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In this paper formulae are developed for the rapid estimation of the hydroelectric powerhouse concrete volume for nine different types of surface powerhouses, containing high head vertical or horizontal shaft impulse units; high head Francis units intermediate head Francis, Kaplan, or fixed blade propellor units; low head horizontal shaft tube, rim generator, or bulb units; and low head vertical shaft Kaplan or fixed blade propellor units. Heads range from a minimum of 4.65 m up to a maximum of 825 m. Unit size ranges from a minimum of 3000 kVA to a maximum of 615 000 kVA. The formulae are based on statistics derived from 93 hydro developments. In addition formulae are developed for generator casing diameters as a prerequisite to the development of a chart which indicates whether the turbine or the generator will influence powerhouse concrete volume for intermediate head powerplants. Finally, the formulae are used to compare concrete volumes for horizontal and vertical shaft low head powerplants.

Keywords: hydroelectric powerhouse, concrete volume.

Le présent text comprend des formules mises au point en vue de calculer rapidement le volume de béton d'une centrale hydro-électrique pour neuf types différents de centrales de surface utilisant des turbines à action à axe vertical ou horizontal de très hautes chutes; des turbines Francis de très hautes chutes; des turbines Francis, Kaplan ou turbines-hélices à aubes fixes pour des hauteurs de chute intermédiaires; des groupes bulbes, à alternateur peripherique, ou tubes à axe horizontal pour basses chutes; et des turbines Kaplan à axe vertical ou turbines-hélices à aube fixe pour basses chutes. Les hauteurs de chute varient entre 4,65 m minimum et 825 m maximum. Les capacités des turbines varient entre 3000 kVA minimum et 615 000 kVA maximum. Les formules sont basées sur des données statistiques provenant de 93 aménagements hydro-électriques. De plus, les formules sont établies pour déterminer le diamètre du bâti de l'alternateur en tant que donnée préalablement requise pour l'élaboration d'un diagramme indiquant si c'est le turbine ou l'alternateur qui déterminera le volume de béton de la centrale pour des usines à hauteurs de chute intermédiaires. Enfin, les formules servent à faire la comparaison entre les volumes de béton pour les turbines à axe horizontal et vertical de basses chutes.

Mots-clés: volume de béton, central hydro-électrique.

During feasibility and pre-feasibility assessment of hydroelectric projects, much time and effort is spent on determining the volume of concrete in the powerhouse, since this item alone comprises the major portion of the civil works cost of the powerhouse. In an effort to reduce this work, a detailed review of powerhouse drawings and construction quantities has enabled the development of formulae for rapid estimation of power-house concrete quantities for most types of surface powerhouses. Powerhouse concrete volumes have been obtained from published data and from personal communications and, with few exceptions, are based on construction quantities.

Another use for the formulae lies in the optimization of powerhouse layouts during feasibility studies and project design. There are a few general rules which serve as guidelines for the powerhouse layout, and others for the integrity and stability of the structure, but none to indicate when an optimum layout has been attained which will produce a minimum cost structure characterized by minimum use of concrete. In such cases the formulae can be used to compare the estimated concrete volume with that of other similar projects.

It should be mentioned that this analysis is confined to surface powerhouses on competent rock foundations. Concrete in the powerhouse substructure required for functions other than to surround and support the units and the repair bay is not included in the analysis. For example:

—Extra concrete required to stabilize the foundation is not included.

—Mass concrete required to fill in a river valley below the powerhouse draft tube is not included.

—Concrete in a penstock anchor block beside the powerhouse is not included.

—Concrete in the powerhouse superstructure is not included, except where such concrete is required to guard against a high tailwater level, and except for low head horizontal shaft units.

—Concrete associated with the intake structure is not included, except in the case of low head powerplants where the intake forms an integral part of the power-plant.

Concrete included in this analysis is shown in the typical cross sections of nine types of powerhouses as illustrated in Fig. 1. In this analysis, it was found that
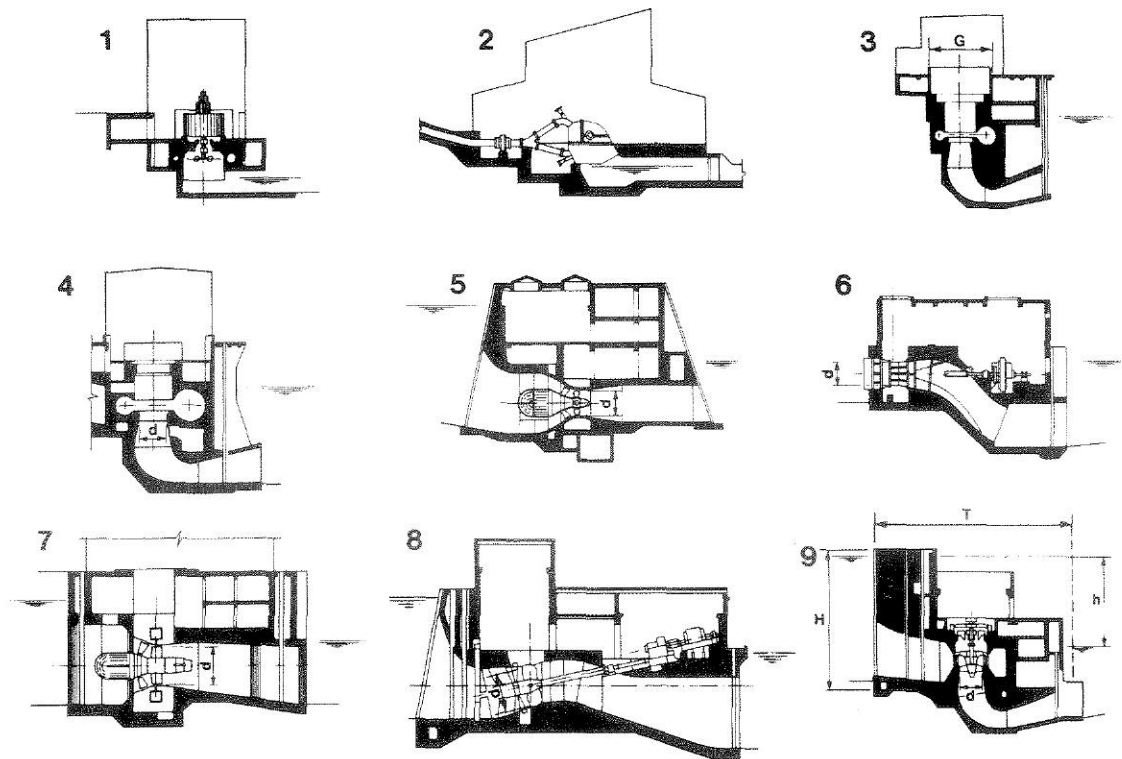
FIG. 1. Schematic of powerhouse types equipped with the following power units. Impulse turbines: 1. High head vertical shaft. 2. High head horizontal shaft. Reaction turbines: 3. High head vertical shaft Francis. 4. Intermediate vertical shaft Francis, propellor, or Kaplan turbines. 5. Low head horizontal shaft bulb turbine. 6. Low head horizontal shaft tube turbine. 7. Low head horizontal shaft rim generator turbine. 8. Low head inclined shaft tube turbine. 9. Low head vertical shaft propellor or Kaplan turbine.

concrete quantities were related to the type of powerhouse, and that several types of powerhouse could be used under the same head. For example, at a head of 20 m, powerhouses types 4, 5, 6, 7, 8, and 9 could all be used, the selection depending on the type of unit and local topography. Similarly, at a higher head of 300 m, powerhouse types 1, 2, or 3 could be used.

With respect to the development of the formulae, the size of a hydroelectric powerhouse is determined by, among other factors:
—the number and size of units,
—the extent of repair bay facilities.
Powerhouse statistics usually quote the total powerhouse concrete volume, which is not sufficient for purposes of comparison or analysis. Instead, the volume of concrete in one unit bay is needed. This can be determined provided the number of units is known along with length of the repair bay and the unit spacing. Experience has indicated that the volume of concrete in the repair bay per metre length is about half the volume of concrete per metre length in a turbine unit bay. Hence the "equivalent number of units" (N_e) can be

determined from:

$$[1] \quad N_e = N + 0.5RS^{-1}$$

where N is the number of units, R the repair bay length, and S the unit spacing. For some powerplants, it is not easy to determine where the unit bay ends and the repair bay begins. For these plants the repair bay length can be simply determined as the total length of the powerplant (L) less the number of units times the unit spacing:

$$[2] \quad R = L - NS$$

The value of N_e for powerplants described in this article is given in Table 1, where the powerplants are listed in alphabetical order. Data for the powerplants have been obtained from Pawson (1927) for Bryson; from the Tennessee Valley Authority (1941, 1949a, b, 1952) publications for Chickamauga, Fort London, Kentucky, Guntersville, Pickwick, and Watts Bar; from Creager and Justin (1950) for Conowingo; from personal communication (AGK 1980) and from Kuluk and Janzen (1978) for Jenpeg; from Knight and MacPherson (1969) for Kettle; from personal commu-

TABLE 1. Determination of equivalent number of units

Powerplant	Number of turbines N	Turbine spacing S, m	Repair bay length R, m	$\frac{0.5R}{S}$	$N_e = N + \frac{0.5R}{S}$
Bryson	3	17.4	20.4	0.59	3.59
Cat Arm	2	18.0	16.2	0.45	2.45
Chickamauga	4	24.4	24.4	0.50	4.50
Chururaqui	2	9.9	10.8	0.55	2.55
Conowingo	7	22.0	47.8	1.09	8.09
Fort Loudoun	4	21.3	36.6	0.86	4.86
Guntersville	4	23.8	17.9	0.38	4.38
Jenpeg	6	18.9	55.9	1.48	7.48
Kentucky	5	23.6	27.4	0.58	5.58
Kettle	12	28.0	29.3	0.52	12.52
Kpong	4	28.7	28.7	0.50	4.50
Kundah 1	3	15.2	16.0	0.53	3.53
Kundah 2	5	15.2	16.0	0.53	5.53
La Grande 1	10	26.0	47.0	0.90	10.90
Limestone	10	26.5	34.0	0.64	10.64
Long Spruce	10	26.5	32.5	0.61	10.61
Maskeliya	2	16.5	11.0	0.33	2.33
Pickwick	6	24.4	30.5	0.62	6.62
Safe Harbor	7.71[a]	18.9	11.0	0.29	8.00
Sainani	1	12.2	3.6	0.15	1.15
H.S. Truman	5	16.6	40.2	1.21	6.21
Watts Bar	5	22.2	27.4	0.62	5.62
Webbers Falls	3	19.8	15.7	0.40	3.40

[a]Refer to text. Safe Harbor has two service units occupying space equivalent to 0.71 of a large turbine.

nication (LHA 1981) and from Quartey and Allen (1981) for Kpong; from Ludwig and Olive (1980) and personal communication (RAO 1981) for La Grande 1; from personal communication (CA 1982) for Long Spruce and Limestone; from personal communication (AE 1981) and from Higgins (1933) for Safe Harbor; from personal communication (LAD 1981) for Truman and Webber Falls; and from company data for Cat Arm, Chururaqui, Kundah 1 and 2, Maskeliya, and Sainani.

Table 1 gives a clear indication of the wide range in repair bay lengths as a percentage of unit spacing, ranging from a minimum of 30% at Sainani, to a maximum of 300% at Jenpeg. The recommended rule of thumb (Wolf 1961) is 100–125% of unit spacing. This wide range of repair bay lengths indicates the importance of including the repair bay in any estimate of powerhouse concrete volume.

The concrete in one turbine-generator unit bay (V_u) can then be obtained by simply dividing the total powerhouse concrete (V_t) by the equivalent number of units:

[3] $V_u = V_t N_e^{-1}$

Using the above formulae, data on 93 powerplants have been examined to determine whether V_u can be expressed as a simple function of some other easily determined parameter. As would be expected, the volume of concrete in one turbine-generator unit bay was found to be a function of:
—the size of the turbine,
—the size of the generator,
—the type of generating unit.

The size of the turbine can be expressed as a function of the turbine throat diameter (d) and the size of the generator as a function of the casing diameter (G). For surface powerplants containing vertical shaft reaction turbines with steel spiral casings, previous work (Gordon 1981) has indicated that when G/d exceeds a value of 2.9 then the generator size determines unit spacing within the powerhouse (type 3) and therefore the unit concrete volume. Conversely, when G/d is less than 2.9 the size of the turbine water passages determines unit spacing (type 4 powerhouse) and therefore concrete volume. This previous work indicated that at heads over about 110 m the generator will influence concrete volumes, and below 110 m the turbine will influence. However, further work as outlined later in this paper indicates that the head at which the change occurs is also influenced by the unit capacity and generator inertia.

The other factor which affects concrete volume is the

TABLE 2. High head impulse turbine powerhouse data

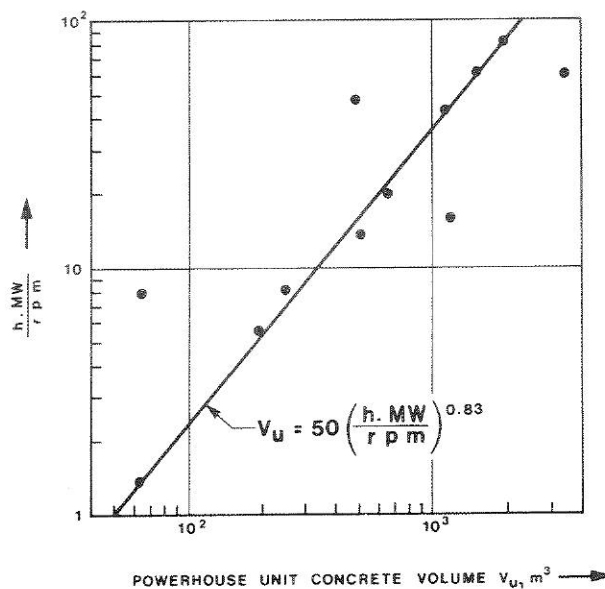| Powerhouse	Unit capacity, MW	Head h, m	Shaft horiz. or vert.	Unit speed, rpm	Concrete V_t	N_e	$V_u = V_t/N_e$	$\dfrac{h \cdot MW}{rpm}$
Caribou	21.1	350	[a]	171	3 590	3.2	1120	43.2
Cat Arm	67.2	381	V	327	4 500[b]	2.45	1836	78.3
Chururaqui	13.0	369	H	600	630	2.55	250	6.00
Corani	13.5	586	H	600	995	2	500	13.2
Kundah 1	20.0	317	V	428	4 130	3.53	1170	14.8
Kundah 2	35.0	713	V	428	18 835	5.53	3405	58.3
Maskeliya	50.0	519	V	428	3 491	2.33	1500	60.6
Phoenix	1.9	362	[a]	514	76	1.2	64	1.34
Sainani	9.9	273	H	500	219	1.15	190	5.41
Santa Isabel	18.0	825	H	750	1 300	2	650	19.8
Spring Gap	7.1	569	[a]	514	76	1.2	64	7.9
Tiger Creek	28.5	371	H	225	970	2.2	490	47.00

[a]Data not available.
[b]Estimated quantity.

FIG. 2. High head impulse turbine powerhouse types 1 and 2. Unit concrete volume turbine head, capacity, and speed relation.

FIG. 3. High head Francis turbine powerhouse type 3. Unit concrete volume – generator casing diameter relation.

type of unit. Obviously the volume of concrete surrounding a horizontal shaft low head tube-type turbogenerator will be very different from that surrounding a vertical axis impulse turbo-generator, as illustrated in Fig. 1. Accordingly it is necessary to examine data for each type of powerplant.

High head impulse turbine powerhouse types 1 and 2

Data for 12 power plants have been tabulated in Table 2. The statistics for Caribou, Phoenix, Spring Gap, and Tiger Creek were obtained from Creager and Justin (1950), where a power factor of 0.9 was assumed
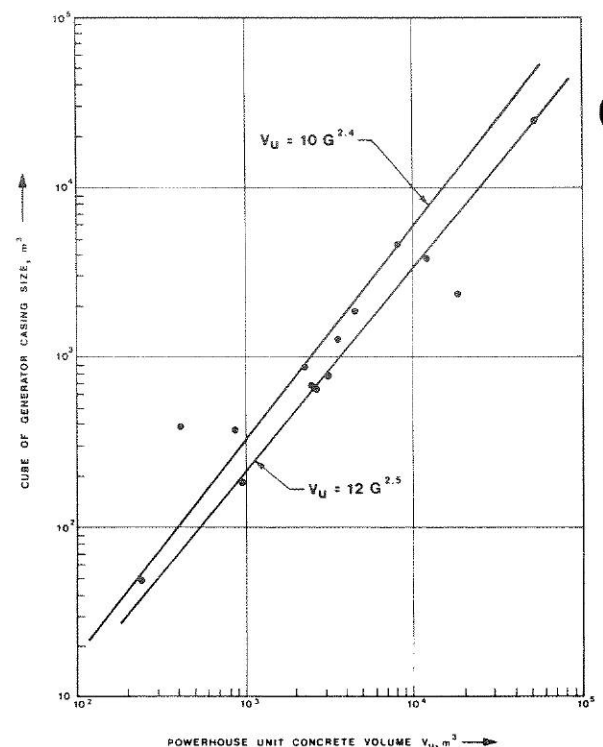
to obtain MW along with repair bay lengths of 0.4 times unit bay width. For the other plants, Cat Arm will contain two vertical shaft impulse units in a layout similar to that at Maskeliya, Chururaqui contains two horizontal shaft double runner impulse units with the powerhouse consisting of a simple slab on grade with
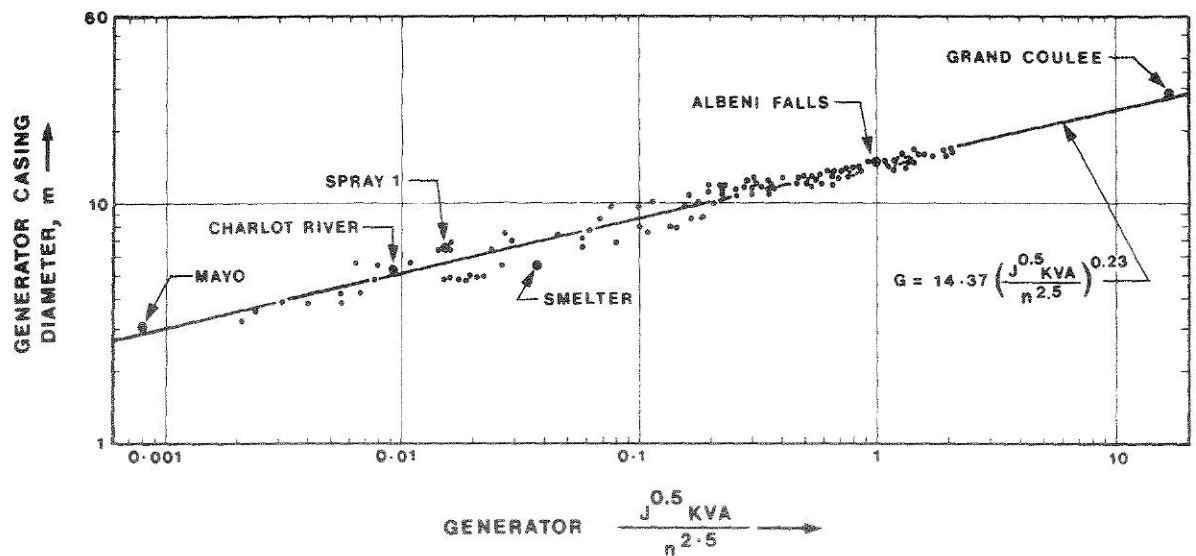
FiG. 4. Generator casing diameter relation.

below grade water passages to the tailrace, and a steel superstructure. Corani is an extension to an existing plant in Bolivia, and a section through the unit is included in Fig. 1.2. The two Kundah powerplants are located in Madras state, India, and were constructed as part of the Colombo plan in the late fifties. The Maskeliya Oya stage II powerhouse in Sri Lanka contains two vertical shaft impulse units (Gordon *et al.* 1972); a section through one of these is shown in Fig. 1.1. Sainani is similar to Chururaqui, with the lower ouput being a result of the lower head. Santa Isabel is another powerhouse extension in Bolivia similar in layout to that at Corani, and has been described by Abela and Schittler (1973).

A plot of unit concrete volume against the function, capacity times head divided by unit speed, is shown in Fig. 2, from which the folowing equation can be developed.

[4] $V_u = 50(\text{h} \cdot \text{MW/rpm})^{0.83}$

At first glance the form of this equation would appear to be incorrect, since head appears in the numerator instead of the denominator. However, the force acting on the powerplant is a function of head times capacity and, as mentioned previously, the size of a high head powerplant is a function of the generator size, which in turn is a function of capacity per rpm. Hence the form of the equation can be rationalized.

Four vertical shaft powerplants are included in this analysis, one at Maskeliya, another at Cat Arm, and two at Kundah. Both Maskeliya and Cat Arm plot on the same line as the horizontal shaft units, but unit concrete volumes at both Kundah projects are about twice those predicted by [4]. An examination of the Kundah powerhouse drawings indicates a generous unit spacing (compare Kundah 2 with Maskeliya) and a relatively long tailrace section included within the powerhouse, which accounts for the larger than expected concrete volumes on these two projects.

Further data were not available on the two projects, Spring Gap and Tiger Creek, which indicate substantially less unit concrete volume than predicted by the formula.

High head Francis turbine powerhouse type 3

A detailed analysis of substructure concrete volume for powerhouse types 3 and 4 has been undertaken by the author (Gordon 1981, 1982). The formulae and figures for these powerhouses are summarized in this paper.

Based on data for 14 powerplants with heads in excess of 100 m, a relationship has been found between generator casing size (G) and powerhouse unit concrete volume as shown in Fig. 3, from which the following formulae can be determined:

[5] $V_u = 12G^{2.5}$ (max.)

[6] $V_u = 10G^{2.4}$ (min.)

For preliminary estimates, where the generator casing size is not known, this can be determined as indicated in the following section.

Determination of generator casing diameter

An examination of data from 120 generators indicated that the generator casing diameter is a function of the inertia, capacity, and speed, where the generator

TABLE 3. Generator characteristics

	Generator rating, kVA	Generator speed, rpm	Inertia ratio, J	Factor $J^{0.5}$ kVA$n^{-2.5}$	Casing diameter G, m	Remarks
Grand Coulee	615 385	72.0	1.371	16.38	28.90	Max. kVA
Mayo	3 000	450	1.302	0.00080	3.05	Min. kVA
Spray 1	47 500	450	1.856	0.0151	6.40	Max. rpm
Albeni Falls	15 778	54.4	1.712	0.946	14.78	Min. rpm
Charlot River	5 700	257.1	2.85	0.0091	5.20	Max. J
Smelter	40 000	257	0.975	0.0373	5.49	Min. J

casing diameter (G) is defined as the diameter of the generator steel housing, or the *outside* diameter of the concrete encasement.

In order to simplify the work, it was decided to express the generator inertia as a ratio J, and J being defined as the generator inertia divided by normal inertia, with normal inertia (Gordon 1978) determined from:

[7] $\quad I_n = 310,000(MVA/n^{1.5})^{1.25}$

In this equation the inertia is expressed as a function of the diameter of gyration squared, which is four times the radius of gyration squared, normally used in the North American imperial system of units. Since inertia is a function of diameter squared, and the housing size should be a function of diameter, it was decided to plot the function of capacity times the square root of the inertia ratio, all divided by the speed, against casing diameter. Several trials indicated that the best fit could be obtained by using speed raised to the power 2.5 as indicated in Fig. 4. All the data are based on vertical shaft umbrella-type synchronous generators operating at 13.8 kV with some at 6.9 kV, and are too extensive to list in this paper. Instead, the ranges of maxima and minima for the various generator parameters are listed in Table 3, and these generators are named in Fig. 4.

Based on the data plotted on Fig. 4, the following equation has been determined:

[8] $\quad G = 14.37(J^{0.5}kVA/n^{2.5})^{0.23}$

which fits the plotted data with a correlation coefficient of 0.978. Also from Fig. 4, it will be noted that the scatter of points decreases with increasing unit capacity. For the smaller generators it was noted that the lower voltage 6.9 kV generators usually had larger diameters, as would be expected with greater use of copper.

Distinction beween powerhouse types 3 and 4

For medium head powerhouses containing vertical shaft Francis-type turbines there is difficulty determining whether the generator size will govern the concrete volume, or whether the turbine size will govern.

As indicated previously, for medium size units of about 100 MW capacity, the change will occur at about 110 m head, but for other size units the change will occur at different heads. This difficulty can be resolved by combining the equations developed for generator casing diameter with those developed for the determination of turbine throat diameter so as to estimate the ratio of G/d for various unit capacities, heads, and inertias— and hence to determine under what combination of circumstances the generator diameter influences the powerhouse concrete volume instead of the turbine diameter.

For vertical runner Francis-type units, Pavel and Zarea (1965) developed the following equation for the Francis turbine throat diameter:

[9] $\quad d = \left[0.7 + \dfrac{83}{n_s} - \dfrac{1000}{n_s^2}\right]\dfrac{Q^{0.5}}{h^{0.25}}$

Many authors have developed equations relating specific speed to net turbine head. For this work, it was decided to use the relationship:

[10] $\quad n_s = 2850/h^{0.554}$

Using [7], [9], and [10], a relationship between unit capacity, net head, generator inertia, and the ratio G/d = 2.9 was developed as shown on Fig. 5, in which it was assumed that all generators would have a power factor of 0.9. Two lines are shown on Fig. 5, indicating the required combination of head and capacity for $G = 2.9d$ with inertia ratios of $J = 1$ and $J = 2$. For units plotting above these lines, the generator will influence concrete volume and, below the lines, the turbine will influence. The shaded area indicates the latitude of deviation for the $G = 2.9d$ lines, based on the range of generator diameters indicated in Fig. 4.

Figure 5 confirms previous work, wherein it was found that the generator influenced powerhouse concrete at heads above about 110 m. To be more precise, the changeover between turbine and generator can occur at about 120 m head for smaller 20 MW units, decreasing to about 85 m head for larger 600 MW units of standard inertia. As would be expected, the change-
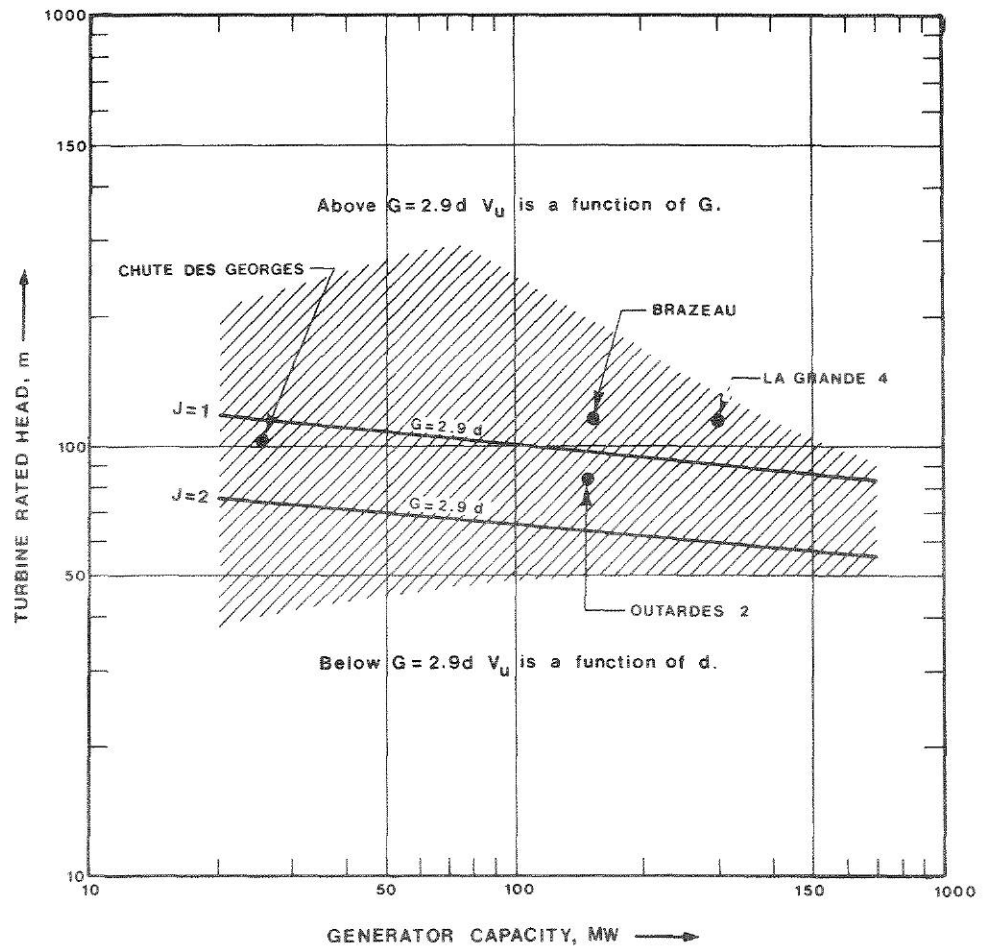
FIG. 5. Relationship between turbine-generator diameters and powerhouse concrete.

over occurs at lower heads with generators having higher inertias. As a check on Fig. 5, the projects shown in Figs. 3 and 6 were plotted on Fig. 5, and this identified two projects, at Chute Des Georges and Outardes 2, which had previously been misclassified as having type 4 powerplants whereas the G/d ratio was found to be 3.5 and 3.2 respectively. These projects are now included as high head Francis installations, i.e., type 3 in Fig. 1.

Intermediate head Francis, propellor, or Kaplan turbine powerhouse type 4

Based on data for 31 powerplants with heads between 18 and 120 m, all containing vertical shaft fixed blade propellor, Kaplan, or Francis units with steel spiral casings, some with valves, most without, a relationship has been found (Gordon 1981, 1982) between the turbine throat diameter and the unit concrete volume as shown in Fig. 6, from which the following formula can be determined:

[11] $\quad V_u = 140d^{2.4}$

Although there is a fairly wide scatter of the data on Fig. 6, most of this can be explained by the effect of foundation conditions. Four of the powerhouses with less concrete per unit than indicated by the formula contain single units on competent foundations requiring only sufficient rock excavation to contain the spiral casing, thus reducing concrete quantities. Seven of the powerhouses requiring substantially more concrete than indicated by the formula can be explained by the measures necessary to overcome soft foundations, or to provide mass concrete support below the powerhouse to foundation rock.

Where the turbine throat diameter is not known, a relationship was found between the capacity per metre head and substructure unit concrete volume as shown in Fig. 7, which gives the following formula:

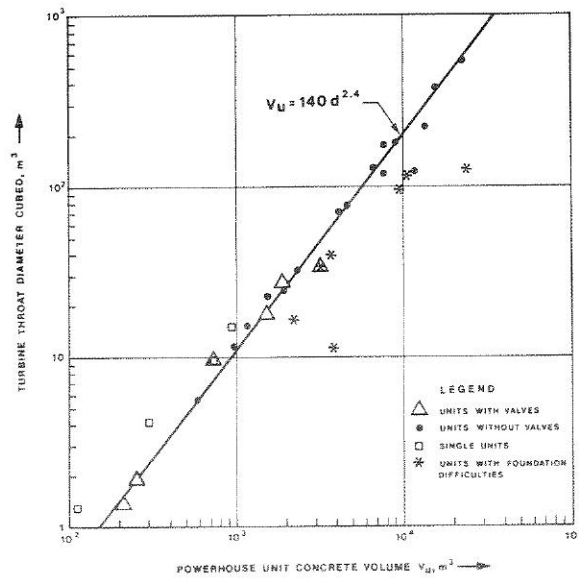[12] $\quad V_u = 1.05 \, (kW/h)^{1.2}$

FIG. 6. Intermediate head, Francis, propellor, or Kaplan turbine powerhouse type 4. Unit concrete volume – turbine throat diameter relation.
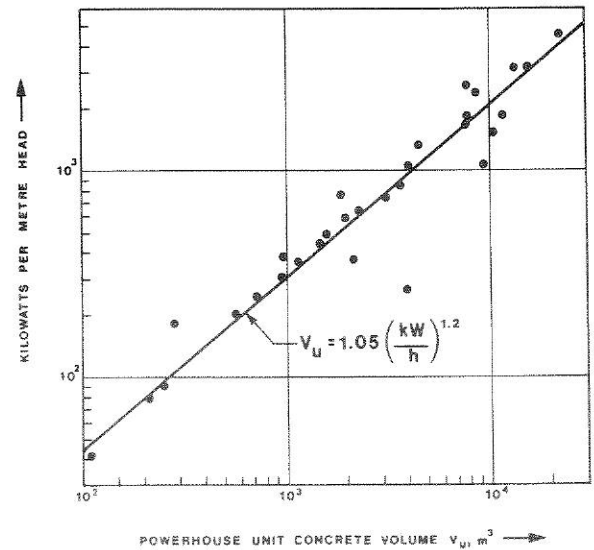

FIG. 7. Intermediate head, Francis, propellor, or Kaplan turbine powerhouse type 4. Unit concrete volume – capacity per metre head relation.

TABLE 4. Horizontal shaft low head reaction units—project statistics

Project	Powerhouse type (Fig. 1)	Turbine Throat d, m	Turbine Head h, m	Turbine Type	Eq. No. of units	Concrete volume Total PH, m^3	Concrete volume Per unit V_u, m^3
Barker Mill	6	1.50	14.0	Tube	1	367	367
Gisbourne	6	2.00	19.0	Tube	1	760	760
PEC 22.7	6	2.65	15.8	Tube	1	1 323	1 323
Andenne	7	3.55	5.25	Stra	3	9 000	3 000
Ampsin Neuville	5	3.60	4.65	Bulb	4	20 000	5 000
Lawrence	5	4.00	5.8	Bulb	2	7 548	3 774
W. T. Love	5	6.10	8.4	Bulb	3.0	29 074	9 690
Riv. Prairies	5	6.25	8.5	Bulb	1	10 600	10 600
Saint Vallier	5	6.25	9.8	Bulb	4.9	91 500	18 550
Vaugris	5	6.25	6.7	Bulb	4	67 200	16 800
Belley	5	6.40	15.0	Bulb	2	42 900	21 450
Chautagne	5	6.40	15.0	Bulb	2	42 900	21 450
H. S. Truman	8	6.45	13.0	Abia[a]	6.21	142 740	22 980
Caderousse	5	6.90	8.3	Bulb	6.4	117 100	18 300
St. Mary's	5	7.10	5.7	Bulb	3	39 000	13 000
Rock Island	5	7.40	12.1	Bulb	8	128 650	16 080
Jenpeg	5	7.50	7.3	Bulb	7.48	124 100	16 590
Annapolis	7	7.60	5.5	Stra	1	10 008	10 008
Racine	5	7.70	6.8	Bulb	2	27 500	13 750
Webbers Falls	8	8.00	6.7	Abia[a]	3.40	70 150	20 630

[a]Adjustable blade, inclined axis tube turbine with reversible pump-turbine capability at the H. S. Truman Dam.

Note that in this case the head component appears in the denominator, and that the concrete volume is a function of kW per metre head, which is a recognized measure of turbine size.

Low head horizontal reaction turbine powerhouse types 5, 6, 7, 8

Data for 20 powerplants with horizontal or inclined tube units, or bulb turbines, are given in Table 4, in-
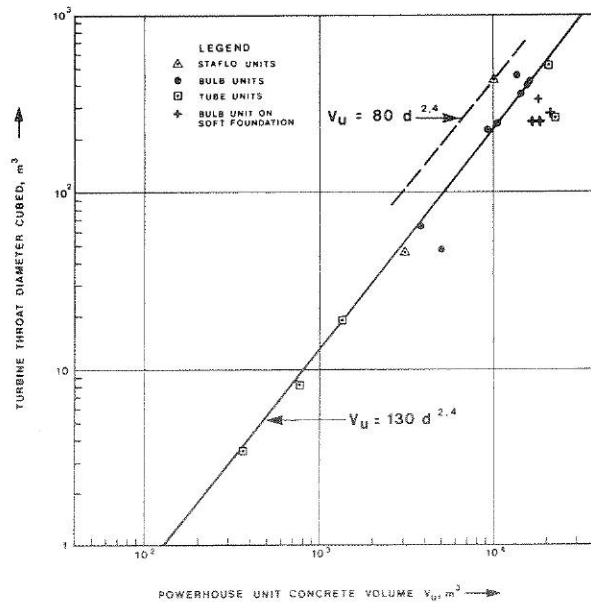
FIG. 8. Low head horizontal reaction turbine powerhouse types 5, 6, 7, and 8. Unit concrete volume – turbine throat diameter relation.

cluding data on two STRAFLO units. In this table, projects are listed in ascending order of unit size. For these plants a relationship between turbine throat diameter and unit concrete volume (which includes superstructure concrete, and intake concrete where the intake forms an integral part of the powerhouse) has been found as shown in Fig. 8. Most of the data included in Table 4 were obtained from personal communications; Barker Mill (SCE 1981); Gisbourne and Annapolis (AD 1981); PEC 22.7 (LJB 1980); Andenne and Ampsin (GDS 1981); Lawrence (DRB 1980); St. Marys (KO 1981); Rock Island (WWW 1981); Racine (WWS 1981); Truman and Webbers Falls (LAD 1981).

Based on Fig. 8, the following formula has been derived:

[13] $V_u = 130d^{2.4}$

It is surprising to find such a close correlation for these units, especially since some are tube units and others bulb units. As for the projects, Barker Mill contains a small Allis Chalmers tube turbine, and so does Gisbourne. However, Gisbourne also includes a small relief valve required because of the long upstream tunnel. PEC 22.7 is a powerhouse in the northwestern U.S.A. on an irrigation canal drop structure (Bakar 1981), and contains one Tampella tube unit as shown in Fig. 1.6. The Lawrence project in Massachusetts has been described by Burns and Holway (1979). A section through the unit is included in Fig. 1.5. The H.S. Truman project (formerly named the Kaysinger Bluff

project) contains adjustable blade inclined axis pump-turbines which require a submergence of 7.9 m and a powerhouse length of 10.2 times turbine throat diameter, which accounts for the larger than expected use of concrete. The St. Mary's project contains three bulb turbines, and has been described in detail by Overbeeke and McLean (1981). The Rock Island second power-plant on the Columbia River contains eight bulb turbines (Stewart and Wayne 1974) supplied by Alsthom-Neyrpic. The Racine project on the Ohio River includes two bulb units. The Annapolis project is currently under construction in Nova Scotia (Douma and Stewart 1981), and will contain one Dominion Bridge-Sulzer rim generator unit as shown in Fig. 1.7.

At the W.T. Love generating station near the Green-up Locks on the Ohio River, a new concept has been used for the powerhouse substructure. This was formed in steel, and included the equipment. It was floated into place (Bazin 1980) to rest on seven trapezoidal footing beams, and weighted with superplastic concrete poured into the interior, along with a concrete roof. There is a downstream cast-in-place concrete draft tube section designed to resist the thrust imposed by the turbine (WML 1981). Concrete volume is: roof 2575 m³; superplastic 14 159 m³; draft tubes 10 500 m³; footing beams 1840 m³; for a total of 29 074 m³. It is interesting to note that total concrete volume for the three units is very close to that predicted by formula [13] at 29 900 m³.

Five powerplants which have substantially more concrete per unit as indicated by Fig. 8 are in the Rhone Valley at Belley, Chautagne, Caderousse, Saint Vallier, and Vaugris. All are located on "non-rock" foundations (CLG 1981), hence additional concrete was required for foundation slab strength and to resist sliding. At two of these plants, Caderousse and Saint Vallier, the end units have substantially more concrete than the inside units, hence the equivalent number of units has been increased to 6.4 and 4.9 respectively.

At Andenne and Lixhe, the length of the powerhouse is about 7 times the STRAFLO turbine throat diameter of 3.55 m, and a study for these powerplants (Coumans et al. 1980, 1981) found a saving in powerhouse length of 16% and in civil works cost of about 15% over comparable bulb turbine units.

At Annapolis the length of the powerhouse is only about 6 times the turbine throat diameter, whereas at Lawrence and St. Mary's, this figure is closer to 9, which accounts for the relatively lower volume of substructure concrete at Annapolis. If the Annapolis powerhouse can be considered as representative of powerplants with large rim generator units, then the volume of concrete in such powerplants (type 7) can be estimated from:

[14] $V_u = 80d^{2.4}$

TABLE 5. Horizontal shaft low head reaction units capacity, head, and unit concrete volume

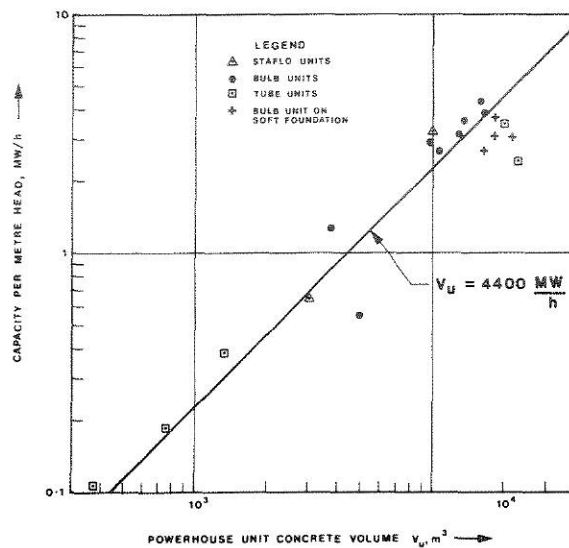| Project	Capacity, MW	Head h, m	Concrete V_u, m³	MW/h
Barker Mill	1.50	14.00	367	0.107
Gisbourne	3.50	19.00	760	0.184
PEC 22.7	6.10	15.80	1 323	0.386
Andenne	3.40	5.25	3 000	0.648
Ampsin Neuville	2.57	4.65	5 000	0.553
Lawrence	7.40	5.80	3 774	1.276
W. T. Love	24.30	8.41	9 690	2.889
Riv. Prairies	23.00	8.50	10 600	2.706
Saint Vallier	30.00	9.80	18 550	3.061
Vaugris	18.00	6.70	16 800	2.686
Belley	45.00	15.00	21 450	3.000
Chautagne	45.00	15.00	21 450	3.000
H. S. Truman	31.60	13.00	22 980	2.431
Caderousse	30.00	15.00	18 300	3.614
St. Mary's	18.00	5.70	13 000	3.158
Rock Island	53.00	12.10	16 080	4.380
Jenpeg	28.00	7.30	16 590	3.834
Annapolis	17.80	5.50	10 008	3.236
Racine	24.00	6.80	13 750	3.529
Webbers Falls	23.00	6.70	20 630	3.433

FIG. 9. Low head horizontal reaction turbine powerhouse types 5, 6, 7, and 8. Unit concrete volume – MW/h relation.

It is interesting to note that the relationship between the constants, 130 and 80 in [13] and [14], is similar to that between representative powerhouse lengths for the two formulae measured in turbine diameters, i.e., 9 for Lawrence and St. Mary's versus 6 for Annapolis.

For preliminary estimates, where the turbine throat diameter is not known, a relationship can be established between the unit concrete volume and the capacity per metre head, as indicated in Table 5. The data has been plotted in Fig. 9, from which the following formula has been derived

[15] $V_u = 4400 \text{ MW}/h$

For bulb-turbine units, [13] and [15] should only be used where the head is less than about 13 m. As outlined in the analysis at the end of this paper, higher head units require more concrete.

Low head vertical unit powerhouse type 9

In developing the formula for this type of powerhouse, it was first assumed that the "powerhouse" portion of the structure would enclose a turbine for which the concrete volume could be determined by [13]. To this would be added the concrete required in the intake portion of the structure, for which it was further assumed that the intake concrete volume would be a function of:

—The width of the intake, which is identical to the unit width, which is a function of the concrete semispiral width, and hence a function of the turbine throat diameter d.

—The height of the intake as defined by the height of the intake deck above foundation rock, H.

—The thrust on the intake, which is a function of the head acting on the turbine, h.

All are illustrated in Fig. 1.9, which is a section through a Kettle generating unit.

Data on 16 powerplants are given in Table 6, all of

TABLE 6. Low head vertical unit powerplants

Project	Turbine Diam. d, m	Turbine Head h, m	Intake height H, m	Equiv. number units	Concrete total vol., m³	Concrete per unit, m³	Formula [15] V_u, m³	Error, %
Bearspaw	4.45	14.6	17.8	1.00	7 300	7 300	7 680	+5.2
Bryson	4.33	18.3	16.2	3.59	27 436	7 640	7 720	+1.0
Chickamauga	6.71	11.0	32.0	4.50	108 570[a]	24 100	18 700	−22.4
Conowingo	4.93	27.1	32.6	8.09	148 550[c]	18 360	17 300	−5.8
Fort Loudoun	5.63	21.3	32.6	4.86	89 720	18 460	18 420	0.2
Guntersville	6.75	11.0	24.4	4.38	71 550	16 340	17 400	+6.5
Kentucky	6.55	15.5	44.5	5.58	140 555	25 190	23 600	−6.3
Kettle	7.37	30.0	42.4	12.52	504 600	40 300	40 100	0.5
Kpong	8.30	11.75	18.2	4.50	110 000	24 440	25 500	+4.3
La Grande 1	7.94	28.2	40.5	10.90	384 000[d]	35 200	42 350	+20.3
Limestone	7.92	28.2	43.5	10.64	380 540[d]	35 770	43 920	+22.8
Long Spruce	7.92	24.4	37.0	10.61	279 530	26 350	37 250	+41.4
Menihek	2.95	10.4	12.3	2.00	5 300[e]	2 650	2 725	+2.8
Pickwick	7.41	13.1	34.5	6.62	159 050[a]	24 000	24 600	+2.5
Safe Harbor	5.59	16.77	22.9	8.00	115 680[b]	14 460	13 670	−5.5
Watts Bar	5.78	15.8	28.6	5.62	83 820[a]	14 920	15 550	+4.2

[a]Includes superstructure.
[b]Includes superstructure and administration offices.
[c]Turbine has steel spiral casing.
[d]Estimate.
[e]Initial construction, first two units.

which contain either Kaplan or fixed blade propellor units. Four of the projects need some explanation of how the total concrete volume was derived, since the quoted figures include concrete in empty unit bays, or smaller service units.

At Guntersville the total concrete in three completed units plus one empty bay is quoted as 63 920 m³ (TVA 1941), to which has been added an estimated volume of concrete required for completion of the fourth unit equal to 60% of $130d^{2.4}$ or 7630 m³ to give a total of 71 550 m³.

At Menihek, the intake was built to accommodate four units, only two of which were installed initially (Carey 1954). There is no repair bay, since sufficient room to set down the equipment is available around and between the units. Total volume of concrete poured in the four unit intake and two unit powerhouse was 7262 m³. No concrete was poured in the powerhouse area for the two future units. Total concrete volume in the two completed unit bays was estimated by subtracting two intake volumes of $2.6dhH$ (refer to [16]) from the total poured quantity to obtain 5300 m³.

At Pickwick landing, concrete volumes are quoted (TVA 1941) for both completed and uncompleted units, hence the volume quoted for the completed substructure and superstructure over the first two units was tripled to obtain an estimate of concrete for the six unit powerhouse, to which was added the service bay concrete.

At Safe Harbor there are seven main generating units with a turbine throat diameter of 5.59 m. Five of these units operate at 60 cycles and have a rated capacity of 32 MW (Higgins 1933), the other two operate at 25 cycles and have a rated capacity of 33 MW (Ghai and Strobel 1979). In addition there are two service units of 4 MW capacity with throat diameters of 1.71 m. In order to simplify the analysis, it was decided to convert the 4 MW units into "equivalent" 32 MW units based on unit width. Since, for the same head, capacity is proportional to runner diameter squared, and unit width is proportional to runner diameter, this produces a total of 7.71 equivalent units, and explains the odd number of units in the second column of Table 1.

Based on the data outlined in Table 6, where the projects are listed in alphabetical order, the following formula was derived:

$$[16] \quad V_u = 2.6dhH + 130d^{2.4}$$

It will be noted that the formula has two parts, with the first, $2.6dhH$, representing the intake volume, and the second $130d^{2.4}$ representing the powerhouse volume.

An alternative approach to the method used to incorporate the concrete volume associated with the service units at Safe Harbor would be to substitute into the following formula, which has been derived by combining [3] and [16]:

TABLE 7. Data for formula [17]

Project	Unit length T, m	Ratio $TS/30d^2$	Formula [17] V_u, m³	Error, %
Kettle	58.4	1.00	40 100	0.0
La Grande 1	60.4	0.83	35 150	0.0
Limestone	61.0	0.86	37 800	+5.6
Long Spruce	53.0	0.75	27 900	+6.0

NOTE: For values of S and d refer to Tables 1 and 6.

$$[17] \quad V_t = (2.6d_1hH + 130d_1^{2.4})(N_1 + 0.5RS_1^{-1})$$
$$+ (2.6d_2hH + 130d_2^{2.4})N_2$$

where the subscript 1 corresponds to the large main units and subscript 2 to the smaller auxiliary units. The total powerhouse concrete volume can thus be calculated at 103 990 m³, or 10% below the poured concrete quantity. In this case the underestimate can be explained by the method of calculation, which assumes that the powerhouse in the area of the service units can be reduced in size. This is clearly not possible, since the crane span must remain the same, and the length of water passages in the small units must remain close to the water passage length for the larger units. Hence the former "equivalent" unit method of calculating quantities in a powerhouse containing service units is preferred.

Formula [16] underestimates by a large amount the concrete in the four unit Chickamauga powerhouse. However, in this case considerable difficulty was encountered during construction of the powerhouse where "excavation was heavy to obtain a satisfactory foundation" (TVA 1952) due to solution cavities in the limestone rock.

On the other hand, the formula overestimates the concrete placed in the Long Spruce project by 41%, and in the two projects currently in the design stage, namely Limestone and La Grande 1, by 23 and 20% respectively.

An explanation of this can be derived from an examination of the projects listed in Table 6. With the exception of Kpong, all the projects which have concrete volumes within ±7% of that predicted by the formula were designed prior to 1970. More recent designs for La Grande 1, Limestone, and Long Spruce have indicated that substantial reductions in concrete volume can be achieved. An excellent illustration of this can be obtained by comparing dimensions of the Kettle and Long Spruce powerplants. At Kettle, the unit spacing is 3.8 times turbine throat diameter, whereas at Long Spruce (Osiowy and Matthews 1978) this ratio decreased to 3.3. Also, the horizontal length of the intake to the powerhouse draft tube exit at Kettle is 8.01 times tur-

bine throat diameter, but only 6.95 at Long Spruce.

In other words, the area occupied by one intake–powerhouse unit at Long Spruce is only $22.9d^2$, whereas this ratio is $30.4d^2$ at Kettle. Expressed as a ratio of turbine diameter squared, the Long Spruce area is only 75% of that at Kettle, indicating the economies in design and powerhouse layout achieved at Long Spruce, and accounting for the difference between the formula estimate of concrete and the actual poured quantity. An examination of the La Grande 1 and Limestone drawings indicates a similar conclusion.

If sufficient data could be obtained, [16] could be refined by adding terms for unit spacing and unit length. Preliminary indications are that these factors could be incorporated as follows:

$$[18] \quad V_u = (2.6dhH + 130d^{2.4})(TS/30d^2)$$

where T is the horizontal distance between the upstream face of the intake and a vertical plane drawn midway between the downstream face of the draft tube piers and the draft tube exit, as illustrated in Fig. 1.9. As indicated by Table 7, formula [18] fits the data reasonably well, being within +6% for the four projects where quantities are known.

The terms in [18] could be combined. However, for the present, until further data become available, it would appear expedient to keep the ratio $TS/30d^2$ separate, to be used only as a refinement of [16], where economies in design and layout can be expected.

Formula [18] cannot be applied to the Kpong project, since the tailwater at Kpong is above the generator floor level, approaching the upstream water level during flood periods.

Low head powerplant concrete volume comparison

Formulae [13] and [16] will help to resolve the discussion on whether a vertical or horizontal shaft unit should be used in a low head powerplant. These formulae indicate that the volume of concrete in a bulb or tube unit powerhouse is less than would be required in an equivalent vertical unit powerhouse, an observation which can be verified by comparing the Pickwick powerplant on the Tennessee River with the Rock Island
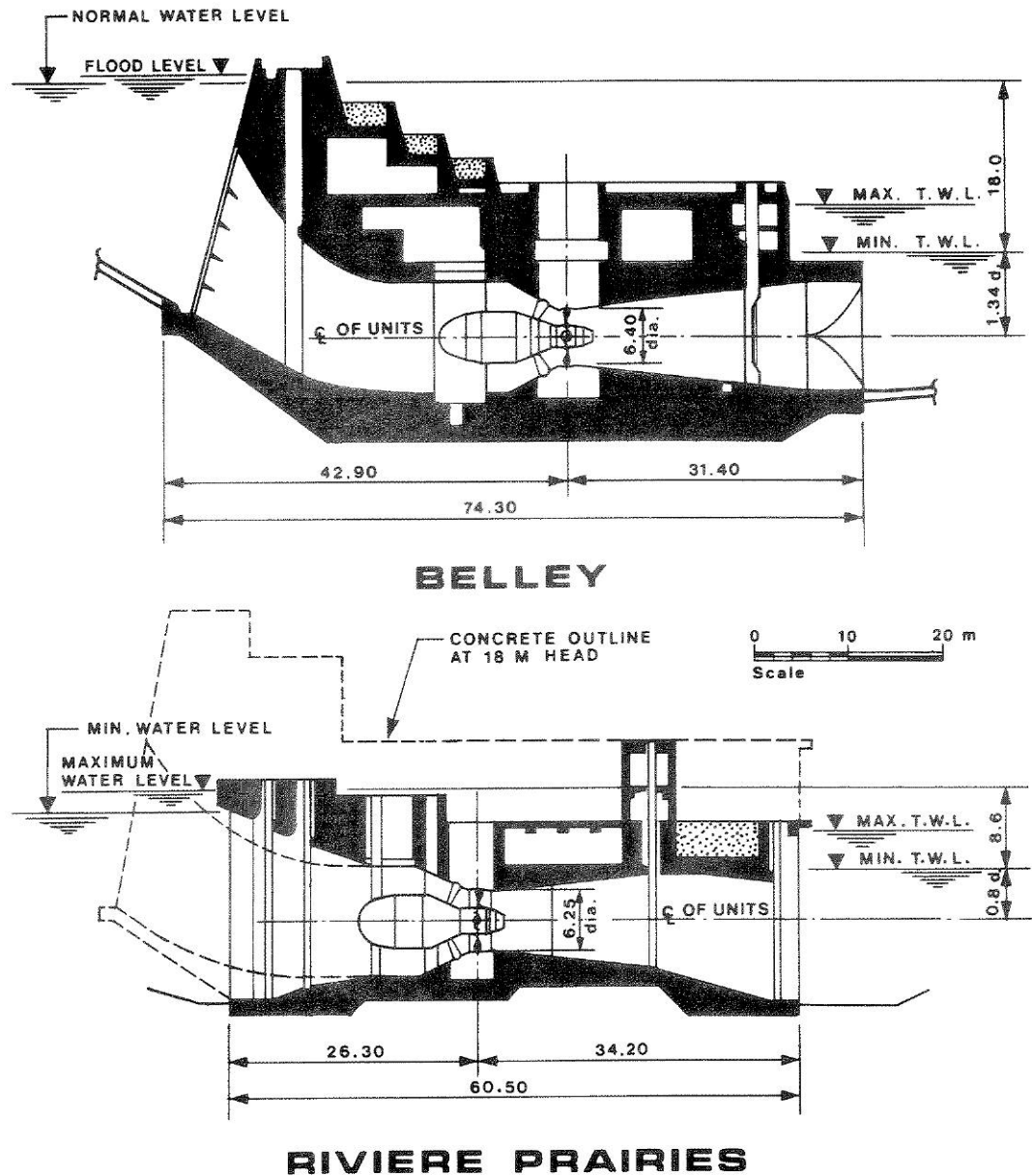
NORMAL WATER LEVEL
FLOOD LEVEL ▽

MAX. T.W.L. ▽
MIN. T.W.L. ▽

18.0

1.34 d

Ȼ OF UNITS
6.40 dia.

42.90   31.40
74.30

BELLEY

CONCRETE OUTLINE
AT 18 M HEAD

0   10   20 m
Scale

MIN. WATER LEVEL
MAXIMUM
WATER LEVEL ▽

MAX. T.W.L. ▽
MIN. T.W.L. ▽

8.6

0.8 d

6.25 dia.
Ȼ OF UNITS

26.30   34.20
60.50

RIVIERE PRAIRIES

FIG. 10. Comparison of high and low head bulb turbine powerhouse concrete.

second powerplant on the Columbia River. Both contain turbines with throat diameters of 7.4 m, and there is a difference of only 8% in their heads, 12.1 and 13.1 m. Yet the concrete per unit bay is only 16 080 m^3 for the horizontal shaft bulb turbine unit at Rock Island, but almost 50% more at Pickwick where the vertical shaft Kaplan turbined powerplant required 24 000 m^3 per unit bay. Unfortunately, this is not a fair comparison, since some of the extra concrete at Pickwick can be attributed to the high flood level.

However, a comparison based on equal turbine throat diameters is not correct, since a horizontal shaft unit with relatively straight water passages can develop more power from a given flow area and head than a vertical shaft turbine, where the water passages are more convoluted. In other words, the unit horsepower (defined as the horsepower which would be produced if the turbine were reduced to 1 m diameter, operating under a head of 1 m) for a horizontal shaft turbine is higher than that for a vertical shaft turbine. Thus, a vertical shaft unit requires a turbine throat diameter about 8% larger than that of a horizontal shaft unit to

obtain the same power with the same head. Since powerhouse concrete volume is proportional to the turbine throat diameter raised to the power 2.4, an 8% increase in diameter becomes a 20% increase in concrete volume, to which must be added the intake concrete in a vertical shaft unit powerhouse.

For example, the Rock Island bulb turbines are rated at 63,600 HP (metric) at 10.76 m head, increasing to 72 000 HP at 12.1 m maximum head. The diameter of an equivalent vertical shaft Kaplan turbine can be determined using the procedures developed by Pavel and Zarea (1965) at 8.01 m, or 8.2% larger than the 7.40 m diameter runners at Rock Island. This is equivalent to a 21% increase in the powerhouse concrete volume, to which must be added the intake concrete. Using [16], the volume of concrete in one unit bay required for such a vertical shaft Kaplan turbine would be:

$$v_u = 2.6 \times 8.01 \times 10.76 \times 36 + 130 \times 8.01^{2.4}$$
$$= 27\ 200\ m^3$$

or about 20 000 m³ with a compact design as achieved at Long Spruce, which can be compared with the 16 080 m³ unit concrete volume required for the horizontal shaft adjustable blade bulb turbines installed at Rock Island. Other disadvantages of the vertical shaft unit for this case would be the width of the unit bay, estimated to be about 26 m for the vertical unit, compared with the 17.68 m actually required for the horizontal unit and the slower speed of about 70.5 rpm, instead of the actual 85.7 rpm, for the bulb turbine. On the other hand, concrete formwork and reinforcing in a horizontal shaft bulb-turbine unit costs more than in a vertical shaft unit because of the larger area of curved formwork, the more precise tolerance, the larger number of blockouts, and the greater use of reinforcing steel (ENR 1981) which can exceed 100 kg/m³, whereas only about half this figure would be needed in a vertical shaft unit.

Another factor which must be taken into account in any comparison of horizontal and vertical units is the effect of submergence. In Table 4, all the bulb units where the concrete volume can be determined from [13] have rated heads below about 12 m. For higher rated heads, the unit submergence increases by about 0.3 m per metre of increment head and this has a marked effect on unit concrete volume as can be seen in Fig. 10, where sections through two units having about the same throat diameter, but different rated heads of 15.0 and 8.6 m, are shown. The Belley development is located on the Rhone River in France, about 10 km southeast of Bourget Lake, where two 45 MW bulb units have been installed to operate up to a maximum head of 18.0 m. The submergence of the Belley units is 5.4 m above the upper runner periphery, whereas this would only be about 1.9 m for a lower head unit, such as that proposed

TABLE 8. Summary of estimating formulae

Powerhouse type (Fig. 1)	Concrete volume per unit
1,2	$V_u = 50(h \cdot MW/rpm)^{0.83}$
3	$V_u = 10G^{2.4}$ to $12G^{2.5}$
4	$V_u = 140d^{2.4}$
4	$V_u = 1.05(kW/h)^{1.2}$
5, 6, 7, 8	$V_u = 130d^{2.4}$
5, 6, 7, 8	$V_u = 4400MW/h$
9 (old)	$V_u = 2.6dhH + 130d^{2.4}$
9 (new)	$V_u = (2.6dhH + 130d^{2.4})(TS/30d^2)$
	Total concrete volume
All types	$V_t = V_u(N + 0.5R/S)$

for the Riviere Prairies project. Unit concrete volume at Belley is about twice that predicted by [13] at 21 450 m³; however, some of this extra concrete is due to the soft foundation.

If the head at Riviere Prairies were 18 m and unit submergence increased to about 5 m, then unit concrete volume would increase to about 17 400 m³. Using [18], and a value of 0.83 for the ratio $TS/30d^2$, the unit concrete volume for a comparable powerhouse with a vertical Kaplan unit having a throat diameter 8% larger at 6.75 m, an intake height of 27 m, and a head of 18 m, can be estimated at 17 600 m³. Thus at higher heads, of about 18 m, it can be shown that powerhouse unit concrete volumes will be identical for vertical and horizontal shaft units of the same capacity.

At lower heads, below about 13 m, it is apparent that less concrete will be used in a low head horizontal shaft unit powerhouse than in an equivalent vertical shaft unit powerhouse. Furthermore, an increase in concrete cost per cubic metre (including forms and re-steel) of at least 25% would be needed before a horizontal unit concrete structure would equal the cost of a vertical unit concrete structure.

Conclusions

It is interesting to note that in the formulae, which are based on some linear dimensional measurement of the unit size, such as the generator casing or turbine throat diameter, the concrete volume is a function of this dimension raised to the power 2.4 or 2.5. An exponent of 2.0 would represent a hollow cube of constant wall thickness, while an exponent of 3.0 would represent a solid cube. Since the formulae have exponents midway between these values, they represent a hollow cube with wall thickness increasing as a function of the unit dimension, which is what would happen in practice. Hence the formulae are rational and are summarized in Table 8.

The total volume of concrete in a powerhouse can

thus be obtained by combining [1] and [3] with the appropriate formula for unit concrete volume. For example, total concrete in a low head vertical shaft reaction turbine powerhouse can be estimated from:

[19] $V_1 = (2.6dhH + 130d^{2.4})(N + 0.5R/S)$

obtained by combining [1], [3], and [16].

The formulae can also be used to prove that concrete requirements for a horizontal shaft powerhouse, where the head is less than 13 m, are substantially less than concrete requirements for an equivalent vertical shaft powerhouse, and that this relation reverses as the head increases beyond about 18 m.

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List of symbols

d = turbine throat diameter, m

G = generator casing diameter, m

h = turbine rated head, m

H = height of intake deck above rock, m

I_n = normal generator inertia, $Mg \cdot m^2$

J = ratio generator inertia divided by I_n

L = length of powerhouse measured along unit centerlines, m

n = unit rotational speed, rpm

n_s = turbine specific speed

N = number of turbine-generator units

N_e = equivalent number of turbine-generator units

Q = turbine flow, m^3/s

R = repair bay length, m

S = unit spacing, m

T = horizontal distance between upstream face of intake and a vertical plane drawn midway between downstream face of draft tube piers and draft tube exit

V_t = total volume of concrete in powerhouse, m^3

V_u = volume of concrete in one turbine-generator unit bay, m^3