Figure 13 to show the newly calibrated WK flow curves/equations compared to the discharges measured with the Accusonic meters. There is good agreement for discharges greater than about 12,000 cfs.

These figures also compare the new calibrations to those established in 1983 for all three tap configurations. Discharge estimates using the 1983 calibrations do not agree well with current test results as they are about 3% - 8% lower depending on the flow rate. This difference is curious given the good agreement to GE's test results from 2017 (previously shown in Figure 5). One explanation may be that the 2017 Accusonic discharge measurements included Path 4 in the result which was also bad at that time and was not removed in postprocessing. Another explanation may be wear or damage near the pressure taps that could have altered the pressure measurements. This is possible as spot repairs were done to the coating in the scroll case and penstock as part of a G24 overhaul in 2014 which may have affected the WK pressure taps. Finally, the 1983 WK calibrations were based on pressure-time (Gibson method) discharge measurements, which have been known to indicate lower than actual flow rates.

Table 3. Discharge and pressure differential readings from unit G24 testing.

Test #	Accusonic Flow Meter	WK ΔP			Notes
		A-D	B-D	C-D	
-	*cfs*	*inch Hg*			-
5	5,317	0.19	0.14	0.01	No air
6	5,327	0.19	0.14	0.01	Air on thru inlet
7	8,876	0.97	0.82	0.57	No air
8	8,860	0.98	0.81	0.55	Air on thru inlet
9	10,818	1.53	1.32	0.99	No air
10	10,832	1.57	1.37	1.03	Air on thru inlet
11	12,906	2.33	2.05	1.59	No air, unit getting louder
12	12,882	2.26	1.98	1.54	air thru inlet
13	12,905	2.29	2.02	1.57	air thru cone
14	14,807	3.12	2.76	2.18	no air
15	14,806	3.08	2.69	2.12	air thru cone
16	14,764	3.13	2.66	2.05	air thru inlet
17	18,938	5.25	4.50	3.55	no air
18	18,946	5.27	4.55	3.61	air thru cone
19	22,859	7.76	6.70	5.36	no air
20	22,801	7.75	6.69	5.33	air thru cone
21	24,728	9.14	7.90	6.34	no air

Test #	Accusonic Flow Meter	WK ΔP			Notes
		A-D	B-D	C-D	
-	*cfs*	*inch Hg*			-
22	24,762	9.15	7.91	6.32	air thru cone
23	25,655	9.81	8.48	6.79	no air
24	25,678	9.89	8.54	6.83	air thru cone
25	26,729	10.66	9.25	7.42	no air, occasional banging and vibrations
26	26,719	10.70	9.26	7.41	air thru cone, banging significantly reduced
27	30,495	13.83	12.07	9.77	no air
28	30,370	13.88	12.07	9.73	air thru cone
29	31,872	15.26	13.22	10.68	No air
30	31,825	15.14	13.22	10.74	air thru cone
31	33,204	16.55	14.51	11.76	no air
32	34,639	18.06	15.78	12.79	no air

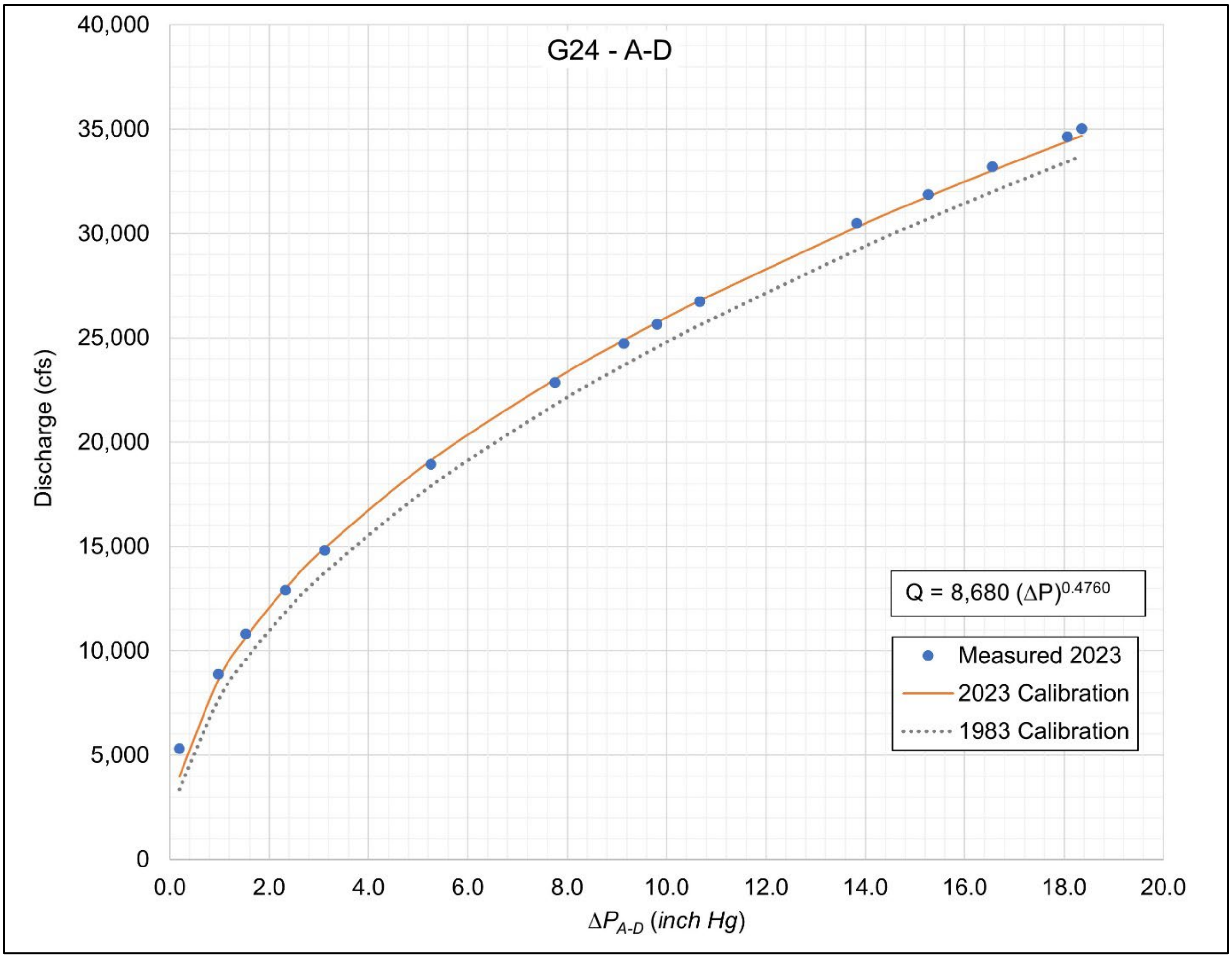


Figure 10. Plot of G24 measured discharge vs. WK configuration A-D differential pressures, with new 2023 calibration curve and old 1983 calibration.

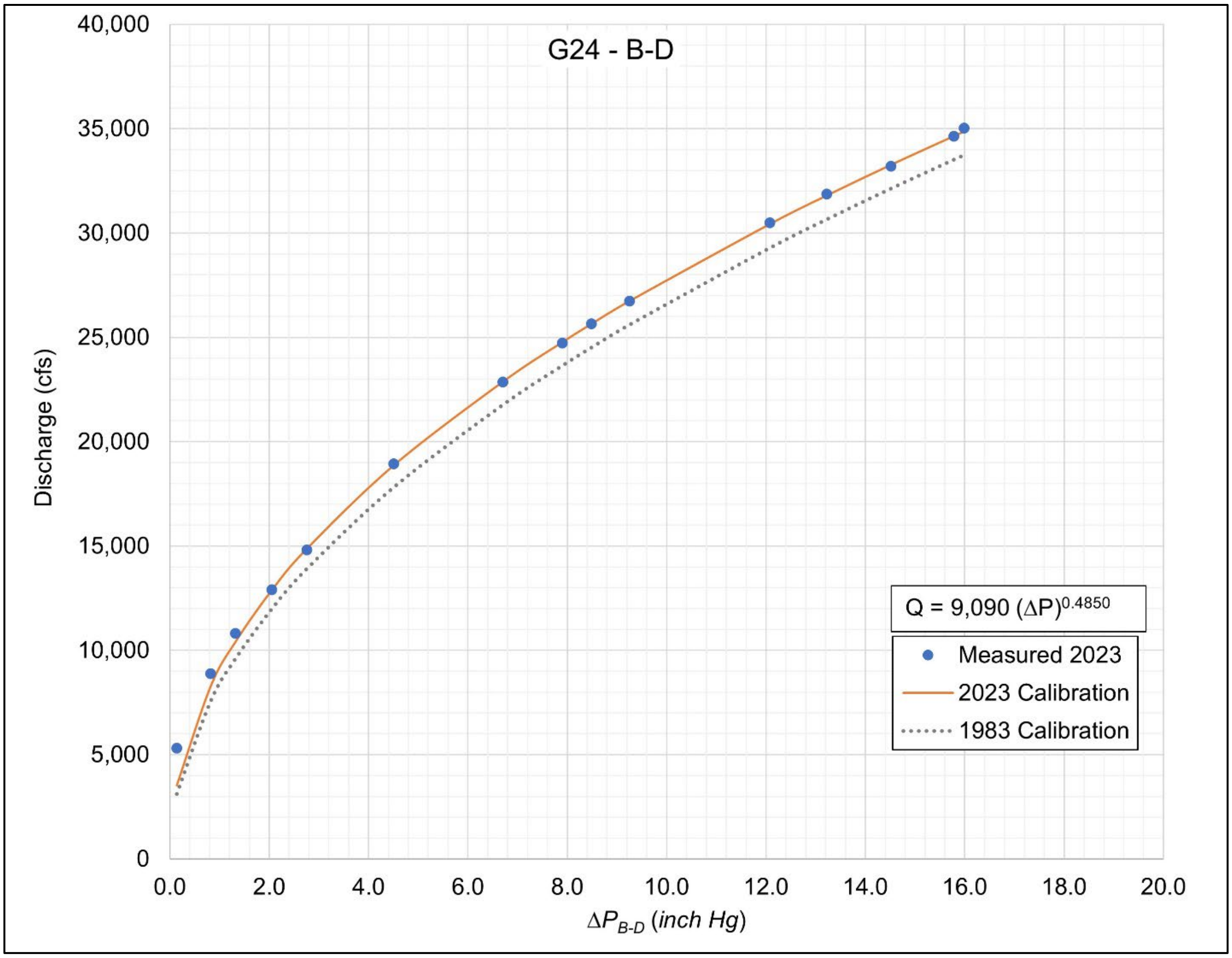


Figure 11. Plot of discharge vs. G24 configuration B-D differential pressures comparing measured data and calibrated data from 2023 testing to the 1983 calibration.

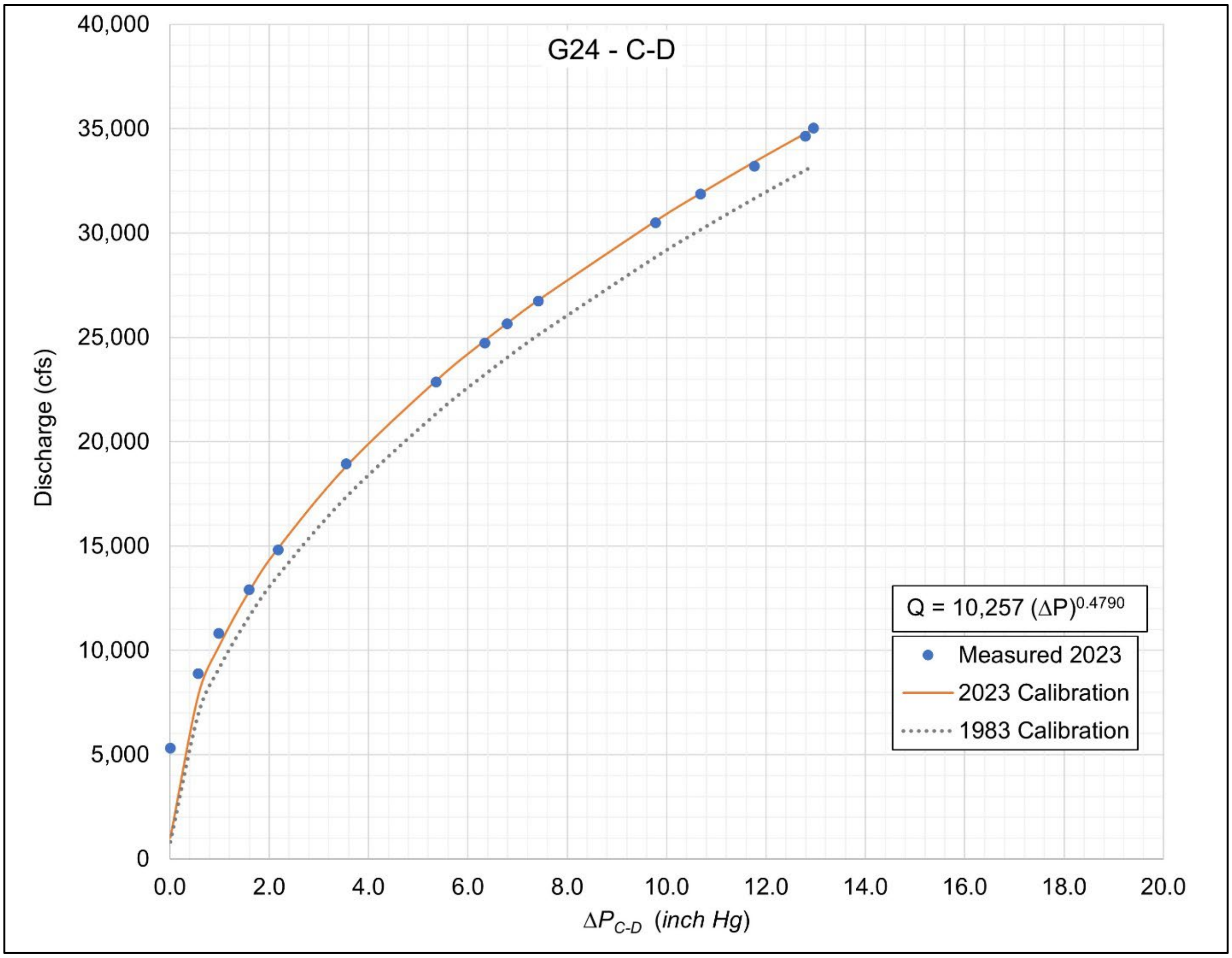


Figure 12. Plot of discharge vs. G24 configuration C-D differential pressures comparing measured data and calibrated data from 2023 testing to the 1983 calibration.

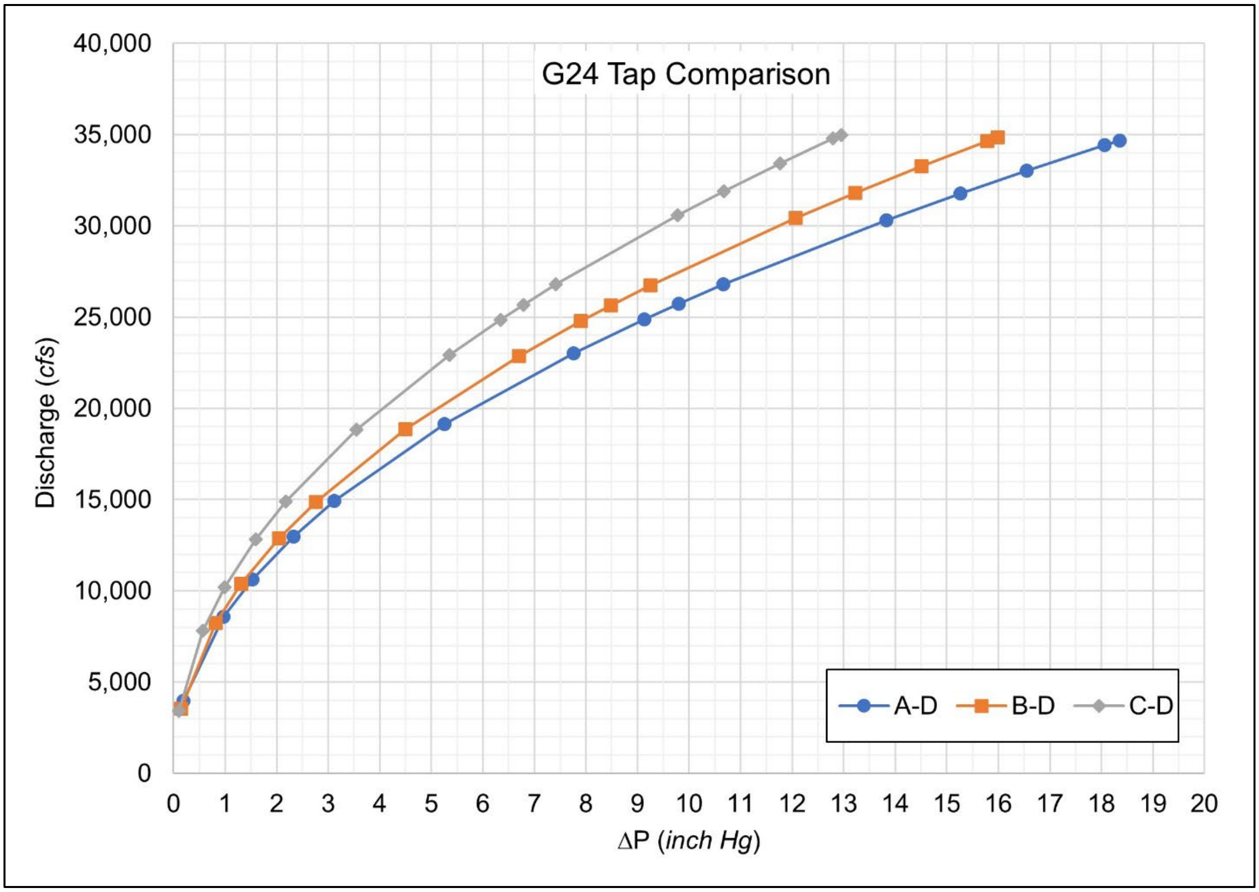


Figure 13. Plot of discharge vs. G24 differential pressures comparing 2023 calibrated data from all three WK pressure tap configurations.

Unit G20

Testing was completed for both WK pressure tap configurations for G20 over a range of operating conditions. The resulting coefficients, exponents, data correlation values, and total uncertainties for each configuration are summarized in Table 4. These *K* and *n* values are to be used for future WK flow measurements. These values were adjusted manually to optimize the curve fit visually and produce the highest R^2 result possible for flows greater than 7,000 cfs. The R^2 values near 1 show a strong correlation between the Accusonic discharge and differential pressure measurements. The total uncertainties for discharge estimated from the WK equation are near 0.6% and apply to all flows greater than 7,000 cfs. WK flow estimates below this discharge will provide inaccurate flow results. Uncertainties remain valid assuming there is no change within the penstock, scroll case, or pressure taps that would influence the differential pressure reading.

For G20 Path 3 velocities were removed during postprocessing, also due to a malfunction, but resulted in an Accusonic uncertainty of 0.6%. This is better than the estimate error of 1.0% from G24 due to the path location, more stable flow condition, and a faster refresh rate of the equipment on G20. When combined with uncertainty from the WK pressure measurements this produced an uncertainty of about 0.65% for WK flow estimates.

Table 4. Unit G20 coefficients, exponents, and uncertainty.

Pressure Taps	K	n	R^2	Uncertainty
A-C	8923.0	0.4775	0.949	0.64%
B-C	9810.0	0.4950	0.961	0.66%

Discharge and differential pressure readings for G20 testing are shown in Table 5, including notes about air injection at the turbine runner which was an important component for concurrent efficiency and cavitation testing. Test data are also presented in Figure 14 through Figure 16 to show the measured flows in comparison to the new WK calibration curves and equations. The new calibration agrees well for measured discharges greater than about 7,000 cfs.

Table 5. Discharge and pressure differential readings from unit G20 testing.

Test #	Accusonic Flow Meter	WK ΔP		Notes
		A-C	B-C	
-	*cfs*	*inch Hg*	*inch Hg*	-
1	32,636	15.06	11.30	No air, flow reading went over range - need to repeat test
2	32,643	15.12	11.36	repeat of test 1
3	30,411	13.10	9.88	no air
4	30,368	12.91	9.80	air thru cone
5	29,180	11.89	9.01	no air
6	29,166	11.95	9.02	air thru runner band
7	27,901	10.80	8.20	no air
8	27,826	10.79	8.23	air thru cone
9	26,514	9.76	7.44	no air
10	26,482	9.65	7.37	air thru runner band
11	25,051	8.69	6.59	no air
12	25,035	8.67	6.65	air thru cone
13	23,418	7.54	5.75	no air
14	23,402	7.54	5.77	air thru runner band
15	21,556	6.31	4.85	no air
16	21,524	6.38	4.92	air thru cone
17	17,855	4.30	3.38	no air
18	17,842	4.27	3.36	air thru runner band
19	13,929	2.53	2.05	no air
20	13,865	2.49	2.04	air thru cone
21	9,819	1.14	1.00	no air
22	9,796	1.14	1.00	air thru runner band
23	9,929	1.18	1.03	air thru cone, extra test
24	6,489	0.38	0.42	no air, scatter in channel 1 (B-C tap)
25	6,559	0.39	0.44	air thru cone, scatter of B-C decreased some with air
26	4,913	0.12	0.22	no air

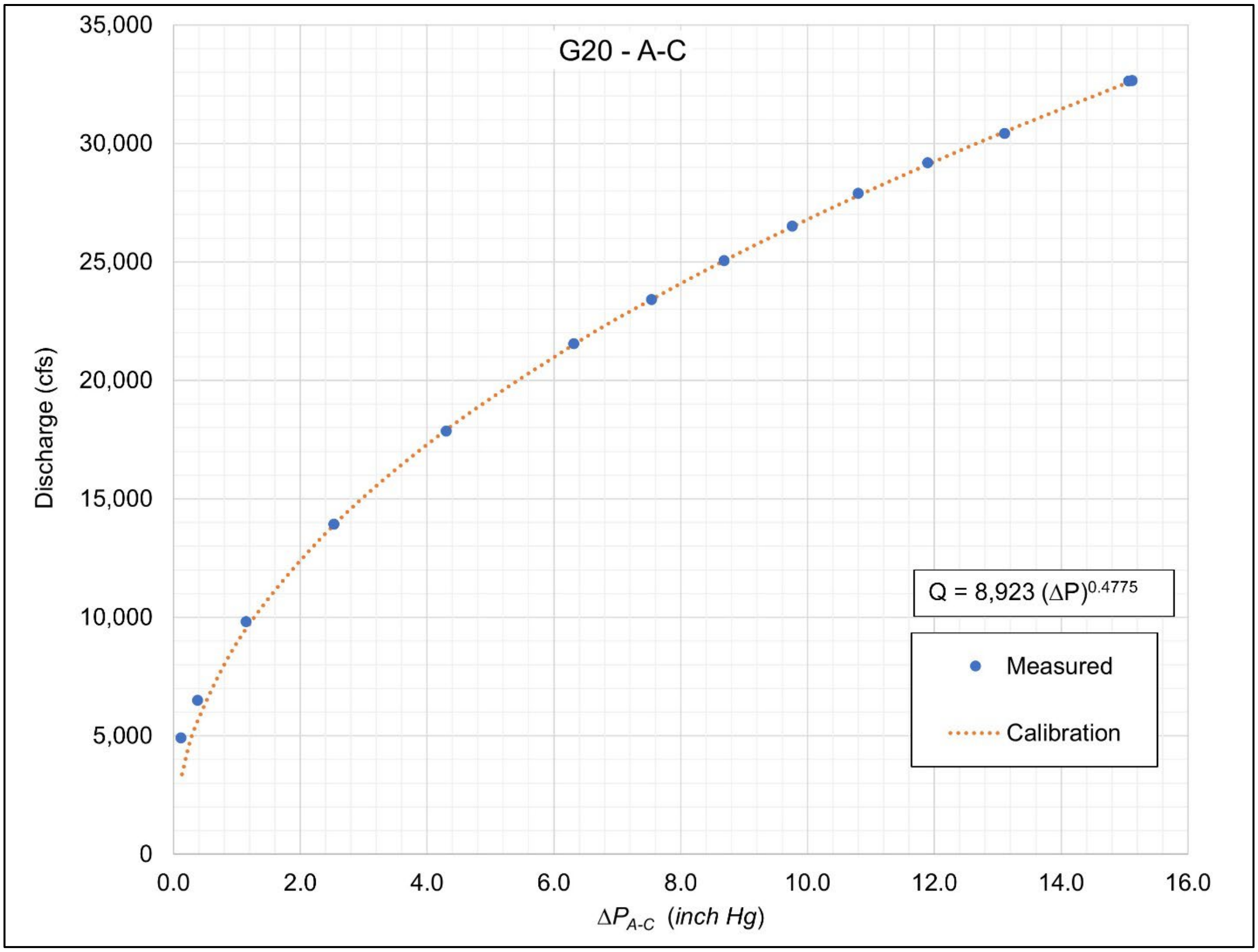


Figure 14. Plot of G20 measured discharge vs. $\Delta P_{\text{A-C}}$ differential pressures and new WK calibration curve.

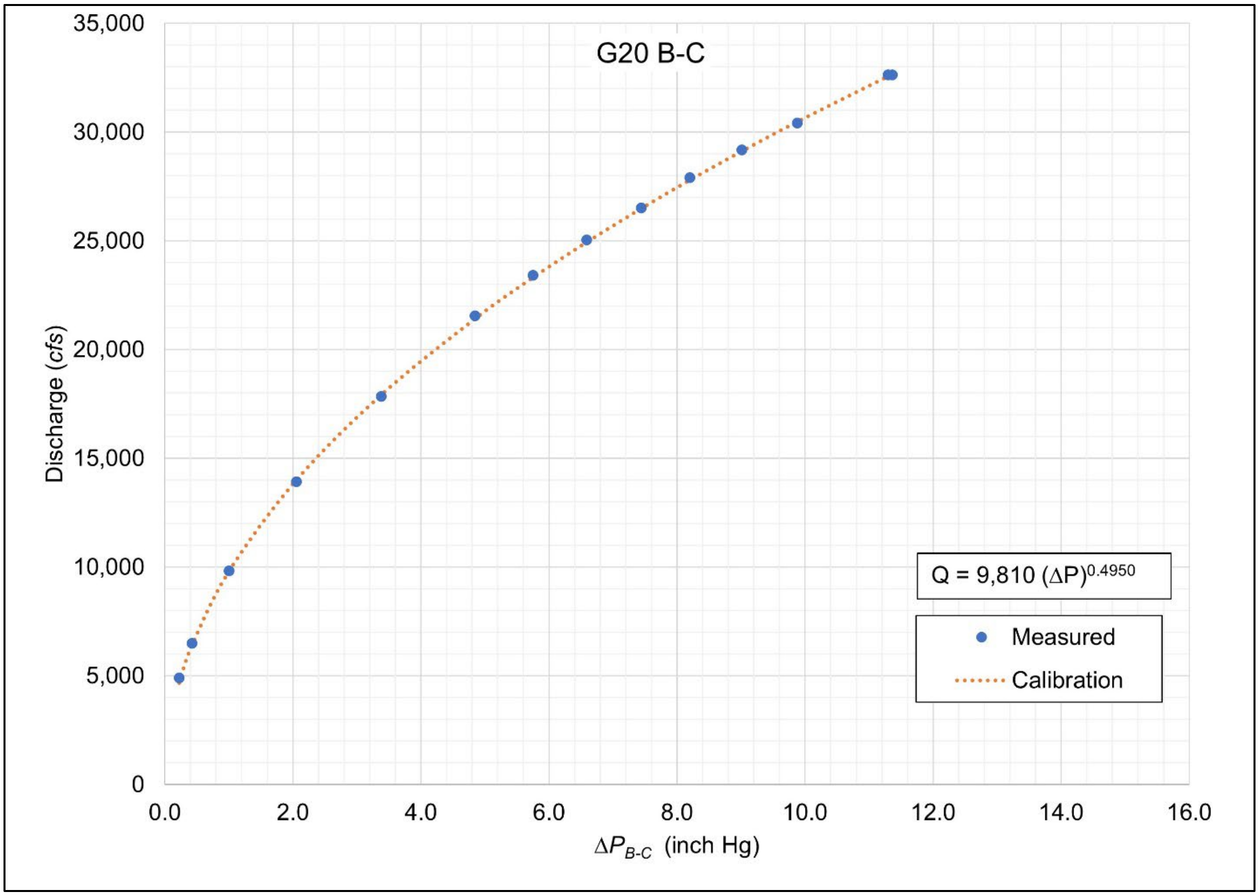


Figure 15. Plot of G20 measured discharge vs. $\Delta P_{B\text{-}C}$ differential pressures and new WK calibration curve.

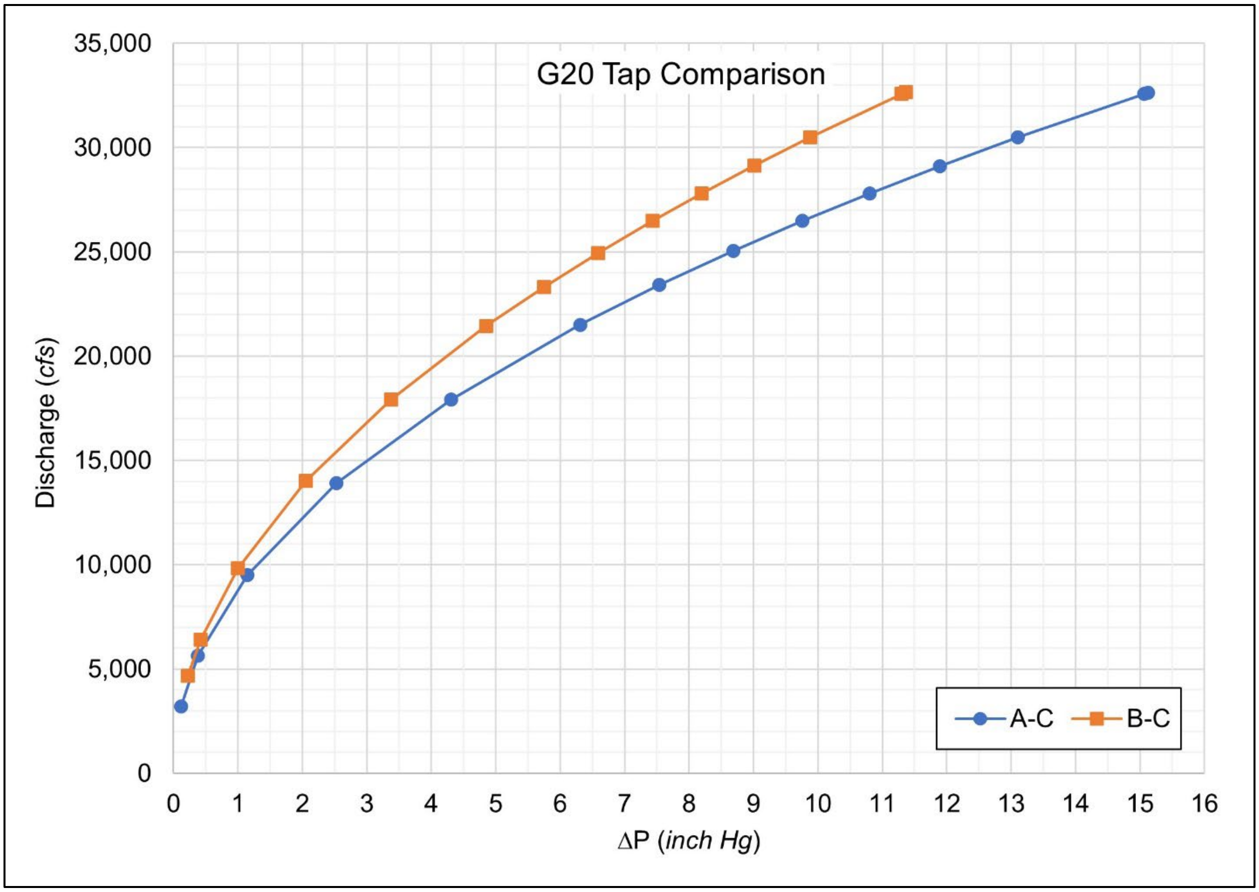


Figure 16. Plot of discharge vs. G20 differential pressures comparing 2023 calibrated data from both WK pressure tap configurations.

Air Injection Effects

For both G24 and G20, air injection at the turbine runner is commonly used to reduce problems with rough operation (draft tube surging) at partial load. Air injection had negligible effects on WK flow measurements. This is shown by the direct comparison of WK flow estimates without air to those with air in Figure 17 and Figure 18 for all pressure tap configurations of both G24 and G20, respectively. Differences were less than 2% for both units, and there is no consistent difference related to the air injection location. This result was expected since the points of air injection are far downstream from the WK pressure taps. Future use of air injection should not hinder accurate flow measurement.

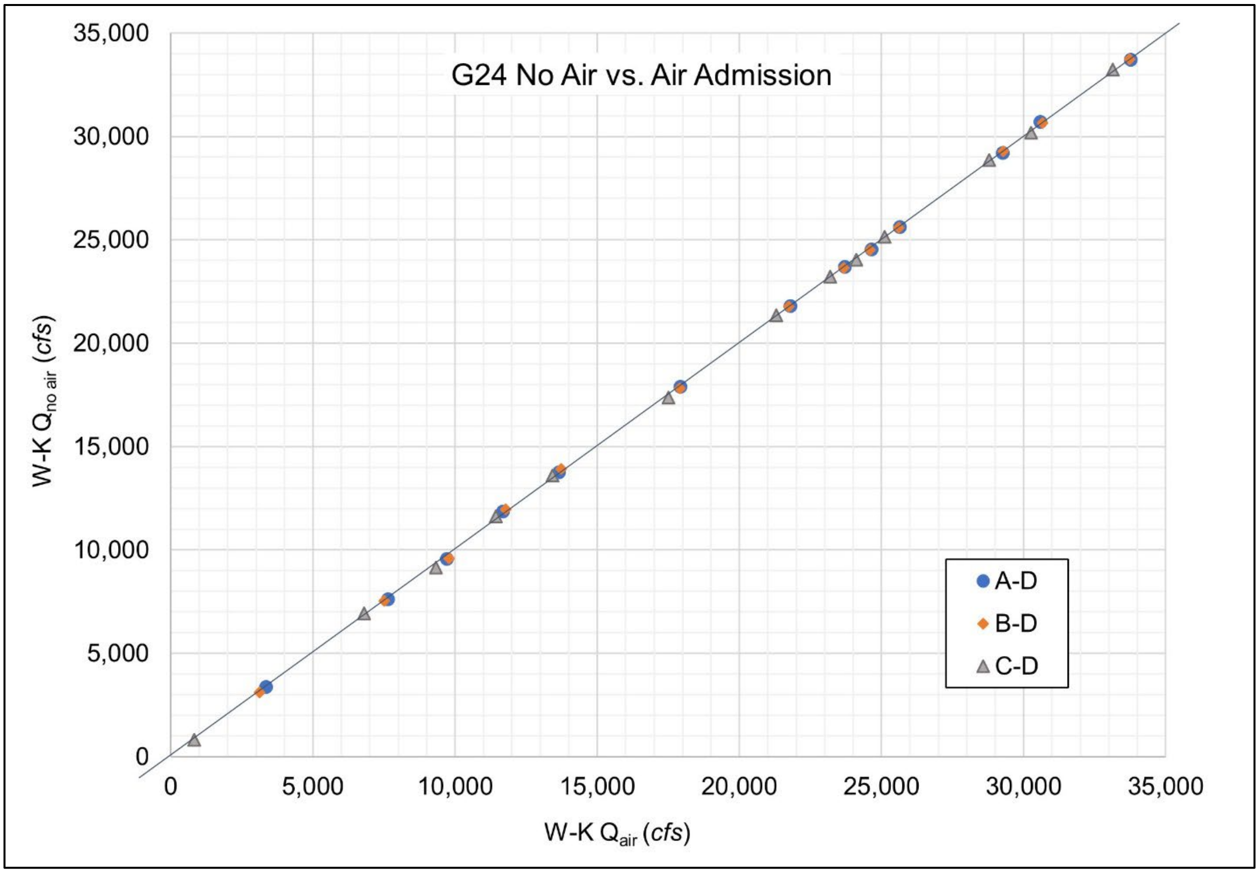


Figure 17. Comparison of G24 discharge estimates from WK pressure tap readings with and without air injected to the turbine runner during testing.

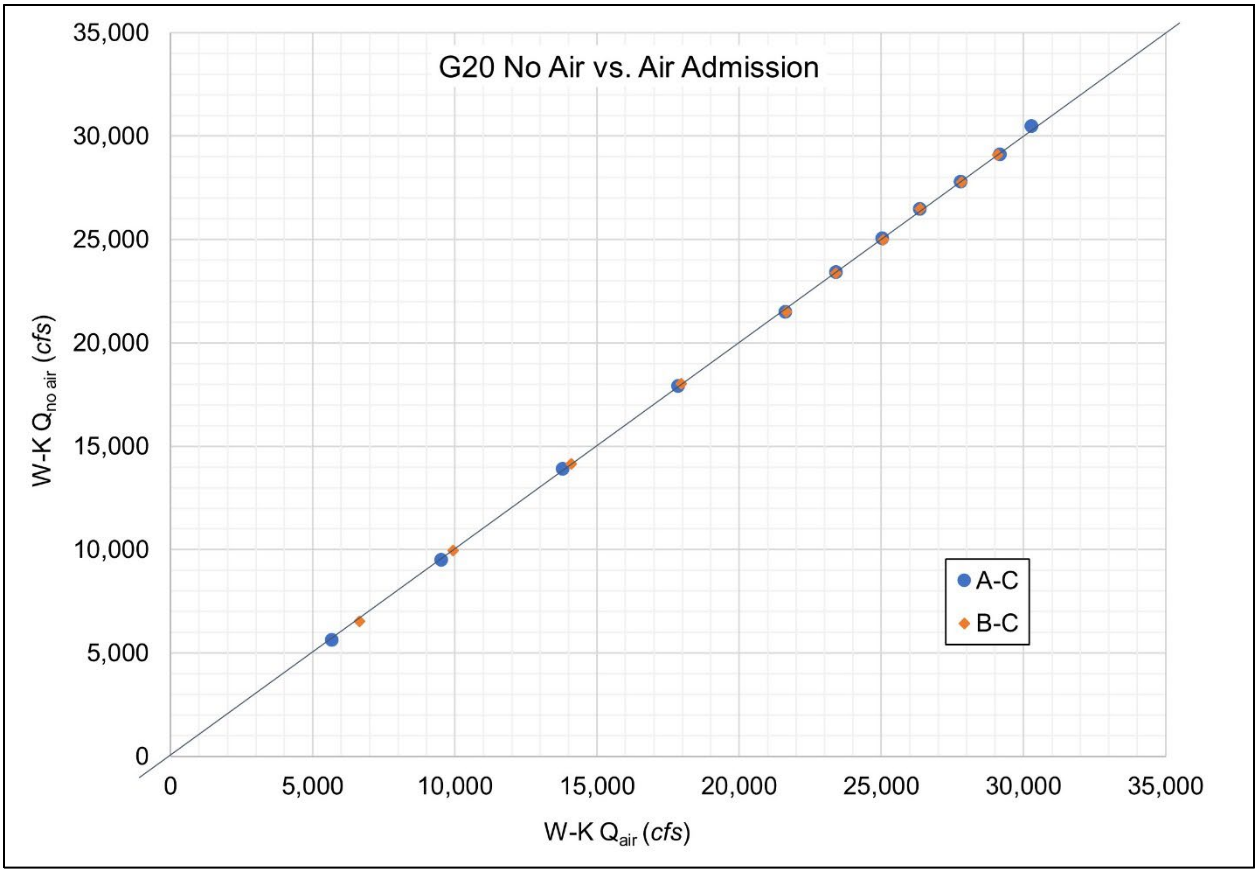


Figure 18. Comparison to G20 discharge estimates from WK pressure tap readings with and without air injected to the turbine runner during testing.

Practical Considerations

While new WK flow equation coefficients have been established for all pressure tap configurations for both G24 and G20, some practical aspects of measuring the differential pressures are also important to produce an accurate discharge reading. First is the condition of the pressure taps in the scroll case. These should be flush with the inside surface with no irregularities in the vicinity of the taps that would affect the local pressure. These may include wear, coating damage, welding, or other surface flaws. Larger scale modifications to the intake, penstock, scroll case, or turbine runner that could alter the flow distribution at the pressure taps could also affect the WK flow measurements (Rau & Eissner, 2014). Any changes to or near the pressure taps will warrant a new test to reestablish flow coefficients.

Correct operation of the differential pressure sensors is also important for accurate measurements. Care should be taken to avoid over pressurizing one side of the sensor by opening flow from one tap before the other. When opening valves on the piping both sides of the sensor should be pressurized evenly. Built-in valves on the sensor manifold (different than the shutoff valves of the piping manifold) will help facilitate this. When starting up, flow should be allowed to flush from each pressure tap for several minutes to ensure all air bubbles and debris have been removed from the tap piping.

Any of the pressure tap configurations may be used for WK flow measurement if the respective coefficient and exponent are applied to the flow equation correctly. It may be preferred to use the first configuration for flow measurements (A-D for G24 and A-C for G20) as they provide the greatest range of differential pressures to be measured.

Conclusions and Recommendations

Flow (Accusonic flow meter) and differential pressure (Winter-Kennedy taps) readings were recorded over a range of operating conditions with and without air injection on units G24 and G20 in the Grand Coulee Third Powerhouse concurrently with testing for unit efficiency. These measurements established new coefficients and exponents for the Winter-Kennedy flow equation for each unit and each respective pressure tap configuration. Uncertainties associated with these flow measurements were also estimated for each configuration. The coefficients and exponents determined for G24 replace those previously established from 1983 testing. Air injection at the turbine runner did not affect the Winter-Kennedy readings. Any modifications to key components of the penstock that may alter flow conditions near the Winter-Kennedy taps (e.g., surface irregularities, coating damage, welding, etc.) will likely affect pressure readings and require recalibration.

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