Photo 5.17

Globe and rotary valves (figure 5.28) have lower head losses than the slide and butterfly gate valves and are also commonly used in spite of their higher price.

The radial gates (figure 5.29), conceptually different, are a method of forming a moveable overflow crest and allow a close control of headwater and tailwater. In photo 5.19 it can be seen the housing of the sector on a concrete pier. The radial gate is operated by raising or lowering to allow water to pass beneath the gate plate. The curved plate that forms the upstream face is concentric with the trunnions of the gate. The trunnions are anchored in the piers and carry the full hydrostatic

Photo 5.18

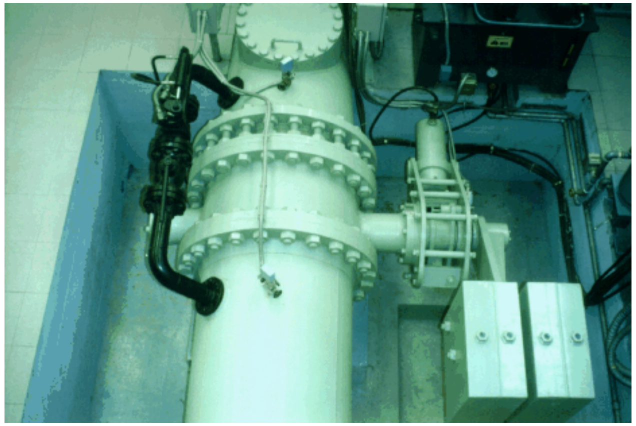


Photo 5.19

load. Because the hydrostatic load passes through the trunnions, the lifting force required by the hoisting mechanism is minimised. The head losses in gates and valves are relatively high, especially when are operated as regulating devices. For further details refer to Chapter 2, Section 2.2.4 and the enclosed bibliography.

5.2.4 Open channels

5.2.4.1 Design and dimensioning

The flow conveyed by a canal is a function of its cross-sectional profile, its slope, and its roughness. Natural channels are normally very irregular in shape, and their surface roughness changes with distance and time. The application of hydraulic theory to natural channels is more complex than for artificial channels where the cross-section is regular in shape and the surface roughness of the construction materials - earth, concrete, steel or wood - is well documented, so that the application of hydraulic theories yields reasonably accurate results.

Table 2.4, Chapter 2, illustrates the fundamental geometric properties of different channel sections.

In small hydropower schemes the flow in the channels is in general in the rough turbulent zone and the Manning equation can be applied

$$Q = \frac{AR^{2/3}S^{1/2}}{n} = \frac{A^{5/3}S^{1/2}}{nP^{2/3}} \tag{5.6}$$

where n is Manning's coefficient, which in the case of artificial lined channels may be estimated with reasonable accuracy, and S is the hydraulic gradient, which normally is the bed slope. Alternatively

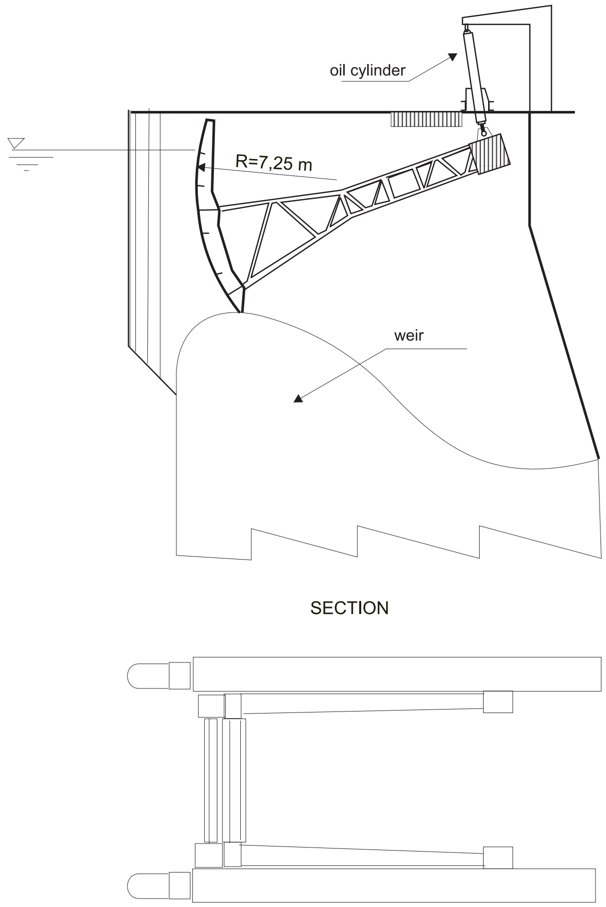


figure 5.29

$$S = \left(\frac{QnP^{2/3}}{A^{5/3}}\right)^2 = \left(\frac{Qn}{AR^{2/3}}\right)^2 \qquad (5.7)$$

Equation 5.7 applies when metric or S.I. units are used. To use Imperial or English units the equation must be modified to

$$Q = \frac{1.49\,A^{5/3}S^{1/2}}{nP^{2/3}}$$

where Q is in ft³/s; A in ft² and P in ft. *n* has the same value as before

Table 5.1 Typical values of Manning's n.

Type of Channel	Manning's *n*
Excavated earth channels	
Clean	0.022
Gravelly	0.025
Weedy	0.030
Stony, cobbles (or natural streams)	0.035
Artificially lined channels	
Brass	0.011
Steel, smooth	0.012
Steel, painted	0.014
Cast iron	0.013
Concrete, well finished	0.012
Concrete, unfinished	0.014
Planed wood	0.012
Clay tile	0.014
Brickwork	0.015
Asphalt	0.016
Corrugated metal	0.022
Rubble masonry	0.025

Equation 5.7 shows that for the same cross-sectional area A, and channel slope S, the channel with a larger hydraulic radius R, delivers a larger discharge. That means that for a given cross-sectional area, the section with the least wetted perimeter is the most efficient hydraulically. Semicircular sections are consequently the most efficient. A semicircular section however, unless built with prefabricated materials, is expensive to build and difficult to maintain. The most efficient trapezoidal section is the half hexagon, whose side slope is 1 v. 0.577 h. Strictly this is only true if the water level reaches the level of the top of the bank. Actual dimensions have to include a certain freeboard (vertical distance between the designed water surface and the top of the channel bank) to prevent water level fluctuations overspilling the banks. Minimum freeboard for lined canals is about 10 cm, and for unlined canals this should be about one third of the designed water depth with a minimum of fifteen centimetres. One way to prevent overflow of the canal is to provide spillways at appropriate intervals; any excess water is conveyed, via the spillway, to an existing streambed or to a gully.

It should be noted that the best hydraulic section does not necessarily have the lowest excavation cost. If the canal is unlined, the maximum side slope is set by the slope at which the material will permanently stand under water. Clay slopes may stand at 1 vertical, 3/4 horizontal, whereas sandy soils must have flatter slopes (1 vert., 2 hoz.)

Table 5.2 defines for the most common canal sections the optimum profile as a function of the water depth y, together with the parameters identifying the profile.

Table 5.2

Channel section	Area A	Wetter perimeter P	Hydraulic radius R	Top width T	Water depth d
Trapezoid: half hexagon	$1.73\ y^2$	3.46 y	0.500 y	2.31 y	0.750 y
Rectangle : half square	$2\ y^2$	4 y	0.500 y	2 y	y
Triangle: half square	y^2	2.83 y	0.354 y	2 y	0.500 y
Semicircle	$0.5\ \pi y^2$	π y	0.500 y	2 y	$0.250\ \pi y$

In conventional hydropower schemes and in some of the small ones, especially those located in wide valleys, when the channels must transport large discharges, these are built according to figure 5.30. According to this profile, the excavated ground is used to build the embankments, not only up to the designed height but to provide the freeboard, the extra height necessary to foresee the height increase produced by a sudden gate closing, waves or the excess arising in the canal itself under heavy storms.

These embankment channels although easy to construct are difficult to maintain, due to wall erosion and aquatic plant growth. The velocity of water in these unlined canals should be kept above a minimum value to prevent sedimentation and aquatic plant growth, but below a maximum value to prevent erosion. In earth canals, if the water temperature approaches 20ºC, a minimum speed of 0.7 m/s is necessary to prevent plant growth. If the canal is unlined and built in sandy soil, the velocity should be limited to 0.4-0.6 m/s. Concrete-lined canals may have clear water velocities up to 10 m/s without danger. Even if the water contains sand, gravel or stones, velocities up to 4 m/s are acceptable. To keep silt in suspension after the intake, the flow velocity should be at least 0.3-0.5 m/s.

The wall-side slope in rock can be practically vertical, in hardened clay ¼:1 whereas if it has been build in sandy ground should not exceed 2:1.

In high mountain schemes the canal is usually built in reinforced concrete, so much so that environmental legislation may require it to be covered and

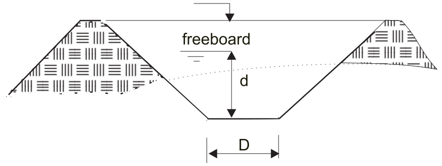


figure 5.30

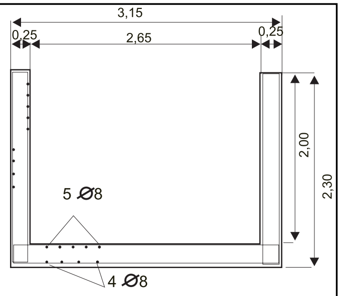


figure 5.31

revegetated. Figure 5.31 shows the schematic section of a rectangular reinforced concrete canal in the Cordiñanes scheme, referred to in chapter 4 and photo 5.20 shows the same canal not yet covered with the concrete slab that would serve as a basis for new ground and new vegetation. . Sometimes to ensure that no seepage will occur, the canal is lined with geotextile sheets, to prevent landslides consequent on the wetting of clayey material.

As is shown in the following examples, once the canal profile has been selected it is easy to compute its maximum discharge,

Photo 5.20

Example 5.1

Assuming a flow depth of 1 m, a channel base width of 1.5 m. and side slopes of 2 vert: 1 hoz, a bed slope of 0.001 and a Manning's coefficient of 0.015, determine the discharge (Q), the mean velocity (V).
According to Table 2.4 for b=1.5 x=1/2 and y=1

$$A=(1.5+0.5\times1)\times1=2m^2;\ P=1.5+2\times\sqrt{1+0.5^2}=3.736m$$

Applying 5.6 for A=2 and P=3.736

$$Q=\frac{1}{0.015}\times\frac{2^{5/3}}{3.736^{2/3}}\times\sqrt{0.001}=2.78\,m^3/s;\ V=\frac{2.78}{2}=1.39\,m/s$$

Example 5.2

Determine the slope knowing the discharge and the canal's dimensions. Assuming a canal paved with smooth cement surface (n=0.011), a channel base of 2 m, side slopes with inclination 1v:2h and a uniform water depth of 1.2 m, determine the bed slope for a discharge of 17.5 m3/s.
Applying the formulae of table 2.4 and equation 5.6

$$S=\left(\frac{17.5\times0.011}{5.28\times0.717^{2/3}}\right)^2=0.002$$

When the canal section, the slope and discharge are known and the depth "d" is required, equation 5.6 – nor any other - does not provide a direct answer so iterative calculations must be used.

Example 5.3

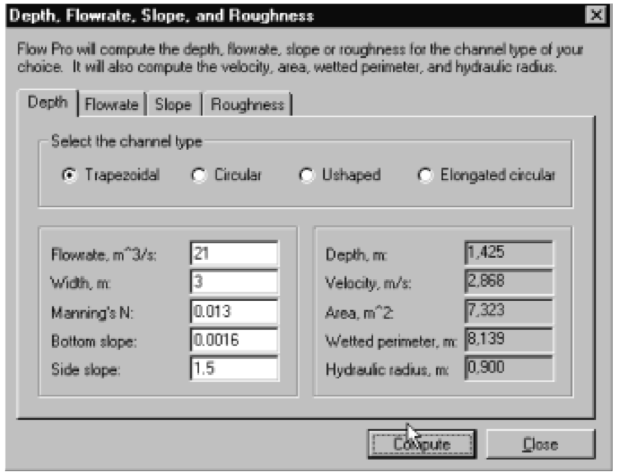
A trapezoidal open channel has a bottom width of 3 m and side slopes with inclination 1.5:1. The channel is lined with unfinished concrete. The channel is laid on a slope of 0.0016 and the discharge is 21 m^3/s. Calculate the depth
According to 5.6 the section factor

$A=(b+zy)y = (3 + 1.5y)y$ $P=b+2y(1+z^2)^{0.5}= 3+3.6y$

Compute the factor section for different values of y, up to find one approaching closely 6.825:
For y = 1.5 m A=7.875, R=0.937, $AR^{2/3}$=7.539
For y = 1.4 m A=7.140, R=0.887. $AR^{2/3}$=6.593
For y = 1.43 m A=7.357, R=0.902, $AR^{2/3}$=6.869

According to the above results the normal depth is slightly under 1.43. Using the software program FlowPro 2.0, mentioned in chapter 2 it would be instantaneously calculated, as shown in the enclosed captured screen: a depth of 1.425, with A=2.868, P=8.139, R=0.900 and a section factor 6.826

Summarising, the design of fabricated channels is a simple process requiring the following steps:



- Estimate the coefficient *n* from table 5.1
- Compute the form factor $AR^{2/3}=nQ/S^{1/2}$ with the known parameters in second term
- If optimum section is required apply values in table 5.2. Otherwise use values in table 2.4
- Check if the velocity is high enough to form deposit or aquatic flora
- Check the Froude number N_F to determine if it is a subcritical or a supercritical flow
- Define the required freeboard

Example 5.4

Design a trapezoidal channel for an 11 m^3/s discharge. The channel will be lined with well-finished concrete and the slope 0.001
Step 1. Manning n = 0.012
Step 2. Compute form factor

$$AR^{2/3}=\frac{nQ}{\sqrt{S}}=\frac{0.012\times11}{\sqrt{0.001}}=4.174$$

Step 3. Not intended to find the optimum section.
Step 4. Assuming a bottom width of 6 m and side slopes with inclination 2:1 compute the depth d by iteration as in example 5.3
d = 0.87 m A = 6.734 m^2
Step 5. Compute the velocity
V = 11/6.734 = 1.63 m/s OK
Step 6. Total channel height. The tables of the US Bureau of Reclamation (USA) recommend a freeboard of 0.37 m.

Needles to say that the FlowPro software would provide all this in one shot.

Photo 5.21

To ensure that the channel never overflows endangering the slope stability, and in addition to provide a generous freeboard, a lateral spillway (as in Photo 5.21) should be provided.

Before definitely deciding the channel route, a geologist should carefully study the geomorphology of the terrain. Take into consideration the accidents detailed in Chapter 4, section 4.4. The photo 5.22 shows clearly how uplift can easily ruin a power channel, 6 m wide and 500 m long, in a 2 MW scheme. On one particular day, a flood occurred which was later calculated to be a 100 year event. At the time the flood occurred, the head race channel had been empty, and uplift pressures became a reality, so the channel was destroyed.

Photo 5.22

Photo 5.23

5.2.4.2 Circumventing obstacles

Along the alignment of a canal obstacles may be encountered, and to bypass them it will be necessary to go over, around or under them.

The crossing of a stream or a ravine requires the provision of a flume, a kind of prolongation of the canal, with the same slope, supported on concrete or steel piles or spanning as a bridge. Steel pipes are often the best solution, because a pipe may be used as the chord of a truss, fabricated in the field. The only potential problem is the difficulty of removing sediment deposited when the canal is full of still water. Photo 5.23 shows a flume of this type in China.

Inverted siphons can also solve the problem. An inverted siphon consists of an inlet and an outlet structure connected by a pipe. The diameter calculation follows the same rules as for penstocks, which are analysed later.

5.2.5 Penstocks

5.2.5.1 Arrangement and material selection for penstocks.

Conveying water from the intake to the powerhouse -the purpose of a penstock- may not appear a difficult task, considering the familiarity of water pipes. However deciding the most economical arrangement for a penstock is not so simple. Penstocks can be installed over or under the ground, depending on factors such as the nature of the ground itself, the penstock material, the ambient temperatures and the environmental requirements.

A flexible and small diameter PVC penstock for instance, can be laid on the ground, following its outline with a minimum of grade preparation. Otherwise larger penstocks

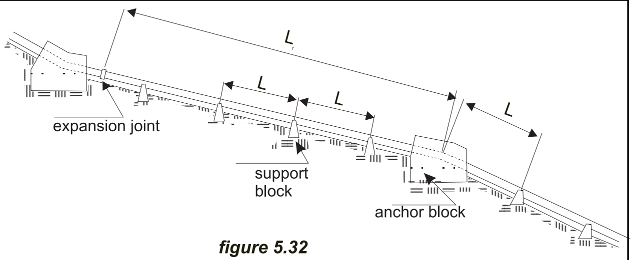


figure 5.32

must be buried, provided there is a minimum of rock excavation. The sand and gravel surrounding the pipe provides good insulation, and eliminates anchor blocks and expansion joints. Buried penstocks must be carefully painted and wrapped to protect the exterior from corrosion, but provided the protective coating is not damaged when installed, further maintenance should be minimal. From the environmental point of view the solution is optimal because the ground can be returned to its original condition, and the penstock does not constitute a barrier to the movement of wildlife.

A penstock installed above ground can be designed with or without expansion joints. Variations in temperature are especially important if the turbine does not function continuously, or when the penstock is dewatered for repair, resulting in thermal expansion or contraction. Usually the penstock is built in straight or nearly straight lines, with concrete anchor blocks at each bend and with an expansion joint between each set of anchors (Fig 5.32). The anchor blocks must resist the thrust of the penstock plus the frictional forces caused by its expansion and contraction, so when possible they should be founded on rock. If, due to the nature of the ground, the anchor blocks require large volumes of concrete, thus becoming rather expensive, an alternative solution is to eliminate every second anchor block and all the expansion joints, leaving the alternate bends free to move slightly. In this case it is desirable to lay the straight sections of the penstock in steel saddles, made to fit the contour of the pipe and generally covering 120 degrees of the invert (Fig 5.33). The saddles can be made from steel plates and shapes, with graphite asbestos sheet packing placed between saddle and pipe to reduce friction forces. The movement can be accommodated with expansion joints, or by designing the pipe layout with bends free to move.

If a pipeline system using spigot and socket joints with O-ring gaskets is chosen, then expansion and contraction is accommodated in the joints.

Today there is a wide choice of materials for penstocks. For the larger heads and diameters, fabricated welded steel is probably the best option. Nevertheless spiral machine-welded steel pipes should be considered, due to their lower price, if they are available in the required sizes. For high heads, steel or ductile iron pipes are preferred, but at medium and low heads steel becomes less competitive, because the internal and external corrosion protection layers do not decrease with the wall thickness and because there is a minimum wall thickness for the pipe to be handled.

For smaller diameters, there is a choice between manufactured steel pipe, supplied with spigot and socket joints and rubber "O" gaskets, which eliminates field welding,

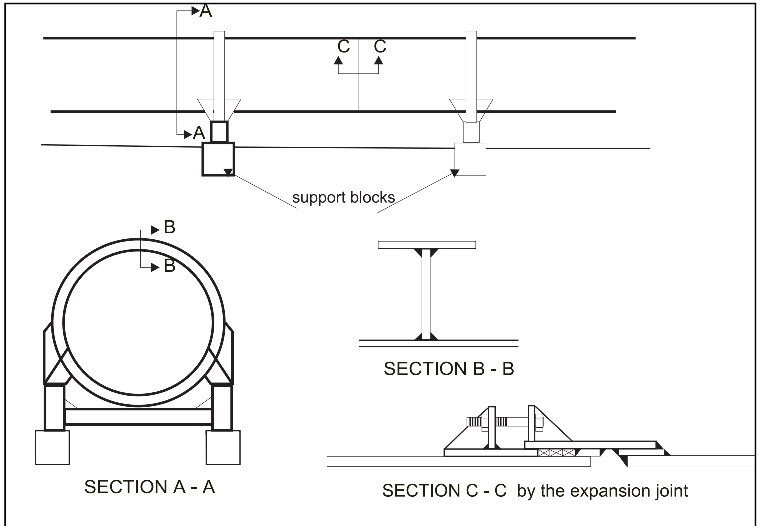


figure 5.33

or with welded-on flanges, bolted on site (Fig 5.34); plain spun or pre-stressed concrete; ductile iron spigot and socket pipes with gaskets; cement-asbestos; glass-reinforced plastic (GRP); PVC or polyethylene (PE) plastic pipes. Plastic pipe[14] is a very attractive solution for medium heads - a PVC pipe of 0.4 m diameter can be used up to a maximum head of 200 meters - because it is often cheaper, lighter and more easily handled than steel and does not need protection against corrosion. PVC[15] pipes are easy to install because of the spigot and socket joints provided with "O" ring gaskets. PVC pipes are usually installed underground with a minimum cover of one meter. Due to their low resistance to UV radiation they cannot be used on the surface unless painted coated or wrapped. The minimum radius of curvature of a PVC pipe is relatively large - 100 times the pipe diameter - and its coefficient of thermal expansion is five times higher that for steel. They are also rather brittle and unsuited to rocky ground.

Pipes of PE[16] - high molecular weight polyethylene - can be laid on top of the ground and can accommodate bends of 20-40 times the pipe diameter -for sharper bends, special factory fittings are required -. PE pipe floats on water and can be dragged by cable in long sections but must be joined in the field by fusion welding, requiring a special machine. PE pipes can withstand pipeline freeze-up without damage, but for the time being, may be not available in sizes over 300 mm diameter.

Concrete penstocks, both pre-stressed with high tensile wires or steel reinforced, featuring an interior steel jacket to prevent leaks, and furnished with rubber gasket spigot and socket joints constitute another solution. Unfortunately their heavy

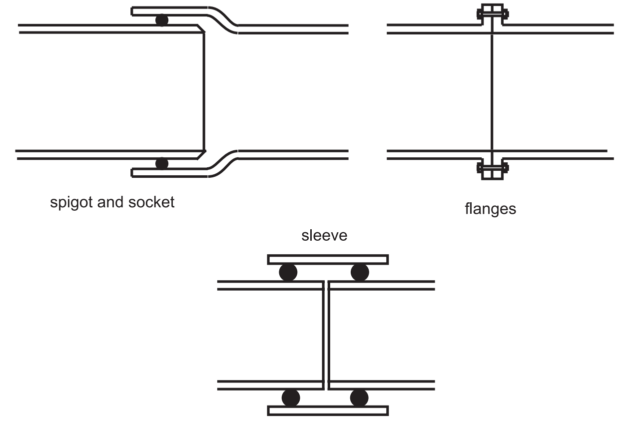


figure 5.34

weight makes transportation and handling costly, but they are not affected by corrosion.

In less developed countries, pressure creosoted wood-stave, steel-banded pipe is an alternative that can be used in diameters up to 5.5 meters and heads of up to 50 meters - which may be increased up to 120 meters for a diameter of 1.5 meters. The advantages include flexibility to conform to ground settlement, ease of laying on the ground with almost no grade preparation, no requirement of expansion joints and no necessity for concrete supports or corrosion protection. Wood stave pipe is assembled from individual staves and steel bands or hoops that allow it to be easily transported even over difficult terrain. Disadvantages include leakage, particularly in the filling operations, the need to keep the pipe full of water when repairing the turbine, and considerable maintenance such as spray coating with tar every five years.

Table 5.4 Materials used in pressure pipes

Material	Young's modulus of elasticity E (N/m^2)E9	Coefficient of linear expansion a (m/m ºC)E6	Ultimate tensile strength (N/m^2)E6	n
Welded steel	206	12	400	0.012
Polyethylene	0.55	140	5	0.009
Polyvinyl chloride (PVC)	2.75	54	13	0.009
Asbestos cement	n.a	8.1	n.a	0.011
Cast iron	78.5	10	140	0.014
Ductile iron	16.7	11	340	0.015

Table 5.4 shows the main properties of the above materials[17,18]. Some of these properties are typical only; particularly the values of the Hazen Williams coefficient which depends on the surface condition of the pipe.

5.2.5.2 Hydraulic design and structural requirements

A penstock is characterised by materials, diameter, wall thickness and type of joint.

- the material is selected according to the ground conditions, accessibility, weight, jointing system and cost.
- the diameter is selected to reduce frictional losses within the penstock to an acceptable level
- the wall thickness is selected to resist the maximum internal hydraulic pressure, including transient surge pressure that will occur.

Penstock diameter.

The diameter is selected as the result of a trade-off between penstock cost and power losses. The power available from the flow Q and head H is given by the equation:

$$P = QH\gamma\eta$$

where Q is the discharge in m^3/s, H the net head in m, γ the specific weight of water in kN/m3 and η the overall efficiency.

The net head equals the gross head minus the sum of all losses, including the friction and turbulence losses in the penstock, that are approximately proportional to the square of the velocity of the water in the pipe. To convey a certain flow, a small diameter penstock will need a higher water velocity than a larger-diameter one, and therefore the losses will be greater. Selecting a diameter as small as possible will minimise the penstock cost but the energy losses will be larger and vice versa. Chapter 2 details the friction loss calculations, putting special emphasis on the graphic representation of the Colebrook equations –the Moody diagram and the Wallingford charts- and on the Manning's formula. In this chapter the above principles are used and some examples will facilitate their application in real cases.

A simple criterion for diameter selection is to limit the head loss to a certain percentage. Loss in power of 4% is usually acceptable. A more rigorous approach is to select several possible diameters, computing power and annual energy. The present value of this energy loss over the life of the plant is calculated and plotted for each diameter (Figure 5.35). In the other side the cost of the pipe for each diameter is also calculated and plotted. Both curves are added graphically and the optimum diameter would be that closest to the theoretical optimum.

Actually the main head loss in a pressure pipe are friction losses; the head losses due to turbulence passing through the trashrack, in the entrance to the pipe, in bends, expansions, contractions and valves are minor losses. Consequently a first approach will suffice to compute the friction losses, using for example the Manning equation

$$\frac{h_f}{L} = 10.3\frac{n^2Q^2}{D^{5.333}} \tag{5.8}$$

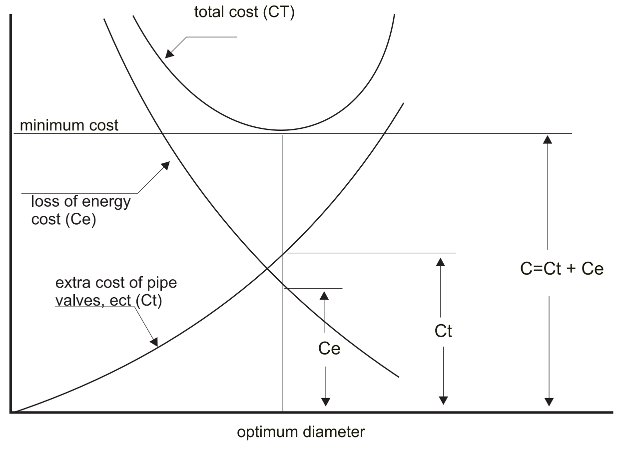


figure 5.35

Examining equation (5.8) it can be seen that dividing the diameter by two the losses are multiplied by 40. From equation (5.8)

$$D = \left(\frac{10.3 n^2 Q^2 L}{h_f} \right)^{0.1875} \qquad (5.9)$$

If we limit h_f at 4H/100, D can be computed knowing Q, n and L, by the equation

$$D = 2.69 \left(\frac{n^2 Q^2 L}{H} \right)^{0.1875} \qquad (5.10)$$

Example 5.5

A scheme has a gross head of 85 m, a discharge of 3 m³/s, and a 173-m long penstock in welded steel. Calculate the diameter so the power losses due to friction do not surpass 4%.

According to (5.10) $D = 2.69 \left(\frac{3^2 \times 0.012^2 \times 173}{85} \right)^{0.1875} = 0.88\text{m}$

We select a 1-m steel welded pipe and compute all the losses in the next example

Example 5.6

Compute the friction and turbulence head losses in a scheme as the illustrated in figure 5.36. The rated discharge is 3 m³/s and the gross head 85 m. The steel welded penstock diameter 1.0 m. The radius of curvature of the bends are four times the diameter. At the entrance of the power intake there is a trashrack with a total surface of 6 m², inclined 60º regarding the horizontal. The bars are 12-mm thick stainless steel bars, and the distance between bars 70-mm.

The flow velocity approaching the screen is according to (5.4) with K_1=1

$$V_0 = 3 \times \frac{70+12}{70} \times \frac{1}{6} \times \frac{1}{0.866} = 0.7\,\text{m/s}$$

The head loss through the trashrack is given by the Kilchner formula

$$h_f = 2.4 \times \left(\frac{12}{70} \right)^{4/3} \times \frac{0.7^2}{2 \times 9.81} \times 0.866 = 0.0049\,\text{m}$$

The head loss at the inlet of the penstock (a bad design) is given in figure 2.11, Chapter 2: K=0.08. The velocity in the penstock is 3.82 m/s, so the head loss at the inlet:

h_e= 0.08 x 3.82²/(2 x 9.81) = 0.06 m

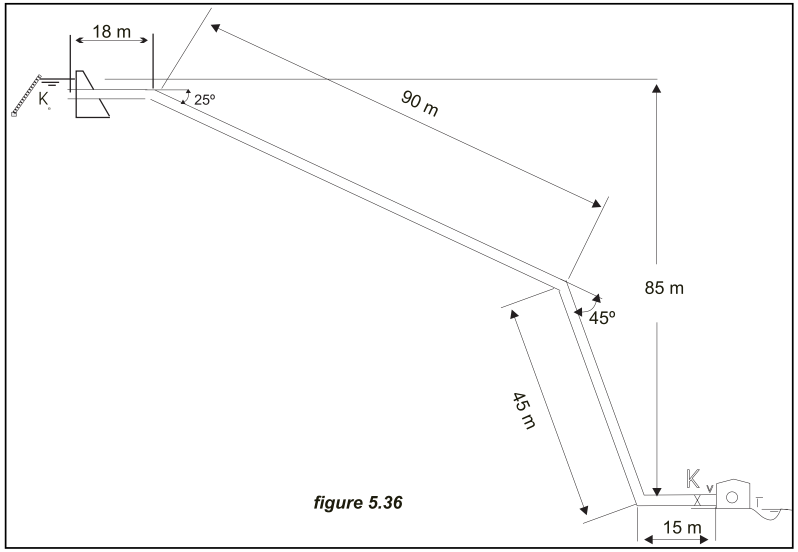


figure 5.36

The gross head at the beginning of the penstock is therefore
85-0.005-0.06=84.935 m
The friction loss in the penstock, according Manning equation (2.15)

$$h_f = \frac{10.3 \times 0.012^2 \times 3^2}{1.0^{5.333}} \times 173 = 2.30\,\mathrm{m}$$

The K_b coefficient for the first bend is 0.05 (28% of the corresponding to a 90º bend as in 2.2.23). The coefficient for the second bend K_b=0.085 and for the third bend K_b=0.12. The head losses in the three bends amount to
(0.05 + 0.085 + 0.12) x 3.82²/(2 x 9.81) = 0.19 m.
The head loss in the gate valve 0.15 x 3.82²/(2 x 9.81) = 0.11 m
Summarising: head loss in trashrack plus pipe inlet: 0.065 m
head loss in three bends and valve : 0.30 m
head loss by friction in the penstock: 2.30 m
Total head loss: 2.665 m equivalent to 3.14% of the gross power.

Wall thickness

The wall thickness required depends on the pipe material, its ultimate tensile strength (and yield), the pipe diameter and the operating pressure. In steady flows - discharge is assumed to remain constant with time - the operating pressure at any point along a penstock is equivalent to the head of water above that point. The wall thickness in this case is computed by the equation:

$$e = \frac{P_1 D}{2\sigma_f} \tag{5.11}$$

where e = Wall thickness in mm
P_1= Hydrostatic pressure in kN/mm²
D = Internal pipe diameter in mm
σ_f= Allowable tensile strength in kN/mm²

In steel pipes the above equation is modified by

$$e = \frac{P_1 D}{2\sigma_f k_f} + e_s \tag{5.12}$$

where e_s= extra thickness to allow for corrosion
k_f= weld efficiency
k_f= 1 for seamless pipes
k_f= 0.9 for xray inspected welds
k_f= 1.0 for xray inspected welds and stress relieved
σ_f= allowable tensile stress (1400 kN/mm²)

The pipe should be rigid enough to be handled without danger of deformation in the field. ASME recommends a minimum thickness in mm equivalent to 2.5 times the diameter in metres plus 1.2 mm. Other organisations recommend as minimum thickness t_{min}=(D+508)/400, where all dimensions are in mm.

In high head schemes it can be convenient to use penstock of uniform diameter but with different thicknesses as a function of the hydrostatic pressures.

A certain area of the penstock can remain under the Energy Gradient Line (page 13) and collapse by sub-atmospheric pressure. The collapsing depression will be given by

$$P_c = 882500 \times \left(\frac{e}{D}\right)^3 \tag{5.13}$$

where e and D are respectively the wall thickness and diameter of the pipe in mm.

This negative pressure can be avoided by installing an aeration pipe with a diameter in cm given by

$$d = 7.47\sqrt{\frac{Q}{\sqrt{P_c}}} \tag{5.14}$$

provided $P_c \leq 0.49\,\mathrm{kgN/mm^2}$; otherwise $d = 8.94\sqrt{Q}$

Sudden changes of flow can occur when the plant operator or the governing system opens or closes the gates rapidly. Occasionally the flow may even be stopped suddenly due to full load rejection, or simply because an obstruction become lodged in the nozzle of a Pelton turbine jet. A sudden change of flow rate in a penstock may involve a great mass of water moving inside the penstock. The pressure wave which occurs with a sudden change in the water's velocity is known as waterhammer; and although transitory, can cause dangerously high and low pressures whose effects can be dramatic: the penstock can burst from overpressure or collapse if the pressures are reduced below ambient. The surge pressures induced by the waterhammer phenomenon can be of a magnitude several times greater than the static pressure due to the head, and must be considered in calculating the wall thickness of the penstock.

Detailed information on the waterhammer phenomenon can be found in texts on hydraulics[19,20], but sufficient information has been given in Chapter 2, section 2.2.3. Some examples will show the application of the recommended formulae.

As explained in chapter 2, the pressure wave speed c (m/s) depends on the elasticity of the water and pipe material according to the formula

$$c = \sqrt{\frac{10^{-3}K}{1 + \frac{KD}{Et}}} \tag{5.15}$$

where K = bulk modulus of water 2.1x10⁹ N/m²
E = modulus of elasticity of pipe material (N/m²)
D = pipe diameter (mm)
t = wall thickness (mm)

The time taken for the pressure wave to reach the valve on its return, after sudden closure is known as the critical time

$$T = 2L/c \tag{5.16}$$

For instantaneous closure – the pressure wave reaches the valve after its closure- the increase in pressure, in metres of water column, due to the pressure wave is

$$P = \frac{c\Delta_v}{g} \tag{5.17}$$

where Δ_v is the velocity change

Examples 6.4 and 6.5 show that surge pressures in steel pipes are more than three times greater than in PVC, due to the greater stiffness of the steel.

Example 5.7

Calculate the pressure wave velocity, for instant closure, in a steel penstock 400mm-dia and 4mm-wall thickness

Applying 5.15

$$c = \sqrt{\frac{2.1\times10^6}{1+\frac{2.1\times10^9\times400}{2.1\times10^{11}\times4}}} = 1024 \text{ m/s}$$

b) The same for a PVC pipe 400mm dia. 14 mm wall thickness

$$c = \sqrt{\frac{2.1\times10^6}{1+\frac{2.1\times10^9\times400}{2.75\times10^9\times14}}} = 305 \text{ m/s}$$

Example 5.8

What is the surge pressure, in the case of instant valve closure, in the two penstocks of example 5.7, if the initial flow velocity is 1.6 m/s?

a) steel penstock:

$$P_s = \frac{1024\times4}{9.8} = 417 \text{ m}$$

b) PVC penstock:

$$P_s = \frac{305\times4}{9.8} = 123 \text{ m}$$

As the example 5.8 shows, the surge pressure in the steel pipe is three times higher than in the PVC pipe, due to the greater rigidity of the steel

If the change in velocity occurs in more than ten times the critical time T, little or no overpressure will be generated and the phenomenon may be ignored. In between, if T>2L/c, P_s will not develop fully, because the reflected negative wave arriving at the valve will compensate for the pressure rise. In these cases the Allievi formula may compute the maximum overpressure:

$$\Delta_P = P_0\left(\frac{N}{2}\pm\sqrt{\frac{N^2}{4}+N}\right) \tag{5.18}$$

where P_0 is the hydrostatic pressure due to the head and

$$N = \left(\frac{LV_0}{gP_0t}\right)^2 \tag{5.19}$$

where: V_0 = water velocity in m/s
L = total penstock length (m)
P_0 = gross hydrostatic pressure (m)
t = closing time (s)

The total pressure experienced by the penstock is $P = P_0 + \Delta_P$

The next example illustrates the application of the Allievi formula, when the closure time is at least twice but less than 10 times the critical time.

Example 5.9

Calculate the wall thickness in the penstock analysed in example 5.6 if the valve closure time is 3 seconds.

Summarising the data,	Gross head :	84.935 m
	Rated discharge:	3 m³/s
	Internal pipe diameter	1.0 m
	Total pipe length:	173 m

Estimating in a first approach at 5 mm the wall thickness to compute the wave speed c

$$c = \sqrt{\frac{2.1\times10^6}{1+\frac{2.1\times10^9\times1000}{2.1\times10^{11}\times5}}} = 836.7 \text{ m/s}$$

The closure time is bigger than the critical one (0.41 s) but smaller than 10 times its value, so the Allievi formula can be applied.
The water velocity in the pipe is 3.82 m/s

$$V = \frac{4\times3}{\pi\times1.0^2} = 3.82 \text{ m/s}$$

N would be computed for a gross head in the pipe of 84.935 m

$$N = \left(\frac{3.82\times173}{9.81\times84.935\times3}\right)^2 = 0.070$$

and therefore

$$\Delta_P = 84.935\left(\frac{0.07}{2}\pm\sqrt{0.07+\frac{0.07^2}{4}}\right) = +25.65 \text{ m}; -19.58 \text{ m}$$

The total pressure would be 84.935+25.65 = 110.585 tf/m² = 11.06 kN/mm².
It requires a wall thickness .

$$e = \frac{11.06 \times 1000}{2 \times 1400} + 1 = 4.95 \text{ mm}$$

That agrees with the initial estimation and covers the specs for handling the pipes in the field (t_{min}=2.5x1+1.2=3.7 mm)
To compute the air vent pipe diameter:

$$P_c = 882500\left(\frac{5}{1000}\right)^3 = 0.11 \text{ kN / mm}^2$$

And the diameter $d = 7.47\sqrt{\frac{3}{\sqrt{0.11}}} = 22.46 \text{ cm}$

The waterhammer problem becomes acute in long pipes, when the open channel is substituted by a pressure pipe all along the trace. For a rigorous approach it is necessary to take into consideration not only the elasticity of fluid and pipe material, as above, but also the hydraulic losses and the closure time of the valve. The mathematical approach is cumbersome and requires the use of a computer program. For interested readers, Chaudry [19], Rich [20], and Streeter and Wylie [21] give some calculation methods together with a certain number of worked examples.

To determine the minimum pipe thickness required at any point along the penstock two waterhammer hypotheses should be taken into consideration: normal waterhammer and emergency waterhammer. Normal waterhammer occurs when the turbine shuts down under governor control. Under these conditions, the overpressure in the penstock can reach 25% of the gross head, in the case of Pelton turbines, and from 25% to 50% in the case of reaction turbines -depending on the governor time constants- The turbine manufacturer's advice should be taken into consideration. Emergency waterhammer, caused for example by an obstruction in the needle valve of a Pelton turbine, or a malfunction of the turbine control system, must be calculated according to equation (5.17).

In steel penstocks, the compounded stresses -static plus transitory- are a function both of the ultimate tensile and yield strength. In the case of normal waterhammer, the combined stress should be under 60% of the yield strength and 38% of the ultimate tensile strength. In the case of emergency waterhammer, the combined stress should be under 96% of the yield strength and 61% of the ultimate tensile strength.

Commercial pipes are often rated according to the maximum working pressure under which they are designed to operate. The pressure rating of a pipe already includes a safety factor, and sometimes may include an allowance for surge pressures. Safety factors and surge pressure allowances depends on the standard being used.

If the scheme is liable to surge pressure waves a device to reduce its effects must be considered. The simplest one is the surge tower, a sort of large tube, connected at its base to the penstock and open to the atmosphere. The fundamental action of a surge tower is to reduce the length of the column of water by placing a free water

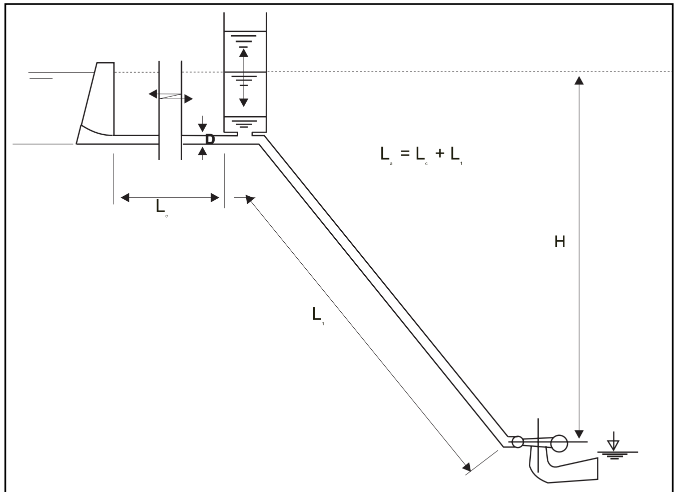


figure 5.37

surface closer to the turbine (figure 5.37). Some authors[21] consider that the surge tower is unnecessary if the pipe length is inferior to 5 times the gross head. It is also convenient to take into account the water acceleration constant t_h in the pipe

$$t_h = \frac{VL}{gH}$$

where L = length of penstock (m),
V = flow velocity (m/s) and
H = net head (m).

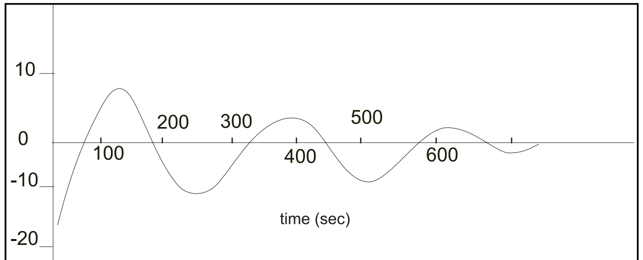


figure 5.38

Photo 5.24

If t_h is inferior to 3 seconds the surge tower is unnecessary but if surpass 6 seconds, either a surge tower or another correcting device must be installed to avoid strong oscillations in the turbine controller.

With the valve open and a steady flow in the penstock, the level of the water in the tower will correspond to the pressure in the penstock - equivalent to the net head. When by a sudden closure of the valve the pressure in the penstock rises abruptly, the water in the penstock tends to flow into the tower, raising the level of the water above the level in the intake. The level in the tower then begins to fall as the water flows from the tower into the penstock, until a minimum level is reached. The flow then reverses and the level in the tower rise again and so on. Fig 5.38 shows a graph plotting the surge height versus time. The maximum height corresponds to the overpressure in the penstock due to the waterhammer. The throttling introduced by a restricted orifice will reduce the surge amplitude by 20 to 30 per cent. The time t_h plays an important role in the design of the turbine regulation system. In a badly designed system, the governor and the tower surge can interact, generating speed regulation problems too severe for the governor to cope with.

In instances, when the closure time of the turbine valves must be rapid, a relief valve placed in parallel with the turbine, such that it opens as the turbine wicket gates close, can be convenient. This has the effect of slowing down the flow changes in the penstock. In the ESHA NEWS issue of spring 1991 there is a description of such a valve. Photo 5.24 shows the water jet getting out of the open valve.

5.2.5.3 Saddles, supporting blocks and expansion joints

The saddles are designed to support the weight of the penstock full of water, but not to resist significant longitudinal forces. The vertical component of the weight to be supported, in kN, has a value of

$$F_1 = \left(W_p + W_w\right) L \cos F$$

where W_p = weight of pipe per meter (kN/m)
W_w = weight of water per meter of pipe (kN/m)
L = length of pipe between mid points of each span (m)
Φ = angle of pipe with horizontal

The design of support rings is based on the elastic theory of thin cylindrical shells. The pipe shell is subject to beam and hoop stresses, and the loads are transmitted to the support ring by shear. If penstocks are continuously supported at a number of points, the bending moment at any point of penstock may be calculated assuming that it is a continuous beam, and using the corresponding equation. The rings are welded to the pipe shell with two full length fillet welds and are tied together with diaphragm plates

The span between supports L is determined by the value of the maximum permissible deflection L/65 000. Therefore the maximum length between supports is given by the equation

$$L = 182.61 \times \frac{\sqrt[3]{(D+0.0147)^4 - D^4}}{P}$$

where D = internal diameter (m) and P = unit weight of the pipe full of water (kg/m)

5.2.6 Tailraces

After passing through the turbine the water returns to the river trough a short canal called a tailrace. Impulse turbines can have relatively high exit velocities, so the tailrace should be designed to ensure that the powerhouse would not be undermined. Protection with rock riprap or concrete aprons should be provided between the powerhouse and the stream. The design should also ensure that during relatively high flows the water in the tailrace does not rise so far that it interferes with the turbine runner. With a reaction turbine the level of the water in the tailrace influences the operation of the turbine and more specifically the onset of cavitation. This level also determines the available net head and in low head systems may have a decisive influence on the economic results.

Bibliography

1. J.L. Brennac. "Les Hauses Hydroplus", ESHA Info n° 9 verano 1993
2. Para más información acudir a la página de 1NTERNET http://www.obermeyerhydro.com
3. H.C. Huang and C.E. Hita, «Hydraulic Engineering Systems» Prentice Hall Inc., Englewood Cliffs, New Jersey 1987
4. British Hydrodynamic Research Association «Proceedings of the Symposium on the Design and Operation of Siphon Spillways», London 1975
5. Allen R.Inversin, «Micro-Hydopower Sourcebook», NRECA International Foundation, Washington, D.C.
6. USBR Design of Small Dams 3rd ed, Denver, Colorado,1987
7. USBR, Design of Small Canal Structures, Denver, Colorado, 1978a.
8. USBR, Hydraulic Design of Spillways and Energy Dissipators. Washington DC, 1964
9.T. Moore, «TLC for small hydro: good design means fewer headaches», HydroReview/April 1988.
10. T.P. Tung y otros, «Evaluation of Alternative Intake Configuration for Small Hydro». Actas de HIDROENERGIA 93. Munich.
11 ASCE, Committee on Intakes, Guidelines for the Design of Intakes for Hydroelectric Plants, 1995
12. G. Munet y J.M. Compas «PCH de recuperation d'energie au barrage de «Le Pouzin»».Actas de HIDROENERGIA 93, Munich
13. «Rubber seals for steel hydraulic gates, G.Schmausser & G.Hartl, Water Power & Dam Construction September 1988
14 ISO 161-1-1996 Thermoplastic pipes for conveyance of fluids - Nominal outside diameters and nominal pressures -- Part 1:Metric series
15 ISO 3606-1976 Unplasticized polyvinyl chloride (PVC) pipes. Tolerances on outside diameters and wall thickness
16 ISO 3607-1977 Polyethylene (PE) pipes. Tolerances on outside diameters and wall thickness
17 ISO 3609-1977 Polypropylene (PP) pipes. Tolerances on outside diameters and wall thickness
18 ISO 4065-1996 Thermoplastic pipes -- Universal wall thickness table
19 H.Chaudry «Applied Hydraulic Transients» Van Nostrand Reinhold Company, 1979.
20 J.Parmakian, «Waterhammer Analyses», Dover Publications, Inc, New York, 1963
21 Electrobras (Centrais Eléctricas Brasileiras S.A.) Manual de Minicentrais Hidrelétricas

6 Electromechanical equipment

6.0 Powerhouse

In a small hydropower scheme the role of the powerhouse is to protect from the weather hardships the electromechanical equipment that convert the potential energy of water into electricity. The number, type and power of the turbo-generators, their configuration, the scheme head and the geomorphology of the site controls the shape and size of the building.

Fig. 6.1 is a schematic view of an integral intake indoor powerhouse suitable for low head schemes. The substructure is part of the weir and embodies the power intake with its trashrack, the vertical axis open flume Francis turbine coupled to the generator, the draught tube and the tailrace. The control equipment and the outlet transformers are located in the generator forebay.

In some cases the whole superstructure is dispensed with, or reduced to enclose only the switchgear and control equipment. Integrating turbine and generator in a single waterproofed unit that can be installed directly in the waterway means that a conventional powerhouse is not required. Figure 6.2 and Photo 6.1 shows a submerged Flygt turbine with a sliding cylinder as control gate and with no protection for the equipment. Siphon units provide an elegant solution in schemes with heads under 10 meters and for units of less than 1000 kW installed. Photo 6.2 shows a recent installation in France with the electromechanical equipment simply protected by a steel plate.

Otherwise to mitigate the environmental impact the powerhouse can be entirely submerged (see chapter 1, figure 1.6). In that way the level of sound is sensibly reduced and the visual impact is nil.

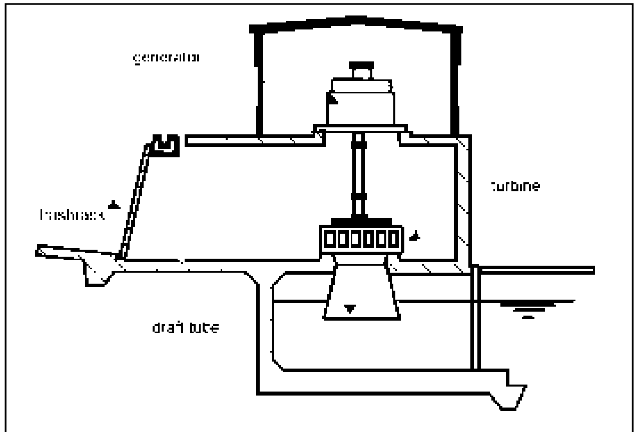


figure 6.1

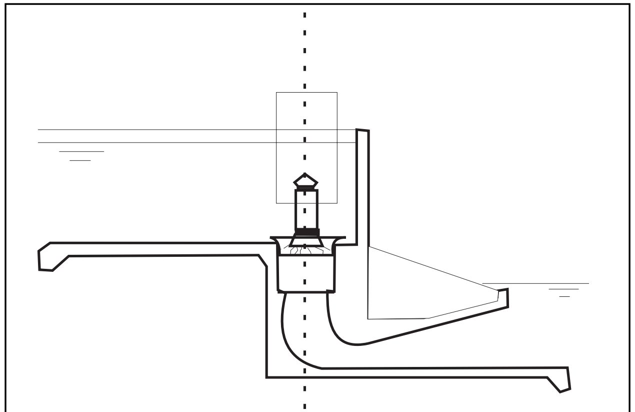


figure 6.2

In low-head schemes the number of Kaplan turbine configurations is very large (pit, in S, right angle, etc.) as shown in figures 6.18 to 6.25. In medium and high head schemes powerhouses are more conventional (figure 6.3) with an entrance for the penstock and a tailrace. This kind of powerhouse is sometimes located in a cave, either natural or excavated for the purpose.

The powerhouse can also be at the base of an existing dam, where the water arrives via an existing bottom outlet or an intake tower. Figure 1.4 in chapter 1 illustrates such a configuration.

Photo 6.1

Photo 6.2

6.1 Hydraulic turbines

The purpose of a hydraulic turbine is to transform the water potential energy to mechanical rotational energy. Although this handbook does not define guidelines for the design of turbines (a role reserved for the turbine manufacturers) it is appropriate to provide a few criteria to guide the choice of the right turbine for a particular application and even to provide appropriate formulae to determine its main dimensions. These criteria and formulae are based on the work undertaken

Photo 6.3

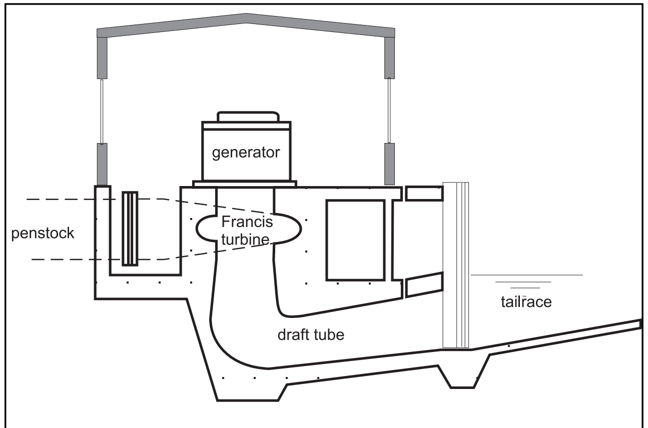


figure 6.3

by Siervo and Lugaresi, Austerre and Verdehan[1], Giraud and Beslin[2], Belhaj[3], Gordon and others, which provide a series of formulae by analysing the characteristics of installed turbines. It is necessary to emphasize however that no advice is comparable to that provided by the manufacturer, and every developer should refer to him from the beginning of the development project.

Photo 6.4

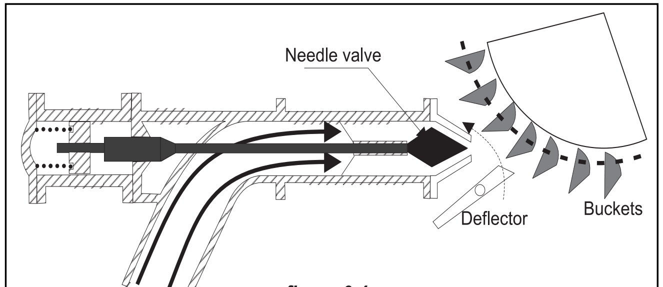


figure 6.4

6.1.1 Classification criteria

6.1.1.1 On the basis of the flow regime in the turbine

The potential energy in the water is converted into mechanical energy in the turbine, by one of two fundamental and basically different mechanisms:

- The water pressure can apply a force on the face of the runner blades, which decreases as it proceeds through the turbine. Turbines that operate in this way are called reaction turbines. The turbine casing, with the runner fully immersed in water, must be strong enough to withstand the operating pressure.
- The water pressure is converted into kinetic energy before entering the runner. The kinetic energy is in the form of a high-speed jet that strikes the buckets, mounted on the periphery of the runner. Turbines that operate in this way are called impulse turbines. As the water after striking the buckets falls into the tail water with little remaining energy, the casing can be light and serves the purpose of preventing splashing.

6.1.1.1.1 Impulse turbines

Pelton turbines

Pelton turbines are impulse turbines where one or more jets impinge on a wheel carrying on its periphery a large number of buckets. Each jet issues through a nozzle with a needle (or spear) valve to control the flow (figure 6.4). They are only used for relatively high heads. The axes of the nozzles are in the plane of the runner (figure 6.5). To stop the turbine – e.g. when the turbine approaches the runaway speed due to load rejection- the jet (see figure 6.4) may be deflected by a plate so that it does not impinge on the buckets. In this way the needle valve can be closed very slowly, so that overpressure surge in the pipeline is kept to an acceptable minimum.

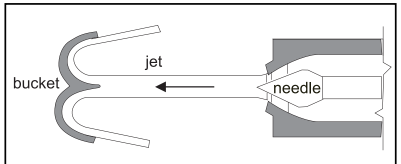


figure 6.5

Any kinetic energy leaving the runner is lost and so the buckets are designed to keep exit velocities to a minimum. The turbine casing only needs to protect the surroundings against water splashing and therefore can be very light.

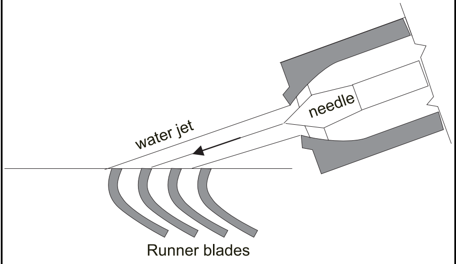


figure 6.6

Turgo turbines

The Turgo turbine can operate under a head in the range of 30-300 m. Like the Pelton it is an impulse turbine, but its buckets are shaped differently and the jet of water strikes the plane of its runner at an angle of 20º. Water enters the runner through one side of the runner disk and emerges from the other (Fig 6.6). (Compare this scheme with the one in Fig.6.5 corresponding to a Pelton turbine). Whereas the volume of water a Pelton turbine can admit is limited because the water leaving each bucket interferes with the adjacent ones, the Turgo runner does not present this problem. The resulting higher runner speed of the Turgo makes direct coupling of turbine and generator more likely, improving its overall efficiency and decreasing maintenance cost.

Cross-flow turbines

This impulse turbine, also known as Banki-Michell in remembrance of its inventors and Ossberger after a company which has been making it for more than 50 years, is used for a wide range of heads overlapping those of Kaplan, Francis and Pelton. It can operate with discharges between 20 litres/sec and 10 m^3/sec and heads between 1 and 200 m.

Water (figure 6.7) enters the turbine, directed by one or more guide-vanes located in a transition piece upstream of the runner, and through the first stage of the runner which runs full with a small degree of reaction. Flow leaving the first stage attempt to crosses the open centre of the turbine. As the flow enters the second stage, a compromise direction is achieved which causes significant shock losses.

The runner is built from two or more parallel disks connected near their rims by a series

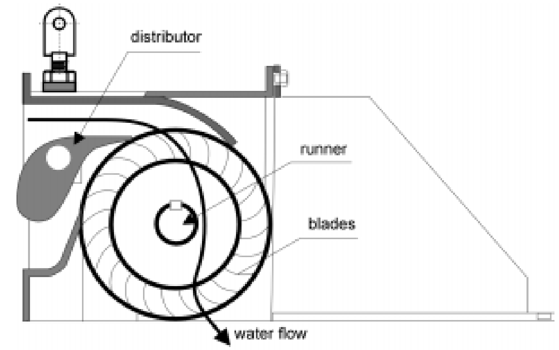


figure 6.7

Photo 6.5

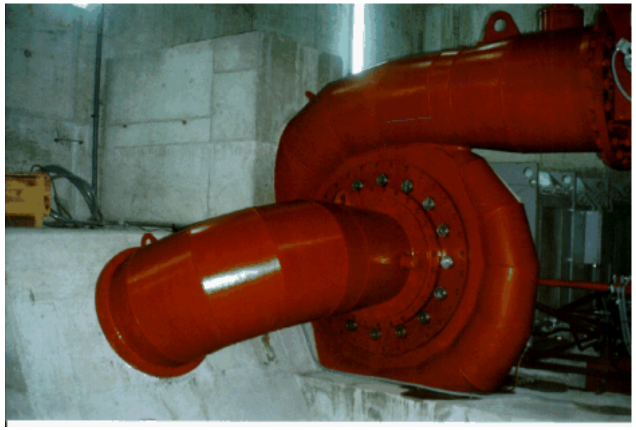
of curved blades). Their efficiency lower than conventional turbines, but remains at practically the same level for a wide range of flows and heads (typically about 80%).

6.1.1.1.2 Reaction turbines

Francis turbines.

Francis turbines are radial flow reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium heads. In the high speed Francis the admission is always radial but the outlet is axial. Photograph 6.4 shows a horizontal axis Francis turbine.

Photo 6.6



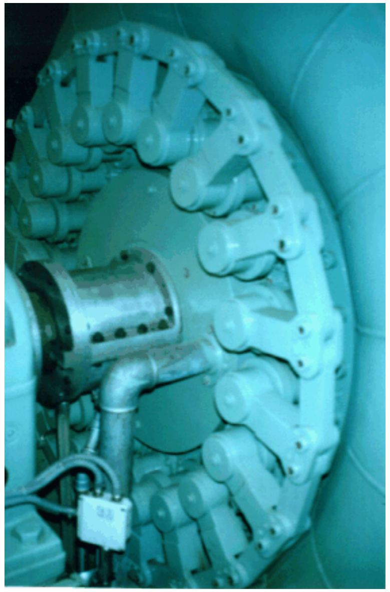


Photo 6.7

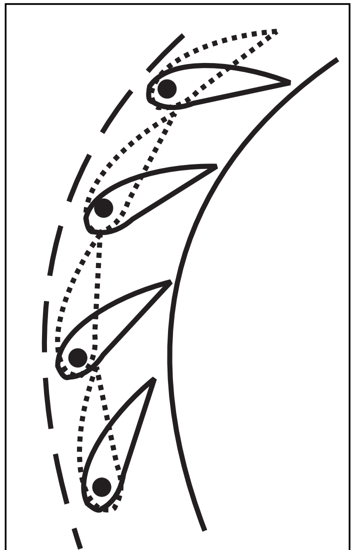


figure 6.9

The water proceeds through the turbine as if it was enclosed in a closed conduit pipe, moving from a fixed component, the distributor, to a moving one, the runner, without being at any time in contact with the atmosphere. Figure 6.8 shows a vertical section of a horizontal axis machine. The figure illustrates how the guide vanes, whose mission is to control the discharge going into the runner, rotate around their axes, by connecting rods attached to a large ring that synchronise the movement off all vanes. It must should be emphasized that the size of the spiral casing contrasts with the lightness of a Pelton casing. In the photo 6.7 the rotating ring and the attached links that operate the guide vanes can be seen.

Figure 6.9 schematically shows the adjustable vanes and their mechanism, both in open and closed position. As can be seen the wicket gates can be used to shut off the flow to the turbine in emergency situations, although their use does not preclude the installation of a butterfly valve at the entrance to the turbine.

Francis turbines can be set in an open flume or attached to a penstock. For small heads and power open flumes are commonly employed. Steel spiral casings are used for higher heads, designing the casing so that the tangential velocity of the water is constant along the consecutive sections around the circumference. As shown in figure 6.8 this implies a changing cross-sectional area of the casing. Figure 6.10 shows a Francis runner in perspective from the outlet end. Small runners are usually made in aluminium bronze castings. Large runners are fabricated from curved stainless steel plates, welded to a cast steel hub.

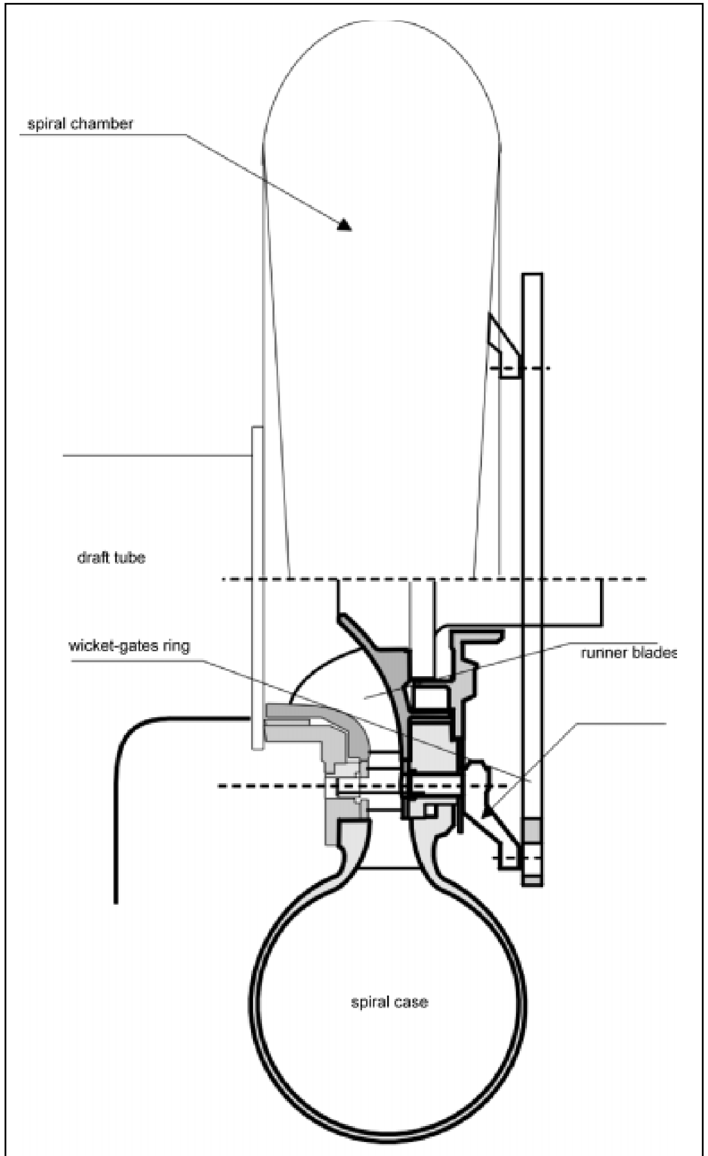


figure 6.8

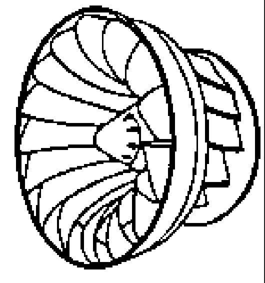


figure 6.10

In reaction turbines, to reduce the kinetic energy still remaining in the water leaving the runner a draft tube or diffuser stands between the turbine and the tail race. A well-designed draft tube allows, within certain limits, the turbine to be installed above the tailwater elevation without losing any head. As the kinetic energy is proportional to the square of the velocity one of the draft tube objectives is to reduce the outlet velocity. An efficient draft tube would have a conical section but the angle cannot be too large, otherwise flow separation will occur. The optimum angle is 7º but to reduce the draft tube length, and therefore its cost, sometimes angles are increased up to 15º. Draft tubes are particularly important in high-speed turbines, where water leaves the runner at very high speeds.

In horizontal axis machines the spiral casing must be well anchored in the foundation to prevent vibration that would reduce the range of discharges accepted by the turbine.

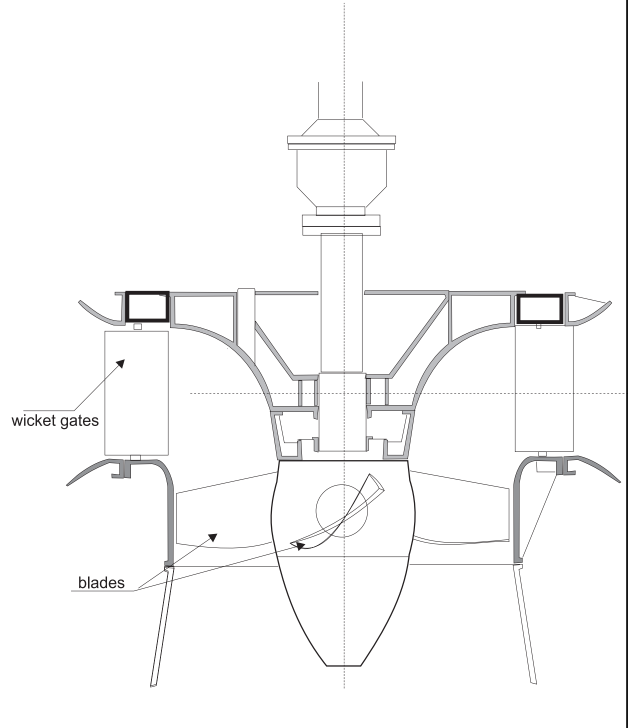


Figure 6.11

Photo 6.8

Kaplan and propeller turbines

Kaplan and propeller turbines are axial-flow reaction turbines, generally used for low heads. The Kaplan turbine has adjustable runner blades and may or may not have adjustable guide- vanes If both blades and guide-vanes are adjustable it is described as "double-regulated". If the guide-vanes are fixed it is "single-regulated". Unregulated propeller turbines are used when both flow and head remain practically constant

The double-regulated Kaplan, illustrated in figure 6.11 is a vertical axis machine with a scroll case and a radial wicket-gate configuration as shown in photo 6.8. The flow enters radially inward and makes a right angle turn before entering the runner in an axial direction. The control system is designed so that the variation in blade angle is coupled with the guide-vanes setting in order to obtain the best efficiency over a wide range of flows. The blades can rotate with the turbine in operation, through links connected to a vertical rod sliding inside the hollow turbine axis.

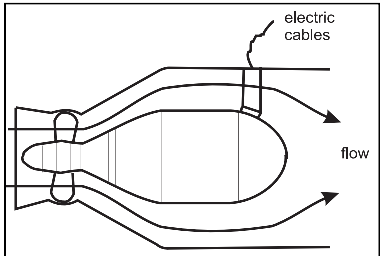


figure 6.12

Bulb units are derived from Kaplan turbines, with the generator contained in a waterproofed bulb submerged in the flow. Figure 6.12 illustrates a turbine where the generator (and gearbox if required) cooled by pressurised air is lodged in the bulb. Only the electric cables, duly protected, leave the bulb .

Pumps working as turbines

Standard centrifugal pumps may be operated as turbines by directing flow through them from pump outlet to inlet. Since they have no flow regulation they can operate only under relatively constant head and discharge[6].

6.1.1.2 On the basis of the specific speed

The large majority of hydraulic structures –spillways, energy dissipators at the outlet of a hydraulic structure, the reduction of energy losses at the water intake, etc.- are designed and built on the basis of the results obtained from preliminary model studies. The behaviour of these models are based on the principles of hydraulic similitude, including dimensional analysis, by which is meant the analysis of the physical quantities involved in the static and dynamic behaviour of water flow in a hydraulic structure. The turbine design does not constitute an exception and actually turbine manufacturers make use of scaled models. The problem of similarity in this case can be summarised as follows: "Given test data on the performance characteristics of a certain type of turbine under certain operating conditions, can the performance characteristic of a geometrically similar machine, under different operating conditions be predicted?" If there is a positive answer to this question the theory of similitude will provide a scientific criterion for cataloguing turbines, that will prove very useful in the process of selection of the turbine best adapted to the conditions of the scheme..

Effectively the answer is positive provided that model and prototype are:

- Geometrically similar
- Have the same volumetric coefficient as defined by $Q/A\sqrt{2gH}$

To be geometrically similar the model will be a reduction of the prototype by maintaining a fixed ratio for all homogeneous lengths. The physical quantities involved in geometric similarity are length, l, area A and volume V. If the lengths ratio is k, the area ratio will be k^2 and the volume ratio k^3. For the model and prototype to have the same volumetric coefficient it will be necessary that:

$$\frac{Q}{Q'} = \sqrt{\frac{2gH}{2gH'}} \times \frac{A}{A'} = \left(\frac{H}{H'}\right)^{1/2} k^2 \qquad (6.1)$$

The power ratio between model and prototype will be:

$$\frac{P}{P'} = \frac{HQ}{H'Q'} = \left(\frac{H}{H'}\right)^{3/2} k^2 \qquad (6.2)$$

where P= power (kW)

But as $\mathrm{v} = \sqrt{2\mathrm{gH}}$; $\frac{v}{v'} = \sqrt{\frac{H}{H'}}$

The ratio of the angular velocities will be

$$\frac{n}{n'} = \frac{v/r}{v'/r'} = \frac{v}{v'} \times \frac{r'}{r} = \left(\frac{H}{H'}\right)^{1/2} \times \frac{1}{k} \qquad (6.3)$$

Substituting in (6.2) the value k obtained from (6.3)

$$\frac{P}{P'} = \left(\frac{H}{H'}\right)^{3/2} \left(\frac{H}{H'}\right)^{2/2} \frac{n'^2}{n^2} = \left(\frac{H}{H'}\right)^{5/2} \left(\frac{n'}{n}\right)^2 \qquad (6.4)$$

If the model tests had been done with a head H' of 1 metre and a discharge Q' such that the generated power is 1 kW, and assuming that the model runner has turned at n' = n_s rpm, equation (6.4) would be rewritten:

$$n_s = n\frac{\sqrt{P}}{H^{5/4}} \qquad (6.5)$$

n_s is known as *specific speed*. Any turbine, with identical geometric proportions, even if the sizes are different, will have the same specific speed. If the model had been refined to get the optimum hydraulic efficiency, all turbines with the same specific speed will also have an optimum efficiency.

Substituting in eq. (6.4) P/P' by HQ/H'Q' :

$$\frac{HQ}{H'Q'} = \left(\frac{H}{H'}\right)^{5/2} \left(\frac{n'}{n}\right)^2 ; \; HQ = H^{5/2}\left(\frac{n_q}{n}\right)^2$$

and hence if H'=1 and n'=n_q

$$n_q = n\frac{Q^{1/2}}{H^{3/4}} \qquad (6.6)$$

Some manufacturers define the specific speed n_q of a turbine as the speed of a unit of the series of such magnitude that it delivers unit discharge at unit head.

The specific speed such as has been defined by eq (6.5) and (6.6) is not a dimensionless parameter and therefore its value varies with the kind of units employed in its calculation. The dimensionless parameter is the specific speed N_s given by the equation:

$$N_s = \frac{\Omega\sqrt{P/\rho}}{(gH)^{5/4}}$$

where Ω is the angular velocity and ρ the water density

In this handbook n_s is always expressed in S.I. units with the kilowatt as power unit and is equivalent to 166 N_s. If n_s were calculated with the horsepower as power unit it would correspond to 193.1 N_s.

Figure 6.13 shows four different designs of reaction runners and their corresponding specific speeds, optimised from the efficiency viewpoint. It can be seen that the runner evolves to reconcile with the scheme conditions. A Francis slow runner will be used in high head schemes, where a high-speed runner would run at an excessive speed. As the runner evolves with the specific speed it reaches a point where the lower ring that keep the runner blades together generates too high a friction, so from there on the ring is abandoned and the blades are built as cantilevers. From that the Kaplan, propeller and Bulb turbines, used in low head schemes, with specific speeds as high as 1200 were evolved.

In general turbine manufacturers specify the specific speed of their turbines. A large number of statistic studies undertaken by De Siervo and Lugaresi[4], Lugaresi and Massa[5], Schweiger and Gregory[6], Gordon[7], Lindestrom, Kpordze and others, on a large number of schemes has established a correlation, for each type of turbine, of the specific speed and the net head. Hereunder some of the correlation formulae graphically represented in figure 6.14.

Pelton (1 jet)	$n_s = 85.49/ H^{0.243}$	(Siervo and Lugaresi, 1978)
Francis	$n_s = 3763/ H^{0.854}$	(Schweiger and Gregory, 1989)
Kaplan	$n_s = 2283/ H^{0.486}$	(Schweiger and Gregory, 1989)
Cross-flow	$n_s = 513.25/ H^{0.505}$	(Kpordze and Warnick, 1983)
Propeller	$n_s = 2702/ H^{0.5}$	(USBR, 1976)
Bulb	$n_s = 1520.26/ H^{0.2837}$	(Kpordze and Warnick, 1983)

Once the specific speed is known the fundamental dimensions of the turbine can be easily estimated.

In one jet Pelton turbines, the specific speed may fluctuate between 12, for a 2000 m head and 26, for a 100 m head. By increasing the number of jets the specific speed increases as the square root of the number of jets. So then the specific speed of a four jets Pelton (only exceptionally they have more than six jets, and then only in vertical axis turbines) is twice the specific speed of one jet Pelton. In any case the specific speed of a Pelton exceeds 60 rpm.

The diameter of the circumference tangent to the jets is known as the Pelton diameter. The velocity v_{ch} leaving the nozzle, assuming a coefficient of losses of 0.97 is given by

$$v_{ch} = 0{,}97\sqrt{2gH} \qquad (6.7)$$

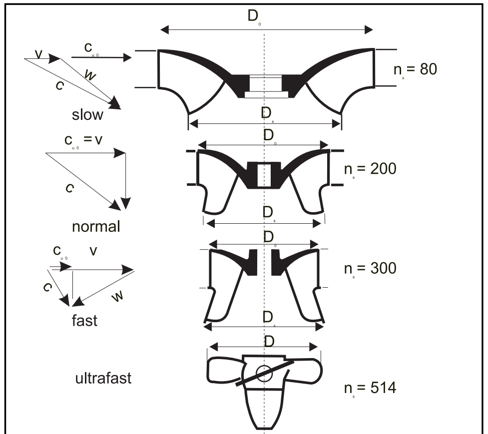


figure 6.13

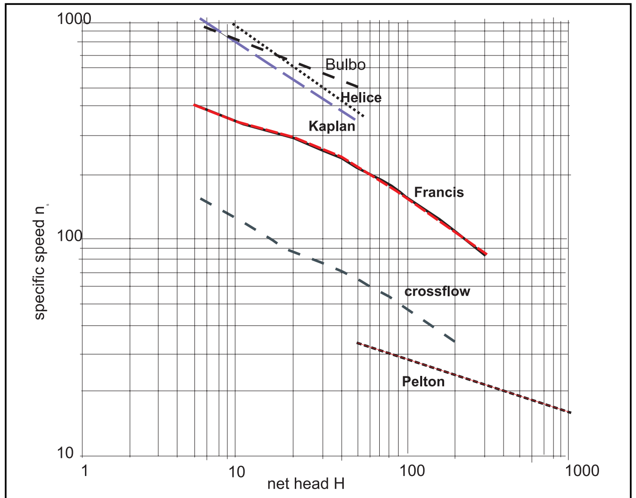


figure 6.14

It can be easily demonstrated from a theoretical approach that the tangential speed V_0 corresponding to the optimum efficiency is one half the jet speed v_{ch}. Actually the optimum efficiency is obtained by a velocity slightly lower (0.47 V_j).

If we know the runner speed its diameter can be estimated by the following equations:

$$V_0 = \frac{\pi D n}{60} = 0{,}47 v_{ch} = 0{,}456\sqrt{2gH}$$

$$D = \frac{60 \times 0{,}456\sqrt{2gH}}{\pi n} = 38{,}567\frac{\sqrt{H}}{n} \qquad (6.8)$$

D is defined as the diameter of the circle describing the buckets centre line.

The jet discharge –in one jet turbine the total discharge- is given by the cross-sectional area multiplied by the jet velocity:

$$Q = \frac{\pi d_j^2}{4} v_j$$ where d_j is the diameter of the jet, so then

$$d_j = \sqrt{\frac{4Q}{\pi v_j}} = \sqrt{\frac{Q}{3.37\sqrt{H}}} \qquad (6.9)$$

If Q is not known, as the power is P=8.33QH

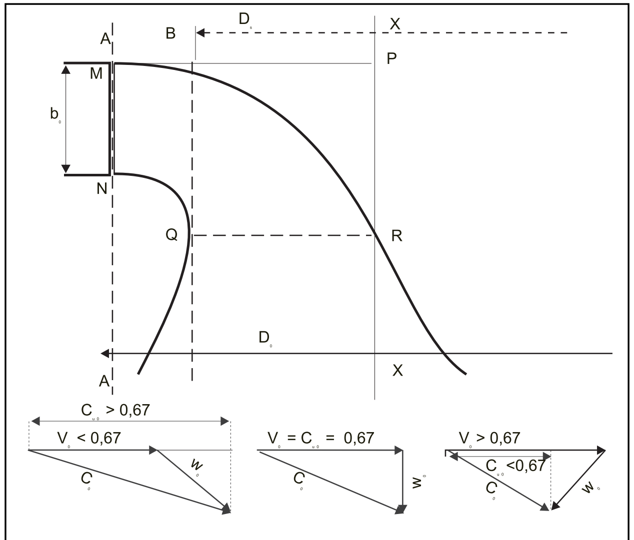


figure 6.15

$$d_j = \sqrt{\frac{P}{28.07H^{3/2}}}$$

The diameter d_j is the jet diameter and not the nozzle-opening diameter. This diameter varies with the nozzle design, but is accepted that a good nozzle produces such a "*vena contracta*" that the ratio of the square of both diameters –jet and nozzle- is close to 0.6. The jet diameter would be then 0.775d_j. The ratio 'nozzle diameter/D diameter' necessary to obtain a good efficiency must lie between 0.12 and 0.06.

The diameter of a Turgo runner is one half the diameter of a Pelton for the same power, so its specific speed will be double. In a cross-flow turbine, as the length of the runner accepts very large discharges even with small diameters the specific speed can reach the 1000 rpm.

Francis turbines cover a wide range of specific speeds, going from the 60 corresponding to a slow Francis to the 400 that may attain the high speed Francis. The slow runners are used in schemes with up to 350 m head, whereas the fast ones are used with heads of only 30 m. According to research undertaken by Schweiger and Gregory[8] on low power turbines, the specific speeds of turbines under 2 MW are sensibly lower than those corresponding to bigger turbines.

Figure 6.15 shows schematically in the upper part of the graphic the runner of a Francis turbine and the entrance velocity triangles for slow, medium and high-speed

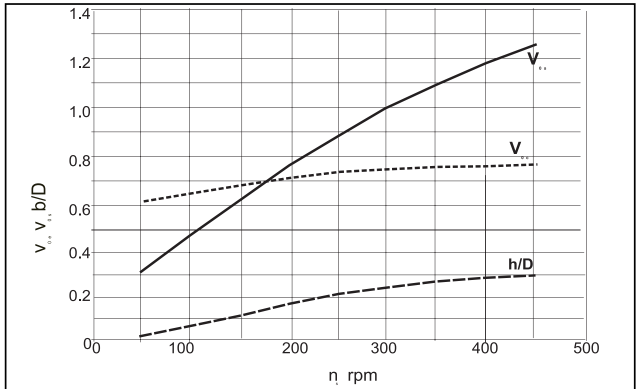


figure 6.16

runners in the bottom. The absolute velocity C_0 is the vectorial sum of the moving frame velocity V_0 and the relative velocity W_0. The absolute velocity C_0 has a radial component C_{m0} perpendicular to the turbine axis, and a tangential C_{u0} that in the scheme of figure 6.15 would be perpendicular to the drawing plan. Multiplying C_{m0} by the outlet section of the distributor –right-angled with it- will give the turbine discharge.

When the projection of the absolute velocity C_0 over the moving frame velocity V_0 is bigger than V_0 the runner is an slow one; If both are of the same order the runner is a normal one and if is smaller is a fast one.

With the aid of figure 6.16 the coefficient of the entrance velocity v_{0e}, the coefficient of the exit velocity v_{0s}, and the ratio b/D (respectively height of distributor and internal diameter of distributor) can be estimated in function of the specific speed n_s. The moving frame velocity V_0 is given by

$$V_0 = v_{0e}\sqrt{2gH}$$

and the runner diameter D_0 by

$$D_0 = \frac{60 v_{0e}\sqrt{2gH}}{\pi n} \tag{6.11}$$

and the exit diameter D_s by

$$D_s = \frac{60 v_{0s}\sqrt{2gH}}{\pi n} \tag{6.12}$$

whenever the turbine axis does not cross the diffuser. If it does it would be necessary to enlarge the diameter to compensate by the loss of section caused by the axis, a section easy to compute in function of the turbine torque.

The Kaplan turbines exhibit much higher specific speeds: 325 for a 45-m head and 954 for a 5-m head. Nowadays these turbines, in the range of power used in small hydro plants, are standardised, using a certain number of common components with the objective of decreasing their cost price. Some manufactures can supply all possible configurations by using only 6 runner diameters –1.8, 2.0, 2.2, 2.5, 2.8 and 3.2 metres-, three turbine axis diameters per runner, three distributor configurations, and three different speed increasers.

In the preliminary project phase the runner diameter can be calculated by the formula (D and H in m and Q in m3/sec)

$$D = \sqrt{\frac{Q}{2{,}2\sqrt{H}}} \qquad (6.13)\ .$$

6.1.2 Turbine selection criteria

The type, geometry and dimensions of the turbine will be fundamentally conditioned by the following criteria:

- Net head
- Range of discharges through the turbine
- Rotational speed
- Cavitation problems
- Cost

Net head

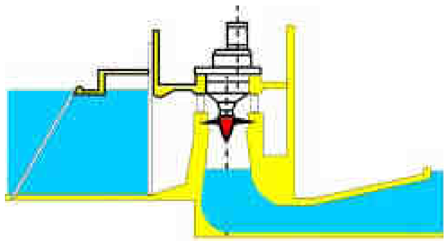
The gross head is the vertical distance, between the water surface level at the intake and at the tailrace for reaction turbines and the nozzle level for impulse turbines. Once the gross head is known, the net head can be computed by simply subtracting the losses along its path, as in example 5.6.

The first criterion to take into account in the turbine's selection is the net head. Table 6.1 specifies for each turbine type its range of operating heads. The table shows some overlapping, so that for a certain head several types of turbines can be used.

Table 6.1 Range of heads

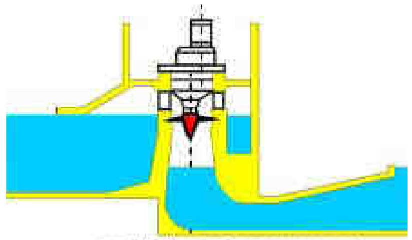
Turbine type	Head range in metres
Kaplan and Propeller	2 < H < 40
Francis	10 < H < 350
Pelton	50 < H <1300
Michell-Banki	3 < H < 250
Turgo	50 < H < 250

The selection is particularly critical in low-head schemes, where to be profitable large discharges must be handled. When contemplating schemes with a head between 2 and 5 m, and a discharge between 10 and 100 m^3/sec, runners with 1.6 – 3.2 metres diameter are required, coupled through a speed increaser to an asynchronous generator. The hydraulic conduits in general and water intakes in particular are very large and require very large civil works, with a cost that generally exceeds the cost of the electromechanical equipment.



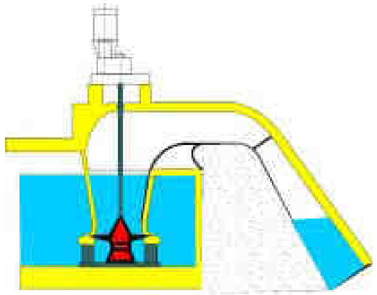
Vertical Kaplan or semi-Kaplan

figure 6.17



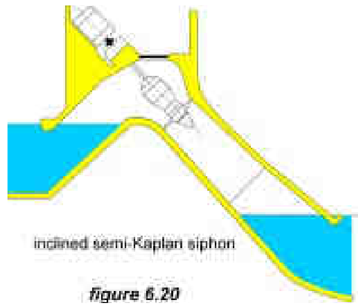
semi-Kaplan in siphon arrangement

figure 6.18



siphon inverted semi-Kaplan

figure 6.19



inclined semi-Kaplan siphon

figure 6.20

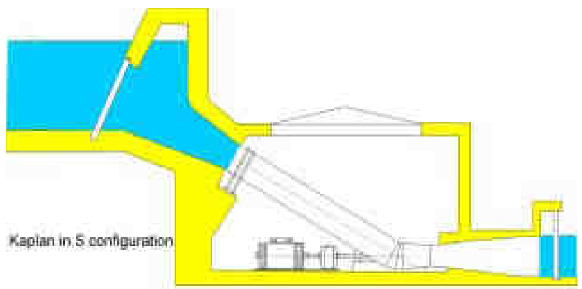


figure 6.21

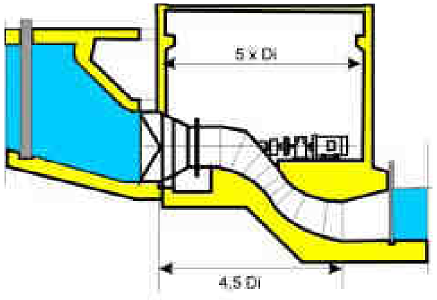


figura 6.22

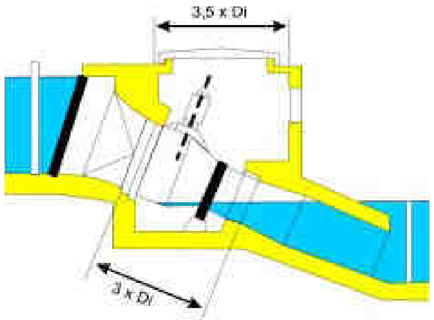


figure 6.23

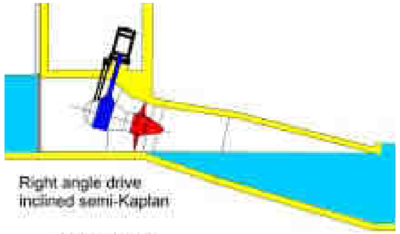


figure 6.24

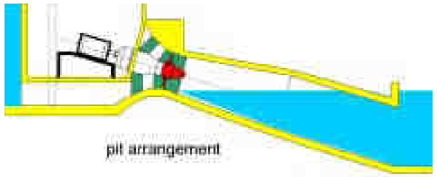


figure 6.25

In order to reduce the overall cost (civil works plus equipment) and more specifically the cost of the civil works, several configurations, nowadays considered as classic, have been devised [9]. All of them include the only turbine type available for this job –the Kaplan- in a double or a single regulated version.

The selection criteria for such turbines are well known:

- Range of discharges
- Net head
- Geomorphology of the terrain
- Environmental requirements (both visual and sonic)
- Labour cost

The configurations differ by how the flow goes through the turbine (axial, radial, or mixed) the turbine closing system (gate or siphon), the speed increaser type (parallel gears, right angle drive, epicycloidal gears).

For those interested in low-head schemes please read the paper presented by J. Fonkenell to HIDROENERGIA 91[11] dealing with selection of configurations, enclosing diagrams with relative costs to facilitate the appropriate choice..

Configuration	Flow	Closing system	Speed increaser	
Vertical Kaplan	Radial	Guide-vanes	Parallel	6.17
Vertical semi-Kaplan siphon	Radial	Siphon	Parallel	6.18
Inverse semi-Kaplan siphon	Radial	Siphon	Parallel	6.19
Inclined semi-Kaplan siphon	Axial	Siphon	Epicycloidal	6.20
Kaplan S	Axial	Gate valve	Parallel	6.21
Kaplan S right angle drive	Axial	Gate valve	Epicycloidal	6.22
Kaplan inclined right angle	Axial	Gate valve	Conical	6.23
Semi-Kaplan in pit	Axial	Gate valve	Epicycloidal	6.24

Siphons are reliable, economic, and prevent runaway turbine speed, but are very noisy. Underground powerhouses are best to mitigate the visual and sonic impact, but are only viable with an S, a right angle drive or a pit configuration.

The right angle drive configuration permits the use of a standard generator turning at 1500 rpm, reliable, compact and cheap, by using a double step speed increaser –planetary gears followed by a conical gear-. The S configuration is becoming very popular although has the disadvantage that the turbine axis has to cross either the entrance or the outlet pipe with consequent headloss. A recent study shows that, in a 4 m head scheme with a 24 m^3/sec discharge, the right angle drive configuration offered an overall efficiency 3% - 5% higher than the S configuration.

The pit configuration has the advantage of easy access to all the equipment components, in particular the coupling of turbine and speed increaser, the speed increaser itself and the generator, facilitating inspection, maintenance and repair. The hydraulic conduits are simplified and gives a higher specific volume.

Since the double regulated turbine has a minimum practical discharge close to 20% of the rated discharge whereas in a single regulated it is close to 40%, whenever a scheme has to cope with flows as low as 40% of the nominal one, the double regulated turbine should be selected.

As a turbine can only accept discharges between the nominal and the practical minimum, it may be advantageous to install several smaller turbines instead of a one large. The turbines would be sequentially started, so all of the turbines in operation except one will operate at their nominal discharges and therefore will exhibit a higher efficiency. Using two or three smaller turbines will mean a lower unit weight and volume and will facilitate transport and assembly on the site. The rotational speed of a turbine is inversely proportional to its diameter, so its torque will be lower and the speed increaser smaller and more reliable. The use of several turbines instead of one large one with the same total power, will result in a lower ratio kilograms of turbine/cubic meter of operating flow, although the ratio equipment cost / cubic meter of operating flow will be larger.

Increasing the number of turbines decreases the diameter of their runners, andconsequently the support components in the powerhouse will be smaller and lighter. As the water conduits are identical the formwork, usually rather sophisticated, can be reused several times decreasing its influence in the concrete cost. Notwithstanding this, generally more turbine means more generators, more controls, higher costs.

Discharge
A single value of the flow has no significance. It is necessary to know the flow regime, commonly represented by the Flow Duration Curve (FDC) [12] as explained in chapter 3, sections 3.3 and 3.6.

The rated flow and net head determine the set of turbine types applicable to the site and the flow environment. Suitable turbines are those for which the given rated flow and net head plot within the operational envelopes (figure 6.26). A point defined as above by the flow and the head will usually plot within several of these envelopes. All of those turbines are appropriate for the job, and it will be necessary to compute installed power and electricity output against costs before taking a decision. It should be remembered that the envelopes vary from manufacturer to manufacturer and they should be considered only as a guide.

Specific speed
The specific speed constitutes a reliable criterion for the selection of the turbine, without any doubt more precise than the conventional enveloping curves, just mentioned.

If we wish to produce electricity in a scheme with 100-m net head, using a 800 kW turbine directly coupled to a standard 1500-rpm generator we should begin by computing the specific speed according equation (6.5).

$$n_s = \frac{1500\sqrt{800}}{100^{1,25}} = 134$$

With this specific speed the only possible selection is a Francis turbine. Otherwise if we accept the possibility of using a speed increaser with a ratio up to 1.3, the turbine itself could turn from 500 to 1500 rpm, corresponding respectively to specific speeds of 45 and 134. In those conditions it could be possible to select, in addition to the Francis, a Turgo, a cross-flow or a 2 jet Pelton. The spectrum of appropriate turbines has been considerably enlarged by the presence of the speed increaser.

If we intend to install a 1500 kW turbine in a 400 m head scheme, directly coupled to a 1000 rpm generator, we will begin computing the specific speed n_s:

$$n_s = \frac{n\sqrt{P}}{H^{1,25}} = \frac{1000\sqrt{1500}}{400^{1,25}} = 21,65$$

which indicates as the only option a 1 jet Pelton, with a diameter D, computed by equation (6.8):

$$D = \frac{38,567\sqrt{400}}{1000} = 0,77m$$

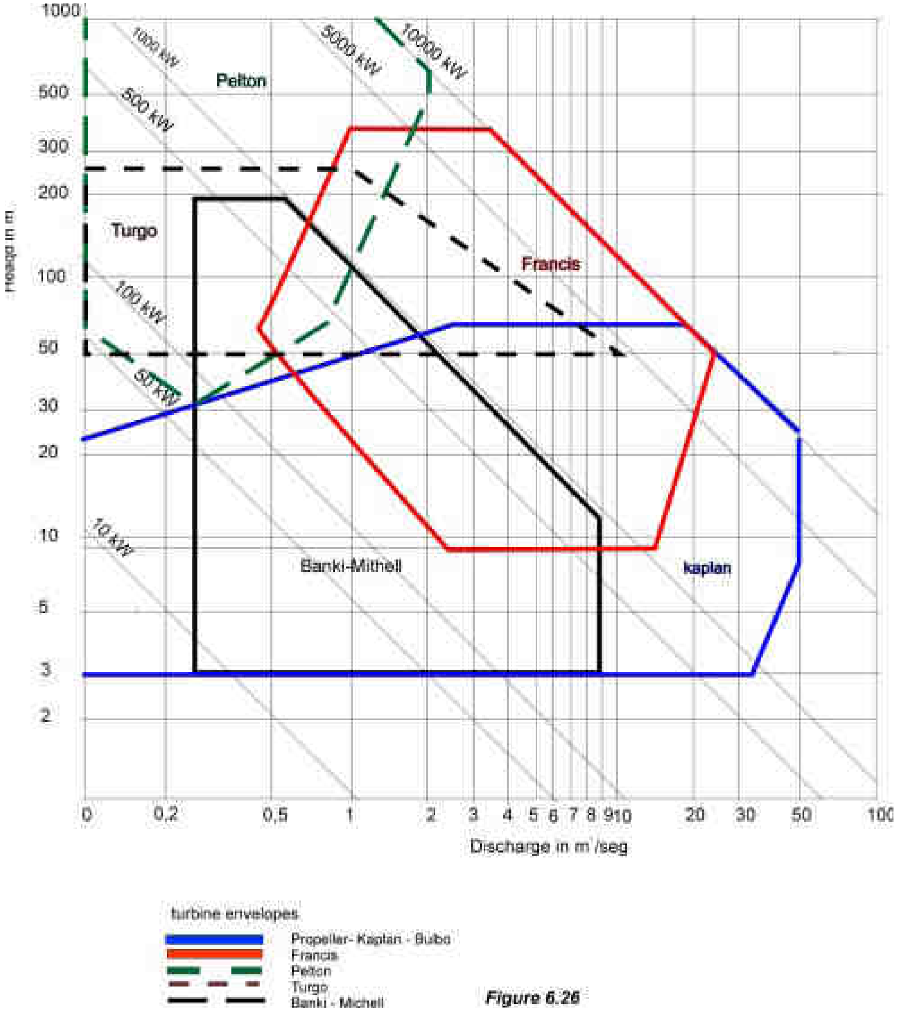


Figure 6.26

Cavitation

When the hydrodynamic pressure in a liquid flow falls below the vapour pressure of the liquid, there is a formation of the vapour phase. This phenomenon induces the formation of small individual bubbles that are carried out of the low-pressure region by the flow and collapse in regions of higher pressure. The formation of these bubbles and their subsequent collapse gives rise to what is called cavitation. Experience shows that these collapsing bubbles create very high impulse pressures accompanied by substantial noise (in fact a turbine undergoing cavitation sounds as though gravel is passing through it). The repetitive action of such pressure waves close to the liquid-solid boundary results in pitting of the material. With time this pitting degenerates into cracks formed between the pits and the metal is spalled from the surface. In a relatively short time the turbine is severely damaged and will require to be shut-off and repaired – if possible.

Experience shows that there is a coefficient, called Thoma's sigma σ_T, which defines precisely enough under which parameters cavitation takes place. This coefficient is given by the equation

$$\sigma_T = H_{sv} / H \qquad (6.13)$$

where H_{sv} is the net positive suction head and H the net head of the scheme.

According to figure 6.27

$$H_{sv} = H_{atm} - z - H_{vap} + V_e^2 / 2g + H_l \qquad (6.14)$$

Where:
- H_{sv} is the net positive suction head
- H_{atm} is the atmospheric pressure head
- H_{vap} is the water vapour pressure
- z is the elevation above the tailwater surface of the critical location
- V_e is the average velocity in the tailrace
- H_l is the head loss in the draft tube

Neglecting the draft-tube losses and the exit velocity head loss, Thoma's sigma will be given by

$$\sigma_T=(H_{atm}-H_{vap}-z)/H \qquad (6.15)$$

To avoid cavitation the turbine should be installed at least at a height over the tailrace water level z_p given by the equation:

$$z_p=H_{atm}-H_{vap}-\sigma_T H \qquad (6.16)$$

The Thoma's sigma is usually obtained by a model test, and it is a value furnished by the turbine manufacturer. Notwithstanding the above mentioned statistic studies also relates Thoma's sigma with the specific speed. Thereunder are specified the equation giving $ó_T$ as a function of n_s for the Francis and Kaplan turbines:

Francis: $$\sigma_T = 7.54\times10^{-5} \times n_s^{1.41} \qquad (6.17)$$

Kaplan: $$\sigma_T = 6.40\times10^{-5} \times n_s^{1.46} \qquad (6.18)$$

It must be remarked that H_{vap} decreases with the altitude, from roughly 10.3 m at the sea level to 6.6 m at 3000 m above sea level. So then a Francis turbine with a specific speed of 150, working under a 100 m head (with a corresponding $ó_T$ = 0.088), that in a plant at sea level, will require a setting:

z = 10.3 – 0.09 – 0.088 x 100 = 1.41 m

installed in a plant at 2000 m above the sea level will require

z = 8.1 – 0.09 – 0.088 x 100 = -0.79 m

a setting requiring a heavy excavation

Rotational speed

According to (6.5) the rotational speed of a turbine is a function of its specific speed, and of the scheme power and net head. In the small hydro schemes standard generators should be installed when possible, so in the turbine selection it must be borne in mind that the turbine, either coupled directly or through a speed increaser, should reach the synchronous speed, as given in table 6.2

Table 6.2 Generator synchronisation speed (rpm)

Number of poles	Frequency 50 Hz	60Hz	Number of poles	Frequency 50 Hz	60Hz
2	3000	3600	16	375	450
4	1500	1800	18	333	400
6	1000	1200	20	300	360
8	750	900	22	272	327
10	600	720	24	250	300
12	500	600	26	231	277
14	428	540	28	214	257

Runaway speed

Each runner profile is characterised by a maximum runaway speed. This is the speed, which the unit can theoretically attain when the hydraulic power is at its maximum and the electrical load has become disconnected. Depending on the type of turbine, it can attain 2 or 3 times the nominal speed. Table 6.3 shows this ratio for conventional and unconventional turbines

It must be remembered that the cost of both generator and gearbox may be increased when the runaway speed is higher, since they must be designed to withstand it.

Table 6.3

Turbine type	Normal speed n (rpm)	Runaway speed nmax/n
Kaplan single regulated	75-100	2.0 – 2.4
Kaplan double regulated	75-150	2.8 – 3.2
Francis	500 – 1500	1.8 – 2.2
Pelton	500 – 1500	1.8 – 2.0
Cross-flow	60 – 1000	1.8 – 2.0
Turgo	600 – 1000	2

6.1.3 Turbine efficiency

The efficiency guaranteed by turbine manufacturers is that which may be verified in accordance with the "International Code for the field acceptance tests of hydraulic turbines" (publication IEC-141) or, if applied, in accordance with the "International Code for model acceptance tests" (publication IEC-193). It is defined as the ratio of power supplied by the turbine (mechanical power transmitted by the turbine shaft) to the absorbed power (hydraulic power equivalent to the measured discharge under the net head).

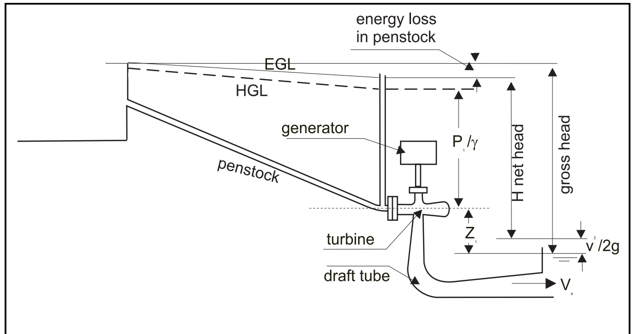


figure 6.27

It is to be noted that for impulse turbines (Pelton, Turgo and Cross-Flow), the head is measured at the point of impact of the jet, which is always above the downstream water level. This effectively amounts to a reduction of the head. The difference is not negligible for low-head schemes, when comparing the performance of impulse turbines with those of reaction turbines that use the entire available head.

Due to the head losses generated in reaction turbines the runner only uses a head H_u lower than the net head H_n , such as defined in figure 6.27. These losses are essentially friction losses in the spiral case, guide-vanes and runner blades plus velocity head losses in the draft tube. The draft–tube or diffuser is designed to recover the biggest possible fraction of the velocity head generated by the velocity of the water leaving the blades. This loss is particularly critical in the high specific speed runners, where it may reach up to 50% of the net head (whereas in the slow Francis runner it rarely exceeds 3%-4%). The head used by the runner is in fact the equivalent to the net head diminished by the kinetic energy dissipated in the draft-tube, quantified by the expression V_e / 2g, where V_e is the average velocity of the water leaving the draft-tube. To reduce the velocity the draft tube is commonly designed with a conical section. Small divergence angles require long, and consequently costly, diffusers, but otherwise the angle cannot exceed about 7º without danger of flow separation. Trying to find equilibrium between flow separation and cost some designers increase the angle up to about 15º. The draft-tube design has such implications on the turbine operation that it is strongly recommended to leave it to the turbine manufacturer or at least fabricate it under his advice and drawings.

At present no IEC code defines the net head across a cross-flow turbine or its efficiency. Care must be taken in comparing reaction turbine efficiencies with cross-flow efficiencies [11]. Anyhow cross-flow peak efficiencies calculated from the net head definition given by the IEC code for impulse turbines, reach a ceiling slightly over 80%, but retain this efficiency value under discharges as low as a sixth of the maximum.

Fig 6.28 indicates the mean efficiency guaranteed by manufacturers for several types of turbine. To estimate the overall efficiency the turbine efficiency must be

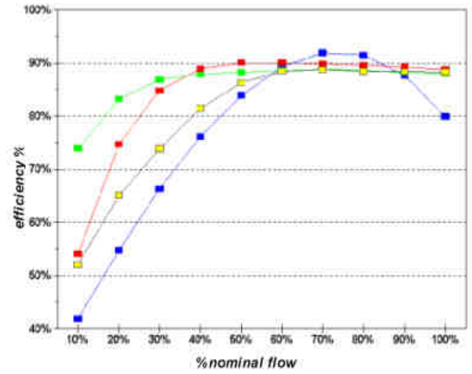


figure 6.28

multiplied by the efficiencies of the speed increaser (if used) and the alternator. A turbine is designed to operate at or near its best efficiency point, usually at 80 per cent of the maximum flow rate, and as flow deviates from that particular discharge so does the turbine's hydraulic efficiency.

Double regulated Kaplan and Pelton turbines can operate satisfactorily over a wide range of flow -upwards from about one fifth of rated discharge. Single regulated Kaplans have acceptable efficiency upward from one third and Francis turbines from one half of rated discharge. Below 40% of the rated discharge, Francis turbines may show instability resulting in vibration or mechanical shock.

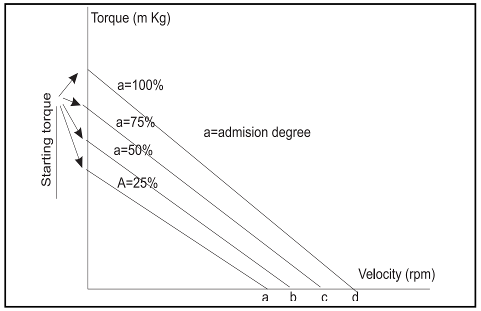
Propeller turbines with fixed guide vanes and blades can operate satisfactorily only over a very limited range close to their rated discharge. It should be noted that with single-regulated propeller turbines the efficiency is generally better when it is the runner that is adjustable.

6.1.4 Turbine performance characteristics

Turbine manufacturers use scaled models to obtain different curves correlating their characteristics.

Torque-velocity characteristic

This graphically represents the correlation between the rotational speed and the turbine torque for different admission degrees. According to figure 6.29 the torque, for the same admission degree, decreases linearly with the rotational speed. The maximum torque corresponds to a null speed, hence the high starting torque of hydraulic turbines. The speed corresponding to the point where the curve cut the horizontal axis is called runaway speed.



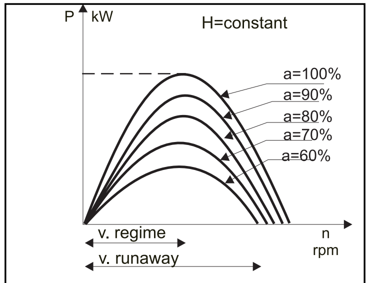


figure 6.30

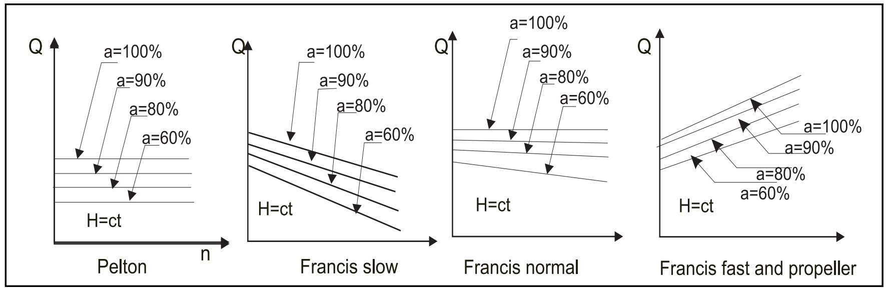
Power-velocity characteristic
This represents graphically how under a given head the power evolves, at different degrees of admission, with the velocity. The parabolic curves (figure 6.30) cut the horizontal axis in two different points, corresponding respectively to the null speed and the runaway speed.

Flow-velocity characteristic
This practically linear (figure 6.31) representing the flow admitted by the turbine at different speeds, under a constant head, and a variable admission degree. In the Pelton turbines the straight lines are almost horizontal; drooping in the slow Francis (when the speed increases the turbines accept less and less flow), and ascendant in the fast Francis.

Turbine performance
In the flow-velocity plane, by connecting the points that have the same efficiency, iso-efficiency curves are obtained (figure 6.32), that look like contour lines on a topographic map. Compounding these curves with the power as the third axis, they will form a sort of "hill", the so called "hill charts".

6.1.5 Turbine performance under new site conditions

When rehabilitating a site there are many occasions when, the turbine being



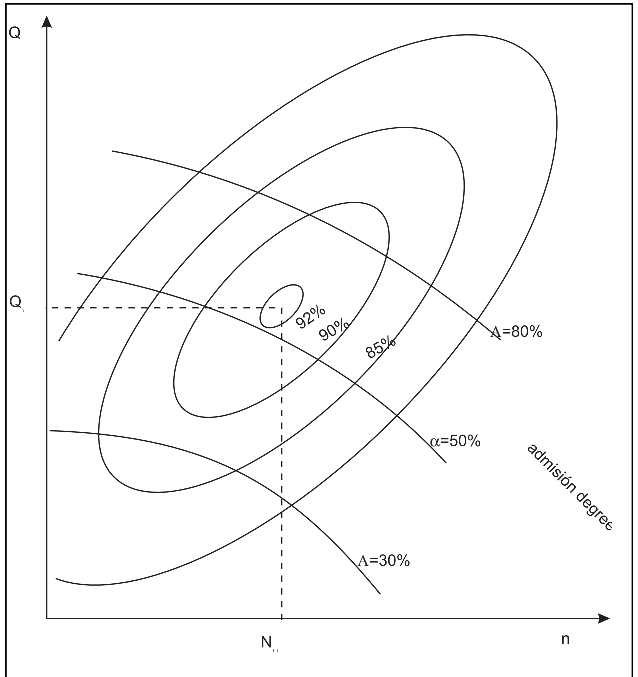


figure 6.32

irreparable, an existing second hand turbine with rating parameters somewhat similar to the site parameters can be installed.

It is well known that the flow, speed, and power output for any turbine are site specific and are functions of the net head under which the turbine operates. According to the similarity laws, a turbine manufactured to operate under certain design parameters, characterised by the suffix 1, will show different characteristics operating under the new parameters, characterised by the suffix 2. The flow "Q" like the flow through an orifice is proportional to H:

$$\frac{Q_2}{Q_1} = \frac{\sqrt{H_2}}{\sqrt{H_1}} \text{ therefore } Q_2 = Q_1 \frac{\sqrt{H_2}}{\sqrt{H_1}}$$

The speed "n" of a turbine is proportional to the flow velocity within the turbine so:

$$\frac{n_2}{n_1} = \frac{\sqrt{H_2}}{\sqrt{H_1}} \text{ therefore } n_2 = n_1 \frac{\sqrt{H_2}}{\sqrt{H_1}}$$

When the turbine installed at the site is run at "n_2" speed, the power output "P" is proportional to the product of head and flow:

$$\frac{P_2}{P_1} = \frac{Q_2}{Q_1}\frac{H_2}{H_1} = \left(\frac{H_2}{H_1}\right)^{3/2} \quad or\ P_2 = P_1\left(\frac{H_2}{H_1}\right)^{3/2}$$

The turbine shaft is designed to transmit a certain torque (T) directly proportional

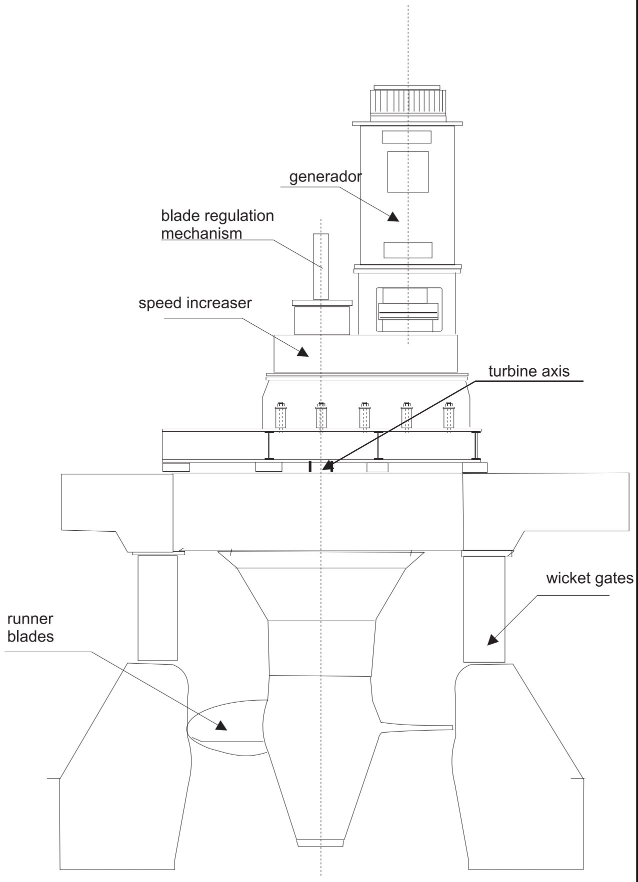


figure 6.33

to the power and inversely proportionally to the turbine speed.

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{n_1}{n_2} = \left(\frac{H_2}{H_1}\right)^{3/2}\left(\frac{H_1}{H_2}\right)^{1/2} = \frac{H_2}{H_1}$$

As the torque is proportional to the cube of the shaft diameter

$$d_{s2} = d_{s1}\left(\frac{H_2}{H_1}\right)^{1/3}$$

It can be deduced that if the shaft of the proposed turbine is adequately dimensioned, it will be adequate for the new site provided the head is smaller than the head for which the turbine was designed. The same reasoning can be applied to every turbine component: wicket-gates, blades, seals etc. The speed increaser will also have to be checked. If the new head is slightly lower than the original, both turbine and speed increaser can be used without difficulties. If the head is slightly higher, both the speed increaser and the generator should be checked to verify that they could handle the increased power. If the new head is significantly higher than the original one, the torque shaft should be checked and probably reinforced, but the generator could remain unchanged if the speed increaser has been modified so it runs at the proper speed. If the new turbine is a reaction turbine its setting also needs to be recalculated.

6.2 Speed increasers

When the turbine and the generator operate at the same speed and can be placed so that their shafts are in line, direct coupling is the right solution; virtually no power losses are incurred and maintenance is minimal. Turbine manufactures will recommend the type of coupling to be used, either rigid or flexible although a flexible coupling that can tolerate certain misalignment is usually recommended. In many instances, particularly in the lowest power range, turbines run at less than 400 rpm, requiring a speed increaser to meet the 1 000-1 500 rpm of standard alternators. In the range of powers contemplated in small hydro schemes this solution is always more economical than the use of a custom made alternator.

6.2.1 Speed increaser types

Speed increasers according to the gears used in their constructionare classified as

Parallel-shaft

using helicoid gears set on parallel axis and are especially attractive for medium power applications. Figure 6.33 shows a vertical configuration, coupled to a vertical Kaplan turbine.

Bevel gears:

commonly limited to low power applications using spiral bevel gears for a 90º drive. Figure 6.34 shows a two-phased speed increaser: the first is a planetary gearbox and the second a bevel gear drive.

Photo 6.9

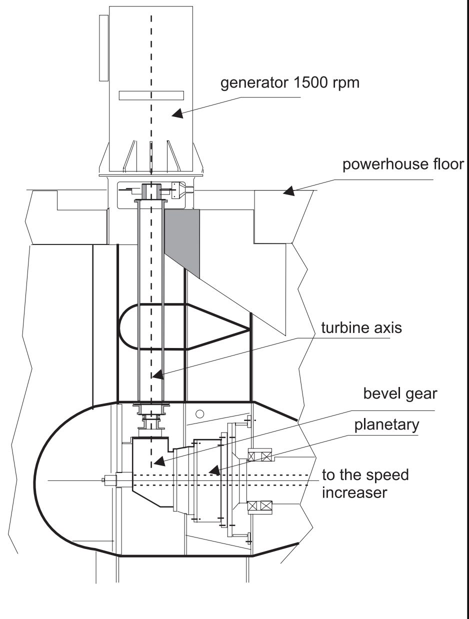


figure 6.34

Epicycloidal:

extremely compact and specially adequate for turbines over 2 MW capacity.

6.2.2 Speed increaser design

The gearbox should be designed to ensure, under the most unfavourable conditions, the correct alignment of its components. They are usually fabricated in welded steel with heavy stiffeners to resist the turbine torque without apparent deformation.

A lack of synchronism, a full load rejection, or any other accident in the system can generate very high critical stresses on the gears. To protect gears against these exceptional strains the speed increaser should incorporate a torque limiter, so that the connector breaks when there is an abnormal force.

To ensure the required level of reliability good lubrication is essential. It is very important that the quality, volume, viscosity and temperature of the oil always stay within specifications. A double lubrication system with two pumps and two oil filters would contribute to the system reliability.

Speed increasers are designed according to international standards (AGMA 2001, B88 or DIN 3990) using very conservative design criteria. These criteria conflict with the need to reduce costs, but no cost savings are possible or recommended without a thorough analysis of the fatigue strains, and a careful shaving of the heat treated gears, a satisfactory stress relieving of the welded boxes, all of which are essential to ensure the durability of a speed increaser. Metallurgical factors including knowledge of the respective advantages and disadvantages of hard casing or nitruring of gears are also essential to optimise the speed increaser.

Selection of journal bearings is also crucial. Under 1 MW the use of roller bearings is acceptable, but for a higher power it becomes difficult to find roller bearings capable of sustaining their role for the required life of the increaser. That is why from 1 MW onwards designers prefer to use hydrodynamic lubricated bearings that present the following advantages:

- The life of the roller bearings is limited by fatigue whereas the hydrodynamic bearings have a practical unlimited life.
- Hydrodynamic bearings permit a certain oil contamination, whereas roller bearings do not.

6.2.3 Speed increaser maintenance

At least 70% of speed increaser malfunctioning is due to the poor quality or to the lack of the lubricant oil. Frequently the oil filters clog or water enters the lubrication circuit. Maintenance should be scheduled either based on predetermined periods of time or –better by periodic analysis of the lubricant to check that it meets specifications.

Speed increasers substantially increase the noise in the powerhouse and require careful maintenance as their friction losses can exceed 2% of the outlet power, so other alternatives have been investigated. Figure 6.35 shows a successful application of a flat belt as speed increaser. In smaller plants the use of V belts are also becoming popular.

6.3 Generators

Generators transform mechanical energy into electrical energy. Although most early hydroelectric systems were of the direct current variety to match early commercial electrical systems, nowadays only three-phase alternating current generators are used in normal practice. Depending on the characteristics of the network supplied, the producer can choose between:

- **Synchronous generators** equipped with a DC excitation system (rotating or static) associated with a voltage regulator, to provide voltage, frequency and phase angle control before the generator is connected to the grid and supply

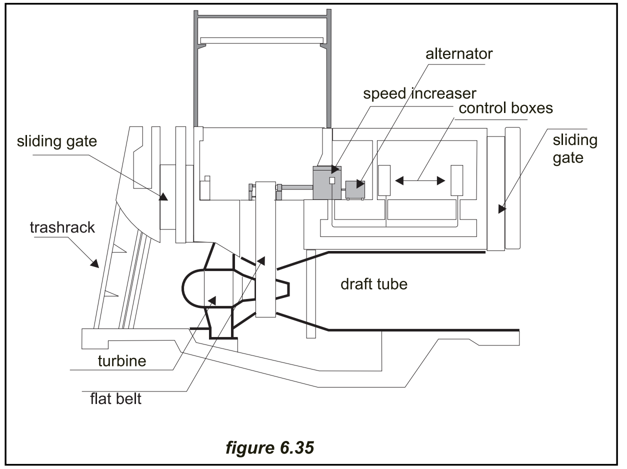


figure 6.35

the reactive energy required by the power system when the generator is tied into the grid. Synchronous generators can run isolated from the grid and produce power since excitation is not grid-dependent

- **Asynchronous generators** are simple squirrel-cage induction motors with no possibility of voltage regulation and running at a speed directly related to system frequency. They draw their excitation current from the grid, absorbing reactive energy by their own magnetism. Adding a bank of capacitors can compensate for the absorbed reactive energy. They cannot generate when disconnected from the grid because are incapable of providing their own excitation current.

Synchronous generators are more expensive than asynchronous generators and are used in power systems where the output of the generator represents a substantial proportion of the power system load. Asynchronous generators are cheaper and are used in large grids where their output is an insignificant proportion of the power system load. Their efficiency is 2 to 4 per cent lower than the efficiency of synchronous generators over the entire operating range. In general, when the power exceeds 5000 kVA a synchronous generator is installed.

Recently, variable-speed constant-frequency systems (VSG), in which turbine speed is permitted to fluctuate widely, while the voltage and frequency are kept constant and undistorted, have entered the market. This system can even "synchronise" the unit to the grid before it starts rotating. The key to the system is the use of a series-resonant converter in conjunction with a double feed machine[12]. Unfortunately its cost price is still rather high and the maximum available power too low.

The working voltage of the generator varies with its power. The standard generation voltages are 380 V or 430 V up to 1400 kVA and at 6000/6600 for bigger installed

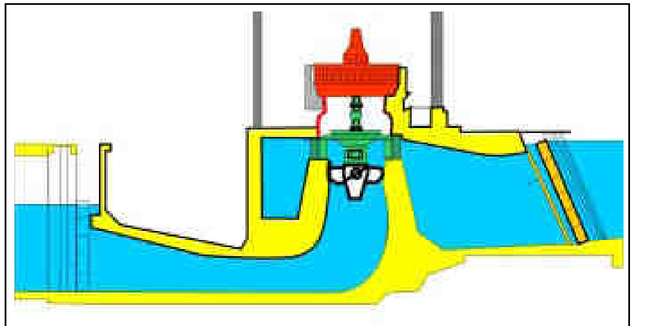


figure 6.36

power. Generation at 380 V or 430 V allows the use of standard distributor transformers as outlet transformers and the use of the generated current to feed into the plant power system. Generating at medium voltage requires an independent transformer MT/LT to supply the plant services.

6.3.1 Generator configurations

Generators can be manufactured with horizontal or vertical axis, independently of the turbine configuration. Figure 6.36 shows a vertical axis Kaplan turbine turning at 214 rpm directly coupled to a custom made 28 poles alternator. Photo 6.9 shows the same type of turbine coupled to a standard generator through a parallel gear speed increaser. A flywheel is frequently used to smooth-out speed variations and assists the turbine control.

Another criterion characterising generators is how their bearings are positioned. For example it is common practice to install a generator with extra-reinforced bearings supporting the cantilevered runner of a Francis turbine. In that way the turbine axis does not need to cross the draft tube so improving the overall efficiency. The same solution is frequently used with Pelton turbines.

When these generators are small, they have an open cooling system, but for larger units it is recommended to use a closed cooling circuit provided with air-water heat exchangers.

6.3.2 Exciters

The exciting current for the synchronous generator can be supplied by a small DC generator, known as the exciter, to be driven from the main shaft. The power absorbed by this dc generator amounts to 0.5% - 1.0% of the total generator power. Nowadays a static exciter usually replaces the DC generator, but there are still many rotating exciters in operation.

Rotating exciters.
The field coils of both the main generator and the exciter generator are usually mounted on the main shaft. In larger generators a pilot exciter is also used. The pilot exciter can be started from its residual magnetic field and it then supplies the exciting current to the main exciter, which in turn supplies the exciting current for the rotor of the generator. In such way the current regulation takes place in the smaller machine.

Brushless exciters
A small generator has its field coils on the stator and generates AC current in the rotor windings. A solid state rectifier rotates with the shaft, converting the AC output from the small generator into the DC which is the supplied to the rotating field coils of the main generator without the need of brushes. The voltage regulation is achieved by controlling the current in the field coils of the small generator.

Static exciters
The exciting current is taken out, via a transformer, from the output terminals of the main generator. This AC current is then rectified in a solid state rectifier and injected in the generator field coils. When the generator is started there is no current flowing through the generator field coils. The residual magnetic field, aided if needed by a battery, permits generation to start to be then stabilised when the voltage at the generator terminals reaches a preset value. This equipment is easy to maintain has a good efficiency and the response to the generator voltage oscillations is very good.

6.3.3 Voltage regulation and synchronisation

6.3.3.1 Asynchronous generators

An asynchronous generator needs to absorb a certain power from the three-phase mains supply to ensure its magnetisation even, if in theory, the generator can receive its reactive power from a separate source such as a bank of capacitors. The mains supply defines the frequency of the stator rotating flux and hence the synchronous speed above which the rotor shaft must be driven.

On start-up, the turbine is accelerated up to 90-95% of the synchronous speed of the generator, when a velocity relay close the main line switch. The generator passes immediately to hyper-synchronism and the driving and resisting torque are balanced in the area of stable operation.

6.3.3.2 Synchronous generators

The synchronous generator is started before connecting it to the mains by the turbine rotation. By gradually accelerating the turbine the generator is synchronised with the mains, regulating the voltage, frequency and rotating sense, When the generator reaches a velocity close to synchronous, the exciter regulates its field coils current so the generator voltage is identical to the mains voltage.

When the synchronous generator is connected to an isolated net, the voltage controller maintains a predefined constant voltage, independent of the load. If it is connected to the main supply, the controller maintains the reactive power at a predefined level.

6.4 Turbine control

Turbines are designed for a certain net head and discharge. Any deviation from these parameters must be compensated for, by opening or closing control devices such as the wicket-vanes or gate valves to keep constant, either the outlet power, the level of the water surface in the intake or the turbine discharge.

In schemes connected to an isolated net, the parameter to be controlled is the runner speed, which control the frequency. The generator becomes overloaded and the turbine slows-down. In this case there are basically two approaches to control the runner speed: either by controlling the water flow to the turbine or by keeping the water flow constant and adjusting the electric load by an electric ballast load connected to the generator terminals.

In the first approach, speed (frequency) regulation is normally accomplished through flow control; once a gate opening is calculated, the actuator gives the necessary instruction to the servomotor, which results in an extension or retraction of the servo's rod. To ensure that the rod actually reaches the calculated position, feedback is provided to the electronic actuator. These devices are called "speed governors"

In the second approach it is assumed that, at full load, constant head and flow, the turbine will operate at design speed, so maintaining full load from the generator; this will run at a constant speed. If the load decreases the turbine will tend to increase its speed. An electronic sensor, measuring the frequency, detects the deviation and a reliable and inexpensive electronic load governor, switches on preset resistances and so maintains the system frequency accurately.

The controllers that follow the first approach do not have any power limit. The Electronic Load Governors, working according to the second approach rarely exceeds 100 kW capacity.

6.4.1 Speed Governors

A governor is a combination of devices and mechanisms, which detect speed deviation and convert it into a change in servomotor position. A speed-sensing element detects the deviation from the set point; this deviation signal is converted and amplified to excite an actuator, hydraulic or electric, that controls the water flow to the turbine. In a Francis turbine, where to reduce the water flow you need to rotate the wicket-gates a powerful governor is required to overcome the hydraulic and frictional forces and to maintain the wicket-gates in a partially closed position or to close them completely.

Several types of governors are available varying from purely mechanical to mechanical-hydraulic to electrohydraulic. The purely mechanical governor is used with fairly small turbines, because its control valve is easy to operate and does not requires a big effort. These governors use a flyball mass mechanism driven by the turbine shaft. The output from this device –the flyball axis descends or ascends according to the turbine speed- directly drive the valve located at the entrance to the turbine.

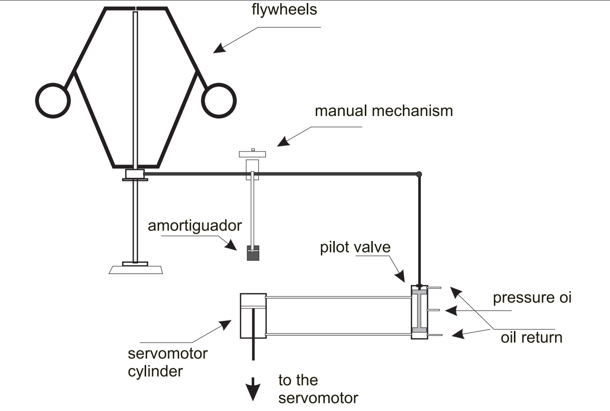
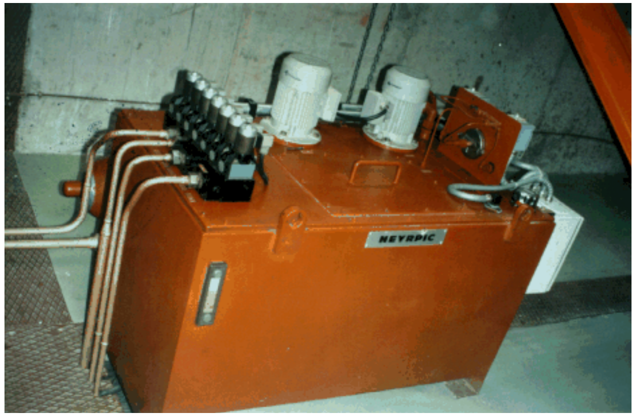


figure 6.37

The most commonly-used type is the oil-pressure governor (Fig 6.37) that also uses a flyball mechanism lighter and more precise than that used in a purely mechanical governor. When the turbine is overloaded, the flyballs slowdown, the balls drop, and the sleeve of the pilot valve rises to open access to the upper chamber of the servomotor. The oil under pressure enters the upper chamber of the servomotor to rotate the wicket-gates mechanism and increase the flow, and consequently the rotational speed and the frequency.

In an electrohydraulic governor a sensor located on the generator shaft continuously senses the turbine speed. The input is fed into a summing junction, where it is compared to a speed reference. If the speed sensor signal differs from the reference signal, it emits an error signal (positive or negative) that, once amplified, is sent to the servomotor so this can act in the required sense. In general the actuator is powered by a hydraulic power unit (photo 6.10) consisting of a sump for oil storage, an electric motor operated pump to supply high pressure oil to the system, an accumulator where the oil under pressure is stored, oil control valves and a hydraulic cylinder. All these regulation systems, as have been described, operate by continuously adjusting back and forth the wicket-gates position. To provide quick and stable adjustment of the wicket-gates, and/or of the runner blades, with the least amount of over or under speed deviations during system changes a further device is needed. In oil pressure governors, as may be seen in figure 6.37, this is achieved by interposing a "dash pot" that delays the opening of the pilot valve. In electrohydraulic governors the degree of sophistication is much greater, so that the adjustment can be proportional, integral and derivative (PID) giving a minimum variation in the controlling process.

An asynchronous generator connected to a large net, from which it takes its reactive power to generate its own magnetism, does not need any controller, because its frequency is controlled by the mains. Notwithstanding this, when the generator is



disconnected from the mains the turbine accelerates up to runaway speed with inherent danger for the generator and the speed increaser, if one is used. In such a case it is necessary to interrupt the water flow, rapidly enough to prevent the turbine accelerating, but at the same time minimising any waterhammer effect in the penstock.

To ensure the control of the turbine speed by regulating the water flow, a certain inertia of the rotating components is required. Additional inertia can be provided by a flywheel on the turbine or generator shaft. When the main switch disconnects the generator the power excess accelerates the flywheel; later, when the switch reconnects the load, the deceleration of this inertia flywheel supplies additional power that helps to minimise speed variation. The basic equation of the rotating system is the following:

$$J\frac{d\Omega}{dt} = T_t - T_L$$

where: J = moment of inertia of the rotating components
Ω = angular velocity
T_t = torque of turbine
T_L = torque due to load

When T_t is equal to T_L, $d\Omega/dt = 0$ and Ω = constant, so the operation is steady. When T_t is greater or smaller than T_L, Ω is not constant and the governor must intervene so that the turbine output matches the generator load. But it should not be forgotten that the control of the water flow introduces a new factor: the speed variations on the water column formed by the waterways.

The flywheel effect of the rotating components is stabilising whereas the water column effect is destabilising. The start-up time of the rotating system, the time required to accelerate the unit from zero rotational speed to operating speed is given by

$$T_m = \frac{J\Omega^2}{P} = \frac{WR^2n^2}{5086P}$$

where the rotating inertia of the unit is given by the weight of all rotating parts multiplied by the square of the radius of gyration: WR^2 , P is the rated power in kW and n the turbine speed (rpm)

The water starting time, needed to accelerate the water column from zero velocity to some other velocity V, at a constant head H is given by:

$$T_w = \frac{\sum LV}{gH} \text{ sec.}$$

where H = gross head across the turbine (m)
L = length of water column (m)
V = velocity of the water (m/s)
g = gravitational constant (9.81 m s^{-2})

To achieve good regulation is necessary that $T_m/T_w > 4$. Realistic water starting times do not exceed 2.5 sec. If it is larger, modification of the water conduits must be considered – either by decreasing the velocity or the length of the conduits by installing a surge tank. The possibility of adding a flywheel to the generator to increase the inertia rotating parts can also considered. It should be noted that an increase of the inertia of the rotating parts will improve the waterhammer effect and decrease the runaway speed.

6.5 Switchgear equipment

In many countries the electricity supply regulations place a statutory obligation on the electric utilities to maintain the safety and quality of electricity supply within defined limits. The independent producer must operate his plant in such a way that the utility is able to fulfil its obligations. Therefore various associated electrical devices are required inside the powerhouse for the safety and protection of the equipment.

Switchgear must be installed to control the generators and to interface them with the grid or with an isolated load. It must provide protection for the generators, main transformer and station service transformer. The generator breaker, either air, magnetic or vacuum operated, is used to connect or disconnect the generator from the power grid. Instrument transformers, both power transformers (PTs) and current transformers (CTs) are used to transform high voltages and currents down to more manageable levels for metering. The generator control equipment is used to control the generator voltage, power factor and circuit breakers.

The asynchronous generator protection must include, among other devices: a reverse-power relay giving protection against motoring; differential current relays against internal faults in the generator stator winding; a ground-fault relay providing system backup as well as generator ground-fault protection, etc. The power transformer protection includes an instantaneous over-current relay and a timed over-current relay to protect the main transformer when a fault is detected in the bus system or an internal fault in the main power transformer occurs.

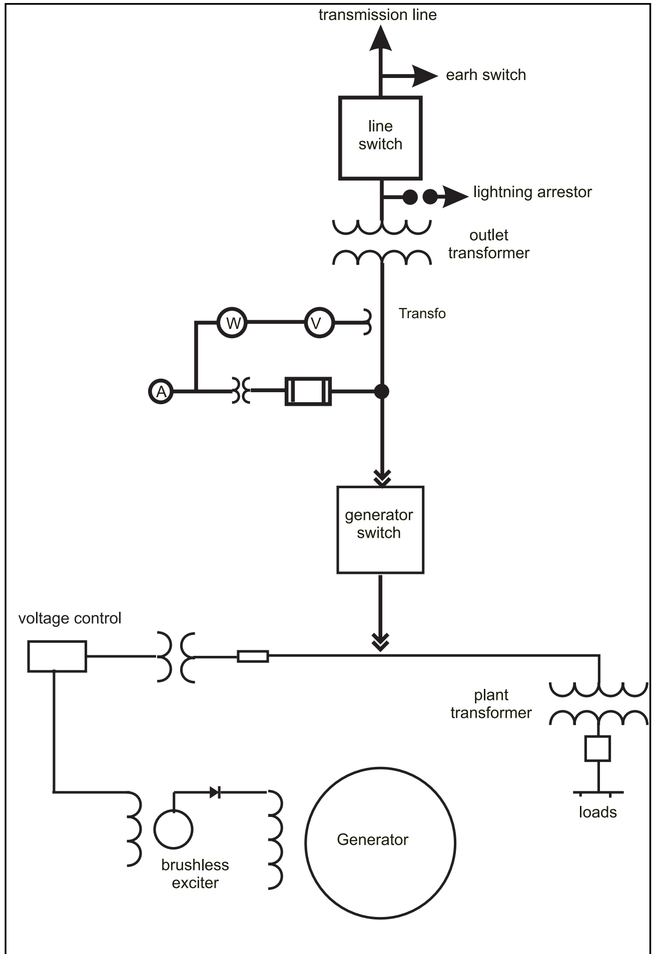


figure 6.39

The independent producer is responsible for earthing arrangements within his installation. The independent producer's earthing arrangement must be designed in consultation with the public utility. The earthing arrangement will be dependent on the number of units in use and the independent producer's own system configuration and method of operation.

Metering equipment must be installed at the point of supply to record measurements to the requirements of the electric utility.

Figure 6.38 shows a single-line diagram corresponding to a power plant with a single unit. In the high voltage side there is a line circuit breaker and a line disconnection switch - combined with a grounding switch - to disconnect the power generating unit and main transformer from the transmission line. Metering is achieved through the corresponding P.T and C.T. A generator circuit breaker is included as an extra protection for the generator unit. A transformer provides energy for the operation of intake gates, shutoff valves, servomotors, oil compressors etc. in the station service.

Greater complexity may be expected in multiunit stations where flexibility and continuity of service are important.

6.6 Automatic control

Small hydro schemes are normally unattended and operated through an automatic control system. Because not all power plants are alike, it is almost impossible to determine the extent of automation that should be included in a given system, but some requirements are of general application[13]:

a) All equipment must be provided with manual controls and meters totally independent of the programmable controller to be used only for initial start up and for maintenance procedures.
b) The system must include the necessary relays and devices to detect malfunctioning of a serious nature and then act to bring the unit or the entire plant to a safe de-energised condition.
c) Relevant operational data of the plant should be collected and made readily available for making operating decisions, and stored in a database for later evaluation of plant performance.
d) An intelligent control system should be included to allow for full plant operation in an unattended environment.
e) It must be possible to access the control system from a remote location and override any automatic decisions.
f) The system should be able to communicate with similar units, up and downstream, for the purpose of optimising operating procedures.
g) Fault anticipation constitutes an enhancement to the control system. Using an expert system, fed with baseline operational data, it is possible to anticipate faults before they occur and take corrective action so that the fault does not occur.

The system must be configured by modules. An analogue-to-digital conversion module for measurement of water level, wicket-gate position, blade angles, instantaneous power output, temperatures, etc. A digital-to-analogue converter module to drive hydraulic valves, chart recorders, etc. A counter module to count generated kWh pulses, rain gauge pulses, flow pulses, etc. and a "smart" telemetry module providing the interface for offsite communications, via dial-up telephone lines or radio link. This modular system approach is well suited to the widely varying requirements encountered in hydropower control, and permits both hardware and software to be standardised. Cost reduction can be realised through the use of a standard system; modular software allows for easy maintenance.

Automatic control systems can significantly reduce the cost of energy production by reducing maintenance and increasing reliability, while running the turbines more efficiently and producing more energy from the available water.

With the tremendous development of desktop computers, their prices are now very low. Many manufacturers supply standardised data acquisition systems. New and cheap peripheral equipment, such as hard disks, PCMCIA cards for portable computers, the "watch-dogs- to monitor and replace control equipment in the event of failure is available and is easy to integrate at low price.

The new programming techniques –Visual Basic, Delphi etc- assist the writing of software using well-established routines; the GUI interfaces, that every body knows thanks to the Windows applications; everything has contributed to erase the old aura of mystery that surrounded the automatic control applications.

6.7 Ancillary electrical equipment

6.7.1 Plant service transformer

Electrical consumption including lighting and station mechanical auxiliaries may require from 1 to 3 percent of the plant capacity; the higher percentage applies to micro hydro (less than 500 kW). The service transformer must be designed to take these intermittent loads into account. If possible, two alternative supplies, with automatic changeover, should be used to ensure service in an unattended plant.

6.7.2 DC control power supply

Plants larger than 500 kW capacity, especially if they are remotely controlled, require a DC system with a battery charger, station batteries and a DC distribution panel. The ampere-hour capacity must be such that, on loss of charging current, full control is ensured for as long as it may be required to take corrective action.

6.7.3 Headwater and tailwater recorders

In a hydro plant provisions should be made to record both the headwater and tailwater. The simplest way is to fix securely in the stream a board marked with meters and centimetres in the style of a levelling staff but someone must physically observe and record the measurements. In powerhouses provided with automatic control the best solution is to use transducers connected to the computer via the data acquisition equipment[14].

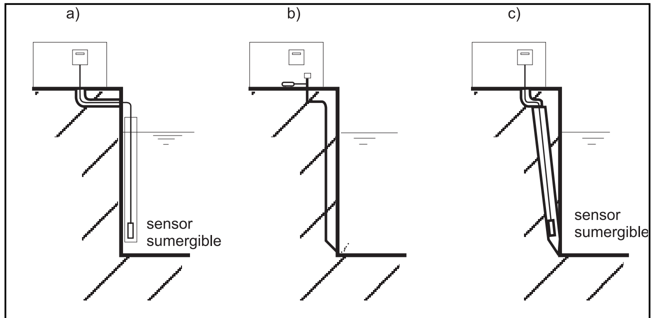
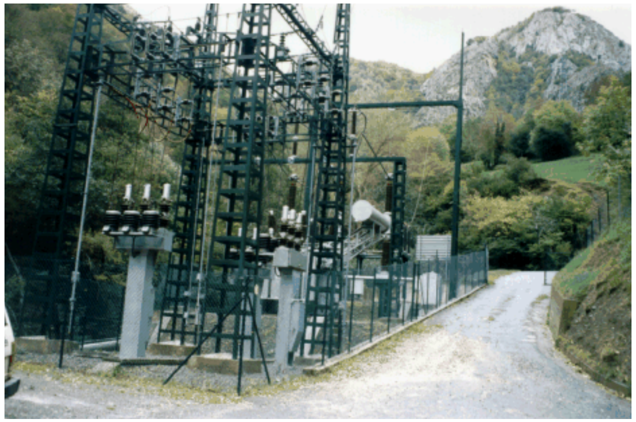


figura 6.39

Nowadays measuring units –a sensor – records the measurement variable and converts it into a signal that is transmitted to the processing unit. The measurement sensor must always be installed at the measurement site, where the level has to be measured - usually subject to rough environmental conditions and of difficult access - whereas the processing unit is usually separated and placed in a well protected environment easily accessible for operation and service.

There is a wide range of sensors each one using a variety of measuring principles. It must be realised that a level measurement cannot determine the level for the forebay, unless the measurement site had been selected in such a way that it represents the whole forebay. According to the Bernoulli principle, a change in the flow rate always causes a change in the height of the water level. If the measurement site is located in the inflow or outflow structures, the measurement will give false

Photo 6.11



results. The level sensor can transmit the signal by using the hydrostatic method (figure 6.39 a) or the pneumatic (bubble) method (figure 6.39 b). In the first method care should be taken so all the tubes for pressure transmission are dimensioned and laid in such way that cannot be obstructed and no air can accumulate within them [17]. In the second, the sensor orifice is located lower than the corresponding level at the start of the measurement, and that no water can penetrate and collect in the lines. In the solution shown in figure 6.39 a) floating material can damage the instrument. The best solution is the concealed assembly of all parts together within the wall as shown in figure 6.39 b) and c).

6.7.4 Outdoor substation

The so-called water-to-wire system usually includes the substation. A line breaker must separate the plant including the step-up transformer from the grid in case of faults in the power plant. PTs and CTs for kWh and kW metering are normally mounted at the substation, at the connecting link between the plant-out conductors and the take-off line to the grid (Photo 6.10). In areas with very high environmental sensitivity the substation is enclosed in the powerhouse, and the transmission cables, leave it along the penstock.

Lightning arrestors for protection against line surges or lightning strikes are usually mounted in the substation structure.

6.8 Examples

Two examples will help to better understand the concepts exposed in this chapter and particularly the use of the specific speed tool.

Example 6.1

Select a turbine to equip a 200-m head scheme with a nominal flow of 1.5 m^3/sec. The powerhouse is located at an altitude of 1000 m over the sea level.

Assuming an overall efficiency at the design point of 85% the installed power will be: $P = QHg\eta = 1.5 \times 200 \times 9.81 \times 0.85 = 2500$ kW

According to figure 6.26 the plot of head and flow falls into the envelopes of a Francis and a Pelton turbine. The turbine speed is given as a function of n_s by:

$$n_s = n\frac{\sqrt{2500}}{200^{5/4}} = 0.0665\, n$$

If we select a Pelton with a rotational speed of 375 rpm, to be coupled via a speed increaser with a ratio 2/1 to a 750-rpm generator, its specific speed will be 24.93, inside, although at the limit, of the Pelton's specific speed range.

The jet velocity would be

$$V_j = 0.97\sqrt{2gH} = 0.97\sqrt{2\times 9.81\times 200} = 60.76\, m/\sec$$

The tangential speed; $V_0 = 0.47V_j = 28.56$ m/sec
The Pelton diameter according to (6.8)

$$D = \frac{60V_0}{n\pi} = \frac{60 \times 28.56}{375\pi} = 1.45\,m$$ a wheel of a reasonable diameter

If we select a Francis to be directly coupled to a generator running at 1500 rpm,
ns = 99.75
From the curves of figure 6.16 V_{0e}=0.69 and the inlet diameter will be

$$D_0 = \frac{60 \times 0.69 \times \sqrt{2 \times 9.81 \times 200}}{1500\pi} = 0.572 \text{ m}$$ and V_{0s}= 0.49 so the diameter

$$D_s = \frac{60 \times 0.49 \times \sqrt{2 \times 9.81 \times 200}}{1500\pi} = 0.391\,\text{m}$$

According to eq. (6.17)

$$\sigma_T = 7.54 \times 10^{-5} \times n_s^{1.41} = 0.0496\,\text{m}$$

and according to eq. (6.16)

$$z = 9.2 - 0.09 - 0.0496 \times 200 = -0.81 \text{ m}$$

a setting that requires important excavation.

If we have selected a Francis running at 1000 rpm we would have had: n_s= 65.5, V_{0e}= 0.60, V_{0s}=0.373, D_0 = 0.79 m, D_s = 0.446 m, σ_T = 0.027 and z= 3.62 m which does not need excavation, and is the best of all three alternatives.

Example 6.2

We want to rehabilitate a 100-m scheme. The turbine is badly damaged, but there is an offer for an almost new Francis turbine that had been operating under the following operating parameters: H = 120 m, P = 1000 kW, n = 750 rpm, and η = 0.90. Compute the nominal discharge when installed in the above scheme, its nominal power and the turbine speed.

The specific speed of the new turbine is given by:

$$n_s = \frac{n\sqrt{P}}{H^{5/4}} = \frac{750\sqrt{1000}}{120^{5/4}} = 59.72$$

and the rated discharge under those parameters

$$Q_1 = \frac{P_1}{H_1\gamma\eta} = \frac{1000}{120 \times 9.81 \times 0.90} = 0.944\,\text{m}^3/s$$

Using the similarity equations computed in 6.1.5 which can be applied because the diameter remains always constant. So:

$$n_2 = n_1\frac{\sqrt{H_2}}{\sqrt{H1}} = 750\sqrt{\frac{100}{120}} = 685 \text{ rpm}$$

$$Q_2 = Q_1\frac{\sqrt{H_2}}{\sqrt{H1}} = 0.944\sqrt{\frac{100}{120}} = 0.862 \text{ m}^3/\text{sec}$$

$$P_2 = P_1\frac{n_2^3}{n_1^3} = 1000\frac{685^3}{750^3} = 762 \text{ kW}$$

Bibliography

1 P.T. Than Hline & P.Wibulswas,"Feasibility of using small centrifugal pumps as turbines". Renewable Energy Review Journal; Vol 9, No.1 June 1987

2 Societé Hydrotechnique de France, "Design, Construction, Commissioning and Operation Guide", May 1985

3 Schweiger & Gregory, "Developments in the design of water turbines", Water Power & Dam Construction, May 1989

3 F. de Siervo & A. Lugaresi, "Modern trends in selecting and designing Francis turbines", Water Power & Dam Construction, August 1976

4 H.Giraud & M.Beslin, "Optimisation d'avant-project d'une usine de basse chute", Symposium A.I.R.H. 1968, Laussane

5 L. Austerre & J.de Verdehan, "Evolution du poid et du prix des turbines en fonction des progrés techniques", Compte rendu des cinquièmes journées de l'hydraulique, 1958, La Houille Blanche

6 T.Belhaj, "Optimisation d'avant-project d'une centrale hydroélectrique au fil de l'eau" Symposium Maroc/CEE Marrackech 1989

7 Pe Than Line & P.Wibulswas, "The feasibility of using small centrifugal pumps as turbines", Renewable Energy Review Journal, Vol 9, Nº.1, June 1987

8 R. Hothersall, "Turbine selection under 1 MW. Cross-flow or conventional turbine?" Hydro Review, February 1987

9 Gordon "A new approach to turbine speed", Water Power & Dam Construction , August 1990

10 Seldon and Logan, "Variable speed pump/turbines", Hydro Review, August 1989

11 J.Cross & J.Burnet,"The development and use of an integrated databasesystem for management and performance analysis of multiple automated hydroelectric sites", Third International Conference on Small Hydro, Cancun, Mexico 1988.

12 J.L.Gordon "Powerhouse concrete quantity estimates", Canadian Journal Of Civil Engineering, June 1983

.

7. Environmental impact and its mitigation

7.0 Introduction

Following the recommendations of the United Nations Conference in Rio on Environment and Development, the European Union committed itself to stabilising its carbon dioxide (CO_2) emissions, primarily responsible for the greenhouse effect, at 1990 levels by the year 2000. Clearly Europe will not be able to achieve this ambitious target without a major increase in the development of renewable energy sources.

Renewable energy can make a significant contribution to CO_2 emissions reduction. The European Commission, through the ALTENER programme, proposed as indicative objectives by 2005 to increase the contribution of renewable energy sources from its current level of 4% in 1991 to 8% of primary energy consumption and to duplicate the electricity produced by renewable sources. For small hydropower this objective will require the European Union to increase the average annual renewable electricity production from 30 TWh to 60 TWh., and the development of 9 000 MW in new schemes. The achievement of this objective will imply an annual reduction of 180 million tonnes of CO_2 emissions.

However under present trends the above objective will not be attained so long as the administrative procedures to authorise the use of water are not accelerated. Hundreds, if not thousands, of authorisation requests are pending approval, the delay being caused mainly by supposed conflict with the environment. Some environmental agencies seem to justify –or at least excuse- this blockade on the grounds of the low capacity of the small plants. Something is basically wrong when, to attain the ALTENER objectives contemplated, in small hydro alone, the duplication of the already existing 9 000 MW (the equivalent to nine last generation nuclear plants) will be required. It seems to be forgotten that by definition renewable energies are decentralised, and that for the time being only small hydro power plants and the wind turbines can significantly contribute to renewable electricity production.

At the same time it should be accepted that, although through having no emissions of carbon dioxide and other pollutants, electricity production in small hydro plants is environmentally rewarding, the fact is that due to their location in sensitive areas, local impacts are not always negligible. The significant global advantages of small hydropower must not prevent the identification of burdens and impacts at local level nor the taking of necessary mitigation actions.

On the other hand because of their economic relevance, thermal plants are authorised at very high administrative levels, although some of their impacts cannot be mitigated at present. A small hydropower scheme producing impacts that almost always can be mitigated is considered at lower administrative levels, where the influence of pressure groups – angling associations, ecologists, etc.– is greater.

It is not difficult to identify the impacts, but to decide which mitigation measures should be undertaken it is not easy, because these are usually dictated by subjective arguments. It is therefore strongly recommended to establish a permanent dialogue with the environmental authorities as a very first step in the design phase. Even if this negotiation must be considered on a project by project basis it would be convenient to provide a few guidelines that will help the designer to propose mitigating measures that can easily be agreed with the licensing authorities.

7.1 Burdens and impacts identification

Impacts of hydropower schemes are highly location and technology specific. A high mountain diversion scheme, being situated in a highly sensitive area is more likely to generate impact that an integral low-head scheme in a valley. The upgrading and extension of existing facilities, which will be given priority in Europe, generates impacts that are quite different from an entirely new scheme. Diversion projects in mountains use the large change in elevation of a river as it flows downstream. The tailwater from the power plant then reenters the river, and entire areas of the river may be bypassed by a large volume of water, when the plant is in operation.

Given below is an exhaustive description of possible impacts, based on European studies[1] dealing with externalities, and made by groups of experts that perform Environmental Impact Assessments. However is not certain that all or most of this list of descriptions will be applicable to a specific project. In the list are identified the event, persons or things affected, impact and priority at local and national levels.

Event	Persons or things affected	Impact	Priority
Electricity generation			
During construction			
Road construction and road traffic	general public	noise	low
		accidents	low
		emissions	low
	wildlife	noise disturbance	low
		collision's accidents	medium
	forest	better access	medium
		future production loss	medium
Accidents	workers	minor injuries	medium
		major injuries	high
		death	high
Jobs created	general public	locally	high
		national	medium
In operation			
Flow alteration	Fish	loss of habitat	high
	Plants	loss of habitat	medium
	Birds	loss of habitat	medium
	Wildlife	loss of habitat	medium
	Water quality	contaminant dilution	low
	General public	loss of waterfalls	high
		loss of recreational activities:	medium
		Aesthetic effects	medium
Excessive noise	workers	0n health	medium
	general public	on health	medium
Dams and damning	Agriculture	loss of grazing area	high
	Forestry	loss future production	high
Aquatic ecosystem	change of habitat	high	
	General public	local clime change	negligible
		global clime change by methane	not proven
	Water quality	eutrophication	low
	Cultural and archeologic. effects	loss of objects	high
Electricity Transmission			
On the construction			
Accidents	workers	minor injuries	medium
	workers	major injuries	high
	workers	death	high
Jobs created and increased income	General public	local and national employment benefits	high
On the operation			
Physical presence	Forestry	lost future production	low
	General public	visual intrusion	medium
	Birds	injury, death	medium
Electromagnetic fields nonexistent	General public	cancers	
Accidents	General public	major injuries	negligible
		Death	negligible
Accidents on maintenance of transmission lines	Workers	Minor injuries	negligible
		Major injuries	negligible
		Death	negligible
Jobs created and increased local income	General public	local and national employment benefits	medium

7.2 Impacts in the construction phase

Schemes of the diversion type, those using a multipurpose reservoir, and those inserted on an irrigation canal or in a water supply system produce very different impacts from one another, both from a quantitative and qualitative viewpoint. The schemes making use of a multipurpose dam practically do not generate unfavourable impacts, since it is understood that when the dam was built the necessary mitigating measures were already incorporated, and in any case the addition of a powerhouse located in its base shall not alter the ecological system. Schemes integrated in an irrigation canal or in a water supply pipe system will not introduce new impacts over those generated when the canal and the pipe system were developed. On the other hand, diversion schemes present very particular aspects that need to be analysed.

7.2.1 Reservoirs

The impacts generated by the construction of a dam and the creation of the adjoining reservoir include, in addition to the loss of ground, the construction and opening of construction roads, working platforms, excavation works, blasting and even –depending of the dam size- concrete manufacturing plants. Other non-negligible impacts are the barrier effect and the alteration of flow consequent to a river regulation that did not exist before.

Otherwise the impacts generated by the construction of a dam do not differ from those induced by a large scale infrastructure, whose effects and mitigating measures are well known.

7.2.2 Water intakes, open canals, penstocks, tailraces, etc.

The impacts generated by the construction of these structures are well known and have been described in table 7.1: e.g. noise affecting the life of the animals; danger of erosion due to the loss of vegetation consequent to the excavation work and affecting the turbidity of the water; downstream sediment deposition, etc. To mitigate such impacts it is strongly recommended that the excavation work should be undertaken in the dry season and the disturbed ground restored as soon as possible. In any case these impacts are always transitory and do not constitute a serious obstacle to the administrative authorisation procedure.

In view of its protective role against riverine erosion is wise to restore and reinforce the river bank vegetation, that may have been damaged during construction of the hydraulic structures. It should be noted that the ground should be revegetated with indigenous species, better adapted to the local conditions.
The impact assessment study should take count of the effects of jettisoning excavated material in the stream, and the unfavourable consequences of a men living during the construction period in an area usually uninhabited. This impact which may be negative if the scheme is located in a natural park, would be positive in a non-sensitive area by increasing the level of its activity. Vehicle emissions, excavation dust, the high noise level and other minor burdens contribute to damage the environment, when the scheme is located in sensitive areas. To mitigate the above impacts the traffic operation must be carefully planned to eliminate unnecessary movements and to keep all traffic to a minimum.

On the positive side it should be noted that the increase in the level of activity in an area usually economically depressed, by using local manpower and small local subcontractors during the construction phase is to be welcomed.

7.3 Impacts arising from the operation of the scheme

7.3.1 Sonic impacts

The allowable level of noise depends on the local population or on isolated houses near to the powerhouse. The noise comes mainly from the turbines and, when used, from the speed increasers. Nowadays noise inside the powerhouse can be reduced, if necessary, to levels of the order of 70 dBA and to be almost imperceptible outside.

Concerning sonic impact the Fiskeby[2] power plant in Norrköping, Sweden, is an example to be followed. The scheme owner wanted a maximum internal sound level of 80 dBA inside the powerhouse at full operation. The maximum allowed external sound level, at night, was set at 40 dBA in the surroundings of some houses located about 100 metres away.

To reach these levels of noise it was decided that all the components –turbines, speed increasers, asynchronous generators- were bought in one package from one well-known supplier. The purchase contract specified the level of noise to be attained in full operation leaving the necessary measures to fulfil the demands to the manufacturer. The supplier adopted the following measures: very small tolerances in the gear manufacturing; sound insulating blankets over the turbine casing; water cooling instead of air cooling of the generator and a careful design of ancillary components. As well as the usual thermal insulation, the building was provided with acoustic insulation. As a consequence the attained level of noise varied between 66 dBA and 74 dBA, some 20 dBA lower than the average Swedish powerhouses. Having a single supplier, the issue of responsibility was eliminated .

The external noise level reduction was obtained by vibration insulation of the powerhouse walls and roof. The principle for the vibration reduction system was to let the base slab, concrete waterways and pillars for the overhead crane be excited by vibration from the turbine units. The other parts of the building such as supporting concrete roof beams and precast concrete elements in the walls were supported by special rubber elements designed with spring constants giving maximum noise reduction. For the roof beams special composite spring-rubber supporting bearings (Trelleborg Novimbra SA W300) were chosen. A similar solution was chosen for the precast wall components. Once built, the sound emission from the powerhouse could not be detected from the other noise sources as traffic, sound from the water in the stream, etc. at the closest domestic building

The underground powerhouse of Cavaticcio[3], located about 200 m from the Piazza Maggiore, the historical heart of Bologna, has also merits in this respect. An acoustic impact study undertaken on Italian schemes showed an average internal level of about 85-dbA . The level of noise in the vicinity of the houses near the proposed powerhouse was 69 dbA by day and 50 dbA by night. The regulations in force required that these values could not increase by more than 5 dbA during the day and 3 dbA during the night. The measures carried out to fulfil the requirements were similar to those undertaken in Fiskeby:

- Insulation of the machine hall, the most noisy room, from the adjacent rooms by means of double walls with different mass, with a layer of glass wool in between.

- Soundproofing doors
- Floors floating on 15 mm thick glass wool carpets
- False ceiling with noise deadening characteristics
- Heavy trapdoors to the ground floor, fitted with soundproof counter trapdoors and neoprene sealing gaskets.
- Vibration damping joints between fans and ventilation ducts
- Low air velocity (4 m/sec) ducts
- Two silencers at the top and rear of the ventilation plant
- Inlet and outlet stacks equipped with noise traps
- Air ducts built with a material in sandwich (concrete, glass wool, perforated bricks and plaster)
- Turbine rotating components dynamic balanced
- Water-cooled brushless synchronous generator
- Precision manufactured gears in the speed increaser
- Turbine casings and speed increaser casings strongly stiffened to avoid resonance and vibrations
- Anchoring of the turbine by special anti-shrinking concrete to ensure the monolithic condition between hydro unit and foundation block
- Turbine ballasting with large masses of concrete to reduce to a minimum the vibration's amplitude

The underground ventilation has three main purposes: dehumidification of the rooms to ensure a correct operation and maintenance of the equipment, fresh air supply for the workers, removal of the heat generated by the various plant components. Even with the maximum air volume circulation estimated at 7000 m^3/hour the air velocity in the air ducts never exceeds 4 m/sec.

It is true that the two above examples are very particular ones but they are included here to show that everything is possible if it is considered necessary and the project profitability admits a significant increase of the investment. It is also true that both examples concern low head schemes implying the use of speed increasers; a high mountain diversion scheme would permit the direct coupling of turbine and generator, so eliminating the component responsible for most of the vibrations.

7.3.2 Landscape impact

The quality of visual aspects is important to the public, who are increasingly reluctant to accept changes taking place in their visual environment. A new condominium in our neighborhood, an artificial beach built with sand coming from a submarine bed - such things are rejected by a part of the population, even if, in many ways they improve the environment including landscaping. The problem is particularly acute in the high mountain hydropower schemes or in schemes located in an urban area with remarkable historical character. This concern is frequently manifested in the form of public comments and even of legal challenges to those developers seeking to change a well-loved landscape by developing a hydropower facility.

Each of the components that comprise a hydro scheme - powerhouse, weir, spillway, penstock, intake, tailrace, substation and transmission lines - has potential to create a change in the visual impact of the site by introducing contrasting forms, lines, colour or textures. The design, location, and appearance of any one feature may well determine the level of public acceptance for the entire scheme.

Most of these components, even the largest, may be screened from view through the use of landform and vegetation. Painted in non-contrasting colours and textures to obtain non-reflecting surfaces a component will blend with or complement the characteristic landscape. An effort of creativity, usually with small effect on the total budget, can often result in a project acceptable to all parties concerned: local communities, national and regional agencies, ecologists etc.

The penstock is usually the main cause of "nuisance". Its layout must be carefully studied using every natural feature - rocks, ground, vegetation - to shroud it and if there is no other solution, painting it so as to minimise contrast with the background. If the penstock can be buried, this is usually the best solution. Expansion joints and concrete anchor blocks can then be reduced or eliminated; the ground is returned to its original state and the pipe does not form a barrier to the passage of wild life.

The powerhouse, with the intake, the penstock tailrace and transmission lines must be skilfully inserted into the landscape. Any mitigation strategies should be incorporated in the project, usually without too much extra cost to facilitate permit approval.

The examination of two schemes carefully designed to shroud their components will convey to potential designers a handful of ideas that should help to convince the environmental authorities that there is no place so environmentally sensitive as to prevent the development of a energy conversion process, so harmless and acceptable. The Cordiñanes scheme in Picos de Europa (Spain) and the scheme on the river Neckar, located in the historical centre of Heidelberg (Germany) are considered below.

Cordiñanes scheme

A small reservoir such as the one existing in Cordiñanes (Photo 7.1) has some positive aspects. The existence of an almost stable level of water, and the tourist attractions (swimming, fishing, canoeing, etc.) that it provides counter balance its negative effects.

Figure 7.1 shows a schematic view of the Cordiñanes scheme. The weir is a relatively airy concrete structure, but being 14 m high it is the most obtrusive compo-

Photo 7.1

Photo 7.2

nent in the scheme (Photo 7.2). It needs to be so high because the water must reach the level of an old tunnel that, once rebuilt, makes part of the diversion canal. That is precisely the reason why the water level in the reservoir cannot vary by more than two metres and confers to the pond the character of a picturesque lake.

And while speaking of dams the Vilhelmina dam in Sweden, constructed of soil materials with an impervious core, should be mentioned (Photo 7.3). The surface of the crest and the downstream slope are protected against erosion by layers of large stones and boulders, which are embedded in reinforced concrete up to half

Photo 7.3

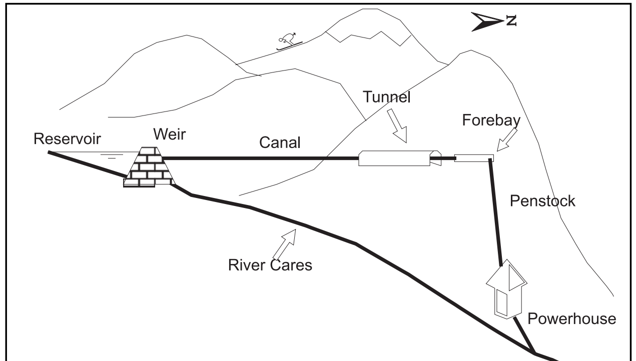


figure 7.1

their height. The downstream slope has a normal inclination of 1:3 except for a part, 40 m wide, where the inclination is 1:10. This design makes it possible for fish to pass the dam up the river. This dam has another environmental advantage since even with a small discharge it has the appearance of a natural rapid.

An open canal built in reinforced concrete leads, from the integral intake (Photo 7.4) leaves, with a section of 2 x 2.5 m and a length of 1335 m, entirely buried and covered by a layer of revegetated terrain. Photographs 7.5, 7.6 and 7.7 show a stretch of the canal in its three construction phases: land excavation reinforced concrete canal and finished canal with the recovered vegetal layer. The presence

Photo 7.4

Photo 7. 5

in the photographs of an electrical pylon – the transmission line between the villages of Posada de Valdeon and Cordiñanes - confirms that it is the same site, because otherwise it could be impossible to identify the buried canal.

Photos 7.8 and 7.9 show how the entrance to the tunnel has been shrouded. In the first one the tunnel being rebuilt can be seen; in the second the canal connecting with the tunnel has been covered, as has the rest of the canal, and the entrance to the tunnel made invisible. It is possible to enter the tunnel through the canal for inspection, after it is dewatered. In fact the tunnel already existed but was unfinished due to the lack of means to cross the colluvium terrain. It has now been rebuilt

Photo 7.6

Photo 7.7

with a wet section of 2 x 1.80 m and with a 1:1000 slope which conducts the water down to forebay, a perfect match with the surrounding rocks, and provided with a semicircular spillway. From the forebay a steel penstock, 1.40 m diameter and 650 m long, brings the water to the turbines. In its first 110 m the pipe has a slope close to 60º, in a 2.5 x 2 m trench excavated in the rock. The trench was filled with coloured concrete to match the surrounding rocks. A trench excavated in the soil, conceals the other 540 m which were covered by a vegetal layer later on.

Few metres before arriving at the powerhouse the pipe bifurcates into two smaller pipes that feed two Francis turbines of 5000 kW installed power each. The power-

Photo 7.8

Photo 7.9

house (Photographs 7.10) is similar to the houses dotting the mountain. Its limestone walls, its roof made of old tiles and its heavy wood windows don't show its industrial purpose. In addition the powerhouse is buried for two thirds of its height improving its appearance. To conceal the stone work of the tailrace a waterfall has been installed.

The substation is located in the powerhouse (Photo 7.11), in contrast with the usual outer substation (see photo 6.11), and the power cables leave the powerhouse over the penstock, under the tunnel and over the open canal. Close to the village where there are several transmission lines the power cables come to the surface, to be buried again when the line transverses the north slope, a habitat of a very rare bird species — the "urogayo".

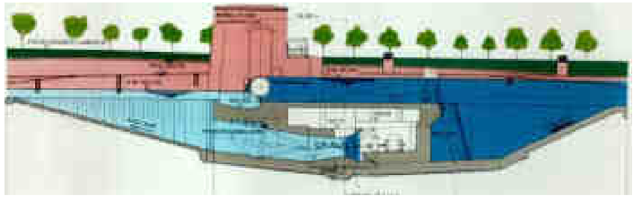
Photo 7.10

Photo 7.11

The Neckar power plant (Photo 7.12) is located in the historical centre of Heidelberg[4] and was authorised under the condition that it would not interfere with the view of the dam built in the past to make the river navigable. The powerhouse, built upstream of the dam, is entirely buried and cannot be seen from the river bank. Photo 7.13 shows better than a thousand words the conceptual design, where stand two Kaplan pit turbines, and each one with a capacity of 1535 kW. The investment cost was of course very high – about 3760 ECU/installed kW.

Photo 7.12

Photo 7.13



7.3.3 Biological impacts

7.3.3.1 In the reservoir

Reservoir projects are very unusual in small hydropower although there are some schemes that store enough water to operate the turbine only during the periods of maximum electrical demand. Such operation is referred to as "peaking" or "peak-lopping". In integral low head schemes peaking can result in unsatisfactory conditions for fish downstream because the flow decreases when the generation is reduced. The lower flow can result in stranding newly deposited fish eggs in spawning areas. The eggs[1] apparently can survive periods of dewatering greater than those occurring in normal peaking operation but small fish can be stranded particularly if the level fall is rapid.

7.3.3.2 In the streambed

A substantial proportion of small hydro plants is of the diversion type, where water is diverted from a stream, or a lake, into a hydroelectric plant perhaps kilometres from the diversion point to take advantage of the gain in head. The reduction in flow in the streambed between the point of diversion and the tailrace downstream of the powerhouse may affect spawning, incubation, rearing, and the passage of anadromous fish and of living space for adult fish. Then in high-flow periods the water spills over the weir and floods the streambed. It is precisely such frequent changes from semi-dry to wet that can ruin aquatic life.

There is here a clear conflict of interest. The developer will maintain that the generation of electricity with renewable resources is a very valuable contribution to mankind, by replacing other conversion processes emitting greenhouse gases. The environmentalists will say, on the contrary, that the water diversion in the stream represents a violation of the public domain.

7.3.3.2.1 Reserved flow

In many countries reserved flow is regulated by a national law that usually only defines a minimum value, but still permits local communities to impose flow values unreasonably higher. The determination of reserved flow can be critical for the development of a site because too large a residual flow can make an otherwise good project economically unfeasible.

All the dominant methodologies for the determination of the reserved flow, in force in Europe and U.S.A., can be classified in two groups:

- Hydrological methods based on an analysis of the historic time-series and subsumed in easily applicable empirical formulae.
- Hydro-biologic methods based on scientific criteria, applicable only to a particular river, and taking into account both hydrologic and biologic parameters.

In the first group there are, worthy of mention -

- Those using a certain percentile (10%, 15%, etc.) of the "module" or long term average flow.
- Those using the Matthey formula (based on the Q_{347} and Q_{330} representing the flows equalled or exceeded respectively 347 and 330 days in a year). This criterion inspires the Swiss and Austrian legislation and is applied with small modifications in the regional governments of Asturias and Navarra in Spain.
- The Tenant method (1976) developed for the Montana, Wyoming and Nebraska rivers in the U.S.A., proposing minimum flows corresponding to different percentiles of the module, variable with the season of the year.

In the second group there are -

- The method of the habitat analysis
- The method of the wetted perimeter (Randolph and White 1984)
- The incremental analysis
- The method of microhabitats by Bovee and Milhous 1978 and Stainaker 1980
- The method of Nehring, that together with the last two ones are considered as the harbingers of the PHASBIM methodology
- The MDDDR and DRB based on the research work of Cacas, Dumont and Souchon (CEMAGREF) in France. They have been largely demonstrated in the French Alps
- The DGB method developed by HydroM [5](Toulouse 1989)
- The APU method developed in Spain by Garcia de Jalon and others

The hydrologic methods are simple and user friendly, but are not supported by a scientific criterion and are consequently arbitrary.

A large majority of the hydro-biologic methodologies are based in the knowledge of the physical structure of the river. For the past two decades the state-of-the-art model for the depiction of the riverine habitat has been the Physical Habitat Simulation Model (PHABSIM), based on one-dimensional hydraulic modelling and requiring an abundance of empirical calibration data and the collection of these data along transects of the river. PHABSIM is expensive and often non-transferable to other streams

For the time being the legislation on a large majority of the E.U. member states is based in hydrologic methodologies, and defines the reserved flow as a percentage of the "module". In France the Law 84-512 (Loi du Pèche, 29-06-84) requires, in watercourses with a long-term average flow under 80 m^3/sec, 10% of the module. Watercourses with a long-term annual average flow over 80 m^3/sec require 5% of the module (Art 232.6 du Code Rural). Those values are a minimum to be respected by the local authorities which can require higher values. In Germany there are the Länder authorities which are responsible for the definition of the reserved flow. In Nordhein-Westfallen for instance it can vary from 0.2 to 0.5 of the module, and in Rheinland-Platz 1% of the module, but in the west of the country where most of the rivers have salmon higher values are required (usually the discharge corresponding to a 30% excedance or Q_{110}). In Italy there is no national norm and there are the regions, which specify the required values. In Regione Piedmont it must be 10% of the instantaneous discharge and the turbines should be stopped when the river flow drop below 120 l/sec in the Anza river, 5 l/s in the Rosso, and 30 l/s in the Ollochia (Bolletino Ufficiale della Regione Piedmont 20/5/1987). In Portugal the flow value, based on the hydrologic and biologic characteristics of the river, is defined by the INAG in the authorisation act. In Austria the norm is based on the Q_{347}, the flow that is equalled or exceeded 347 days a year. In Spain the Water Act (Ley de Aguas, 02-08-1988) requires a minimum equivalent to the average summer flow but not less than 2 l/s per square kilometre of catchment area, but the required value varies with the regional government. In Navarra it is 10% of the module for the rivers with cyprinids but in the salmon rivers is equivalent to the Q_{330} and in Asturias it follows a rather complicated formula.

Once the reserved flow is defined, the hydraulic devices ensuring the achievement of this target must be implemented. In France, for instance, a recent investigation undertaken in the Southern Alps found that in 36 of the 43 schemes investigated, the reserved flow was not respected (in half of the schemes due to the poor quality of the implemented devices). Accordingly it is strongly recommended to take care of this aspect.

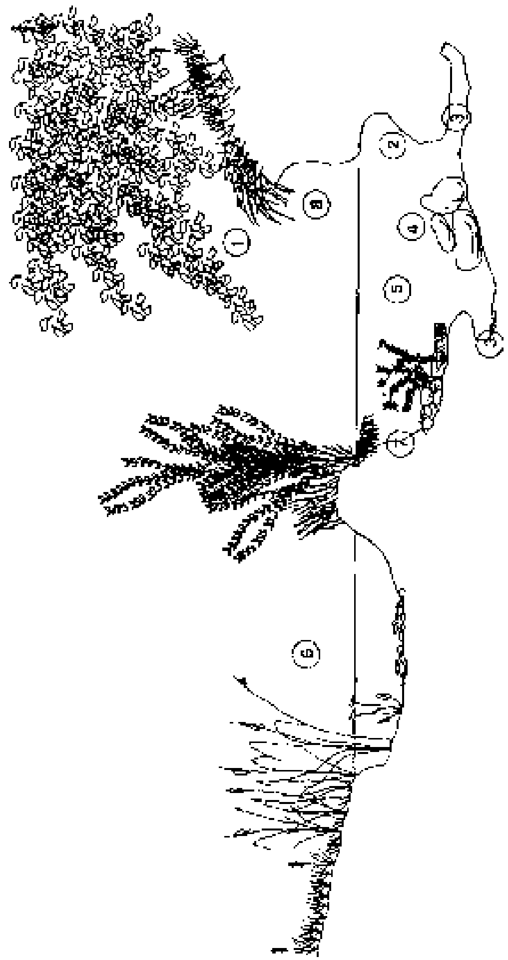
It must be underlined that if any of the biologic methods for the definition of the reserved flow value is implemented, there is a possibility for the developer to decrease the level of the required reserved flow, by modifying the physical structure of the streambed. Actually growing trees on the riverbanks to provide shadowed areas, deposit gravel in the streambed to improve the substratum, reinforce the riverside shrubs to fight erosion, etc.

Figure 7.2 (reproduced from a paper by Dr. Martin Mayo) illustrates the kind of coverage and refuge against the flow and sunshine or to elude a danger, furnished to vertebrates and invertebrates by both natural and artificial elements. The existence of caves and submerged cornices provides a safe refuge against the attacks of a predator. Also the riverine vegetation, which when close to the water provides shadow coverage used by fish of any size to prevent overheating or to provide concealment in face of terrestrial predators (it must be said that the most dangerous terrestrial predator is the freshwater fisherman). All these elements contribute to the concept that in the APU method is known as refuge coefficient. By increasing its importance the required value of the reserved flow may be diminished. In that way a better protection of the aquatic fauna can be combined with a higher energy production.

7.3.3.2.2 Fish passes (upstream fish)

Anadromous fish, which spawn in fresh water but spend most of their lives in the ocean, and catadromous fish, which spawn in the ocean and reach adulthood in fresh water requires passages at dams and weirs. A great variety of fishpass designs[2] are available, depending on the species of fish involved. Otherwise freshwater fish seem to have restricted movements.

Upstream passage technologies are considered well developed and understood for certain anadromous species including salmon. According to OTA 1995 (Office



Elements of natural shelter: 1) shelter due to the river banks, 2) underwater cornices 3) caves, 4 substratum cavities, 5 submerged vegetation, 6) emergent vegetation, 7) stumps roots and submerged wood, 8) open air cornices in the bank

figure 7.2

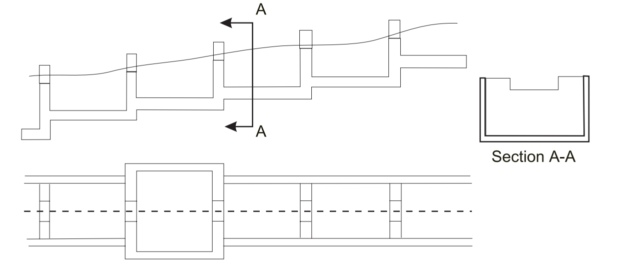


figure 7.3

of Technology Assessment in the U.S.A.) there is no single solution for designing upstream fish passageways. Effective fish passage design for a specific site requires good communication between engineers and biologists and thorough understanding of site characteristics. Upstream passage failure tends to result from a lack of adequate attention to operation and maintenance of facilities.

The upstream passage can be provided for through several means: fish ladders, lifts (elevators or locks), pumps and transportation operations. Pumps are a very controversial method. Transportation is used together with high dams, something rather unusual in small hydropower schemes. Site and species-specific criteria and economics would determine which method is most appropriate.

Fish ladders (pool and weir, Denil, vertical slots, hybrid etc.) can be designed to accommodate fish that are bottom swimmers, surface swimmers or orifice swimmers. But not all kinds of fish will use ladders. Fish elevators and locks are favoured for fish that does not use ladders

Photo 7.14

Photo 7.15

The commonest fishpass is **the weir and pool fishway**, a series of pools with water flowing from pool to pool over rectangular weirs. The pools then play a double role: provide rest areas and dissipate the energy of the water descending through the ladder. The size and height of the pools must be designed as a function of the fish to be handled. The pools can be supported by:

- Baffles provided with slots, so that both fish and bedload, pass through them
- Baffles provided with bottom orifices large enough to allow fish to pass
- Baffles provided both with vertical slots and bottom orifices

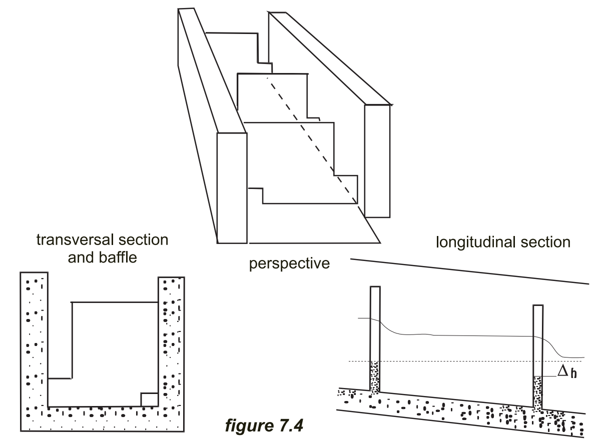


figure 7.4

Pools separated by baffles with bottom orifices only do not have practical interest because are limited to bottom orifice fish swimmers. Salmon do not need them because they can jump over the baffle itself, and shads, for instance, are not bottom swimmers. The system of rectangular weirs (figure 7.3) is the oldest one, but presents the inconvenience that when the headwater fluctuates the fishway flow increases or decreases, resulting in a fishway with too much or too little flow. Moreover this type of ladder will not pass bedload readily and must be designed with bottom orifices for this purpose. Photo 7.14 shows one of these ladders with a rustic construction designed for salmon checking on a river in Asturias (Spain).

Photo 7.15 illustrates a fishladder with vertical slots and bottom orifices that usually yields very good results. The shape and disposition of the baffles are shown in perspective in the figure 7.4; the width of the pools, for lengths varying between 1.8 and 3.0 m, varies from 1.2 m to 2.4 m . The drop between pools is in the order of 25 – 40 cm. Shads require a drop not bigger than 25 cm. TComputer programs[6] optimise the width and length of pools, the drop between pools and the hydraulic load.

The vertical slotted fishway (figure 7.5) is very popular in the U.S.A. but not well known in Europe[7]. Through the baffle's vertical slot passes both fishes and bedload. A standard model has pools 2.5-m wide, 3.3 m long with a slot 30 cm wide. Supporters of this type of ladder praise its hydraulic stability even with large flow variations.

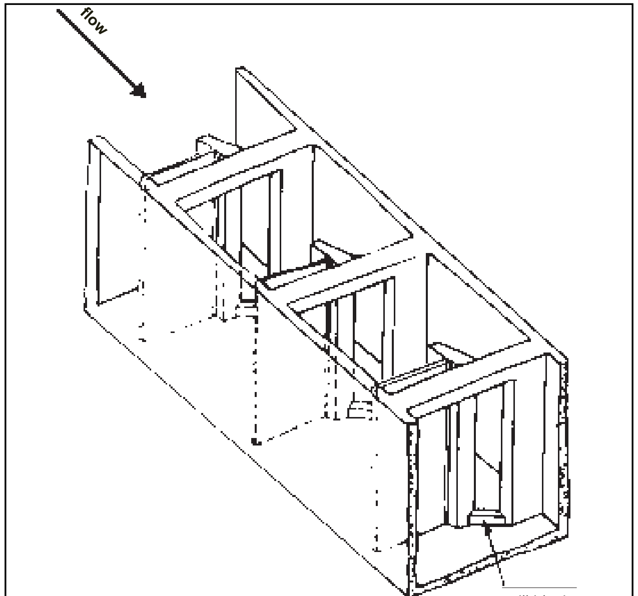
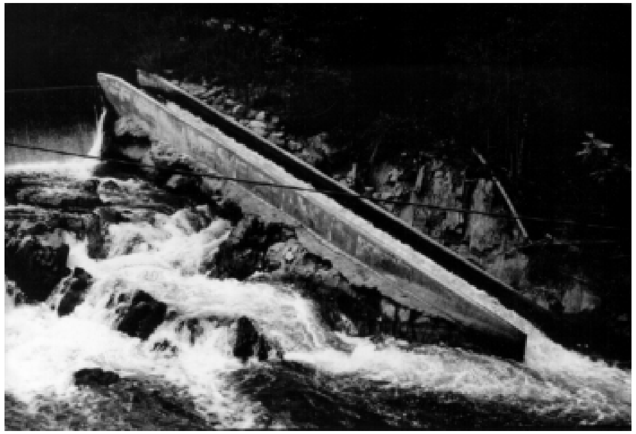


figure 7.5

Photo 7.16



The Denil fishpass (Photo 7.16) consists of fairly steep, narrow chutes with vanes in the bottom and sides as illustrated in figure 7.6. These vanes dissipate the energy providing a low-velocity flow through which the fish can easily ascend. This characteristic allows Denils to be used with slopes up to 1:5. They also produce a turbulent discharge that is more attractive to many fish species than the discharge from pool-

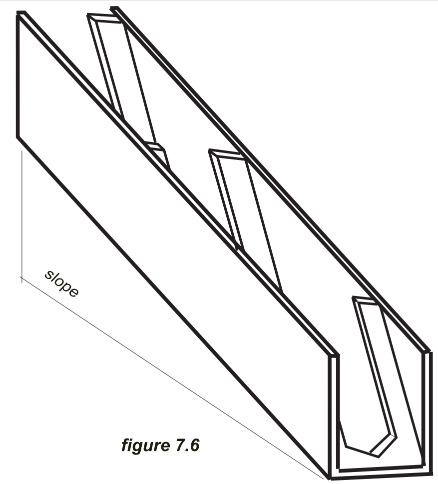


figure 7.6

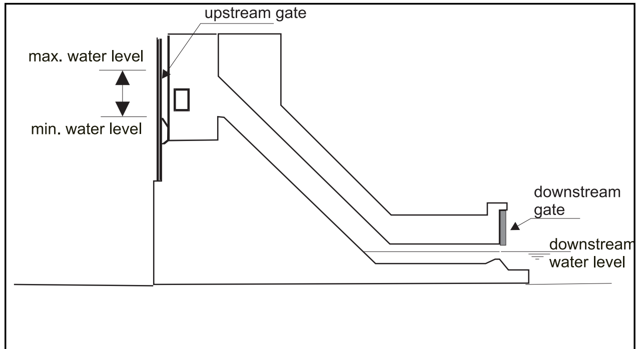


figure 7_7

type fishpasses, and are tolerant of varying water depths. The ladder must be provided with resting areas after approximately 2-m. gain of elevation.

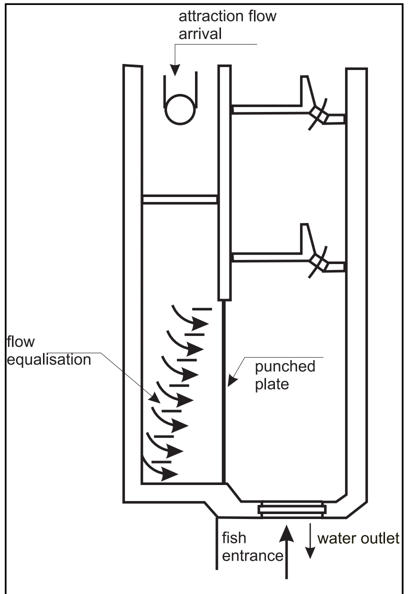


figure 7.8

The Borland lock (figure 7.7) is a relatively cheap solution to transfer fish from the tailrace to the forebay in a medium dam. The fish climb a short fish ladder to the bottom chamber. Then the entrance to the bottom chamber is closed and the shaft rising from it to the top of the dam becomes filled with the water flowing down from the forebay through the top chamber. Once filled, the fish that are attracted by this flow are close to the forebay level into which they can swim.

In higher dams the best solution is to install a lift specifically designed for this purpose. EDF in France has a wide experience with these lifts. The Golfech lift for instance when it was commissioned in 1989 made it possible to pass twenty tonnes of shad (about 66 000 individuals) that were blocked at the base of the dam. Otherwise, the only possible solution is to trap the fish at the base and transport them safely upstream. These devices are discussed in reference [4]. All that is needed is a small fishpass to bring the fish from the tailrace to the trap. There, by mechanical means the fish are concentrated in a trolley hopper, and loaded onto a truck. Eventually the trolley hopper carries them directly over the dam's crest via a cableway and they are discharged into the reservoir.

The most important element of a fishpassage system, and the most difficult to design for maximum effectiveness, is the fish-attraction facility. The fish-attraction facility brings fish into the lower end of the fishpassage [3] and should be designed to take advantage of the tendency of migrating fish to search for strong currents but avoid them if they are too strong. The flow must

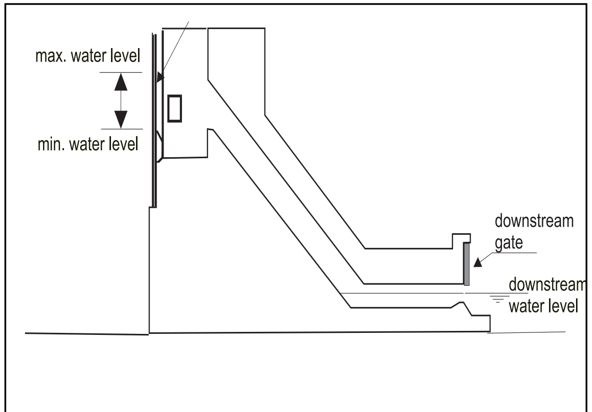


figure 7_7

Photo 7.17

therefore be strong enough to attract fish away from spillways and tailraces. The flow velocities at the entrance of the fishpass vary with the type of fish being passed, but for salmon and trout, velocities from two to three meters per second are acceptable. A lack of good attraction flow can result on delays in migration, as fish become confused, milling around looking for the entrance. If necessary, water must be pumped into the fishpass from the tailwater areas, but usually enough water can be taken at the upstream intake or forebay to be directed down the fishpass. Dealing with salmon the attraction flow should be maintained between 1 m/s and 2 m/s, although if the water is too cold –less than 8º- or too hot –more than 22º- the speed must be decreased because fish become lazy and do not jump. Water can be injected just at the entrance of the fishway avoiding the need to transverse all its length (figure 7.8)

The entrance to the fishpassage should be located close to the weir since salmon tend to look for the entrance by going around the obstacle. In low-head integrated schemes the entrance should be in the bank close to the powerhouse as illustrated schematically in figure 7.9 and shown in photo 7.17.

The upstream outlet of the fishpassage should not be located in an area close to the spillway, where there is a danger of being sent back to the base of the dam, nor in an area of dead circulating waters where the fish can get trapped. Fishpassages must be protected from poachers, either closing it with wire mesh or covering it with steel plates.

The use of **fish pumps** for fish passage at dams is controversial and largely experimental. This technology is relied upon in aquaculture for moving live fish. Several pumps are in the market and new ones are being developed. Pumping of the fish can lead to injury and de-scaling as a result of crowding in the bypass pipe.

7.3.3.2.3 Fishpasses (downstream fish)

In the past downstream migrating fish passed through the turbine. The fish-kill associated with this method varies from a few percent to more than 40% depending on the turbine design and more specifically on the peripheral speed of the runner. In a Francis turbine increasing the peripheral runner speed from 12 m/sec to 30 m/sec increases the percentage mortality from 5% to 35%. Francis turbines, due to their construction characteristics cause greater mortality than Kaplan turbines. Bulb turbines reduce mortality to less than 5%[8].

Apparently head is not a decisive factor. A turbine working at a head of 12 meters produces the same mortality as one working at a head of 120 m. The elevation of the runner above tailwater is a very important factor, quite apart from the effect of cavitation. The more efficient a turbine is, the less mortality it produces. A turbine working at rated capacity consequently causes less mortality than one working at partial load. Mechanical injuries by collision against solid bodies - guide vanes or turbine blades-, exposure to subatmospheric pressures and shear effects produced at the intersections of high velocity flows in opposite directions are the main causes of mortality.

Physical barrier screens are often the only approved technology to protect fish from turbine intake channels, yet the screens are very expensive and difficult to maintain. Factors to be considered in a diverting system include the approach velocity to the screen (depending of the fish size the approach velocity should fluctuate around 1.4 m/s); adequate lateral flow to carry fish and debris past the screen; and facilities for continuous or periodic cleaning of the screen to ensure

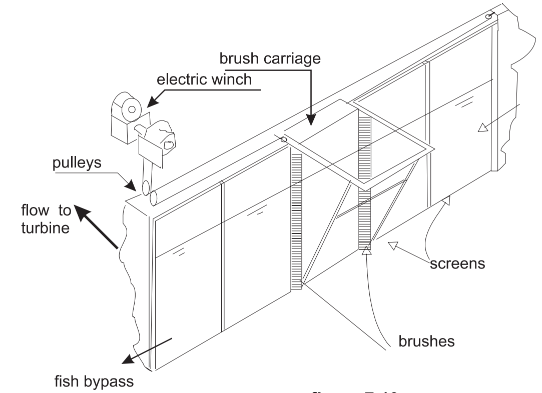


figure 7.10

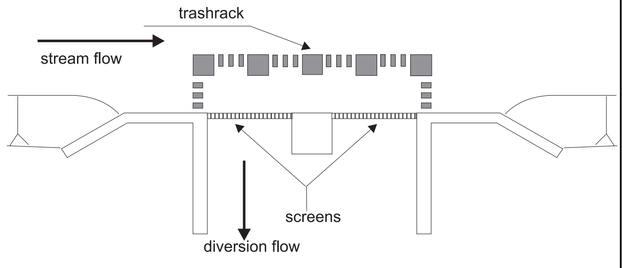


figure 7.11

uniform velocity distribution through them. But the success of any screening system relies on means being provided to take fish from the screen to a safe haven.

The simplest solution is a static standard screen -made of 2mm-punched steel sheet with 4-mm holes on 5.5-mm centres. Such a screen must be placed behind the trash rack at the entrance to the penstock. Usually it is located at right angles with the flow but, like this location is susceptible to clogging. It is better to incline it to the flow, downsloping and ending in a trough so that fish slide in a small quantity of water down the screen and into the trough, while most of the water flow through the screen. There are also examples of upsloping and humpback designs but the downslope is the most effective for self-cleaning. In some installations a brush, driven by a cable and pulley mechanism and powered by a reversible motor continuously clean the screen (figure 7.10). The screen can also be manufactured of stainless steel wire or with synthetic monofilament. The screen made with synthetic monofilament is too flexible to be cleaned by mechanical brushes, but it can be cleaned by flow reversal.

In the classic intake, with its longitudinal axis perpendicular to the river axis, it is recommended to align the screen with the riverbank, so the fish follow the flow line without touching it (figure 7.11). If necessary the riverbanks will be gunited to avoid eddy formations where the fish could get trapped and even be attacked by predators. Although this configuration does not seem to be favourable from a hydrodynamic viewpoint, the head loss generated by the change in direction of the flow is irrelevant. If the screen cannot be located at the entrance a bypass, such as the one illustrated by figure 7.12, should be implemented to send back the fish to the river.

For discharges over 3 m^3/sec fixed screens, due to their large surface areas are difficult to install. In those cases the use of vertical travelling screens or the rotary horizontal drum screens may be recommended . The travelling screens are mechanically more complicated but need less space for their installation.

A typical example of a screen not needing a mechanical cleaning mechanism is the Eicher screen (figure 7.13). This design[9] uses an upsloping elliptical screen of wedge wire, perforate plate or other screening material, within a penstock, and operates under pressure, so that most fish and trash tend to move along near the

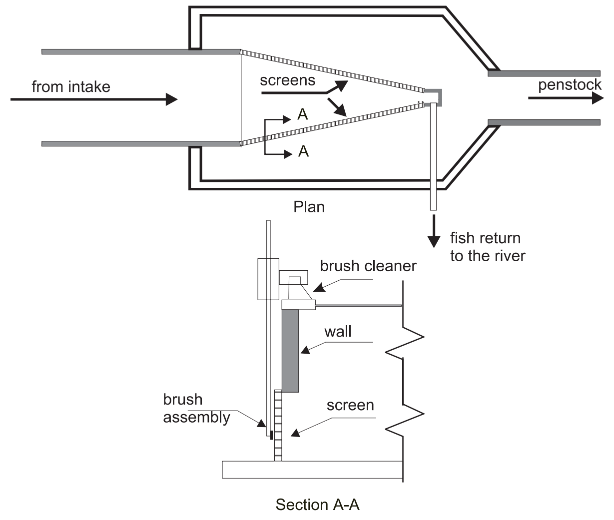


figure 7:12

top of the penstock, having little contact with the screen. A relatively high water velocity moves both fish and trash through the penstock and out of a bypass parallel to the central flow in a few seconds. Full-scale tests of the Eicher Fish Screen performed in 1990 showed the design to be 99% effective in bypassing

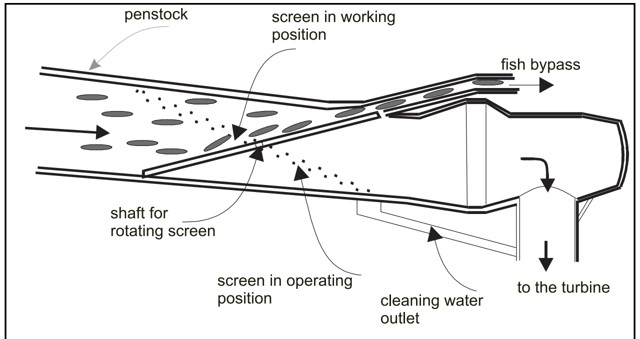


figure 7.13

salmon smolts without mortality [6]. The Eicher screen does not require space in the forebay area, and because it is installed inside the penstock, does not alter the appearance of the installation.

Another screen type tolerating higher approaching velocities is the Modular Inclined Screen (MIS) developed under the EPRI[10] sponsorship. It is a modular design easy to adapt to any scheme, by adding the necessary number of modules. The MIS module (figure 7.14) consists of an entrance with a trashrack, dewatering stop logs, an inclined wedgewire screen set at a shallow angle of 10 to 20 degrees to the flow, and a bypass for diverting fish to a transport pipe. The screen is mounted on a pivot shaft so that it can be cleaned via rotation and backflushing. The module is completely closed and is designed to operate at water velocities ranging from 0.6 m/sec to 3.3 m/sec. The module, depending on the screen angle selected, can screen a maximum of 14 to 28 m^3/sec of water. For bigger discharges it is possible to add more modules. The results of hydraulic model tests demonstrated that the MIS entrance design created a uniform velocity distribution with approach flows skewed as much as 45 degrees. The uniform velocity distribution of the MIS is expected to

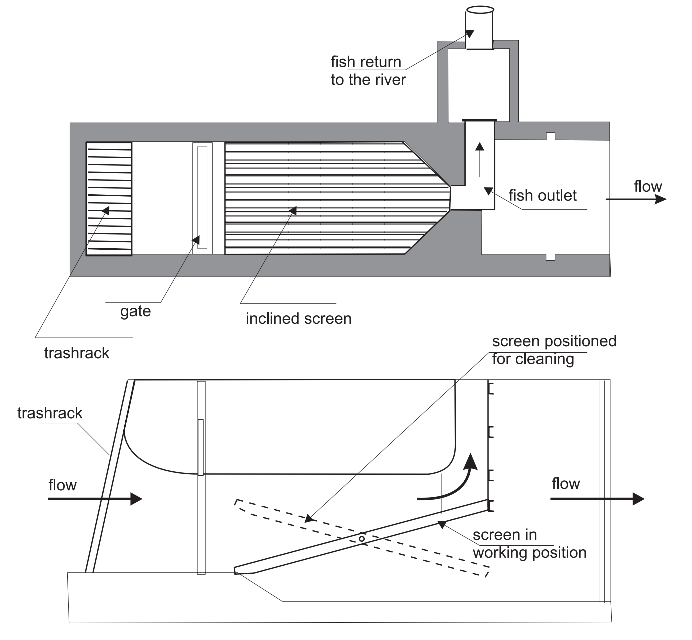


figure 7.14

facilitate fish passage at higher velocities that can be achieved using any other currently available type of screen. Passage survival was calculated as the portion of fish that were diverted live and survived a 72 hours holding period. Passage survival generally exceeded 99% at velocities of 1.83 m/sec. This survival rate was maintained up to 3.05 m/sec for several test groups including Coho salmon, Atlantic salmon smolts and brown trout.

Recently an innovative self-cleaning static intake screen, that does not need power, has been used for fish protection. The screen uses the Coanda[11] effect, a phenomenon exhibited by a fluid, whereby the flow tends to follow the surface of a solid object that is placed in its path. In addition, the V shaped section wire is tilted on the support rods, (figure 7.15) producing offsets which cause a shearing action along the screen surface. The water flows to the collection system of the turbine through the screen slots, which are normally 1 mm wide. Ninety per cent of the suspended solid particles, whose velocity has been increased on the acceleration plate, pass over the screen thus providing excellent protection for the turbine. Aquatic life is also prevented from entering the turbine through the slots. In fact the smooth surface of the stainless steel screen provides an excellent passageway to a fish bypass. The screen can handle up to 250 l/s per linear meter of screen. A disadvantage of this type of screen is that it requires about 1 to 1.20 m. of head in order to pass the water over the ogee and down into the

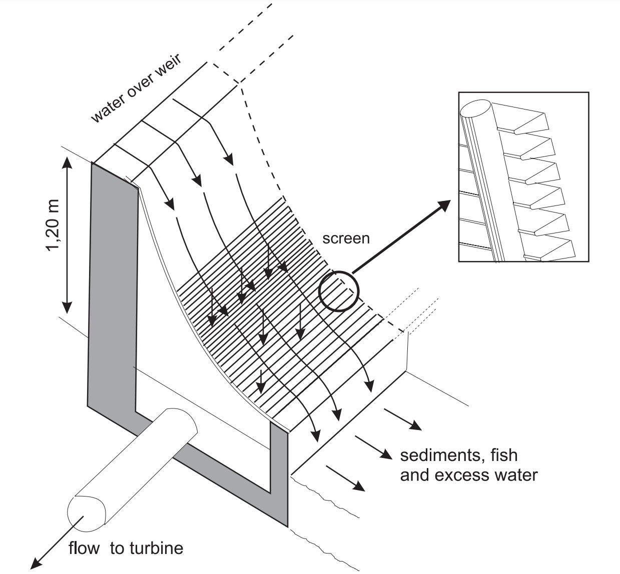


figure 7. 15

Photo 7.18

collection system. This can be uneconomic in low head systems. Photograph 7.18 shows a Coanda screen supplied by DULAS Ltd[12] (e-mail dulas@gn.apc.org). The photo is published by courtesy of this company.

Circular screens [8] make use of wedge-wire in short stubby pods (figure 7.16). The pods can be placed under the streambed to collect water in a manner similar to an infiltration gallery. The slot spacing between the wedge wires controls the size of the fish that are kept out of the turbine. Several circular screens can be disposed to feed water to the penstock, collecting relatively large volumes of water with a reasonable head loss. Compressed air is used for cleaning.

Behavioural guidance systems and a variety of alternative technologies to divert or attract downstream migrants have been recently object of studies by the Electric Power Research Institute (EPRI). These technologies include strobe lights for repelling fish, mercury lights for attracting fish, a sound generating device known as "hammer" for repelling fish as well as quite a number of electrical guidance systems. It has not yet been demonstrated that these responses can be directed reliably. Behavioural guidance techniques are site- and species-specific and it appears unlikely that behavioural methods will perform as well as fixed screens over a wide range of hydraulic conditions[13].

As manifested by Mr. Turpenny of Fawley Aquatic Research Laboratories Ltd U.K.[14], "the disadvantage of behavioural screens over conventional mechanical screens is that they do not exclude 100% of fish, whereas a mechanical screen of sufficiently small aperture will do so. Typical efficiencies for behavioural barriers range from 50% to 90%, depending upon type and environmental and plant conditions. Most fish penetrating the barrier are likely to go on to pass through the turbine , thereby putting them at risk of injury."

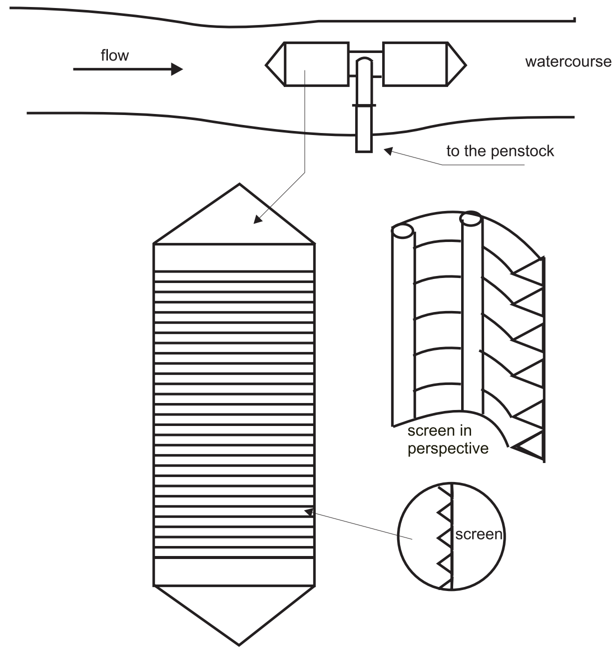


figure 7.16

Figure 7.17 illustrates the disposition of a system of underwater acoustic transducers which transmit their sound into a rising bubble curtain to create a wall of sound to guide fish out of the turbine passage. This type is known as "BioAcoustic Fish Fence" (BAFF) and has shown a 88-100% typical fish exclusion efficiency.

Trapping collection and trucking systems are similar to these employed with upstream migrating fish. The fish must be collected in a trap to be transported in tanks[15]. However the trapping and collecting operation with downstream migrating fish presents more difficulties than with upstream fish because there are not high velocity flows to attract them. Downstream fish must be collected with fishing nets fabricated with synthetic monophilament, or with travelling vertical screens of the same material. The collected fish show symptoms of stress and superficial injuries that make the system questionable. However these systems are the only ones ensuring the exclusion of eggs and larvae, although seem to be proved that both eggs and larvae pass through reaction turbines undamaged.

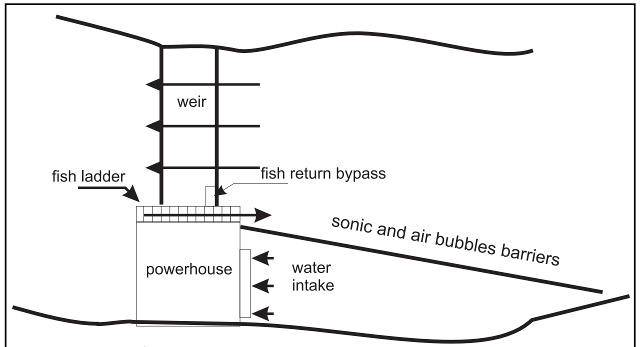


figure 7.17

Bypass routes must be provided to allow fish to move from the area in front of a physical barrier back to the river.

The screens located at the intake entrance do not need any return conduit because fish are entrained by the water flow and return to the river usually over the spillway which is of course less dangerous than the turbines, although it also can be damaging. Surprisingly, high spillways are not necessarily more dangerous for fish than low ones. Terminal velocity, as demonstrated by dropping salmon from helicopters into a pound[11], is reached after about 30 meters of fall, and remains constant thereafter. Eicher mentions an experimental ski-jump spillway, which throws the fish out in free fall to a pool 80 m below with a mortality rate reduced to virtually zero.

When the screen is located in the intake downstream of the entrance, a bypass returning the fish to the river is needed. According to behavioural characteristics migrating downstream fish cannot be expected to swim back upstream to find the entrance, which must be located at the downstream end of the screen, assuming the screen is inclined in the direction of the flow. Fish are frequently reluctant to move into small size entrances A minimum bypass entrance of 45 cm is recommended, especially when dealing with juvenile salmonids. It would be preferable that the entrance width could be adjustable by the use of fabricated metal inserts to reduce the size of the operating opening. The bypass entrance design should provide for smooth flow acceleration into the bypass conduit with no sudden contractions, expansions or bends.

For returning fish from the bypass entrance to the river, fully close conduits or open channels can be used. Fish do not like to enter in conduits with abrupt contrast in lighting. Open channels are better suited for that role. Internal surfaces should be very smooth to avoid fish injury. High-density polyethylenes and PVC are excellent materials for bypass conduits.

Photo 7.8

Abrupt changes in section should be avoided due to their associated turbulence and pressure changes. In full flow conduits pressures below atmospheric should be avoided because they can injure or even kill fish. Air entrainment in a full flow conduit generates hydraulic turbulence and surging thus avoiding gas supersaturation in the water that can be detrimental to fish. Conduit discharge velocities should not be so high relative to the ambient velocities in the outfall as to create shear forces that can injure fish. Velocities close to 0.8 m/sec are recommended.

7.3.3.3 In the terrain

Canals have always constituted an obstacle to the free passage of animals. To avoid this, nowadays open canals are entirely buried, and even revegetated so they do not represent any barrier. In any case in very sensitive areas, as in certain areas of Asturias, where the brown bear still lives, the environmental agencies tend to take extreme measures and even to refuse water use authorisation.

7.3.4 Archaeological and cultural objects

In the construction phase the developer should take great care to avoid damage to archaeologic or cultural objects of a certain value. This may be particularly critical in schemes with reservoirs, where valuable objets or even historical monuments can be submerged. In the Cordiñanes scheme mentioned above, during the excavation works to found the powerhouse, a middle age burial place was found. With the aid of government experts the place was arranged as illustrated in photo 7.19.

Photo 7.20

7.4 Impacts from transmission lines

7.4.1 Visual impact

Above ground transmission lines and transmission line corridors will have a negative impact on the landscape. These impacts can be mitigated by adapting the line to the landscape, or in extreme cases burying it.

The optimal technical and economic solution for a transmission line routing is that which will often create the more negative aesthetic impacts. To achieve optimal clearance from the ground the pylons are placed on the top of the hills, constituting a very dominating element of the landscape, A minimum of bends in the route will reduce the number of angle and ordinary pylons and therefore reduce its cost. Aesthetically neither a high frequency of bends, nor straight routes that are made without consideration for the terrain and landscape factors are preferred.

In sensitive mountain areas where schemes are developed transmission lines can dominate the landscape and therefore damage the beauty of the scenario. It must be remarked that transmission lines exist even without the existence of hydropower schemes. Villages even if they are high in the mountain require electricity to make life livable, and electricity, unless generated by photovoltaic systems, requires transmission lines. It is true that with a right siteing of the lines in relation to larger landscape forms and a careful design of the pylons the impact can be relatively mitigated. Other times, like in Cordiñanes, both stepping up transformer substation and transmission lines are concealed from public view and the situation entirely improved, but it is an expensive solution that only can be offered if the scheme is profitable enough.

7.4.2 Health impact

In addition to the visual intrusion some people may dislike walking under transmission lines because of the perceived risks of health effects from electromagnetic fields. Apart from the fact that this risk is only perceived in high voltage transmission lines, and never is the case in a small hydropower scheme, after several years of contradictory reports, the experts nowadays consider that living in areas close to high voltage transmission lines does not increase the risk of cancer, and more specifically of infant leukaemia. That is the conclusion of a recent Cancer Institute report published in the prestigious medical review “The New England Journal of Medicine”. The report insists that it is time to stop wasting resources on this type of study and focus research to discovering what are the real biological causes of leukaemia.

7.4.3 Birds collisions

Although birds are morphologically and aerodynamically adapted to fly, there are limits in respect of their capability to avoid artificial obstacles. Areas where the electric conductors are located close to the treetops seem to be high-risk wire strike sites. Few collisions [26] seem to take place where it is a dense forest on one or both sides of the line corridor. Wire strikes are especially frequent in areas where the distance to the forest edge is about 50 m or more on one or both sides of the line. However the only way to completely avoid bird collisions is underground cabling. That is the solution adopted in Cordiñanes to traverse the north slope where the “urogayo”, a rare bird specimen in danger of extinction, lives .

Electrocution takes place whenever a bird touches two phase conductor or a conductor and an earth device simultaneously. This restricts the problem to power lines carrying tensions below 130 kV (transmission lines in small hydropower schemes are always 66 kV or lower). Similar to the collisions with the power lines, electrocution has biological, topographical and technical factors, although these are deeply interwoven and not easily separated. Humidity is also an important factor

7.5 Conclusions

A visit to Cordiñanes will show to any bona fide person that a small scale hydropower scheme can be developed in a natural park without this being negatively affected, and at the same time avoiding the emission on other part of the country of thousands of tonnes of greenhouse gases and inducing acid rains.

Bibliography

1 European Commission - "Externalities of Energy - Volume 6 Wind and Hydro" EUR 16525 EN

2 S. Palmer. "Small scale hydro power developments in Sweden and itd environmental consequences". HIDROENERGIA 95 Proceedings. Milano

3 F. Monaco, N. Frosio, A. Bramati, "Design and realization aspects concerning the recovery of an energy head inside a middle european town", HIDROENERGIA 93, Munich

4 J. Gunther, H.P. Hagg, "Volltändig Überflutetes Wasserkraftwerk Karlstor/ Heidelberg am Neckar", HIDROENERGIA 93, Munich

5 M. Mustin and others, “Les méthodes de détermination des débit réservés; Analyse et proposition d'une méthode pratique; Le débit de garantie biologique (DGB)”, Report pour le Comité EDF Hydroécologie.

6 Santos Coelho & Betamio de Almeida, "A computer assisted technique for the hydraulic design of fish ladders in S.H.P." HIDROENERGIA 95, Munich

7 Osborne,J. New Concepts in Fish Ladder Design (Four Volumes), Bonneville Power Administration, Project 82-14, Portland, Oregon, 1985

8 Department of Energy, Washington, USA. "Development of a More Fish-Tolerant Turbine Runner" (D.O.E./ID.10571)

9 George J.Eicher “Hydroelectric development: Fish and wild life considerations” Hydro Review Winter 1984

10 Winchell, F.C. “A New Technology for Diverting Fish Past Turbines”, Hydro-Review December 1990

11 Dulas Ltd. Machynllet, Powys, Wales SY20 8SX. e-mail dulas@gn.apc.org . "Static screening systems for small hydro". HIDROENERGIA97 Conference Proceedings, page 190

12 James J.Strong. “Innovative static self-cleaning intake screen protects both aquatic life and turbine equipment” HYDRO'88 Conference papers.

13 D.R. Lambert, A. Turpenny, J.R. Nedwell "The use of acoustic fish deflection systems at hydro stations", Hydropower&Dams Issue One 1997

14 A. Turpenny, K. Hanson. "Fish passage through small hydro-turbines: Theorical, Practical and Economic Perspectives". HIDROENERGIA 97, Conference Proceedings, page 451.

15 Civil Engineering Guidelines for Planning and Designing Hydroelectric Developments, Volume 4, American Society of Civil Engineers, New York

8 Economic Analysis

8.0 Introduction

An investment in a small hydropower scheme entails a certain number of payments, extended over the project life, and procures some revenues also distributed over the same period. The payments include a fixed component – the capital cost, insurance, taxes other than the income taxes, etc- and a variable component –operation and maintenance expenses-. At the end of the project, in general limited by the authorisation period, the residual value will usually be positive, although some administrative authorisations demand the abandonment of all the facilities which revert to the State. The economic analysis compares the different possible alternatives to allow the choice of the most advantageous or to abandon the project.

From an economic viewpoint a hydropower plant differs from a conventional thermal plant, because its investment cost per kW is much higher but the operating costs are extremely low, since there is no need to pay for fuel.

The economic analysis can be made either by including the effect of the inflation or omitting it. Working in constant mpnetary value has the advantage of making the analysis essentially independent of the inflation rate. Value judgements are easier to make in this way because they refer to a nearby point in time which means they are presented in a currency that has a purchasing power close to present experience. If there are reasons to believe that certain factors will evolve at a different rate from inflation, these must be treated with the differential inflation rate. For instance, if we assume that the electricity tariffs as a consequence of deregulation will grow two points less than inflation, while the remaining factors stay constant in value, the price of the electricity should decrease by 2% every year.

8.1 Basic considerations

The estimation of the investment cost constitutes the first step of an economic evaluation. For a preliminary approach the estimation can be based on the cost of similar schemes [1,2]. IDAE (Instituto para la Diversificación y Ahorro de Energía, Spain) in its recent publication "Minicentrales Hidroeléctricas" [3] analyses the cost of the different components of a scheme –weir, water intake, canal, penstock, power-house, turbines and generators, transformers and transmission lines. Fonkenelle also has published nomograms, but only for low-head schemes[4].

The Departamento Nacional de Aguas e Energía Eléctrica (DNAEE) has written a computer program, FLASH, that is probably the best program for small hydro feasibility studies[5]. Under a contract with the European Commission (DG XVII), the French consultant ISL is developing a computer program, running in Windows 95 and NT, that includes an important database for the estimation of investment costs on small-hydro schemes.

D.R. Miller, ESHA Vice-President has produced a computer program, to estimate the buy-back price necessary for guaranteeing an acceptable return on investment in small hydro, that includes an estimation of the investment cost. The following table calculates the investment cost:

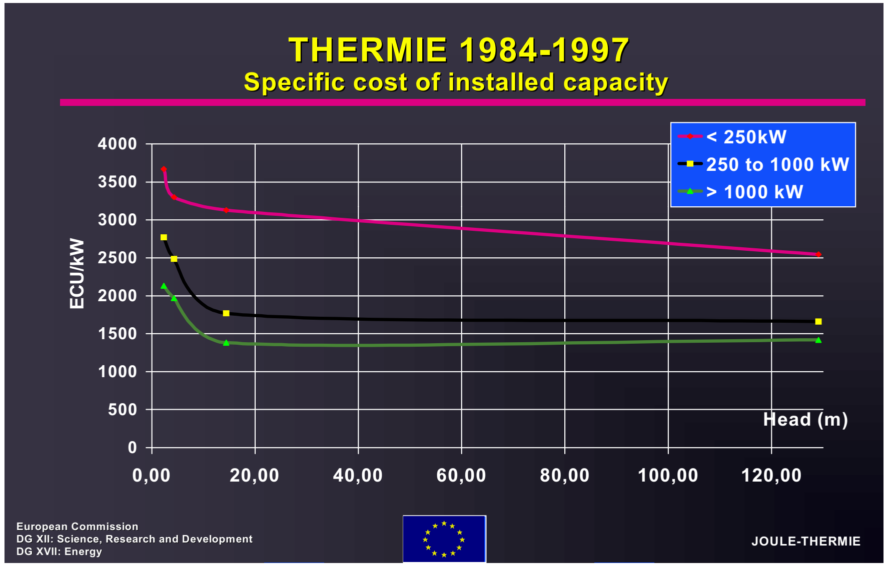
Plant capacity (kW)	cost (ECU)	
250 >P> 200	200 x 2250	+ balance x 2250 x 0,548165
500 >P> 250	250 x 2050	+ balance x 2050 x 0.824336
1000 >P> 500	500 x 1870	+ balance x 1870 x 0,817034
2000 >P> 1000	1000 x 1700	+ balance x 1700 x 0.765111
5000 >P> 2000	2000 x 1500	+ balance x 1500 x 0.777918
10000>P> 5000	5000 x 1300	+ balance x 1300 x 0,661133

The investment cost of a scheme with a capacity of 2650 kW will have an investment cost given by:
2000 x 1500 + 650 x 1500 x 0.777918 = 3758470 ECU or 1418 ECU/kW installed.

The above table doesn't take into account the head, and should be considered useful only for medium and high head schemes.

In his communication to HIDROENERGIA'97 on the THERMIE programme, H. Pauwels of the DG XVII (Energy Technology Department), showed the enclosed graph, summarising data for schemes presented to the above programme, which correlates the investment cost in ECU/kW installed for different power ranges and heads.

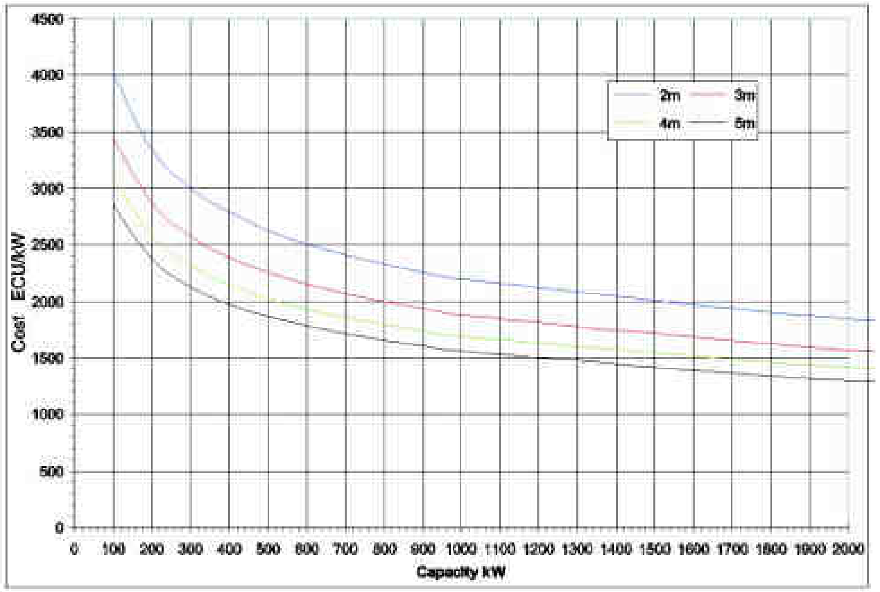
IT Power LTD Stroom Lijn, IEE Kassel 1997, presented also to HIDROENERGIA'97 a computer program, "Hydrosoft", which includes a set of curves correlating the



investment cost in ECU/kW and the installed capacity (between 100 kW and 10 MW) for low head schemes, with 2, 3, 4 and 5 m head. The curves are reproduced here up to a maximum capacity to 2 MW. The computer program, of course, gives the cost directly against the installed capacity and head. A table with numerical data is also provided and makes calculation less dependent on drawn curves.

However, as a cost estimate is essential for economic analysis, it is necessary as a second step, to make a preliminary design including the principal components of the scheme. Based on this design, budget prices for the materials can be obtained from suppliers. Such prices cannot be considered as firm prices until specifications and delivery dates have been provided. This will come later, during the actual design and procurement process.

Do not forget that in a plant connected to the grid, the investment costs of the connection line should be included, because according to various national regulations this line, although it sometimes becomes the property of the grid owner, is always built at the expense of the SHP developer. A plant close to the grid connection point will be always cheaper than one installed far from it. The same reasoning can be applied to telephone lines. In an unmanned plant the telephone line to transmit telemetry and alarm signals is frequently used although occasionally it might be cheaper to use the transmission line itself to establish a radio link or use a digital cellular telephone provided there is good coverage.



Total capacity	capacity/Turbine	2m	3m	4m	5m
100	50	4023	3447	3097	2854
200	100	3344	2865	2574	2372
300	150	3004	2574	2313	2131
400	200	2786	2386	2145	1976
500	250	2628	2251	2023	1864
600	300	2506	2147	1929	1778
700	350	2407	2063	1853	1708
800	400	2326	1992	1790	1650
900	450	2256	1933	1737	1600
1000	500	2196	1881	1690	1558
2000	1000	1839	1575	1416	1304
3000	1500	1659	1422	1277	1177
4000	2000	1543	1322	1188	1095
5000	2500	1460	1251	1124	1036
6000	3000	1395	1195	1074	990
7000	3500	1342	1150	1033	952
8000	4000	1299	1113	1000	921
9000	4500	1261	1081	971	895
10000	5000	1229	1053	946	872

8.2 Financial mathematics

An investment project considers revenues and expenses that take places in very different periods. In any economic analysis involving economic value there are always two variables, money and time. A certain amount of money paid or received at a point in time has a different value if it is paid or received at another point in time. Money can be invested during a certain period of time with the guarantee of a certain benefit. The term "present value" describes a monetary amount now, i.e. at a point in time other than that at which it is paid or received.

For a discounting rate r, the cost C_i (or the benefit B_i), disbursed or received in the year i, is discounted to the year 0 by the equation:

$$C_0 = \left(\frac{1}{(1+r)^i} \right) C_i \qquad (8.1)$$

The fraction within square brackets is known as the "present value factor" (PVF). To find the comparable value of a given sum of money if it were received, or disbursed, at a different time, the above formula may be used, or the corresponding PVF as given in Table 8.1, may be multiplied by the given sum. For instance, if the investor's opportunity earning potential is 8%, 1500 ECU to be received in 5 years from now would be equivalent to receiving now,

$$1.500 \times \frac{1}{(1+0,10)^8} = 1,020.9 \quad \text{ECU}$$

Cash flows occurring at different times can be converted to a common basis,

Table 8.1

Values of PVF for various time periods n and opportunity cost r

	single payment				uniform series of payments			
n	6%	8%	10%	12%	6%	8%	10%	12%
1	0.9434	0.9259	0.9091	0.8929	0.9434	0.9259	0.9091	0.8929
2	0.8900	0.8573	0.8264	0.7972	1.8334	1.7833	1.7355	1.6901
3	0.8396	0.7938	0.7513	0.7118	2.6730	2.5771	2.4869	2.4018
4	0.7921	0.7350	0.6830	0.6355	3.4651	3.3121	3.1699	3.0373
5	0.7473	0.6806	0.6209	0.5674	4.2124	3.9927	3.7908	3.6048
6	0.7050	0.6302	0.5645	0.5066	4.9173	4.6229	4.3553	4.1114
7	0.6651	0.5835	0.5132	0.4523	5.5824	5.2064	4.8684	4.5638
8	0.6274	0.5403	0.4665	0.4039	6.2098	5.7466	5.3349	4.9676
9	0.5919	0.5002	0.4241	0.3606	6.8017	6.2469	5.7590	5.3282
10	0.5584	0.4632	0.3855	0.3220	7.3601	6.7101	6.1446	5.6502
11	0.5268	0.4289	0.3505	0.2875	7.8869	7.1390	6.4951	5.9377
12	0.4970	0.3971	0.3186	0.2567	8.3838	7.5361	6.8137	6.1944
13	0.4688	0.3677	0.2897	0.2292	8.8527	7.9038	7.1034	6.4235
14	0.4423	0.3405	0.2633	0.2046	9.2950	8.2442	7.3667	6.6282
15	0.4173	0.3152	0.2394	0.1827	9.7122	8.5595	7.6061	6.8109
16	0.3936	0.2919	0.2176	0.1631	10.1059	8.8514	7.8237	6.9740
17	0.3714	0.2703	0.1978	0.1456	10.4773	9.1216	8.0216	7.1196
18	0.3503	0.2502	0.1799	0.1300	10.8276	9.3719	8.2014	7.2497
19	0.3305	0.2317	0.1635	0.1161	11.1581	9.6036	8.3649	7.3658
20	0.3118	0.2145	0.1486	0.1037	11.4699	9.8181	8.5136	7.4694
21	0.2942	0.1987	0.1351	0.0926	11.7641	10.0168	8.6487	7.5620
22	0.2775	0.1839	0.1228	0.0826	12.0416	10.2007	8.7715	7.6446
23	0.2618	0.1703	0.1117	0.0738	12.3034	10.3711	8.8832	7.7184
24	0.2470	0.1577	0.1015	0.0659	12.5504	10.5288	8.9847	7.7843
25	0.2330	0.1460	0.0923	0.0588	12.7834	10.6748	9.0770	7.8431
26	0.2198	0.1352	0.0839	0.0525	13.0032	10.8100	9.1609	7.8957
27	0.2074	0.1252	0.0763	0.0469	13.2105	10.9352	9.2372	7.9426
28	0.1956	0.1159	0.0693	0.0419	13.4062	11.0511	9.3066	7.9844
29	0.1846	0.1073	0.0630	0.0374	13.5907	11.1584	9.3696	8.0218
30	0.1741	0.0994	0.0573	0.0334	13.7648	11.2578	9.4269	8.0552
31	0.1643	0.0920	0.0521	0.0298	13.9291	11.3498	9.4790	8.0850
32	0.1550	0.0852	0.0474	0.0266	14.0840	11.4350	9.5264	8.1116
33	0.1462	0.0789	0.0431	0.0238	14.2302	11.5139	9.5694	8.1354
34	0.1379	0.0730	0.0391	0.0212	14.3681	11.5869	9.6086	8.1566
35	0.1301	0.0676	0.0356	0.0189	14.4982	11.6546	9.6442	8.1755
36	0.1227	0.0626	0.0323	0.0169	14.6210	11.7172	9.6765	8.1924
37	0.1158	0.0580	0.0294	0.0151	14.7368	11.7752	9.7059	8.2075
38	0.1092	0.0537	0.0267	0.0135	14.8460	11.8289	9.7327	8.2210
39	0.1031	0.0497	0.0243	0.0120	14.9491	11.8786	9.7570	8.2330
40	0.0972	0.0460	0.0221	0.0107	15.0463	11.9246	9.7791	8.2438

using the discount method, either using the formulae, available on an electronic spreadsheet, or the Table 8.1. In this table the discount factors are calculated from the discount formulas for various time periods and opportunity costs (expressed as rate of discount r). The time periods can be years, quarters, months etc. and the periodic discount rate will be the corresponding to the period (if r is the annual discount rate, r/4 will be the discount rate corresponding to a quarter and 1/12r the corresponding rate for one month)

Although the PVF could be used to solve any present value problem that would arise it is convenient to define a second term in order to speed the arithmetic process: the present value of an annuity. An annuity is a series of equal amounts of money over a certain period of time. The present value of an annuity over n years, with an annual payment C, beginning at the end of the first year, will be the result of multiplying C by a factor a_n, equal to the present value factors:

$$a_n = v^1 + v^2 + v^3 + \ldots + v^n$$

Is easily demonstrated that

$$a_n = \frac{1-v^n}{r} = \frac{(1+r)^n - 1}{r(1+r)^n} = \frac{1-(1+r)^{-n}}{r} \tag{8.2}$$

For instance, the present value of a series of 200 ECU payments over three years, beginning at the end of the first year, will be given by the product of 200 ECU and the value a_n in equation (8.2) or by the PWF in Table 8.2

$$a_3 = \frac{1-(1+0.08)^{-3}}{0.08} = 2.577; \text{then } 200 \times a_3 = 515.42 \text{ ECU}$$

8.3 Methods of economic evaluation

When comparing the investments of different projects the easiest method is to compare the ratio of the total investment to the power installed or the ratio of the total investment to the annual energy produced for each project. Nevertheless this criterion does not determine the profitability of the schemes because the revenues are not taken into account, but constitutes a first evaluation criterion. In the last few years, for example, to be eligible for a grant in the THERMIE program, this ratio could not exceed 2 350 ECU/kW.

8.3.1 Static methods (which do not take the opportunity cost into consideration)

8.3.1.1 Pay-back method

The payback method determines the number of years required for the invested capital to be offset by resulting benefits. The required number of years is termed the payback, recovery, or break-even period.

The measure is usually calculated on a before-tax basis and without discounting, i.e., neglecting the opportunity cost of capital (the opportunity cost of capital is the return which could be earned by using resources for the next available investment purpose rather than for the purpose at hand). Investment costs are usually defined as first costs (civil works, electrical and hydro mechanical equipment) and benefits are the resulting net yearly revenues expected from selling the electricity produced, after deducting the operation and maintenance costs, at constant value money. The pay-back ratio should not exceed 7 years if the small hydro project is to be considered profitable.

However the payback does not allow the selection from different technical solutions for the same installation or choosing among several projects which may be developed by the same promoter. In fact it does not give consideration to cash flows beyond the payback period, and thus does not measure the efficiency of the investment over its entire life.

8.3.1.2 Return on investment method

The return on investment (ROI) calculates average annual benefits, net of yearly costs, such as depreciation, as a percentage of the original book value of the investment.

The calculation is as follows:
ROI = (Average annual net benefits/Original book value) x 100

8.3.2 Dynamic methods

These methods of financial analysis take into account total costs and benefits over the life of the investment and the timing of cashflows

8.3.2.1 Net Present Value(NPV) method

The difference between revenues and expenses, both discounted at a fixed, periodic interest rate, is the net present value (NPV) of the investment.

The formula for calculating net present value, assuming that the cash flows occur at equal time intervals and that the first cash flows occur at the end of the first period, and subsequent cash flow occurs at the ends of subsequent periods, is as follows:

$$\text{VAN} = \sum_{i=1}^{i=n} \frac{R_i - (I_i + O_i + M_i)}{(1+r)^i} + V_r \tag{8.3}$$

where I_i = investment in period i
R_i = revenues in period i
O_i = operating costs in period i
M_i = maintenance and repair costs in period i
V_r = residual value of the investment over its lifetime, whenever the lifetime of the equipment is greater than the assumed working life of the plant (usually due to the expiration of the legal permits).
r = periodic discount rate(if the period is a quarter, the periodic rate will be 1/4 of the annual rate)
n = number of lifetime periods (years, quarters, months)

The calculation is usually done for a period of thirty years, because due to the discounting techniques used in this method, both revenues and expenses become negligible after a larger number of years.

Different projects may be classified in order of decreasing NPV. Projects where NPV is negative will be rejected, since that means their discounted benefits during the lifetime of the project are insufficient to cover the initial costs. Among projects with positive NPV, the best ones will be those with greater NPV.

The NPV results are quite sensitive to the discount rate, and failure to select the appropriate rate may alter or even reverse the efficiency ranking of projects. Since changing the discount rate can change the outcome of the evaluation, the rate used should be considered carefully For a private promoter the discount rate will be such that will allow him to choose between investing on a small hydro project or keep his saving in the bank. This discount rate, depending on the inflation rate, usually varies between 5% and 12%.

If the net revenues are constant in time (uniform series) their discounted value is given by the equation (8.2).

The method does not distinguish between a project with high investment costs promising a certain profit, from another that produces the same profit but needs a lower investment, as both have the same NPV. Hence a project requiring one million ECU in present value and promises one million one hundred thousand ECU profit shows the same NPV as another one with a one hundred thousand ECU investment and promises two hundred thousand ECU profit (both in present value). Both projects will show a one hundred thousand ECU NPV, but the first one requires an investment ten times higher than the second does.

8.3.2.2 Benefit-Cost ratio

The benefit-cost method compares the present value of the plant benefits and investment on a ratio basis. Projects with a ratio of less than 1 are generally discarded. Mathematically the $R_{b/c}$ is as follows:

$$R_{b/c} = \frac{\sum_{0}^{n} \frac{R_i}{(1+r)^i}}{\sum_{0}^{n} \frac{(I_i + M_i + O_i)}{(1+r)^i}} \qquad (8.4)$$

where the parameters have the same meaning as in equation (8.3). Projects with a ratio lower than 1 are automatically rejected.

8.3.2.3 Internal Rate of Return method

The Internal Rate of Return (IRR) is the discount rate r, at which the present value of the periodic benefits (revenues less operating and maintenance costs) is equal to the present value of the initial investment. In other words, the method calculates the rate of return an investment is expected to yield.

The criterion for selection between different alternatives is normally to choose the investment with the highest rate of return.

A process of trial and error, whereby the net cash flow is computed for various discount rates until its value is reduced to zero, usually calculates the rate of the return. Electronic spreadsheets use a series of approximations to calculate the internal rate of return.

Under certain circumstances there may be either no rate-of-return solution or multiple solutions. An example of the type of investment that gives rise to multiple solutions is one characterized by a net benefit stream, which is first negative, then positive and finally negative again.

The following examples illustrate how to apply the above mentioned methods to a hypothetical small hydropower scheme.

8.3.3 Examples

Example 8.1

Small hydropower scheme with the following characteristics
Installed capacity: 4 929 kW
Estimated annual output 15 750 MWh
First year annual revenue 1 005 320 ECU
It is assumed that the price of the electricity will increase every year one point less than the inflation rate

The estimated cost of the project in ECU is as follows:

1. Feasibility study	6 100	
2. Project design and management	151 975	
3. Civil works	2 884 500	
4. Electromechanical equipment	2 686 930	
5. Installation	686 930	
Total	6 416 435	
Unforeseen expenses (3%)	192 493	
Total investment	6 608 928	**ECU**

The investment cost per installed kW would be
6 608 928 / 4 929 = 1 341 ECU/kW
Applying the D.R. Miller curves it will be 6,417,784/4929 = 1,302 ECU/kW close to the above estimation
The investment cost per annual MWh produced
6 608 928 / 15 750 = 420 ECU/MWh
The operation and maintenance cost is estimated at 4% of the total investment moght 6 608 928 x 0.04 = 264 357ECU
In the analysis it is assumed that the project will be developed in four years. The first year will be devoted to the feasibility study and to application for the authorisation. Hence at the end of first year both the entire feasibility study cost and half the cost of project design and management will be charged. At the end of second year the other half of the design and project management costs will be charged. At the end of the third year 60% of the civil works will be finished and

50% of the electromechanical equipment paid for. At the end of the fourth year the whole development is finished and paid. The scheme is commissioned at the end of the fourth year and becomes operative at the beginning of the fifth (year zero). The electricity revenues and the O&M costs are made effective at the end of each year. The electricity prices increases by one point less than the inflation rate. The water authorisation validity time has been fixed at 35 years, starting from the beginning of year –2. The discount rate is assumed to be 8% and the residual value nil. Table 8.2 shows the cash flows along the project lifetime.

Net Present Value (NPV)
Equation (8.3) can be written as follows:

$$\mathrm{NPV} = \sum_{i=4}^{i=36} \frac{R_i - (O_i + M_i)}{(1+r)^i} - \sum_{i=0}^{i=3} \frac{I_i}{(1+r)^i}$$

To compute the above equation it should be taken into account that R_i varies every year because of change in electricity price. Computing the equation manually or using the NPV value from an electronic spreadsheet, the next value is obtained

NPV = 444,802 ECU

Internal Rate of Return (IRR)
The IRR is computed using an iterative calculation process, using different discount rates to get the one that makes NPV = 0, or using the function IRR in an electronic spreadsheet.
NPV using r=8% NPV = 384 200
NPV using r=9% NPV = - 1 770
Following the iteration and computing NPV with r=8.8% NPV = 0
Consequently IRR = 8.8%

Ratio Profit/cost
The net present value at year –4 of the electricity revenues is 7 685 029 ECU
The net present value at year –4 of the expenses (Investment, plus O&M costs) is

5 083 492 + 2 237 268 = 7 300 780
R b/c = 7 685 029 / 7 300 780 = 1.053

Varying the assumptions can be used to check the sensitivity of the parameters. Tables 8.3 and 8.4 illustrate respectively the NPV and IRR, corresponding to example 8.1, for several life times and several discount rates.

Table 8.3
NPV against discount rate and lifetime

r/years	6%	8%	10%	12%
25	986 410	(11 228)	(691 318)	(1 153 955)
30	1 415 131	234 281	(549 188)	(1 070 804)
35	1 702 685	384 270	(419 961)	(1 028 244)

Table 8.2

Investment cost [ECU] 6.608.928
Annual O&M expenses [ECU] 264.357
Disount rate [%] 8%
Lifetime [years] 35

Year	Investment	Revenues	O&M	Cash Flow	Cumulated Cash Flow
-4	82.087	0	0	-82.087	-82.087
-3	75.988	0	0	-75.988	-158.075
-2	3.074.165	0	0	-3.074.165	-3.232.240
-1	3.376.688	0	0	-3.376.688	-6.608.928
0	0	1.005.320	264.357	740.963	-5.867.965
1	0	995.267	264.357	730.910	-5.137.055
2	0	985.314	264.357	720.957	-4.416.098
3	0	975.461	264.357	711.104	-3.704.994
4	0	965.706	264.357	701.349	-3.003.645
5	0	956.049	264.357	691.692	-2.311.953
6	0	946.489	264.357	682.132	-1.629.821
7	0	937.024	264.357	672.667	-957.154
8	0	927.654	264.357	663.297	-293.857
9	0	918.377	264.357	654.020	360.163
10	0	909.193	264.357	644.836	1.004.999
11	0	900.101	264.357	635.744	1.640.743
12	0	891.100	264.357	626.743	2.267.486
13	0	882.189	264.357	617.832	2.885.318
14	0	873.367	264.357	609.010	3.494.328
15	0	864.633	264.357	600.276	4.094.604
16	0	855.987	264.357	591.630	4.686.234
17	0	847.427	264.357	583.070	5.269.304
18	0	838.953	264.357	574.596	5.843.900
19	0	830.563	264.357	566.206	6.410.106
20	0	822.257	264.357	557.900	6.968.006
21	0	814.034	264.357	549.677	7.517.683
22	0	805.894	264.357	541.537	8.059.220
23	0	797.835	264.357	533.478	8.592.698
24	0	789.857	264.357	525.500	9.118.198
25	0	781.958	264.357	517.601	9.635.799
26	0	774.138	264.357	509.781	10.145.580
27	0	766.397	264.357	502.040	10.647.620
28	0	758.733	264.357	494.376	11.141.996
29	0	751.146	264.357	486.789	11.628.785
30	0	743.635	264.357	479.278	12.108.063
31	0	736.199	264.357	471.842	12.579.905
32	0	728.837	264.357	464.480	13.044.385

Table 8.4
R b/c against discount rate and lifetime

r/years	6%	8%	10%	12%
25	1.13	1.00	0.89	0.80
30	1.17	1.03	0.92	0.82
35	1.20	1.05	0.93	0.83

The financial results are very dependent on the price paid for the electricity. Table 8.5 gives the values NPV and R b/c for tariffs 35% and 25% lower and 15% and 25% higher than the assumed in example 8.1.

Table 8.5
NPV and R b/c for different electricity prices
(with r= 8% and lifetime = 35 years)

	65%	75%	100%	115%	125%
NPV	(2 305 495)	(1 536 988)	324 270	1 537 024	2 305 527
R b/c	0.684	0.780	1.053	1.211	1.314

Example 8.2
Show the annual cash flows if the investment is externally financed with the following assumptions:

- 8% discount rate
- development time 4 years
- payments and expenses at the end of the year
- 70% of the investment financed by the bank with two years grace
- finance period 12 year
- bank interest rate 10%
- project lifetime 35 years

The disbursements are identical as in example 8,1. The bank in the first two years collects only the interest on the unpaid debt.

It must be remarked that the example refers to a hypothetical scheme, although costs and revenues are reasonable in southern Europe. The objective is to illustrate a practical case to be followed and later on applied to another scheme with different costs and revenues.

8.4 Financial analysis of some European schemes

In table 8.7 several European schemes has been analysed. It must be remarked that both investment costs and buy-back tariffs correspond to reality in the year 1991, and probably will not reflect the situation as it is nowadays. You can see that ratios of investment per kW installed, or by annual MWh, produced differ considerably from scheme to scheme. Actually civil works and electromechanical

Table 8.6

Investment cost (ECU)	6,608,928		Bank loan		(4,515,597)
O&M costs (ECU)	264,357		Loan term (years)		12
Discount rate (%)	8%		Interest on loan		10.0%
Lifetime (years)	35				

Year	Total Investmen	Bank loan	investor's investment	Principal repayment	Principal residual	Interest on loan	Revenues	O & M	Investor cash-flow	accumulated cash-flow
-4	(82,087)								(82,087)	(82,087)
-3	(75,988)								(75,988)	(158,075)
-2	(3,074,165)	(2,151,916)	(922,250)	0	(2,151,916)				(922,250)	(1,080,325)
-1	(3,376,688)	(2,363,682)	(1,013,006)	0	(4,515,597)	(215,192)			(1,013,006)	(2,093,331)
0				0	(4,515,597)	(451,560)	1,005,320	(264,357)	289,403	(1,803,928)
1				(135,023)	(4,380,574)	(451,560)	995,267	(264,357)	144,327	(1,659,601)
2				(296,835)	(4,083,739)	(438,057)	985,214	(264,357)	(14,036)	(1,673,637)
3				(326,519)	(3,757,220)	(408,374)	975,160	(264,357)	(24,089)	(1,697,726)
4				(359,171)	(3,398,050)	(375,722)	965,107	(264,357)	(34,143)	(1,731,869)
5				(395,088)	(3,002,962)	(339,805)	955,054	(264,357)	(44,196)	(1,776,064)
6				(434,596)	(2,568,366)	(300,296)	945,001	(264,357)	(54,249)	(1,830,313)
7				(478,056)	(2,090,310)	(256,837)	934,948	(264,357)	(64,302)	(1,894,615)
8				(525,862)	(1,564,448)	(209,031)	924,894	(264,357)	(74,355)	(1,968,971)
9				(578,448)	(986,000)	(156,445)	914,841	(264,357)	(84,409)	(2,053,379)
10				(636,293)	(349,708)	(98,600)	904,788	(264,357)	(94,462)	(2,147,841)
11				(349,708)	0	(34,971)	894,735	(264,357)	245,699	(1,902,142)
12							884,682	(264,357)	620,324	(1,281,817)
13							874,628	(264,357)	610,271	(671,546)
14							864,575	(264,357)	600,218	(71,328)
15							854,522	(264,357)	590,165	518,837
16							844,469	(264,357)	580,112	1,098,949
17							834,416	(264,357)	570,058	1,669,007
18							824,362	(264,357)	560,005	2,229,012
19							814,309	(264,357)	549,952	2,778,964
20							804,256	(264,357)	539,899	3,318,863
21							794,203	(264,357)	529,846	3,848,709
22							784,150	(264,357)	519,792	4,368,502
23							774,096	(264,357)	509,739	4,878,241
24							764,043	(264,357)	499,686	5,377,927
25							753,990	(264,357)	489,633	5,867,560
26							743,937	(264,357)	479,580	6,347,139
27							733,884	(264,357)	469,526	6,816,666
28							723,830	(264,357)	459,473	7,276,139
29							713,777	(264,357)	449,420	7,725,559
30							703,724	(264,357)	439,367	8,164,926
31							693,671	(264,357)	429,314	8,594,240
32							683,618	(264,357)	419,260	9,013,500

equipment costs varies from country to country. Environmental requirements – affecting investment costs- - differ not only from country to country but also region to region. Buy-back electricity tariffs can be five times higher in one country than in another.

The figures have been computed in a Quattro electronic spreadsheet for a discount rate of 8% and a lifetime of 30 years. The enclosed table is a copy of the spreadsheet results.

Table 8.7

Country		Germany	France	Ireland	Portugal	Spain
Rated discharge	m3/s	0.3	0.6	15	2	104
Gross head	m	47	400	3.5	117	5
Type of turbine		Francis	Pelton	Kaplan	Francis	Kaplan
Installed capacity	kW	110	1.900	430	1.630	5.000
Investment cost	ECU	486.500	1.297.400	541.400	1.148.000	5.578.928
Working hours	h	8.209	4.105	8.400	4.012	3.150
Annual production	MWh	903	7.800	3.612	6.540	15.750
Average price MWh	ECU	76,13	53,65	23,23	53,54	63,82
Annual revenues	ECU	68.732	418.443	83.907	350.128	1.005.320
O&M expenses	ECU	19,850	51,984	25,176	22,960	157.751
Gross profit	ECU	48,882	366,459	58,731	327,168	847.569
(O&M exp/investment)l	%	4,08%	4,01%	4,65%	2,00%	3,00%
Economic Analysis						
Capital cost per kW installed	ECU	4,424	683	1,259	704	1.132
Capital cost per MWh	ECU	538.86	166.34	149.89	175.55	354,2
Simple payback period	años	9.95	3.54	9.22	3.51	6,61
IRR	%	9.36	14.25	10.25	28.31	13,17
Rb/c		1.10	2.52	1.15	2.83	1,40
NPV	ECU	61,941	2,559,546	112,867	2,294,295	2.456.232

Bibliography

1. IDAE. Manual de Minicentrales Hidroeléctricas. Edición Especial CINCO DIAD. 1997

2. J. Fonkenelle. Comment sélectioner une turbine pour basse chute. Proceedings HIDROENERGIA 91 , AGENCE FRANCAISE POUR LA MAITRISE DE L'ENERGIE.

3. DNAEE "APROVEITAMENTOS HIDRELETRICOS DE PEQUENO PORTE" Volumen V "Avaliaçao de Custos e Benificios de Pequenas Centrais Hidrelétricas" Modelo FLASH, Brasília 1987

4. P. Fraenkel et al "Hydrosoft: A software tool for the evaluation of low-head hydropower esources". HIDROENERGIA97 Conference Proceedings, page 380

9. Administrative procedures

9.0 Introduction

Exploitation of small-scale hydro power plants is the subject of government regulations and administrative procedures, which, for the time being, vary from Member State to Member State.

The regulations actually in force in most member states, include economic, technical and procedural issues. The economic issues mainly refer to who can generate electricity; the maximum installed power to be considered "small" and the conditions for the sale of electricity, including purchasing prices and possible subsidies. The technical issues mainly relate to specifications for connection to the grid. The procedural issues concern water-use licensing, planning permission, construction authorisation and commissioning of the plant.

The authorisation procedures, although somewhat arbitrary, have been until now, well defined. Nowadays the approaching deregulation of the energy market is making the situation more fluid, especially in the aspects related to buy-back prices which it is impossible to describe accurately. Readers interested in the subject, as it was in 1997 should read the 1994 EUR report "Small Hydropower General Framework for Legislation and Authorisation Procedures in the European Union" presented by ESHA under contract No.: 4.1030/E/93.07.

9.1 Economic issues

In most Member States, electricity generation and distribution has been up to now, and in some countries still is, a monopoly of the state-owned utility or of the well-established private utilities. Nevertheless electricity generation by independent producers is also permitted although in some of them the electricity generated must be consumed at the generator's own facilities, any generation surplus being delivered to the grid . In most member states, private generators can deliver to the grid all the generated electricity but they cannot sell it to third parties. Prices for the electricity delivered to the grid vary from country to country, thus making the investment worthwhile in some of them but not in others.

In France the Law 46-628 (8.4.1946) nationalised the electricity industry. Only companies that generated less than 12 gigawatts in 1942 and 1943 were excluded from nationalisation. Nevertheless the amendment of 2.8.1949 (Loi Armengoud) permitted any individual or corporation to generate electricity in plants with a power capacity up to 8000 kVA. The decree 55-662 (20.5.1955) compels EDF to buy electricity produced by private generators, and the decree 56-125 (28.11.1956) fixed the sale and purchase terms and tariffs to be applied; tariffs that evolve in parallel with the E.D.F. tariffs. The private generator can choose between several types of tariffs that take into account different kinds of hourly and seasonal discrimination. Almost all independent producers choose the simplified tariff, with two prices for the kWh: one for the winter season (Nov/March) and another for the summer season (April/Oct), independently of the time of the day the energy is delivered. The Federation of Independent Producers (EAF) negotiated this tariff with EDF, valid for a period of ten years, and applicable to independent producers with hydro plants up to a capacity of 4.500 kW.

In Greece the generation transmission and distribution of electricity constitutes a monopoly of the state utility Public Power Corporation (PPC) established by the Law 1468/50. Nevertheless the Law 1559/1985 permits any individual or corporate body to generate electricity for their own use, in hydroelectric schemes up to 5000 kVA, after approval by PPC. The plant can be connected to the grid to deliver surplus electricity, provided the generated power does not exceed twice the consumption of the generator himself. For that, a contract between P.P.C. and the autoproducer is needed, according to the Ministerial Decree 2769/1988. The Ministerial Decree 2752/1988 established the prices at which P.P.C. purchases electrical energy from the auto-producers

In Italy the Laws no.9/1991, 10/1991 and 308/1992 empower any person, corporate body or local community to generate electricity with renewable resources, in plants with a maximum apparent power of 3.000 kVA. ENEL, the state electrical utility, has to buy the electricity generated by such independent producers and the Provedimento CIP 15/1989, modified in August 1990 and finally revised in September 1992 (CIP 6/92), determines the price to be paid for it. At the time of writting (1998) ENEL is being privatised, and so the past tariffs may not be maintained.

In Portugal according to the Decree 189/88 of 27.05.1988, any person or corporate body, public or private, can generate electricity, provided it employs renewable resources, national fuels, urban or agricultural waste, complies with the technical and safety regulations in force and the apparent power of the scheme does not surpass 10.000 kVA. Local communities can invest in the capital of the above mentioned corporate bodies. Compulsory purchase benefits are granted to private generators. The state utility, EDP, is required by law to buy the electricity produced in the above mentioned circumstances. The situation here is similar to that of Italy because EDP is also likely to be privatised

In Spain the Law 82/1980, Art.7, acknowledges the autoproducer, a person or corporate body that produce electricity to meet a part or the whole of its own needs. The RD 907/1982 develops the Article specifying that, to be considered as auto-producers, they must employ renewable resources, urban or agricultural wastes, or conventional fuel in heat and power schemes. It is understood that his main activity is not the production and distribution of electricity. His installation can be isolated or connected to the grid for an additional supply or to dispose of surpluses. The Law also states that any person or corporate body can generate electricity in small hydroelectric plants with a maximum apparent power of 10.000 kVA, either to meet its needs or to supply to the grid. Buy-back tariffs are now (1998) being discussed as a part of the new Electricity Act.

In the UK the Electricity Act 1989 denationalised the electricity industry, and enabled the Secretary of State for Energy, by Orders, to regulate competition within the privatised industry, and between it and genuine independents. At the time of writing the situation is fluid and contradictory statements emerge quite frequently from the Department of Energy. Section 32 of the Act sets out to protect the public interest through continuity of supply by requiring that the public electricity suppliers (the distributors) contract for some capacity of non-fossil fuelled generation, of which some may be nuclear and some renewable (the non-fossil fuel obligation or NFFO). Section 33 enables the Secretary of State to levy money on sales of fossil-fuelled electricity (the NFFO or), of which some may be nuclear

and some renewable. Section 33 enables the Secretary of State to levy a tax on sales of fossil-fuelled electricity and to distribute the proceedsto cover the added cost of the non-fossil supplies over their cost had they been fossil-fuelled. To implement all that, a Non-Fossil Purchasing Agency (NFPA) has been set up. The NFFO does not apply in Scotland, which already has 50% of non-fossil generation (nuclear and hydro). However a Scottish Renewables Order, or SRO, is issued at (until1988) about 2 years intervals which operates similarly to the NFFO in England and Wales, though the contracted prices are 10-15% lower. As the major part of the small hydropower potential of the UK lies in Scotland, this price differential detracts from its full development.

The price situation is becoming particularly critical at a time when much progress has been achieved towards completion of the Internal Energy Market. Opening the markets for electricity will bring market forces into play in sectors which until recently were for the most part dominated by monopolies. This will provide a challenging new environment for renewable energies, providing more opportunities but also posing the challenge of a very cost-competitive environment. Suitable accompanying measures are needed in order to foster the development of renewables

According to the «White Paper for a Community Strategy and Action Plan on RENEWABLE SOURCES OF ENERGY**»,** COM (97) 599 final (26/11/97): "A comprehensive strategy for renewables has become essential for a number of reasons. First and foremost, without a coherent and transparent strategy and an ambitious overall objective for renewables penetration, these sources of energy will not make major inroads into the Community energy balance. Technological progress by itself can not break down several nontechnical barriers, which hamper the penetration of renewable energy technologies in the energy markets. At present, prices for most classical fuels are relatively stable at historically low levels and thus in themselves militate against recourse to renewables. This situation clearly calls for policy measures to redress the balance in support of the fundamental environmental and security responsibilities referred to above. Without a clear and comprehensive strategy accompanied by legislative measures, their development will be retarded."

The above statement calls for a new Directive dealing with the relations between producers and the Distribution utilities. A greater use of structural funds to support renewables as suggested by the European Parliament would help to develop this market.

"The Member States have a key role to play in taking the responsibility to promote Renewables, through national action plans, to introduce the measures necessary to promote a significant increase in renewables penetration, and to implement this strategy and Action Plan in order to achieve the national and European objectives.

It is the case that certain countries – e.g. Portugal and Spain- had already made a legislative effort to cope with the situation, and others are sure to follow, either by themselves or under pressure of the Commission. The White Paper states that legislative action will be taken at EU level when measures at national level are insufficient or inappropriate and when harmonisation is required across the EU.

9.3 How to support renewable energy under deregulation*

We are moving away from a monopoly on generation toward a competitive market in which customers will have the opportunity to choose among power suppliers. We are moving away from complex regulatory schemes toward greater reliance upon market mechanisms. But as we restructure the electric industry, it will be the essential role of Governments to establish new «market rules» that will guide competition. One essential element of the new market rules is to ensure that those rules drive the restructured market toward cleaner resources that are compatible with the public interest. Fossil fuels are causing enormous damage to the environment, including smog, acid rain, global climate change, and mercury poisoning in lakes. Climate scientists overwhelmingly agree that greenhouse gases are causing the climate to change and believe that serious damage to the earth's environment will result, with enormous consequences for humanity. Renewable energy technologies provide critical environmental benefits; and use indigenous resources that reduce our dependence upon imported fuels.

Governmental options to support renewables fall into four categories. The first category involves a requirement that a certain percentage of generation be renewable, through set asides, portfolio standards, or simple mandates. The second approach focus on setting limits to emissions of fossil fuel generators. The third category contains a variety of approaches, such as green marketing and education. The fourth approach is to set a price (from 80% to 90%) of the average electricity price (total invoices divided by number of kWh invoiced), to be paid by the distributors to the independent producers generating electricity with renewable resources.

Some of the above approaches would require financial aid from the State. How to get the money for that purpose? Clean air is a benefit shared by all, therefore all customers should share the cost. Under most proposed industry structures, the "wires company" would continue to be a regulated monopoly. Since all buyers and sellers would have to use the "wires company", this is the only place that no electricity company can short-circuit. This fund could also finance RD&D, as well as renewable generation projects that are above market prices.

9.5.1 Set asides

A set-aside is a requirement that a portion of new generation capacity be from renewable sources. Currently five USA states and the United Kingdom have set-asides for clean energy, commonly in the form of a requirement on regulated utilities. There have been a number of ways proposed to continue mandated investment in renewables in a competitive market

*Note of the author**: Most of the comments under this section have been obtained through the Electric Library in Internet and in a good part have been inspired on a paper by B. Paulos and C. Dyson "*Policy Options For the Support of Renewable Energy In a Restructured Electricity Industry*"**

9.2.1.1 NFFO (Non Fossil Fuel Obligation)

The UK Government provides support principally through the Non Fossil Fuel Obligation (known as the NFFO) in England and Wales, the Scottish Renewables Obligation (SRO) in Scotland and the Northern Ireland NFFO. The NFFO requires Recs. to purchase specified amounts of electricity from renewable sources. Projects proposed must represent new capacity and must operate on renewable energy. The NFFO is structured to include a *number of technology bands* to enable a variety of technologies to contribute to the obligation. The current bands are landfill gas, hydro, wind, municipal and industrial waste, energy crops, combined heat and power schemes and agricultural and forestry waste.

Support for NFFO and SRO is funded through the Fossil Fuel Levy on electricity sales. This levy, following the flotation of British Energy in July 1996, was reduced to 3.7% for the period November 1996 to 31 March 1997 and to 2.2% from 1 April 1997. In Scotland, the fossil fuel levy to cover renewables obligations rose from 0.5% to 0.7% from 1 April 1997. Financed through this Fossil Fuel Levy, renewable electricity producers get the difference between the NFFO contract price and the electricity pool price

To date, there have been four NFFO orders. The first NFFO-1 order was made in September 1990 for 75 contracts and 152 MW capacity. NFFO-2 was made in October 1991 for 122 contracts and 472 MW capacity. NFFO-3 was made in December 1994 for 141 contracts and 627 MW capacity and NFFO-4 was made in February 1997 for 195 contracts and 843 MW capacity. Proposals for a fifth NFFO order will be made in late 1998. Scottish Office expects to make an announcement in respect of proposals for a third Scottish Renewables Order, SRO-3, shortly.

9.2.1.2 Renewable Portfolio Standard (RPS)

In USA, the most popular way to continue mandated investment in renewables in a competitive market is the "Renewable Portfolio Standard (RPS)", as proposed by the American Wind Energy Association (AWEA) and adopted by the California PUC. The portfolio standard requires retail sellers (or distribution companies) to buy a set amount of renewably generated electricity from wholesale power suppliers. Current proposals set the percentage at the present level of renewable energy production; roughly 21 percent in California.

The requirements would be tradable so those power suppliers who chose not to invest in renewable generators themselves could buy credits from those who did. If a retail seller had sales of 1,000,000-kilowatt hours in one year, they would be required to have generated or purchased 210,000 kilowatt hours using renewable resources to meet the Renewable Portfolio Standard. If they did not meet this requirement, they could purchase credits from a California local distribution utility or other retail seller that had more than 21% of their sales from renewable resources. Credit transactions would not actually result in kilowatt-hours delivered to the retail seller needing the credits. Credit trades would result in a monetary exchange for the right to use the credits.

In this pure form, the portfolio standard would promote only the lowest cost renewables. There is currently pending in the California legislature a bill that would require power suppliers to purchase a minimum amount of electricity from biomass generators. In fact to support technologies that are less competitive, awards could be given to separate bands, like biomass, wind, solar and waste-to-energy, as in the UK's Non Fossil Fuel Obligation.

9.2.2 Emission Taxes, Caps and Credits

Emissions taxes, caps, and credits are all policies, which can promote renewable energy use. Renewable energy sources produce few or no emissions of sulphur dioxide (SO2), carbon dioxide (CO2), oxides of nitrogen, and other air pollutants. Policies, which increase the cost of such emissions, internalise the social costs of pollution, making renewable energy sources more competitive. Under a restructured utility industry, emission-based policies can be a market approach to promoting renewables.

Of this group of emission policies, taxes have been used the least. Emission taxes can be assessed a number of ways. If reasonable estimates of the costs of the emissions to society are available, as they are for SO2, then this is the most equitable method. However, for many emissions, such as CO2, reliable cost estimates are not available. In these cases it may be necessary to base the taxes on the costs of pollution control or some arbitrary amount. The design is intended to make the tax changes revenue neutral, shifting $1.5 billion in state taxes from "goods" like income and property, to a tax on "bads."

Emission credits are permits that allow an electric generator to release an air pollutant. These credits can be traded with other polluters, providing an incentive for companies to reduce emissions below mandated levels. Currently a national market for tradable permits is only available for SO2 emissions. However, the EPA is considering expanding credit trading to NO2 and mercury emissions.

A positive feature of emission taxes and credits is their efficiency in allocating pollution costs. Electricity generators pay directly for the pollution they produce. Low or no emission renewable energy sources are thus able to compete on a more even playing field. Emission taxes also generate revenues that could be used to support renewable generation or renewable research and development

In USA, the recent introduction of commodity markets for emission credits should give utilities more options for managing the uncertainty of future credit prices The biggest problem with energy and emission taxes is that they are politically unpopular.

9.2.3 Green pricing.

Green pricing is an evolving utility service that responds to utility customers' preferences for electricity derived from renewable energy sources such as solar, wind, or biomass. Under green pricing, utilities offer customers a voluntary program or service to support electricity generated from renewable energy systems. Customers are asked to pay a rate premium, which is meant to cover the costs that the utility incurs above those paid today for electricity from conventional fuels. Surveys indicate that in USA and in Denmark many consumers are willing to pay a premium for green power. A 1995 survey conducted by seven USA utilities

found that 45 percent of respondents were willing to pay a surcharge of up to 4 percent for green power; 29 percent were willing to pay up to 9 percent; 18 percent were willing to pay up to 19 percent; and 10 percent were willing to pay up to a 29 percent surcharge

Knowledge of and experience with green-pricing programs is only just developing. These programs tend to fall into one of three categories: (1) a renewable energy contribution fund, which offers customers an opportunity to contribute to a fund to be used in the future to pay for as-yet-unspecified renewable electricity projects; (2) tailored renewable energy projects, in which customers pay a premium price for power generated from a specific renewable electric project; and (3) a renewable electric grid service, for which the utility may bundle power from a number of renewable projects with other power sources for sale to customers.

9.2.4 Imposed tariffs

Germany, and Spain support special tariffs for a certain number of technology bands. In Spain the buyback tariffs for those bands, varies from 80% to 90% of the average national electricity price and are paid by the distribution utilities. The Minister of Industry and Energy fix the bonus to be paid for the electricity generated with the technologies comprised in the different bands. The situation in Germany was very similar after the law issued in December 1996.

9.2.5. Miscellaneous

ESHA Vice President, David R. Miller, made a very interested proposal: the modulated tariff**.** Actually in the cost price or renewable electricity, the influence of the capital cost is decisive. According to the different studies – see chapter 8 – the investment cost per kWh generated decreases with the size of the plant. Figure 9.1 shows the trend in capital cost per kW installed. Consequently, to get a certain return on investment, the price to be paid for the electricity should be higher in smaller plants that in larger plants. In order to make things D. Miller proposes modulate the tariff in function of the amount of electricity delivered to the net.

Calculations indicate that High Head Installations with a 45% output requiring a 10% Real rate of Return over 10 years need price modules as follows:

1st Million Kwh	at 10.58	Ecu cents	yielding	10.58	Ecu cents
2nd Million	8.89	"	"	9.74	"
3rd Million	6.27	"	"	8.58	"
4th Million	5.56	"	"	7.83	"
5th & 6th	5.44	"	"	7.03	"
7–10 Million	5.30	"	"	6.34	"

Let us suppose that '90% of the average selling price' or 'city gate plus the tax' is equivalent to ca. 6.5 Ecu cents, we may then propose that this should be the base price for all Small Hydro Producers. But producers may opt to avail of a modulated tariff as follows:

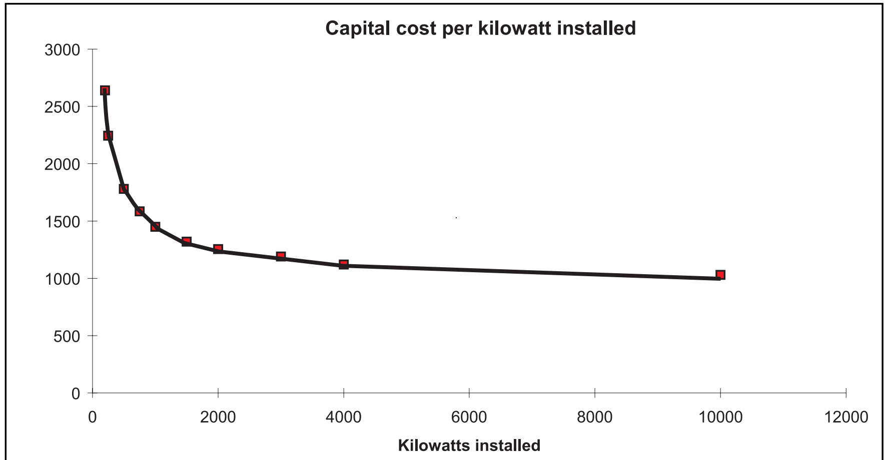


Figure 9.1

1st	Million Kwh at	10.58	yields	10.58	Ecu cents kWh
2nd	Million	8.89	"	9.73	"
3rd	Million	6.20	"	8.55	"
4th	Million	5.52	"	7.80	"
5th and 6th	Million	5.46	"	7.02	"
7-10	Million	5.26	"	6.32	"

9.3 Technical aspects

In all Member States the independent producer must meet a minimum of technical requirements to be connected to the grid, so that end users will not be affected by the service's quality.

In Belgium the technical specifications for the connection to the grid of independent power plants of less than 1 MW installed power are set out in the note C.G.E.E. 2735 of 10.2.1987.

In France the technical requirements for connection to the grid are regulated by EDF bylaws. The connection point will be fixed by E.D.F and in case of disagreement, by the DIGEC. The line between the powerhouse and the grid has to be built at the expense of the independent producer. The same happens in Italy, where ENEL states the technical conditions and the connection fees.

In Greece technical conditions for the connection of private generators to the grid are listed in the Ministerial Decree 2769/1988.

In Portugal the connection point will be chosen by agreement between the parties. In case of disagreement the Directorate General of Energy (DGE) will arbitrate the conflict within 30 days. The line between the powerhouse and the grid has to be built at the expense of the producer but then becomes part of the grid. The maximum nominal apparent total power of the plant will be 100 kVA, if it is connected to a low voltage line or 10.000 kVA if it is connected to a medium or high voltage line. Asynchronous generators when connected to a medium or high voltage line may not exceed 5000 kVA. The apparent power of the plant may not exceed the minimum short-circuit power at the connection point.

The technical requirements for the connection to the grid are specified in a document published by the Ministry of Industry and Energy "Guia Técnico das Instalações de produâo independente de energia eléctrica" (December 1989)

In Spain the OM 5.9.1985 stipulates the technical requirements for the connection to the grid of small hydroelectric plants. The distributor to which the private generator will be connected must indicate the connection point, the connection voltage, and the maximum and minimum short-circuit power. The connection point should be chosen to minimise the investment on the connection line. In case of disagreement the Directorate General of Energy (DGE) or the corresponding regional authority will arbitrate. Asynchronous generators can be connected to a low voltage line, whenever its maximum nominal apparent power does not exceed neither 100 kVA or 50% of the power of the transformer feeding the line. For plants connected to medium or high tension lines, the maximum total nominal apparent power of the generators should not exceed 5.000 kVA if they are asynchronous, or 10.000 kVA if they are synchronous. In both cases the apparent power cannot exceed 50% of the power of the transformer feeding the line.

In the United Kingdom the Electricity Council Regulation G59 specifies requirements for paralleling independent generators with the national distribution system. The main aim is safety, for both parties. Recent developments have enabled manufacturers to meet the requirements at an economic cost, certainly for generators who can supply the distribution system at 15 kW and above, both at single and three phase, 240/415 volts, 50 Hz.

In Scotland the new electricity Companies are in the course of producing their own requirements for grid connections but in the current economic climate there is no incentive to produce and publish these in the near future.

9.4 Procedural issues

The administrative procedures needed to develop a small hydropower site are complex and, in general, very lengthy. These procedures concern water-use licensing, planning permission, construction requirements and commissioning and operation of the plant.

Table 9.1, reproduced from a presentation by George Babalis to HIDROENERGIA 97, identifies the administrative procedures, still in force, in the E.U Member States, for authorisation to use water.

Table 9.1

Country	**Authority granting rights for water use**	**Validity time of the authorisación**
Austria	**< 200 kW local governments** > 200 kW country governments	**usual 30 years** possible more (60-90 years)
Belgium	< 1MW the provinces > 1MW same + Ministry of Energy	undetermined 33 a 99 años
Denmark	Ministry of Energy	undetermined
France	< 4,5 MW Prefecture > 4,5 MW State	in practice up to 40 years
Germany	Länders	30 years
Greece	Ministry of Energy	10 years, renewable
Ireland	Not needed. Riparian rights in force	perpetual
Italy	< 3MW regional authorities > 3MW Ministry of Industry	30 year
Luxemburg	Ministries of Agriculture,Public Works, Environm.& Employment + local authorities	undetermined
Netherlands	National & Local Water Boards	at mínimum 20 years
Portugal	DRARN (Regional Authority for Environ- ment & Natural Resources)	35 years renewable
Spain	Basin authority except in some rivers in Catalunya and Galicia	25 years + 15 of grace
Sweden	Water Court	perpetual (30 years)
U. K.	Environmental Agency In Scotland not required if P<1MW; if P>1 MW Secretary of State	England & Wales 15 years Scotland undetrmined

At present, a developer who decides to invest in the construction of a small hydropower scheme should be prepared for a three years hurdle-race with a high probability of getting a "no" at the end or no answer at all. If the European Commission wishes to achieve its ALTENER objectives, concrete actions aimed at removing the existing barriers to the development of SHP –relationships between utilities and independent producers, administrative procedures and financial constraints- should be undertaken.

In order to attain the ambitious ALTENER objectives in electricity generation through renewables, new schemes must be developed. These never will be possible unless an appropriate framework is set up. To eliminate the procedural barriers, administrations must give authorisation within a reasonable period (18

months), and by introducing the principle that the authorisation is granted, when no answer is given within the fixed period or, based on objective criteria it is denied..

9.5 Environmental constraints

In chapter 7 environmental burdens and impacts have been identified, and some mitigating measures have been advanced. It has been made clear that small hydropower, by not emitting noxious gases – greenhouse or acid rain gases- has great advantages from a global viewpoint. Notwithstanding that, the developer should implement the necessary mitigation measures so that the local environment is minimally affected. Small hydropower uses, but does not consume water, nor does it pollute it. It has been demonstrated, see chapter7, that provided the scheme is profitable enough it may be possible to substantially increase the investment to implement mitigating measures so that development is possible even in the most sensitive natural park. The French position barring the possibility of developing small hydropower schemes on a certain number of rivers, without previous dialogue, is unjustified.

From all the environmental aspect the most crucial and controversial one is the determination of the reserved flow. For the developer the fact of producing electricity without damaging the global atmosphere merits every kind of support without heavy curtailments in the generation capacity; for the environmental agencies a low reserved flow is equivalent to an attack to a public good which is the aquatic fauna. Only a dialogue between the parties based on the methodologies mentioned in chapter 7 can open the way to a mutual understanding.

GLOSSARY

Alternating current (AC): electric current that reverses its polarity periodically (in contrast to direct current). In Europe the standard cycle frequency is 50 Hz, in N. and S. America 60 Hz.

Anadromous fish: fish (e.g. salmon) which ascend rivers from the sea at certain seasons to spawn.

Average Daily Flow: the average daily quantity of water passing a specified gauging station.

Baseflow: that part of the discharge of a river contributed by groundwater flowing slowly through the soil and emerging into the river through the banks and bed.

BFI baseflow index: the proportion of run-off that baseflow contributes.

Butterfly Valve: a disc type water control valve, wholly enclosed in a circular pipe, that may be opened and closed by an external lever. Often operated by a hydraulic system.

Capacitor: a dielectric device which momentarily absorbs and stores electric energy.

Catchment Area: the whole of the land and water surface area contributing to the discharge at a particular point on a watercourse.

Cavitation: a hydraulic phenomenon whereby liquid gasifies at low pressure and the vapour bubbles form and collapse virtually instantaneously causing hydraulic shock to the containing structure. This can lead to severe physical damage in some cases.

Compensation flow: the minimum flow legally required to be released to the watercourse below an intake, dam or weir, to ensure adequate flow downstream for environmental, abstraction or fisheries purposes.

Demand (Electric): the instantaneous requirement for power on an electric system (kW or MW).

Demand Charge that portion of the charge for electric supply based upon the customer's demand characteristics.

Direct Current (DC): electricity that flows continuously in one direction sd contrasted with alternating current.

Draft tube: a tube full of water extending from below the turbine to below the minimum water tailrace level.

Energy: work, measured in Newton metres or Joules. The electrical energy term generally used is kilowatt-hours (kWh) and represents power (kilowatts) operating for some period of time (hours) 1 kWh = $3.6x10^3$ Joules.

Evapotranspiration: the combined effect of evaporation and transpiration.

FDC: flow duration curve:: a graph of discharges against v. the percentage of time (of the period of record) during which particular magnitudes of discharge were equalled or exceeded.

Fish Ladder: a structure consisting e.g. of a series of overflow weirs which are arranged in steps that rise about 30 cm in 3 50 4 m horizontally, and serve as a means for allowing migrant fish to travel upstream past a dam or weir.

Output: the amount of power (or energy, depending on definition) delivered by a piece of equipment, station or system.

(In) Parallel: the term used to signify that a generating unit is working in connection with the mains supply, and hence operating synchronously at the same frequency.

Overspeed: the speed of the runner when, under design conditions, all external loads are removed

P.E.: polyethylene

Peak Load: the electric load at the time of maximum demand.

Peaking Plant: a powerplant which generates principally during the maximum demand periods of an electrical supply network.

Penstock: a pipe (usually of steel, concrete or cast iron and occasionally plastic) that conveys water under pressure from the forebay to the turbine.

Percolation: the movement of water downwards through the soil particles to the phreatic surface (surface of saturation within the soil; also called the groundwater level).

Power: the capacity to perform work. Measured in joules/sec or watts (1MW = 1 j/s). Electrical power is measured in kW.

Power factor: the ratio of the amount of power, measured in kilowatts (kW) to the apparent power measured in kilovolt-amperes (kVA).

Rating curve: the correlation between stage and discharge.

Reynolds Number: a dimesionless parameter used in pipe friction calculations (interalia), and derived from pipe diameter, liquid velocity and kinematic viscosity.

Rip-rap: stone, broken rock or concrete block revetment materials placed randomly in layers as protection from erosion.

Runoff: the rainfall which actually does enter the stream as either surface or subsurface flow.

Run-of-river scheme: plants where water is used at a rate no greater than that with which it “runs” down the river.

SOIL: a parameter of permeability

Stage(of a river): the elevation of water surface

Supercritical flow: rapid flow who is unaffected by conditions downstream

Synchronous speed: the rotational speed of the generator such that the frequency of the alternating current is precisely the same as that of the system being supplied.

Tailrace: the discharge channel from a turbine before joining the main river channel.