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INSTALLATION OF 4 AND 8-PATH ACOUSTIC FLOW METERS IN GURI HYDROELECTRIC POWER PLANT

by

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Résumé:

Après une brève description du complexe Guri et des usines hydro–électriques de la rivière du bas Caroni, cet article décrit l'installation des traducteurs acoustiques dans les conduites existantes, compare les mesures de débit obtenues à l'aide de 4 trajectoires simples versus 8 trajectoires croisées, souligne l'importance d'un choix adéquat pour la localisation du centre acoustique et décrit brièvement la méthode de mesure continue du débit relatif devant être utilisée sur les groupes qui ne sont pas munis de débitmètre acoustique.

Summary:

Following a brief description of Guri and Lower Caroní River Hydro Power Plants, the paper describes the installation of acoustic transducers in the existing penstocks, compares the results of discharge measurements using 4-path single and 8-path crossed acoustic planes, underlines the importance of an appropriate selection of the acoustic center location and briefly describes the method of continuous relative discharge measurement to be used in the Units not provided with acoustic flow meters.

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A. GURI AND LOWER CARONI RIVER HYDROELECTRIC DEVELOPMENT.

Designed in conjunction with Harza Engineering Company, built and operated by C.V.G. Electrificación del Caroní (EDELCA) in Bolívar State in the eastern part of Venezuela, the Guri Power Plant is located on the Caroní River, some 95 km upstream of its confluence with Orinoco. The development was planned and constructed in two principal stages. In the first stage the main concrete and lateral rock filled gravity dams created a reservoir with a useful volume of some 11,000 $\times 10^6$ m^3 between its maximum normal level at EL. 215.00 and the minimum operating level at EL. 195.00. A spillway designed for the P.M.F. of 30,000 m^3/s was constructed and 10 vertical shaft Francis Units were installed in several steps in Powerhouse No. 1. There are 4 groups of Units in Powerhouse No. 1, with turbines ranging in the output from 180 to 400 MW. The turbines were designed to operate at higher heads, but until the final stage construction was finished in 1986, they operated at the average head of 85 m (maximum head of 92 m) and their capacity was 1,810 MW at the average and 2,070 MW at the maximum head. Fig. 1 shows Guri Power Plant just before the final stage construction began.

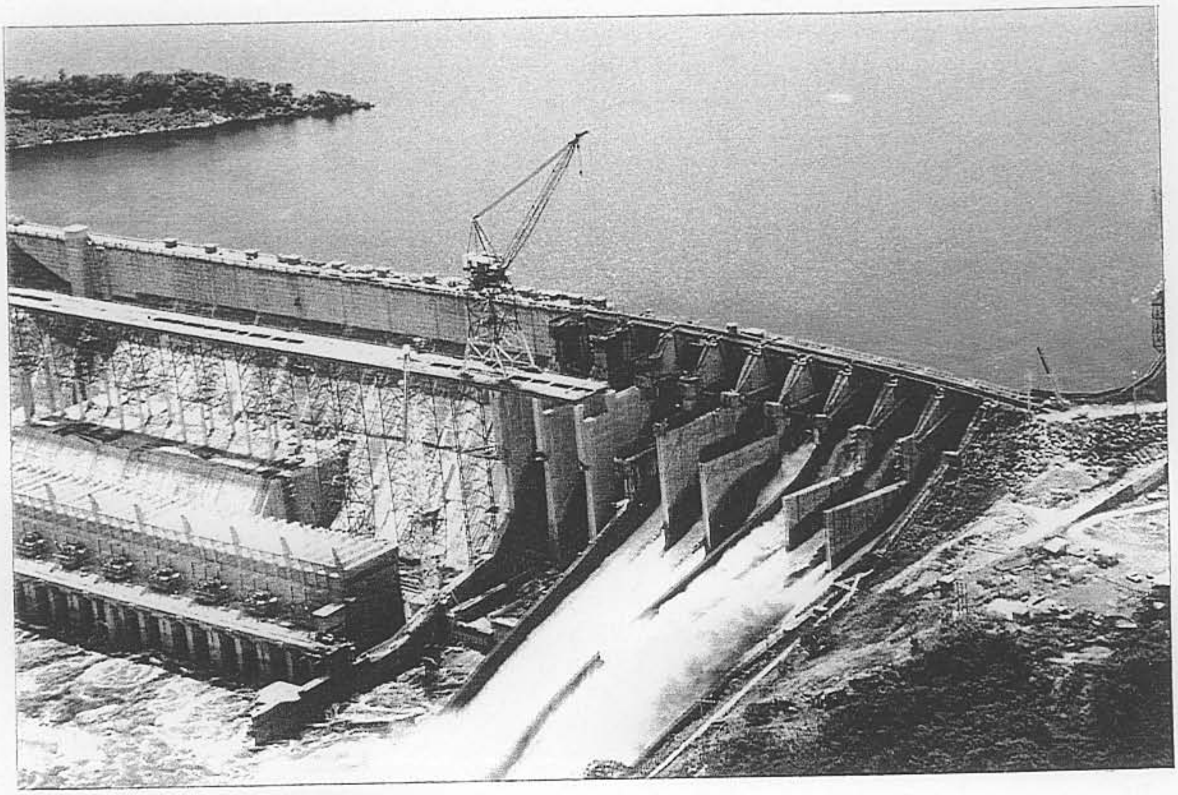

FIG. 1 Guri I Completed

In the final stage the dams and the spillway were gradually raised, the maximum reservoir level was increased by 55 m and the useful reservoir volume, operating between the maximum EL. 270.00 and the minimum design EL. 240.00, went up to 80,900 x 10^6 m^3. Powerhouse No. 2, equipped with 10 - 730 MW Francis turbines designed to operate at the head range of 111 to 146 m was constructed and placed in operation. Powerhouse No. 1 total turbine output was increased to 3,000 MW and the total installed turbine capacity is now 10,300 MW at the maximum net head of 146 m and 9,715 MW at the average head of 138 m. Fig. 2 shows the completed Guri Power Plant.

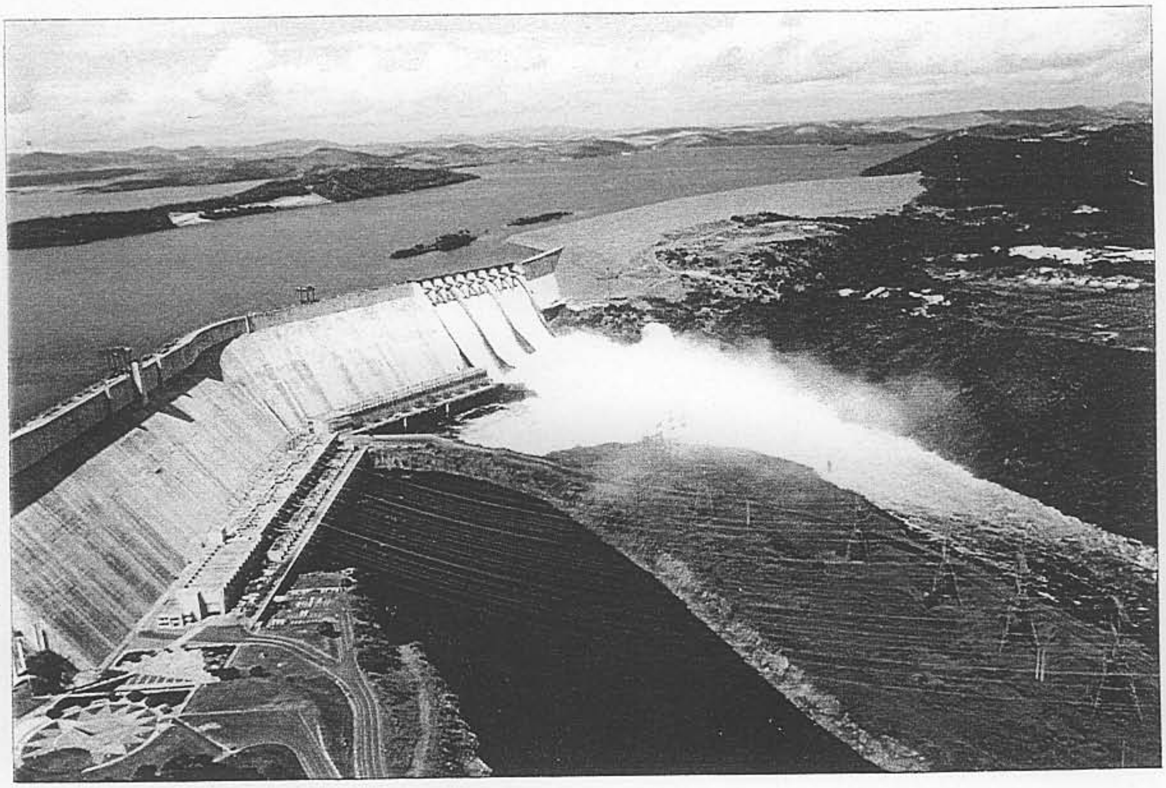

FIG. 2 Guri Final Stage Completed

In an average year Guri generates about 50,000 GWh and covers a substantial part of country's electric energy needs. Its large reservoir, with the capacity for multi annual flow regulation, paved the way for very economical hydroelectric development on Lower Caroní River. Fig. 3 shows the downstream power plants: Tocoma in planning stage, will have installed turbine capacity of 2,260 MW, Caruachi in early construction stage (Fig. 4), with 12 - 188 MW Kaplan turbines and Macagua II under final installation and commissioning stage (Fig. 5), with 12 - 216 MW Francis turbines in Powerhouse No. 2 and 2 - 88.2 MW Kaplan turbines in Powerhouse No. 3. Macagua Powerhouse No. 1, equipped with 6 - 70 MW Francis turbines was constructed and placed in operation in early sixties.

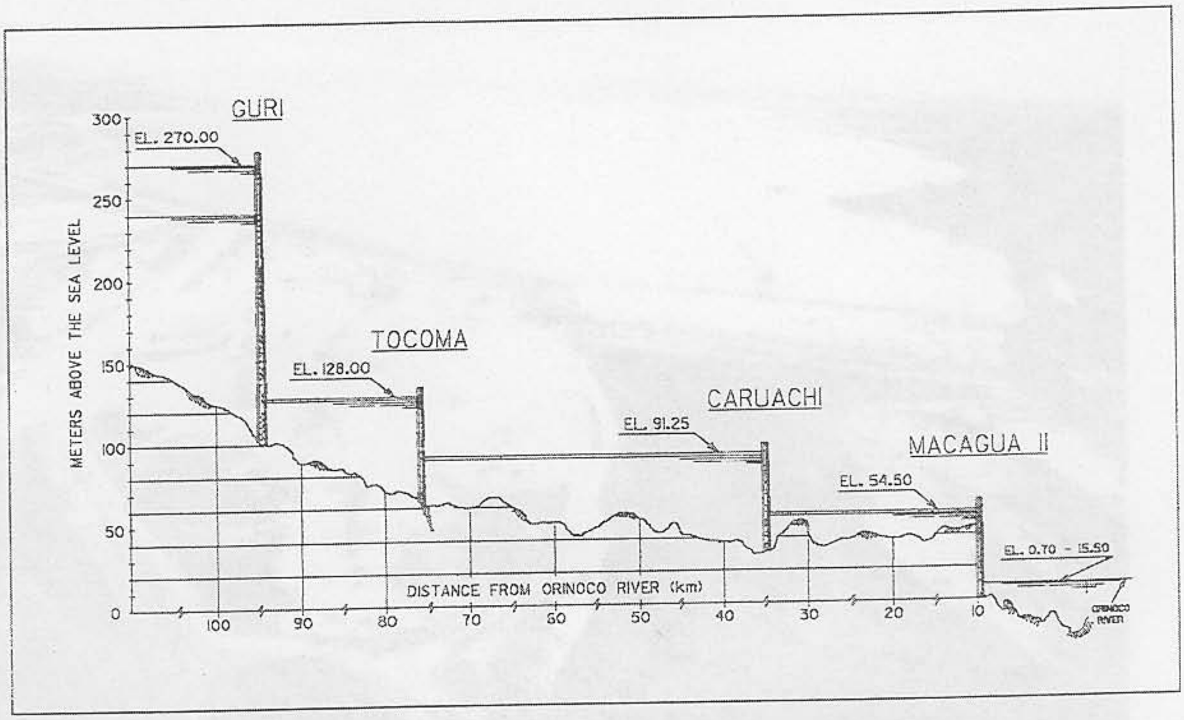

FIG. 3 Guri and Lower Caroní River Hydroelectric Development - Normal Maximum Reservoir Levels

FIG. 4 Caruachi - Early Construction Stage

FIG. 5 Macagua II-Commissioning Stage

When lower Caroní River development is finished, the total installed turbine capacity, Guri included, will be around 17,000 MW and the annual energy production will reach an average of 90,000 GWh.

B. NECESSITY OF TURBINE DISCHARGE MEASUREMENT

The lower Caroní River Hydroelectric Power Plants have rather limited reservoir capacities. To secure the most economical daily operation of the tandem of Power Plants, the System Planning Division must have at its disposal a wide range of information, the discharges from Guri and from the other Plants amongst them. All Lower Caroní turbines (except Macagua, Powerhouse No, 1) are or will be provided with continuous discharge measurement and totalizers of volume of water released from the reservoir over a selected period of time. Since reliable continuous flow measuring equipment was not available when Guri was designed and constructed, this leading plant of the tandem was left with only the Winter - Kennedy relative flow meters which have proven to be rather inaccurate and unreliable. Studies of installation of acoustic transducers in the existing penstocks, ranging from 6.5 to 10.5 m in diameter, were initiated in late eighties and as of 1994, 3 Units in Powerhouse No. 1 and 2 Units in Powerhouse No. 2 are equipped with the acoustic flow meters. One more flow meter in Powerhouse No. 2 will be commissioned by the end of 1996. The discharge measuring system contemplated for the remaining 14 Units is discussed in Part E of this paper.

C. INSTALLATION OF ACOUSTIC TRANSDUCERS IN EMBEDDED PENSTOCKS

Comprehensive studies of acoustic transducer installation were conducted in close cooperation with Accusonic Division, ORE International Inc. of Falmouth Massachusetts. The company offered their 7630 - X45 Series transducers with redundant elements, designed to be mounted on the inside face of the penstock liner (Fig. 6). The problem to be solved was how to get the

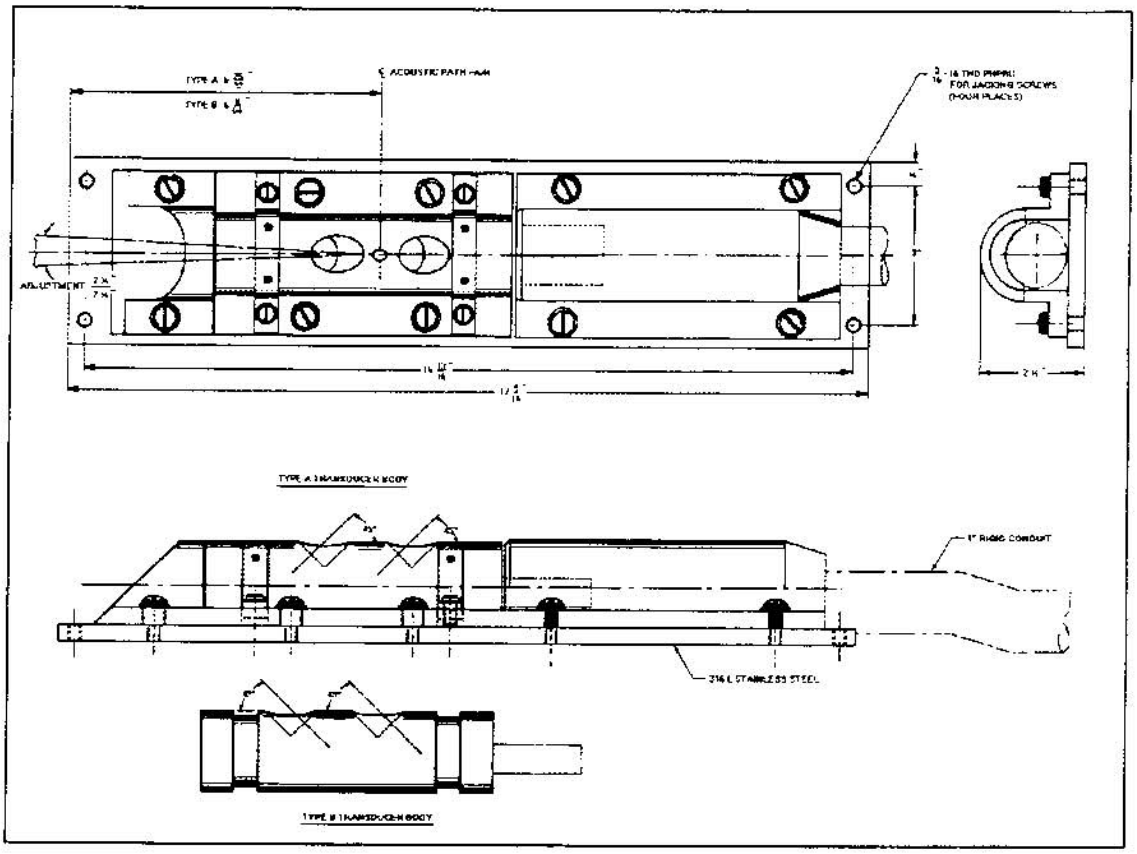

FIG. 6 7630- x 45 Series Acoustic Transducers

cables out of the penstock. One possibility was to route the cables out through the penstock - spiral case drain box and piping. Relatively easy to accomplish, this alternative was rejected since it would require to locate a rather flat acoustic plane just downstream of the penstock reducing elbow and very close to the spiral case conical inlet, or to locate the plane some distance upstream of the elbow and make a very long runs of stainless steel pipes with submarine cables all the way down to the drain box.

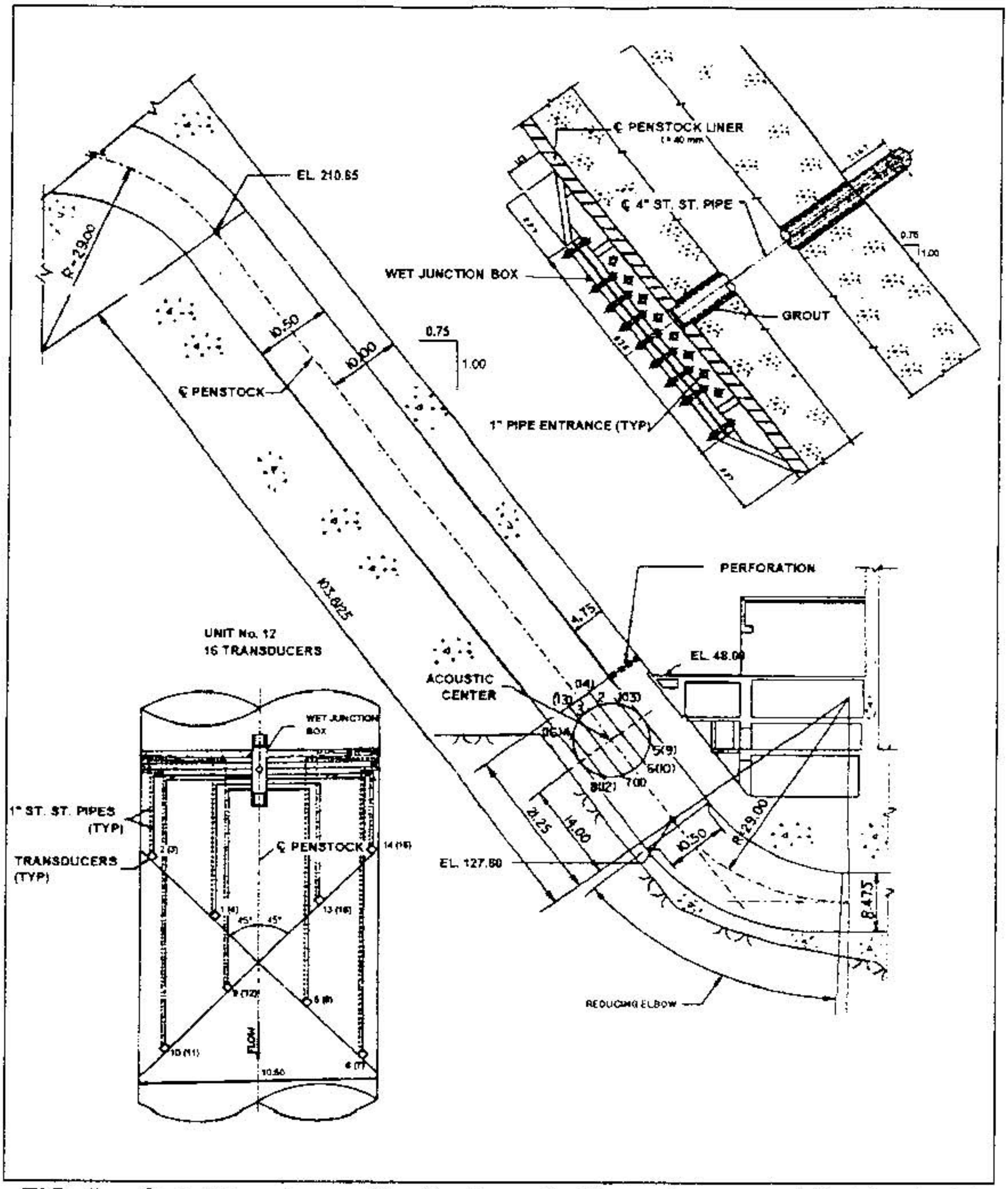

FIG. 7 Guri Powerhouse No. 2 - Acoustic Transducers and Cables inside the Penstock

The solution which was finally adopted is shown in Figures 7 and 8. In Powerhouse No. 2 penstocks (ID 10.5m), the acoustic plane center was placed about 1.45 x penstock ID upstream of the reducing elbow. This leaves approximately 90 m (8.55 x ID) of straight penstock upstream of the acoustic plain center. The transducer cables, placed inside 1 " diameter stainless steel pipes clamped to the base plates welded to the penstock liner, were routed to a robust steel junction box. Before welding the junction box base to the penstock liner, the dam was perforated, a 4 " stainless steel pipe was placed and welded to the liner and the gap between the pipe and the concrete was grouted under pressure. The submarine cable penetrators and the dry junction box are located on the surface of the dam and from there the simple, shielded cables are routed in the shortest feasible way to the flow meter located close to the control board of the corresponding Unit. The cable penetrators and dry junction box on the face of the dam are shown in Fig. 9 (Single acoustic plane - 8 transducers) and Fig. 10 (Crossed plane - 16 transducers). The same concept is used for Powerhouse No. 1 Units except that, due to the different geometry of the penstock dictated by two stages of dam construction, the straight length of penstock upstream of the acoustic plane is somewhat reduced. The acoustic plane in all Units is inclined 45° from the penstock centerline. After some initial difficulties caused mostly by signal interference due to insufficient shielding of transducer cables, all flow meters are functioning well and so far there was no need to replace or realign any of the transducers.

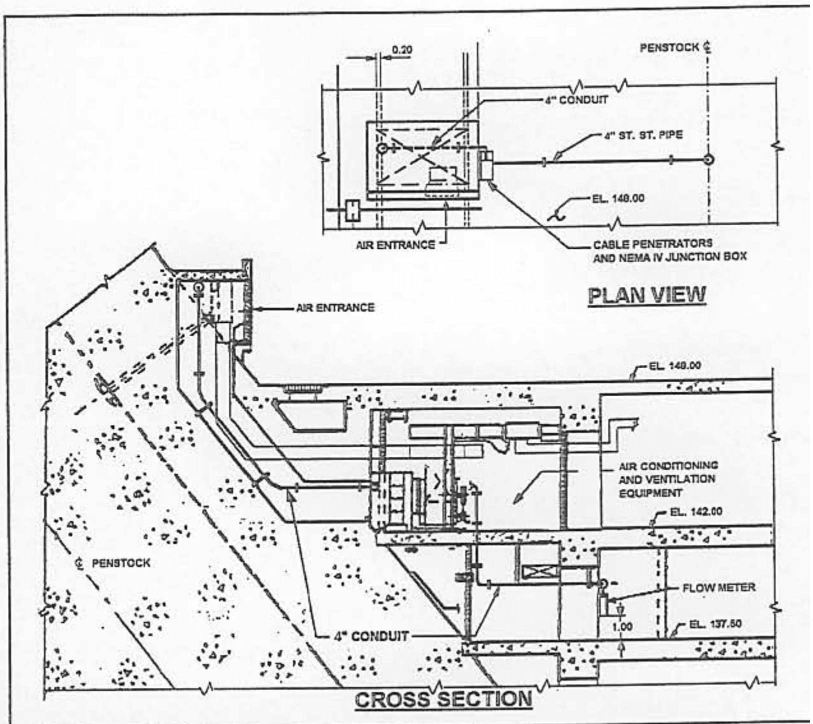

FIG. 8 Routing of Transducer Cables outside the Penstock

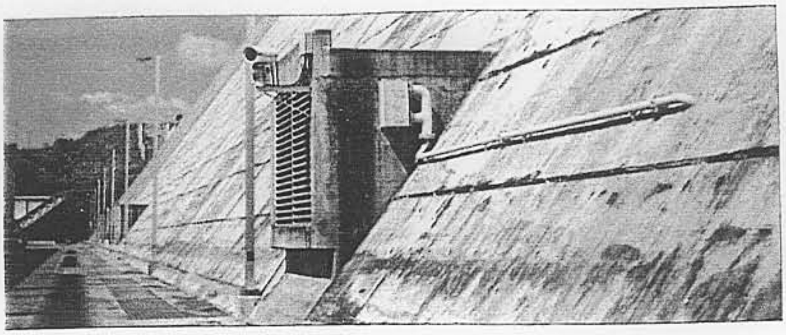

FIG. 9 Cable Penetrators and Dry Junction Box. 4-Path, 8 Transducer Arrangement

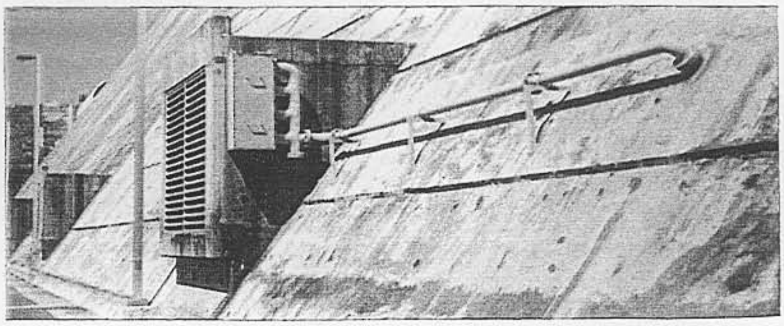

FIG. 10 Cable Penetrators and Dry Junction Box. 8-Path, 16 Transducer Arrangement

D. SINGLE OR CROSSED ACOUSTIC PLANE

Out of the 5 Units provided with the acoustic flow meters, 4 have a single acoustic plane formed by 4 trajectories (8 transducers). Although the repeatability of discharge measurements in the normal operating range is very good, it was decided to check if the precision of discharge measurement could be improved by sampling the velocities in two acoustic planes which are perpendicular to each other (Fig. 11). This was done in the penstock of Unit No. 12 where 16 transducers were installed. Tests were conducted and the results, summarized in Table 1 show that in the normal operating range the error caused by uneven flow distribution is negligible and installation of additional transducers to form the second acoustic plane is not justified. This indicates the importance of appropriate location of the acoustic center, leaving sufficient length of straight penstock upstream and downstream, as well as of the angle of inclination of the acoustic plane which, if possible, should not exceed 45° measured from the penstock centerline.

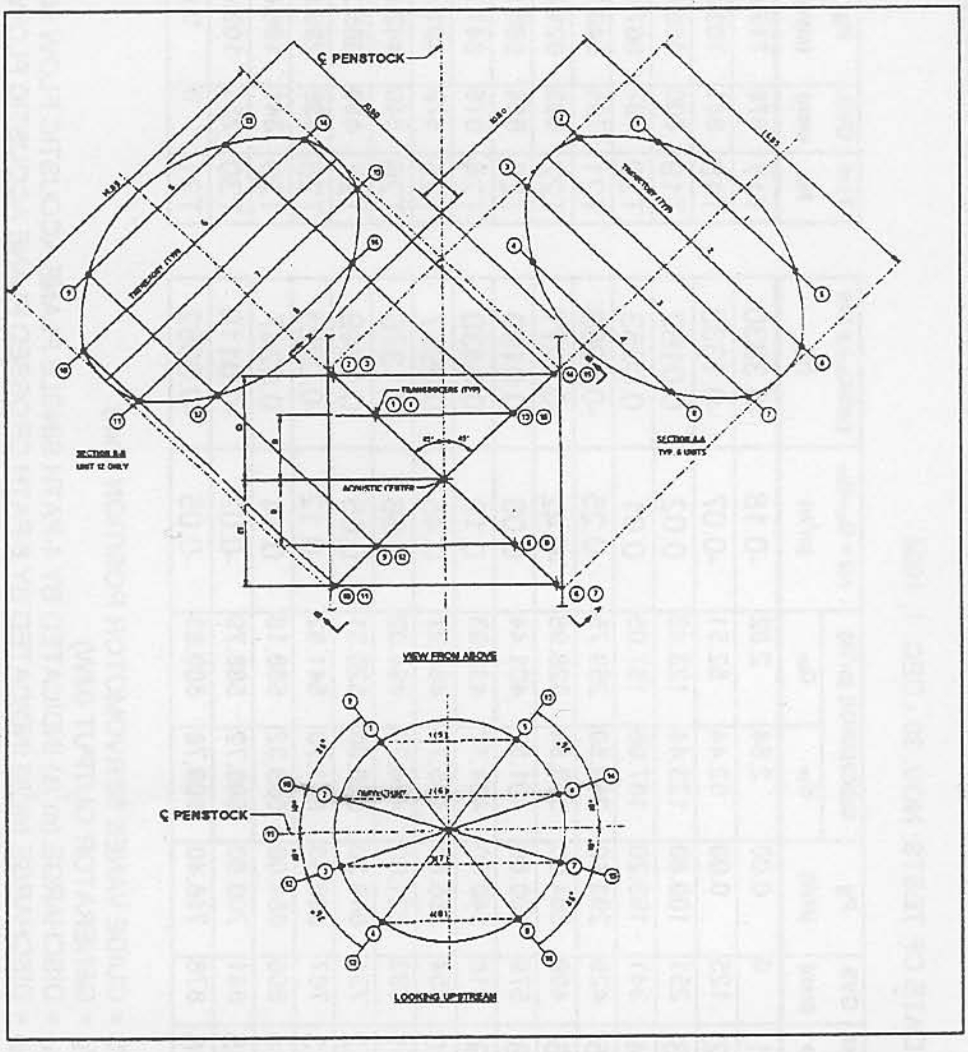

FIG. 11 4-Trajectory Single and 8-Trajectory Crossed Acoustic Planes

TABLE 1

UNIT No. 12 DISCHARGE MEASUREMENTS - SINGLE (4-PATH) AND CROSSED (8-PATH) ACOUSTIC PLANES

DATE OF TESTS: NOV. 30 - DEC. 1, 1994

GROSS HEAD 143.10 m ~ 144.40 m

Test No	GVS (mm)	Pg (MW)	DISCHARGE (m^3/s)		$\Delta Q = Q_{4P}-Q_{8P}$ (m^3/s)	$(\Delta Q/Q_{8P}) \times 100$ (%)
			Q_{4P}	Q_{8P}		
T1	0	0.00	2.64	2.82	-0.18	-6.3830
T2	125	0.00	52.44	52.51	-0.07	-0.1333
T3	251	100.80	123.44	123.42	0.02	0.0162
T4	341	193.20	187.06	187.05	0.01	0.0053
T5	426	293.40	259.50	259.75	-0.25	-0.0962
T6	499	384.00	328.54	328.96	-0.42	-0.1277
T8	579	490.80	401.52	401.44	0.08	0.0199
T9	616	540.60	434.12	433.93	0.19	0.0438
T10	654	586.80	465.72	465.27	0.45	0.0967
T11	693	621.60	494.70	494.02	0.68	0.1376
T12	731	649.20	520.96	520.31	0.65	0.1249
T13	767	666.60	541.70	541.82	-0.12	-0.0221
T14	806	684.00	566.32	566.18	0.14	0.0247
T15	841	700.80	588.72	588.79	-0.07	-0.0119
T16	878	716.40	609.78	609.83	-0.05	-0.0082

Test No	GVS (mm)	Pg (MW)	DISCHARGE (m^3/s)		$\Delta Q = Q_{4P}-Q_{8P}$ (m^3/s)	$(\Delta Q/Q_{8P}) \times 100$ (%)
			Q_{4P}	Q_{8P}		
T17	878	717.60	609.36	609.25	0.11	0.0181
T18	841	703.80	589.80	589.64	0.16	0.0271
T19	806	685.80	568.26	567.74	0.52	0.0916
T20	767	667.80	545.56	545.64	-0.08	-0.0147
T21	731	649.20	522.58	522.43	0.15	0.0287
T22	693	621.00	495.62	495.61	0.01	0.0020
T23	654	588.00	467.66	467.18	0.48	0.1027
T24	616	541.20	435.44	435.78	-0.34	-0.0780
T25	579	491.40	402.70	402.50	0.20	0.0497
T26	540	442.80	368.70	368.53	0.17	0.0461
T27	498	385.20	329.64	329.76	-0.12	-0.0364
T28	426	295.80	262.90	263.07	-0.17	-0.0646
T29	341	198.00	190.78	190.85	-0.07	-0.0367
T30	251	102.60	126.00	126.18	-0.18	-0.1427
T31	* 0	0.00	2.84	2.88	-0.04	-1.3889

GVS = GUIDE VANES SERVOMOTOR POSITION (mm)
Pg = GENERATOR OUTPUT (MW)
Q_{4P} = DISCHARGE (m^3/s) INDICATED BY 4-PATH SINGLE PLANE ACOUSTIC FLOW METER
Q_{8P} = DISCHARGE (m^3/s) INDICATED BY 8-PATH CROSSED PLANE ACOUSTIC FLOW METER

* READINGS TAKEN 30 MINUTES AFTER UNIT SHUT DOWN

Rather large differences in the flow readings can be observed in the Table, indicating the existence of significant secondary flows in the penstock when the Unit is shut down and a very small flow, caused by the leakage around the guide vanes, is measured. This of course, does not have much to do with the main purpose of the discharge measurement in Guri and the additional expenses and time for installation of the second acoustic plane in all Units are not justified.

E. DISCHARGE MEASUREMENT IN THE REMAINING UNITS

By the end of this year 6 out of 20 Guri turbines will be provided with the acoustic flow meters. The acoustic flow meters could also be furnished for the remaining 14 Units to secure the monitoring of the Plant discharge. However, the transducer installation in the penstock is time consuming (about 9 weeks) and expensive and an alternative solution, which would not require to shut down the Unit for more than a week, was to be found.

The forebay and tailrace water levels (the gross head) and the generator output can be permanently monitored. The generator efficiency and the prototype turbine characteristics can be confirmed and/or corrected according to the field test results obtained in similar Units provided with the flow meters. The intake and penstock losses, once measured, can be expressed as a function of the flow and the net head can be established. Having all these elements, the turbine discharge at any given time can easily be computed. This method could yield satisfactory results for turbines of identical hydraulic design, equipped with fabricated, N-C machined runners, when a good hydraulic similarity of all prototypes is secured. For the integrally cast, hand finished runners (like those of Guri) the profile similarity from runner-to-runner and even from blade-to-blade may be rather limited and not negligible differences of turbine characteristics may exist. Therefore, we opted for the turbine discharge simulation based on the net head and guide vane opening. The net head-guide vane opening-discharge relationship established in the field test of similar Units provided with the flow meters is used.

Guide vane servomotor position was utilized to determine the guide vane opening. This was proven to be unreliable and inconsistent. The clearances in the guide vane operating elements, (increasing in time due to the wear) cause histeresis of the mechanisms and the vane opening (angle) is smaller when the new position is reached by opening and larger when the same servomotor position is obtained by closing the guide vanes. This tendency is indicated in Table 2, where discharges measured at the same servomotor position approached by opening or closing the guide vanes are compared. The results are only indicative. The head variation during the tests and small differences between the measured and the true servomotor position have not been evaluated.

TABLE 2

DIFFERENCE IN TURBINE DISCHARGE WHEN THE SERVOMOTOR POSITION IS USED TO DETERMINE THE GUIDE VANE OPENING

OPENING		GVS	CLOSING		$\Delta Q_{C-O} = Q_{8PC} - Q_{8PO}$	$(\Delta Q_{C-O}/Q_{8PO})x100$
Test No.	Q_{8PO} (m^3/s)	(mm)	Q_{8PC} (m^3/s)	Test No.	(m^3/s)	(%)
T3	123.24	215.00	126.18	T30	2.94	2.39
T4	187.05	341.00	190.85	T29	3.80	2.03
T5	259.75	426.00	263.07	T28	3.32	1.28
T8	401.44	576.00	402.50	T25	1.06	0.26
T9	433.93	616.00	435.78	T24	1.85	0.43
T10	465.27	654.00	467.18	T23	1.91	0.41
T11	494.02	693.00	495.61	T22	1.59	0.32
T12	520.31	731.00	522.43	T21	2.12	0.41
T13	541.82	767.00	545.64	T20	3.82	0.71
T14	566.18	806.00	567.74	T19	1.56	0.28
T15	588.79	841.00	589.64	T18	0.85	0.14

GVS = GUIDE VANE SERVOMOTOR POSITION (mm)

Q_{8PO} = DISCHARGE (m^3/s) INDICATED BY 8-PATH ACOUSTIC FLOW METER WHEN THE GVS IS REACHED BY OPENING THE GUIDE VANES

Q_{8PC} = SAME AS ABOVE, WHEN THE GVS IS REACHED BY CLOSING THE GUIDE VANES

* THE RESULTS ARE ONLY INDICATIVE. HEAD VARIATION DURING THE TESTS AND SMALL DEVIATIONS (± .6mm) OF TRUE SERVOMOTOR POSITION INFLUENCE THE READINGS

To eliminate the unnecessary, time-dependent error (up to ± 2 m^3/s for a new Unit) the guide vane stem angle, rather than the servomotor stroke, will be used to determine the free discharge area between the guide vanes. To secure the required precision, the relationship between the angle of a selected guide vane and the sum of the free areas between all pairs of the guide vanes would have to be established for all Units. Then, for equal free area between the guide vanes and equal net head, the same discharge will be assumed for all turbines of the same group. It can be assumed that minor runner blade profile deviations which may have a measurable influence upon turbine efficiency and output, will have no influence on the discharge.

The shut down and dewatering of the turbines required for the scheduled preventive maintenance will be utilized to measure the distributor free discharge areas at different guide vane angles. After the comparative tests done with a pair of Units equipped with the acoustic flow meters, the necessary instrumentation will be installed in all remaining Units. We expect to be able to monitor the Guri total discharge with sufficient precision without the necessity to install the acoustic flow meters in all Units.