The University of Salford
Department of Civil Engineering

Assessment and Design of Small-Scale Hydro-Electric Power Plants

A thesis
presented for the Degree of
Doctor of Philosophy

by
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Assessment and design of small-scale hydro-electric power plants.

Abstract

Appraisal and design of small-scale hydro power plants requires a knowledge of hydraulics, hydrology, civil, mechanical, and electrical engineering, and basic economics. Further, small hydro is site specific in nature and marginal from an economic view point. Methods of appraisal and design are required therefore that will keep engineering fees to a minimum and yet still achieve a reliable evaluation of scheme potential and economics.

In this context it should be appreciated that small hydro is not large hydro scaled down, and that small hydro needs its own experts (Ref. 1).

This thesis considers techniques for appraisal of small hydropower schemes, the selection and specification of scheme components, their costing and economic evaluation. These appraisal techniques are subsequently applied to regional assessment of small-scale hydro-electric potential in the U.K, and to the development and application of a new type of ultra low-head hydropower generator called the Salford Transverse Oscillator (STO).

Although this work is predominately concerned with assessment of scheme potential in the U.K., it also draws on experience gained by the writer during short visits to India and Nepal, and during a six month design appraisal for rehabilitation of mini-hydro schemes in Sri Lanka (Ref. 2).

Assessment of small-scale hydro-electric power plants

CHAPTER 1

1.0 Introduction

1.1 A Brief History

Waterpower has been a source of energy for many centuries. Early developments utilized water wheels to drive mill stones and water pumps, and later, factory machinery. The advent of the water turbine made generation of electricity possible, and there were many small-scale isolated schemes built until comparatively recently. However, due to changing circumstances, a large proportion of these developments became redundant, because either the output they produced was small compared to present demands, or more importantly because the widespread distribution of mains electricity with cheap reliable power made private generation unprofitable.

Hydro-electric generating capacity is now generally concentrated in large, high-head power-stations supplying their output to the national electricity grid.

1.2 Renewed Interest

Increasing fossil fuel prices have prompted many developed countries, including the U.K. (Ref. 2), to review the prospects for small-scale hydro-electric power generation. Further, undeveloped Third World countries see small hydro as a means of meeting often-chronic energy shortages whilst reducing imported fuel costs.

1.3 Scheme Appraisal

Small hydropower generation suffers in that:-

1) its appraisal and development requires a knowledge of hydraulics, hydrology, civil, mechanical and electrical engineering, and basic economics

2) it is site-specific in nature

3) it is marginal from an economic view-point

These factors require that whilst it is necessary to keep engineering fees to a minimum, consistent and reliable techniques are needed for appraisal and design of small hydro-electric power plants. The engineering input allowable for scheme appraisal will be dependent upon the scale of the proposed development and the stage of the project. Initially a preliminary appraisal is required involving perhaps one manday of effort to determine whether a feasibility study or design study is justified. The initial appraisal will determine the power potential, energy yield, provisional scheme costing, revenue and economics.

A detailed feasibility study or design study will follow the preliminary appraisal. This will involve design and costing of all scheme components and detailed evaluation of economics.

1.4 Definition

In the U.K. "small-scale" hydropower is generally taken to refer to schemes with installed capacities of less than 5MW. (In fact in the U.K., Scotland excepted there are few run-of-river schemes with capacities of greater than 2MW). At the lower end of this range further subdivisions exist for mini hydropower 25-250kW, and micro hydropower, less than 25kW.

For this thesis, whilst the methods for assessing basic physical parameters at a site are applicable to all groups within the range up to 5MW, the costing package is not directly applicable to micro-hydropower schemes. Here, economic development usually depends on development on a DIY basis with the owner/developer taking no account of his time and labour in the economic evaluation.

CHAPTER 2

2.0 Scheme Appraisal

2.1 Power Potential

It is necessary to determine the potential power at the outset, and this will be dependent upon the head available, the hydrology of the river catchment, the constraints of the existing civils works and the end use of the energy.

The power potential of a hydro-electric site is evaluated from the formula:-

$$P = W\ Q_i\ H\ \eta_0$$

where P = electrical power output (kW)
W = specific weight of water
= 9.81 (kN/m^3)
Q_i = installed or design flow (m^3/s)
H = head in m
η_0 = overall efficiency of generation

2.2 Scheme Layout and available head

To determine the gross head available at a site it is necessary to layout a provisional scheme. This provisional scheme layout may subsequently be amended during detailed design of the scheme components (section 3).

The layout will be dependent upon scheme type, and involves the location of the intake structure, the powerhouse and the conduit for supplying water between the two. This conduit can take the form of a leat (open channel contour canal), a low pressure pipeline, a high pressure pipeline or a combination of any two or all three.

Various forms of scheme layout are possible

2.2.1 A medium/high head scheme where water is conveyed directly to the powerhouse by a high pressure pipeline (Figure 2.1.1).

2.2.2 A medium/high head scheme where water is carried from the intake structure to the turbine forebay by a leat (or alternatively a low pressure pipeline) and thence to the powerhouse via a high pressure pipeline (Figure 2.1.2).

2.2.3 A low head scheme incorporating a diversion weir and intake works feeding water via a leat (or low pressure pipeline) to the powerhouse. Water is returned to the river by a tailrace channel (Figure 2.1.3).

2.2.4 A powerhouse dam where the head is created by the construction of a dam or barrage incorporating a powerhouse.

The choice of scheme layout is dependent upon a number of factors including topography, access, availability and comparative cost of materials, the skills of the labour force, the requirements of other riparian users and land drainage requirements. In the case of a previously developed hydropower scheme, which has subsequently fallen into disuse, the scheme layout may already be determined to a large extent.

The scheme layout is best determined by a site visit from an experienced engineer, but for a provisional assessment where the cost of such a visit is prohibitive, use can be made of maps, sketches and photographs, to determine whether a site is likely to have potential for development. This provisional appraisal together with an estimate of power will allow a potential developer to determine whether to proceed with commissioning a feasibility study.

The scheme layout determines the head available for generation. The head available is either

(1) the vertical difference in level between the water surface in the turbine forebay and the water surface in the tailrace for schemes using pipelines and reaction turbines (see Section 3.5.2)

or (2) the vertical difference in level between the water surface in the turbine forebay and the turbine runner for schemes using pipelines and impulse turbines (see Section 3.5.1)

or (3) the vertical difference in level between the water surface immediately upstream of the powerhouse and the water surface in the tailrace for low head leated schemes and powerhouse dams. (Note in the case of crossflow turbines (see Section 3.5.1.3) this head should be reduced by a value equal to the turbine runner diameter).

Methods for the measurement of head include a surveyors level or theodolite, an altimeter or simply a surveyors staff, plumbline, tape and builders level. Refs. 4 and 5 provide details for the measurement of head.

2.3 Hydrology - Installed Flow

Estimates of the occurence and volume of flow passing a proposed hydro-electric site must be made if the development is to be properly sized and the installed capacity determined. The selection of rated flow (or maximum turbine flow) is of importance since the sizing and hence cost of all equipment and structures are dependent upon this parameter.

River flows are determined by the hydrology of the catchment area and the consequent runoff and groundwater conditions. The catchment area is the whole of the land (and water surface) contributing to the discharge at a particular location. The river flow of a catchment is dependent upon many factors eg. area, location, orientation, rainfall, climate, topography and geology.

The volume of water in a river available for generation is quantified by the annual mean flow. The appropriate installed or rated turbine flow is dependent upon the optimum sizing of turbo-generator equipment and civil works in relation to the end use for the energy. An analysis of the effect of rated flow on economic returns has been undertaken for a number of sites of differing hydrological and scheme types, and is included as Appendix A. This analysis shows that optimum economic benefit is likely to be obtained when rated flow is set at mean annual flow minus compensation flow (see Section 2.3.2.3), and accordingly this flow provides a reasonable first estimate for use in preliminary appraisal and potential studies.

2.3.1 Mean Flow

Several methods are available for the estimation of annual mean flow as follows:-

(1) Mean flow can be calculated from

$$Qm = \frac{(SAAR - Ea) \times A \times 10^3}{8760 \times 3600}$$

where Qm = annual mean flow (m^3/s)

SAAR = standard annual average rainfall for the catchment (mm)

Ea = actual evapotranspiration (mm)

A = catchment area (km^2)

In the U.K. SAAR can be obtained from isohyetal map produced by the Meterological Office, Ea can be obtained from potential evaporation (Ep) by use of an Institute of Hydrology (IOH) nomogram (Ref. 6), Ep being obtained from a Meteorological Office map.* The quantity SAAR - Ea can be termed net rainfall (ie. rainfall - evapotranspiration losses) or runoff. Methods for measuring and calculating values of SAAR, Ea and Ep at other locations are given in Ref. 7.

(2) Mean flow can be obtained by direct measurement. Flow measurement is usually undertaken by use of a flow measurement structure or by the determination of a flow rating curve for a river section. The design and use of flow measurement structures are detailed in Ref. 8 and methods for the production of rating curves are given in Ref. 7.

Flow data for river gauging stations in the UK are given in an HMSO publication called the Surface Water Year Book.

(3) The mean flow from a nearby gauging station can be used to estimate the mean flow at an ungauged site. Where the difference in catchment area between the gauging station and the ungauged site is small (say less than 10-20%) the gauged mean flow can simply be multiplied by the ratio of the catchment areas to obtain an estimate of the mean flow at the ungauged site with an appropriate adjustment for net annual rainfall.

2.3.2 Flow Duration Curves

The flow duration curve (FDC) shows graphically the

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* Average Annual Potential Evaporation in millimetres for a surface with an Albedo of 0.25, scale 1:2 million, Meteorological Office.

percentage of time that a flow value is equalled or exceeded. Curves can be constructed for daily, monthly or any consecutive period, however it is the annual mean daily flow duration curve which is of most value for assessment of flow variability for small hydro power schemes.

Several methods are available for estimating flow duration curves, and these are detailed in Ref. 6. The appropriate method for constructing the FDC depends on the amount of data available as follows:-

(1) Where there is 10 or more years of data available, the daily flow data can be used directly to produce the one day annual flow duration curve.

(2) Where there is between 2 and 10 years of data, the daily flow data should be divided by the average flow over the period. This overcomes departures due to wet or dry years, and results in an analogue flow duration curve. This analogue FDC can then be converted to give the FDC in m^3/s by multiplying by the mean flow obtained from 2.3.1.

(3) In the case of the ungauged catchment or where there is less than 2 years of data, the catchment characteristics of the ungauged catchment should be compared with those of nearby or similar catchments for which FDC's exist to synthesize a curve. For the UK. this can be undertaken by the Base Flow Index (BFI) method (see Section 2.3.2.2).

One day flow duration curves for periods of time other than yearly are also of use. These seasonal flow duration curves illustrate for any month (eg. all Decembers) or group of months (eg. all January - June periods) the relationship between discharge and the percentage of time discharge is exceeded. For hydropower schemes such curves can be used to estimate the amount of energy that will be generated during a specific period of the year and are thus of use in comparing energy supply and demand and energy value (see Section 2.5).

2.3.2.1 Shape of FDC's

The area under a FDC is volume of water, and hence the shape of the curve is of importance. Two examples of FDC's are shown plotted together in Figure 2.2. (Note the use of log probability paper). The flat curve for the river Itchen at Winchester is typical of a FDC for a river having little daily flow variation and few flood flows, being extensively supplied from groundwater. The steep curve for the river Ogwen at Ogwen Bank indicates a "flashy" river with large daily flow variation, frequent floods and comparatively low flow during dry weather periods.

2.3.2.2 Base Flow Index

In Britain, synthesis of FDC's can be undertaken by the Base Flow Index (BFI) method developed by IOH (Ref. 6). For Northern Ireland modification to this method is adopted and is outlined in Section 5.2.3. BFI is defined as the ratio of the flow under a separated hydograph (ie. the base flow) to the flow under the total hydrograph (Figure 2.3). The IOH method uses BFI and SAAR (and in one case main stream length) in equations derived for specific hydrometric areas in the British Isles, to choose type curves from which specific flow duration curves are obtained. This method thus allows the production of an individual flow duration curve for any location. BFI varies from less than 0.2 for flashy rivers up to 0.95 for rivers fed principally from ground water. Typical daily flow duration curves (with flow expressed as a percentage of mean flow) for a range of BFI are shown in Figure 2.4.

BFI can be calculated from existing flow data or from catchment geology (for Scotland a BFI map has been produced). The former method is of little use for the ungauged catchment case, and the latter method requires a degree of expertise and time not always available for consideration of small hydropower schemes. Another method has been developed therefore for the calculation of BFI, and involves use of SOIL as defined in the Flood Studies Report (Ref. 9)

BFI is related to SOIL by the equation

$$BFI = 0.60+0.23S_1-0.03S_2-0.12S_3-0.17S_4-0.20S_5$$

Where S_1 to S_5 are the proportions of each of the SOIL categories occurring within the catchment.

The five SOIL categories (S_1 to S_5) are obtained from the Flood Studies Report - Winter Rain Acceptance Potential (WRAP) map. The formula relating BFI to SOIL does not allow for the production of FDC's for extreme catchments ie. catchments with either very high or very low BFI values. A modification is used therefore to allow for these catchments by use of the Solid Geology Map of the British Isles at scale 1/625,000; where the catchment contains appreciable amounts of S_1 or S_5 the geology map is used to determine whether these SOIL values are occurring due to the presence of certain rock types known to yield extreme values of BFI.

For S_1 chalk yields a BFI of 0.9, and for S_5 carboniferous limestone, Oxford clay, Weald clay and London clay yield BFI of 0.2. Where these geological formations occur the formula for BFI can be modified for S_1 as

$$BFI = (0.6 + .03S_2 - .12S_3 - .17S_4 - .20S_5)(S_2 + S_3 + S_4 + S_5) + 0.9S_1$$

and for S_5

$$BFI = (0.6 + .23S_1 - .03S_2 - .12S_3 - .17S_4)(S_1 + S_2 + S_3 + S_4) + .2S_5$$

The application of the BFI method is illustrated in Section 5.2.3.

2.3.2.3 Compensation Flow

During the appraisal of hydropower schemes allowance is usually made for the provision of a compensation flow or minimum flow requirement which must be maintained in the river course at all times. This compensation flow, which is required for environmental and fishery interests, has an effect on the flow available to the hydropower generator and hence on the scheme energy yield (Section 2.4).

The magnitude of the compensation flow required is to some degree site specific, however several U.K. Water Authorities have suggested that the 95 percentile flow on the mean daily flow duration curve provides a reasonable allowance. This is approximately the dry weather flow.

2.4 Energy Yield

The energy yield from a potential small-scale hydroelectric scheme is calculated by use of the FDC, together with consideration of the efficiency and part-flow characteristics of the turbine and the overall efficiency of generation.

The requirement for an accurate assessment of annual energy yield cannot be over-stressed, since it is the quantity of energy produced which provides the income for any small hydro plant. In this context it is important that net turbine heads are used and that a reliable FDC is produced. Over estimation of both these parameters will lead to oversizing of generating plant: in the case of head, this will lead to specification of an incorrect rotational speed for the turbine which in turn will lead to operation at reduced efficiency (Ref. 10).

2.4.1 Efficiency and turbine partflow

To calculate the installed capacity, it is necessary to obtain a value for the overall efficiency of generation, usually for output at the electrical generator terminals. This efficiency factor is a product of turbine, drive and electrical generator efficiencies, but should also make allowance for head loss in the pipeline where one is incorporated.

Typical turbine efficiency curves where relative efficiency is plotted against percentage of rated flow are plotted in Figure 2.5, for the main types of turbine used in small hydro. It is useful to note the relatively flat curves for the crossflow and impulse machines when compared to the Francis and propeller. Also of consequence is the range of operation, with crossflow and impulse having good efficiency down to flows of Qi/6 and propeller and Francis to only Qi/3. This factor is worth noting in the selection of turbines for small hydro installations, since where it may be acceptable to install a single crossflow or impulse machine to achieve adequate flow variation, it may be necessary to use two Francis or propellers.

The relative efficiency curves can be used only when a value has been obtained for likely peak efficiency. Peak or maximum efficiency is dependent upon a number of factors: design, size, quality of workmanship, etc. However there is a general increase in efficiency with increase in rated power output, typical values being shown in Table 2.1.

Turbine efficiency must now be combined with a drive efficiency (belts or gearbox) taken as 98% and a peak generator efficiency from the curves of Figure 2.6. It should be noted in the selection of the generator that a generator with maximum rating of 30% greater than the maximum turbine output is usual for small hydro (Ref. 11).

Finally where a pipeline is used, allowance must be made for frictional losses so that gross head is reduced to net head. Pipeline headloss can be considered as an efficiency by dividing net head by gross head. (A further consideration of pipeline headloss is given in Section 3.4.3).

Accordingly

$$\eta_O = \eta_T \times \eta_D \times \eta_G \times \eta_P$$

where η_O = overall efficiency
η_T = turbine efficiency
η_D = drive efficiency
η_G = generator efficiency
η_P = pipeline efficiency

2.4.2 Energy Yield

The method for calculating energy yield is illustrated graphically in Figure 2.7. The steps for calculating yield are:-

1 Select a value for Qi and express it as a proportion of Qm.

2 Set the lower flow limit for generation depending on the turbine type (Qi/6 for crossflow and impulse, Qi/3 for Francis and propeller).

3 Divide the adjusted FDC between Qi and Qmin into bands, usually 5-10% of time depending on the accuracy required.

4 Calculate the average flow within each band.

5 Multiply the average flow in each band by Qm to convert to m^3/s units.

6 Compute turbine power output for each flow value by multiplying by net head, flow, 9.81 and η_T obtained from Table 2.1 and Figure 2.5. For estimating net head a graph of the form shown in Figure 2.8 is of use.

7 Convert turbine output to electrical output by multiplying by drive efficiency (0.98) and generator efficiency from Figure 2.6.

8 Multiply electrical output by proportion of time and 8760 hours per year to calculate energy in each band.

9 Sum energy values to obtain annual energy yield.

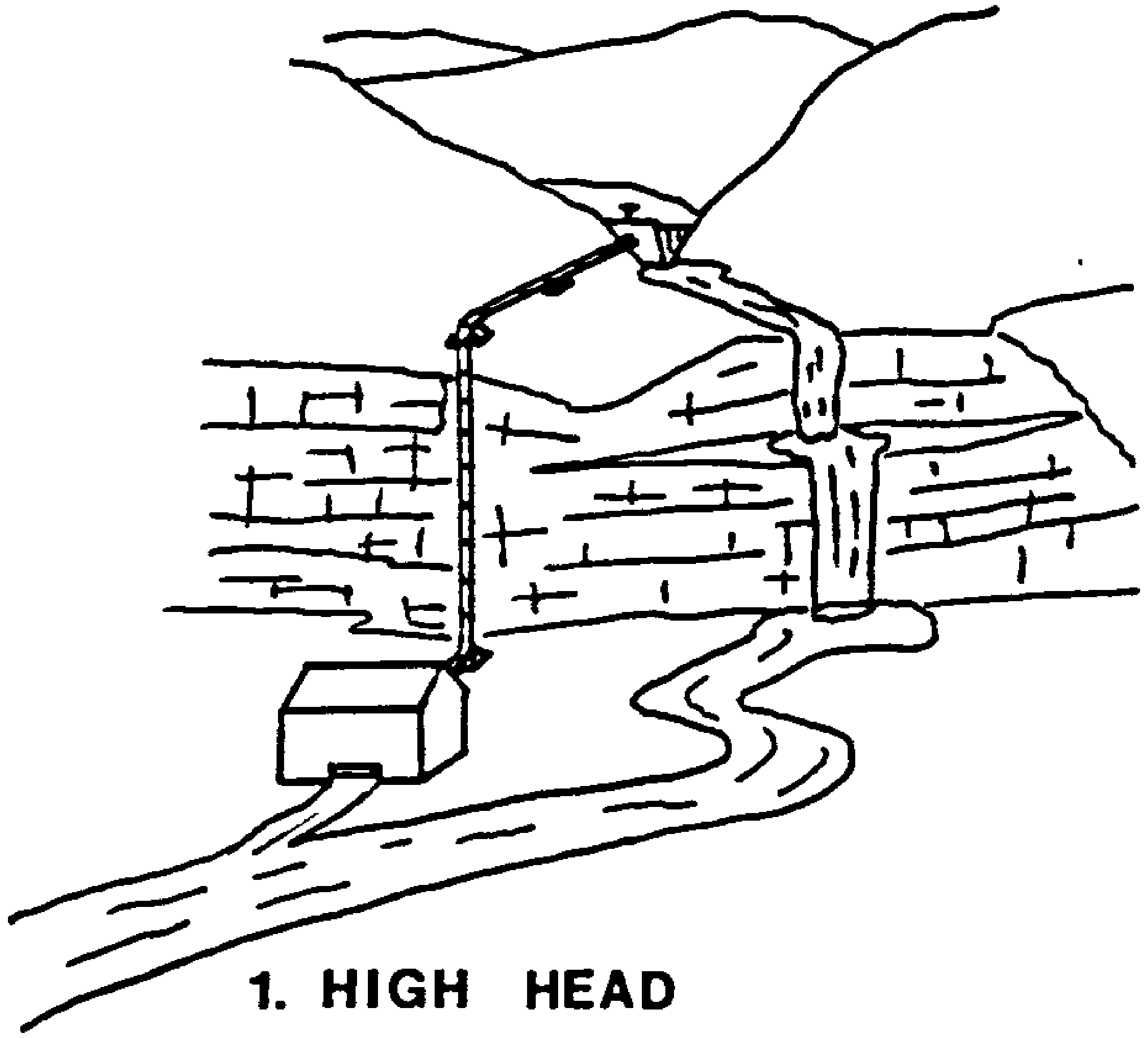
When undertaken by hand the calculation should be performed in tabular form, but the method is readily adaptable for computer computation.

2.5 Energy Value

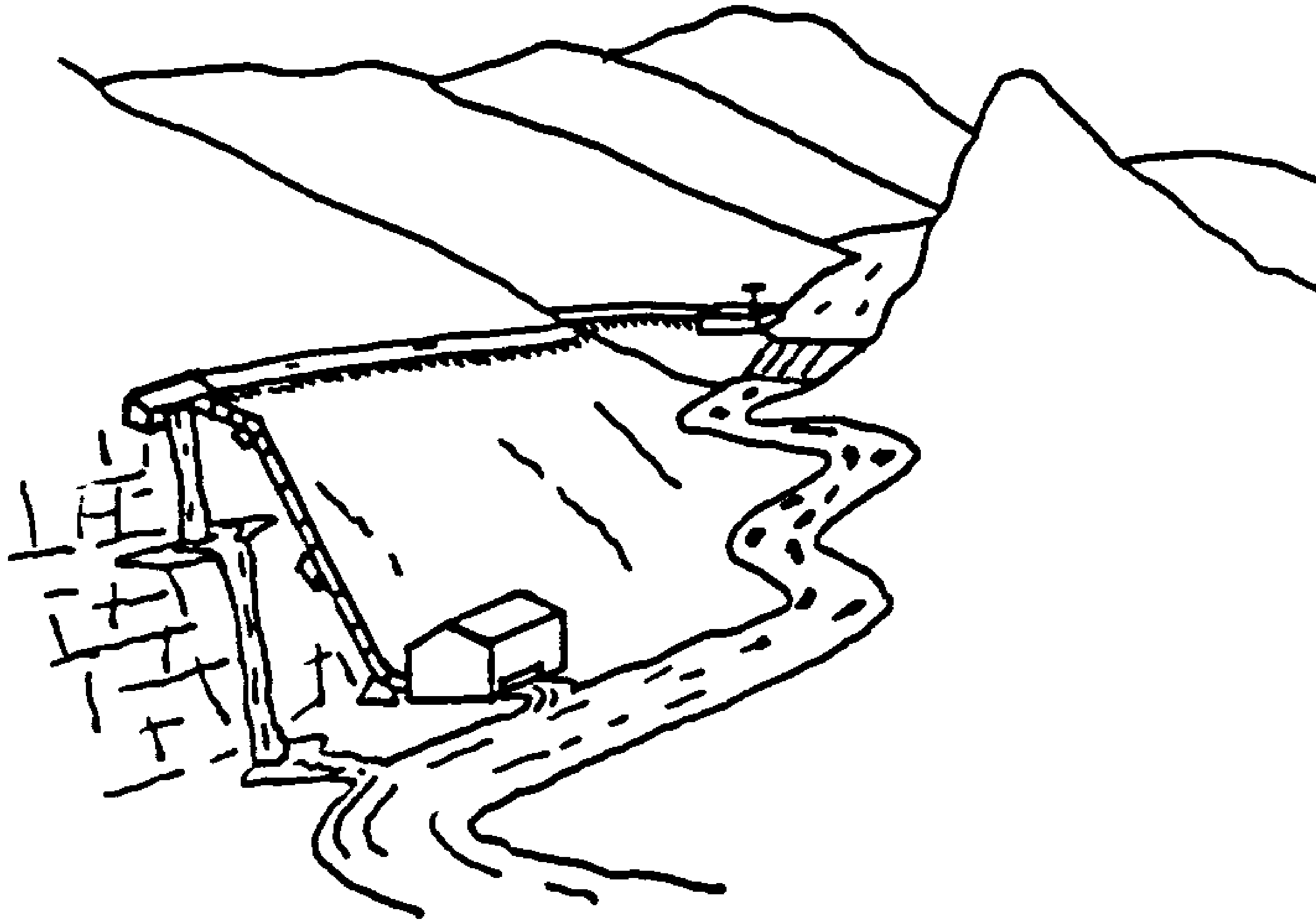
Having calculated energy yield, it is now possible to calculate the value of the energy generated. This will be dependent upon the end use for the energy, a consideration of which is given in Section 4.4.

Rated Power (kW)	Typical Maximum Efficiency (%)			
	Crossflow	Impulse	Francis	Propeller FD. VB
2000	--	90	93	89
1000	83	88.5	91.5	87.5
500	83	87	90	86
150	83	85	87.5	84
75	83	83	85	82
35	75	75	77	74

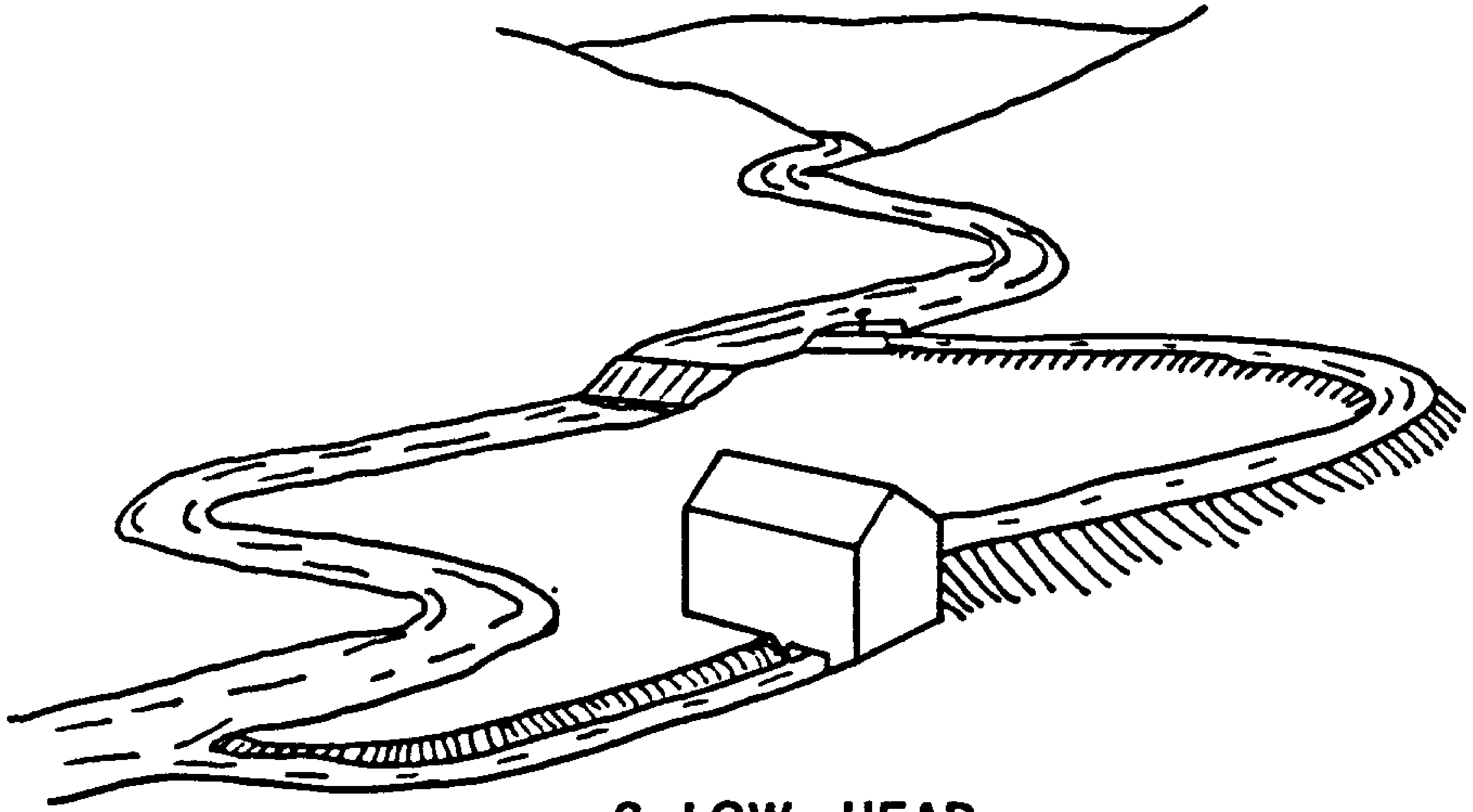
Table 2.1 Typical Maximum Turbine Efficiencies at Various Rated Powers



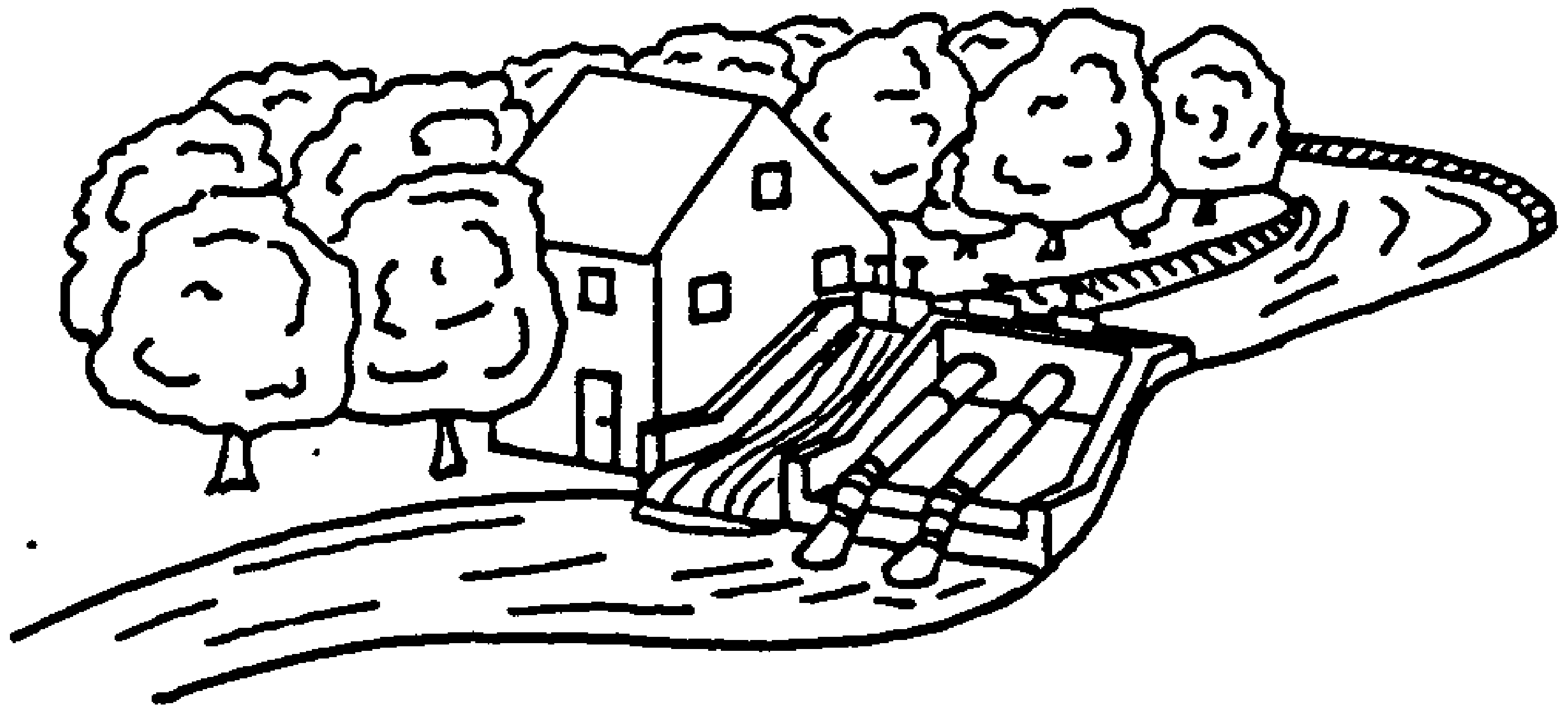
1. HIGH HEAD



2. HIGH HEAD WITH LEAT



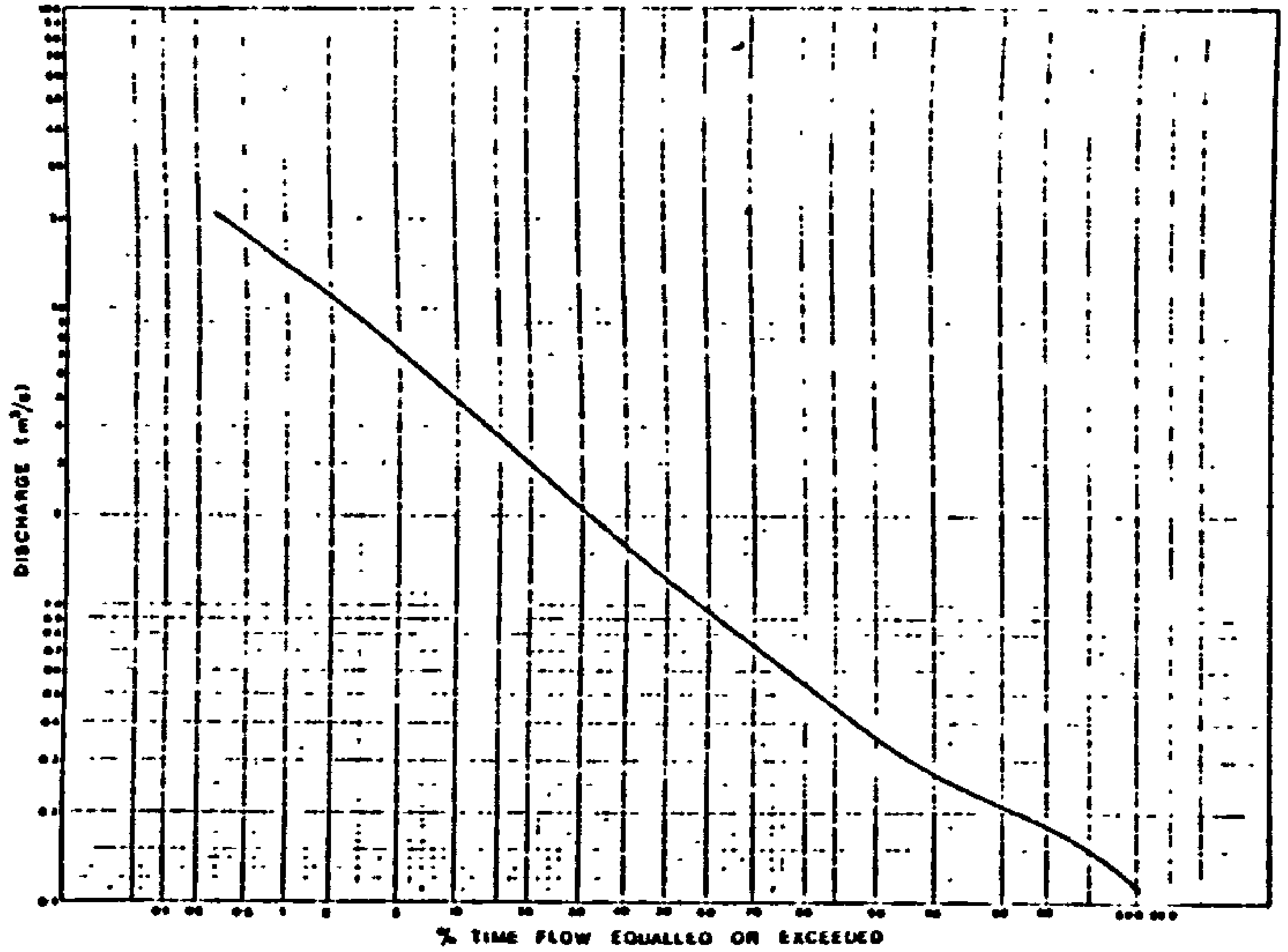
3. LOW HEAD



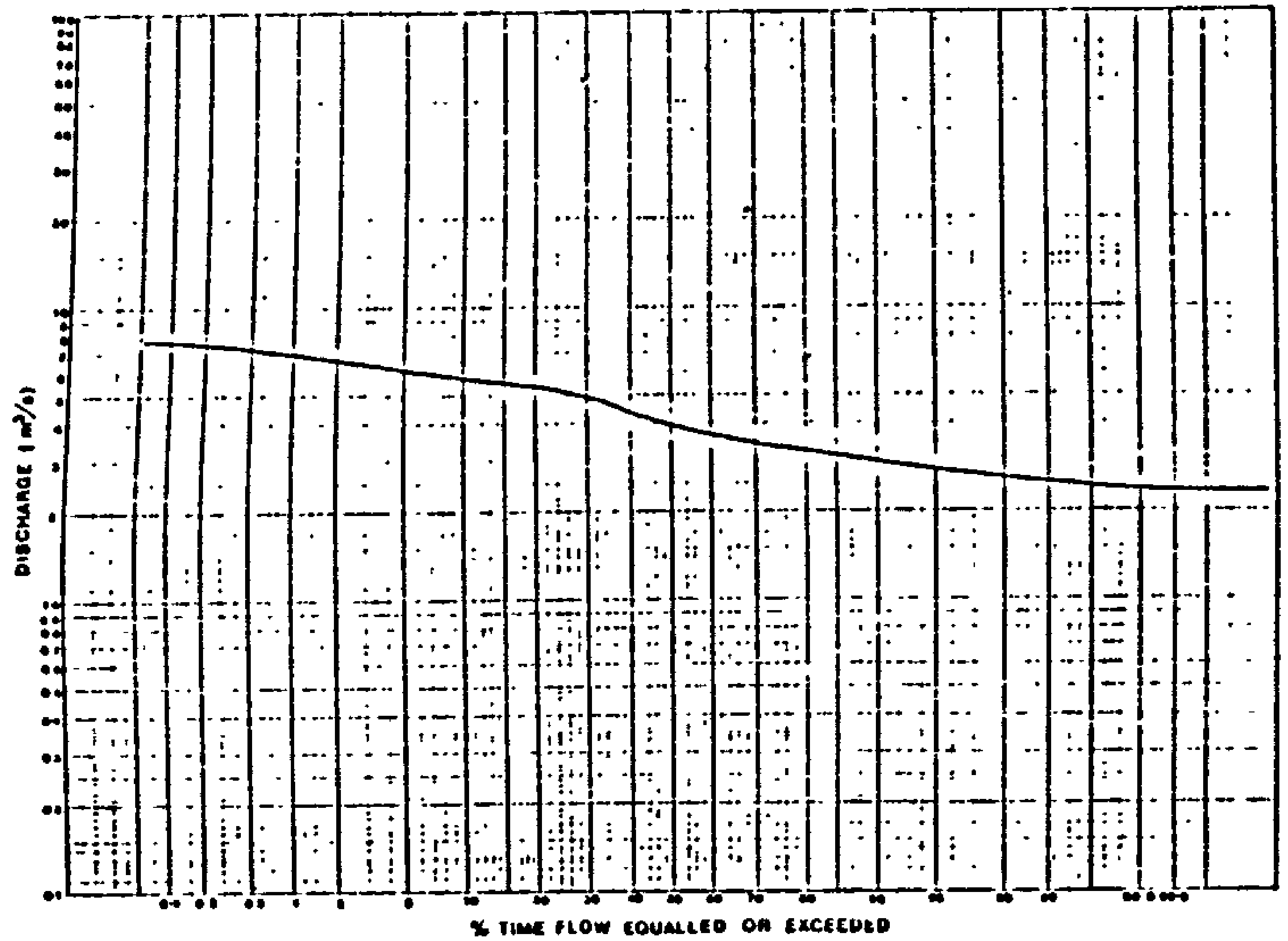
4. POWERHOUSE DAM

TYPICAL SCHEME LAYOUTS

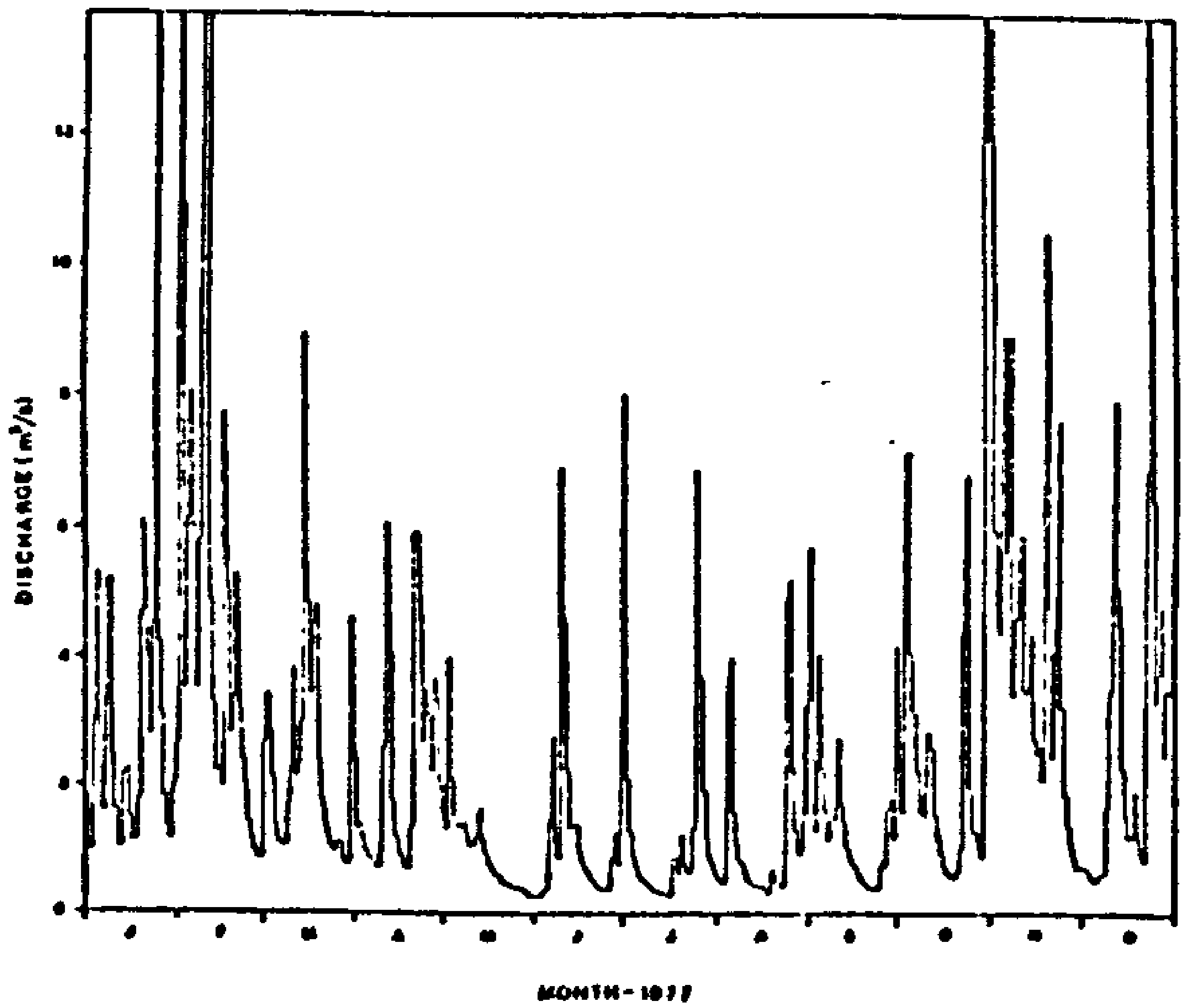
FIG 2.1



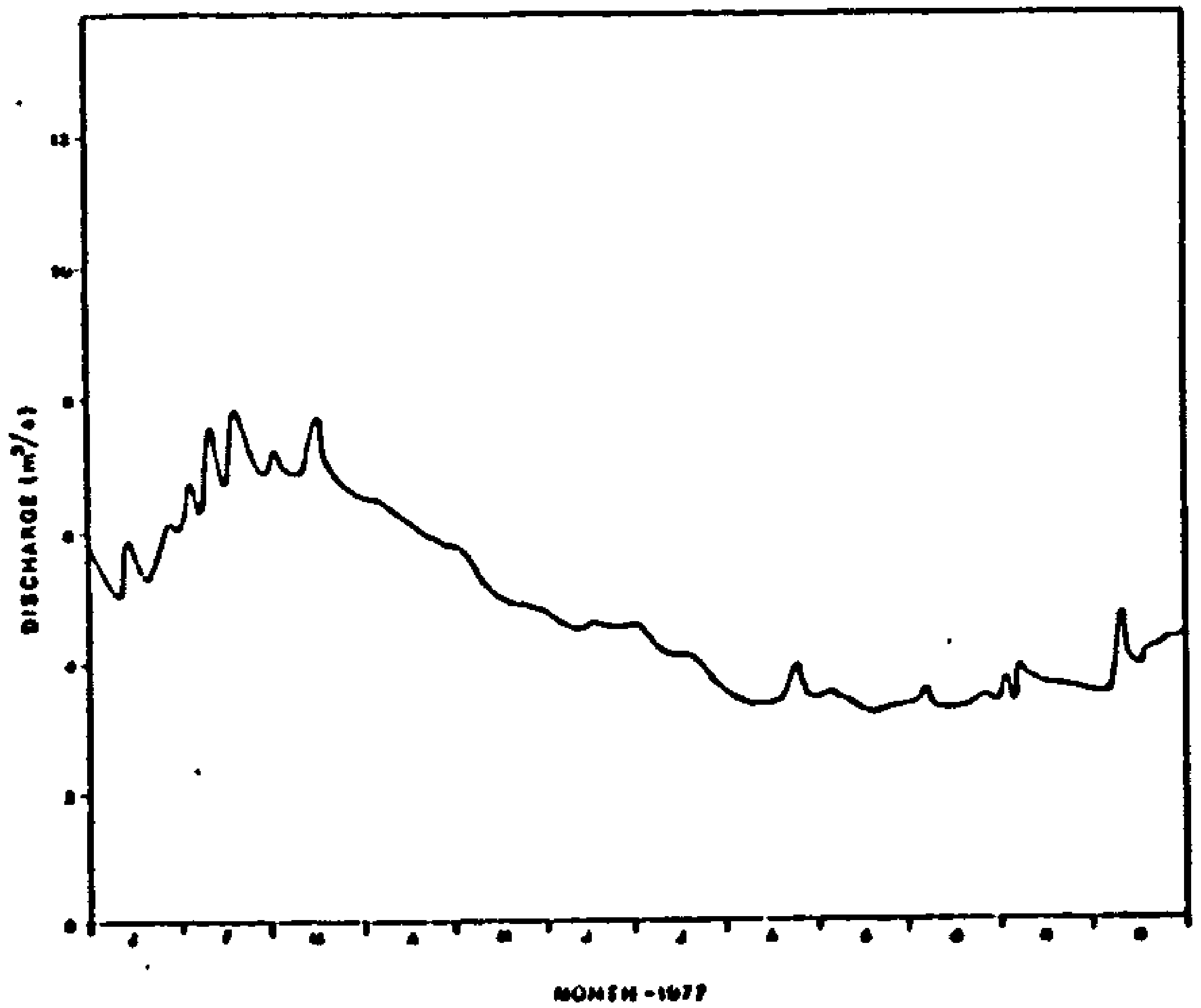
F D C FOR RIVER OGWEN



F D C FOR RIVER ITCHEN



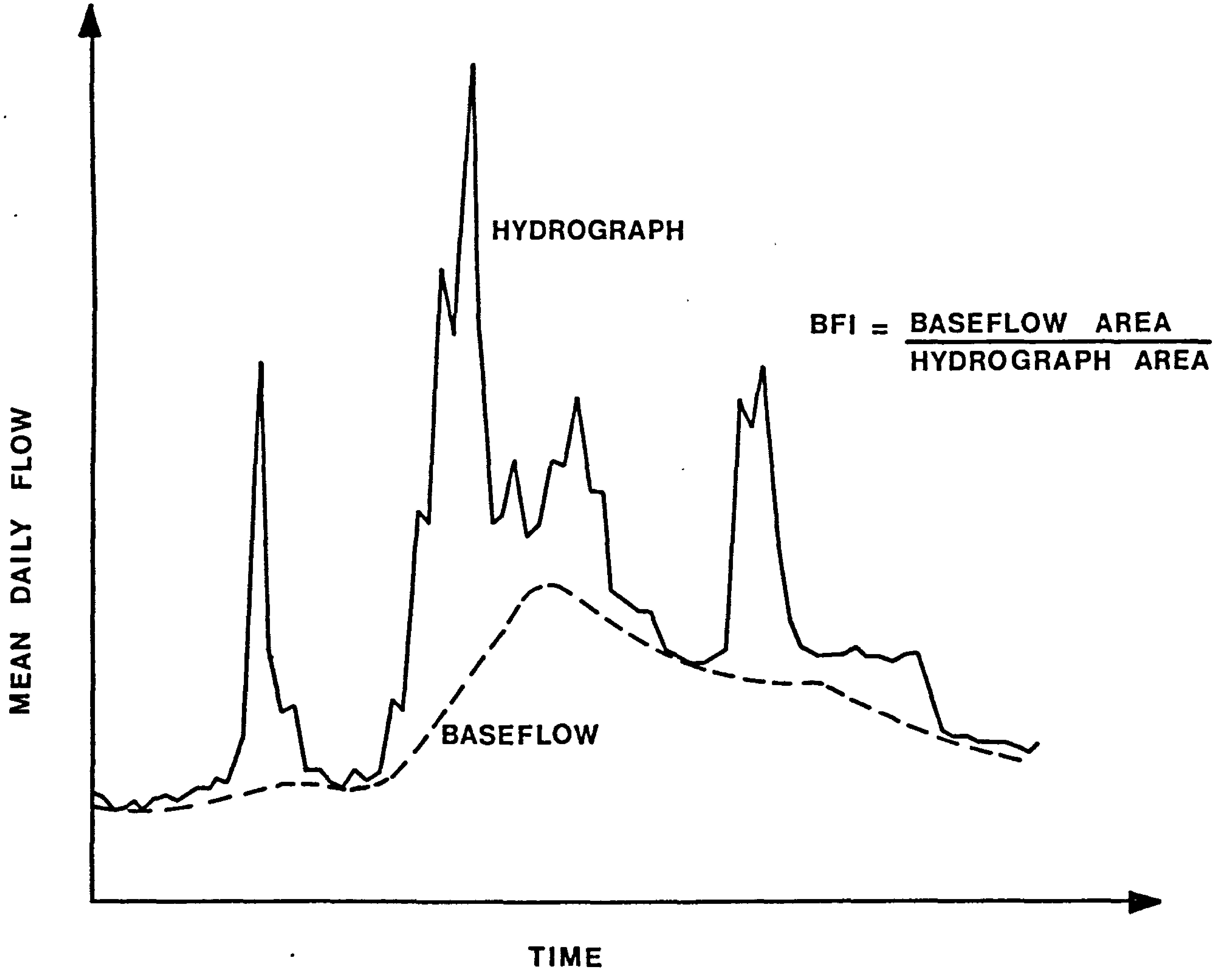
AVERAGE DAILY FLOWS FOR RIVER OGWEN-1977



AVERAGE DAILY FLOWS FOR RIVER ITCHEN-1977

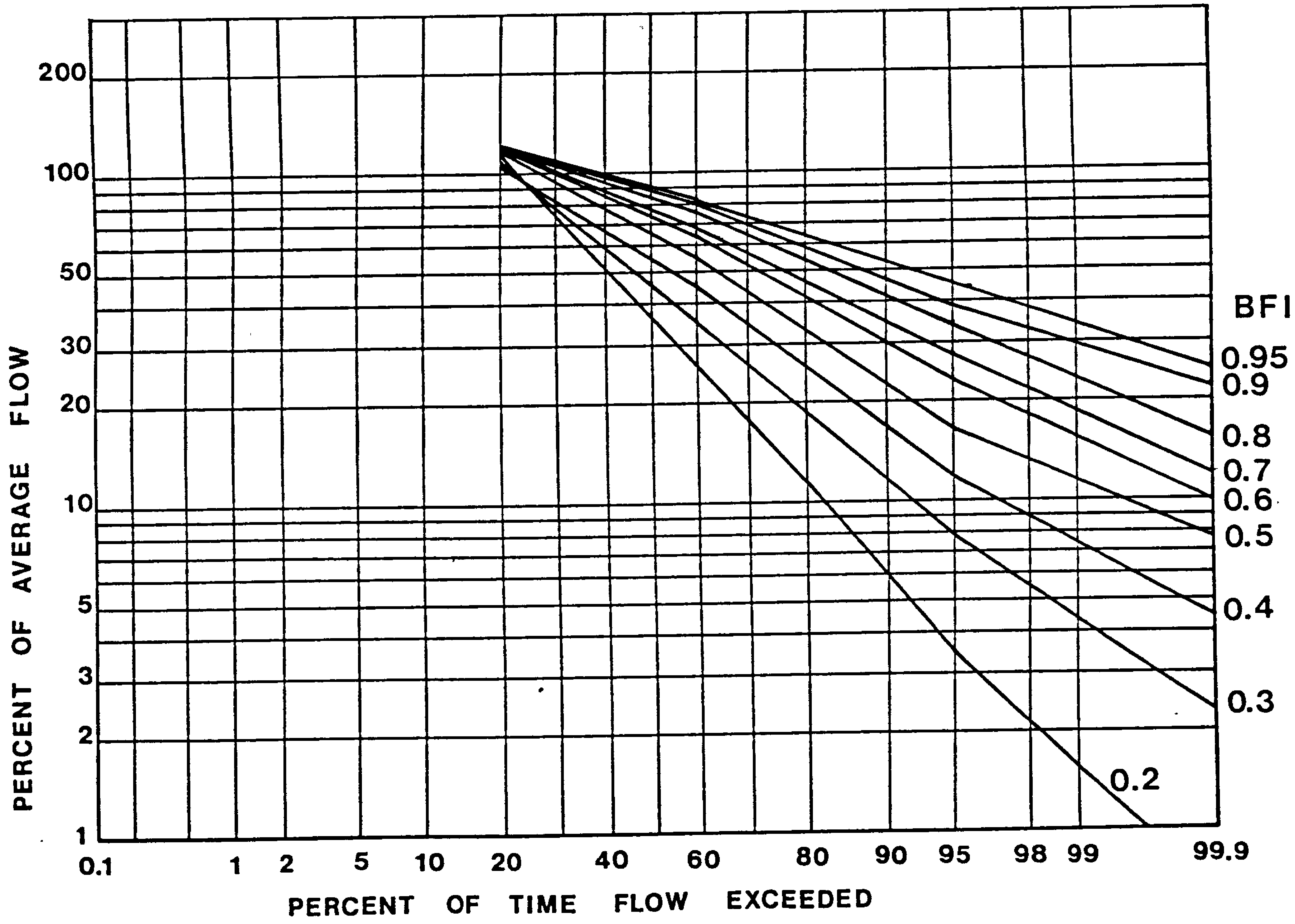
COMPARISON OF FDCs

FIG 2.2



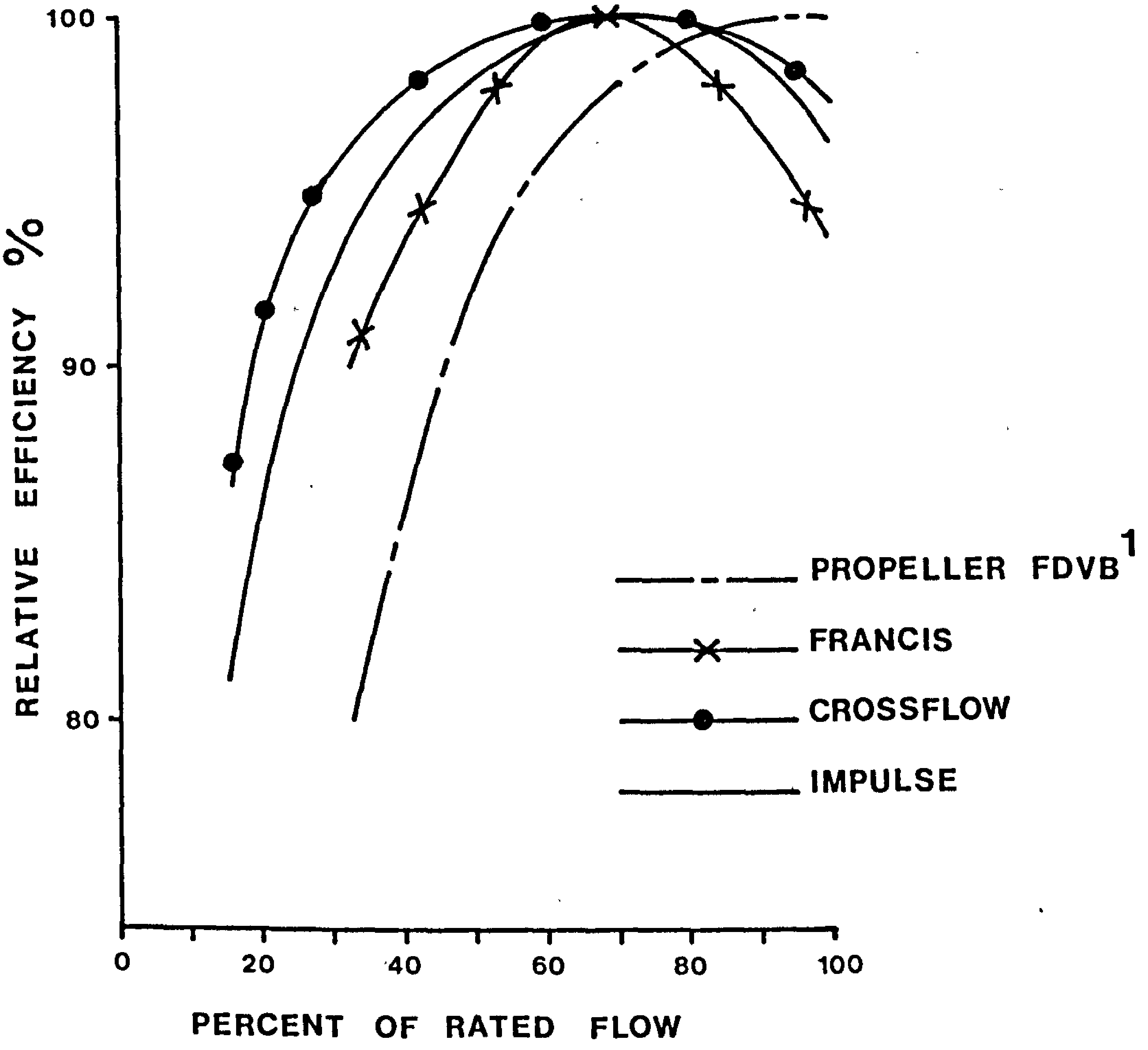
BASEFLOW INDEX

FIG 2.3



FLOW DURATION CURVES FOR VALUES OF BFI

FIG 2.4

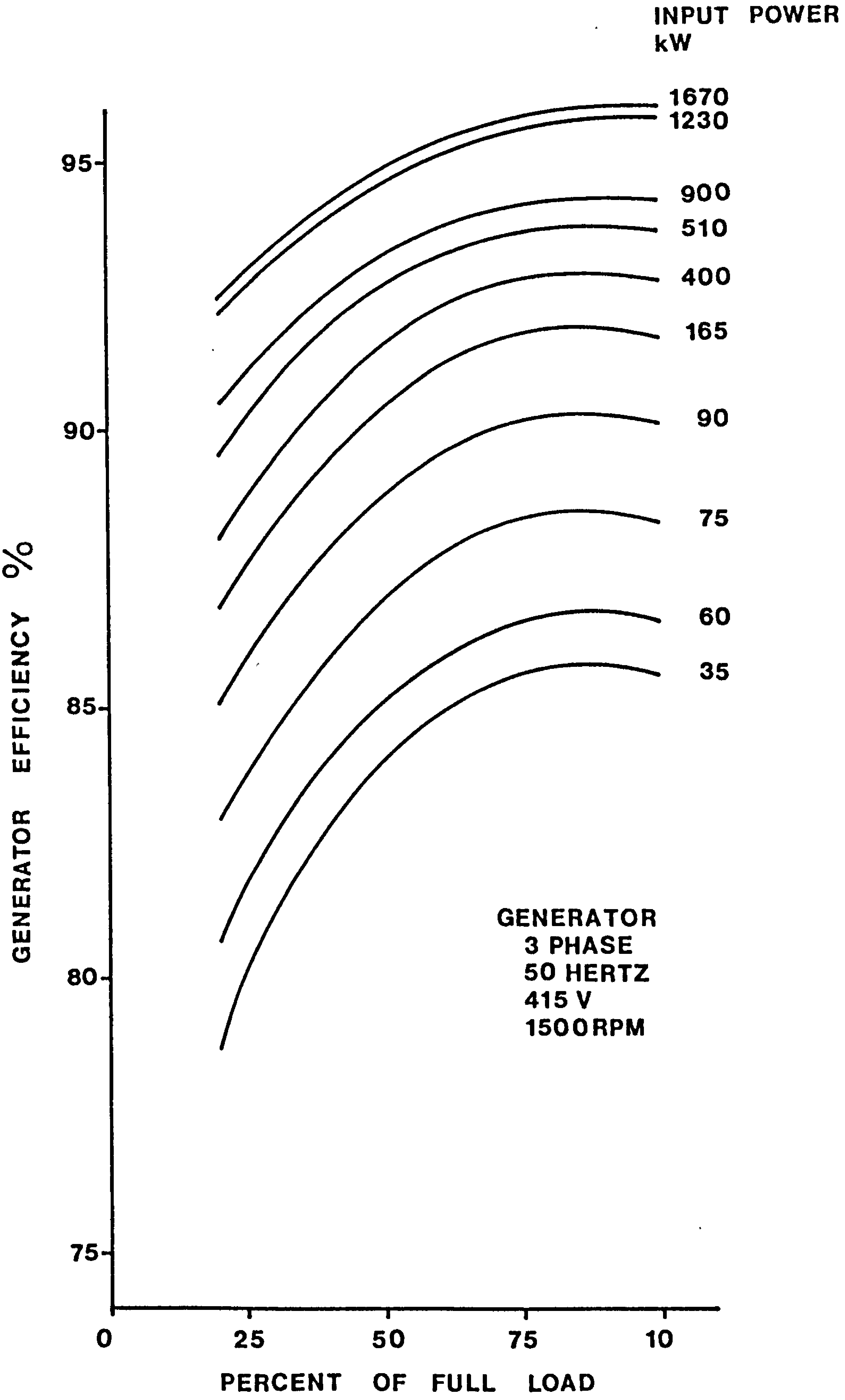


TYPICAL TURBINE EFFICIENCY CURVES

MANUFACTURER'S DATA

FIG 2.5

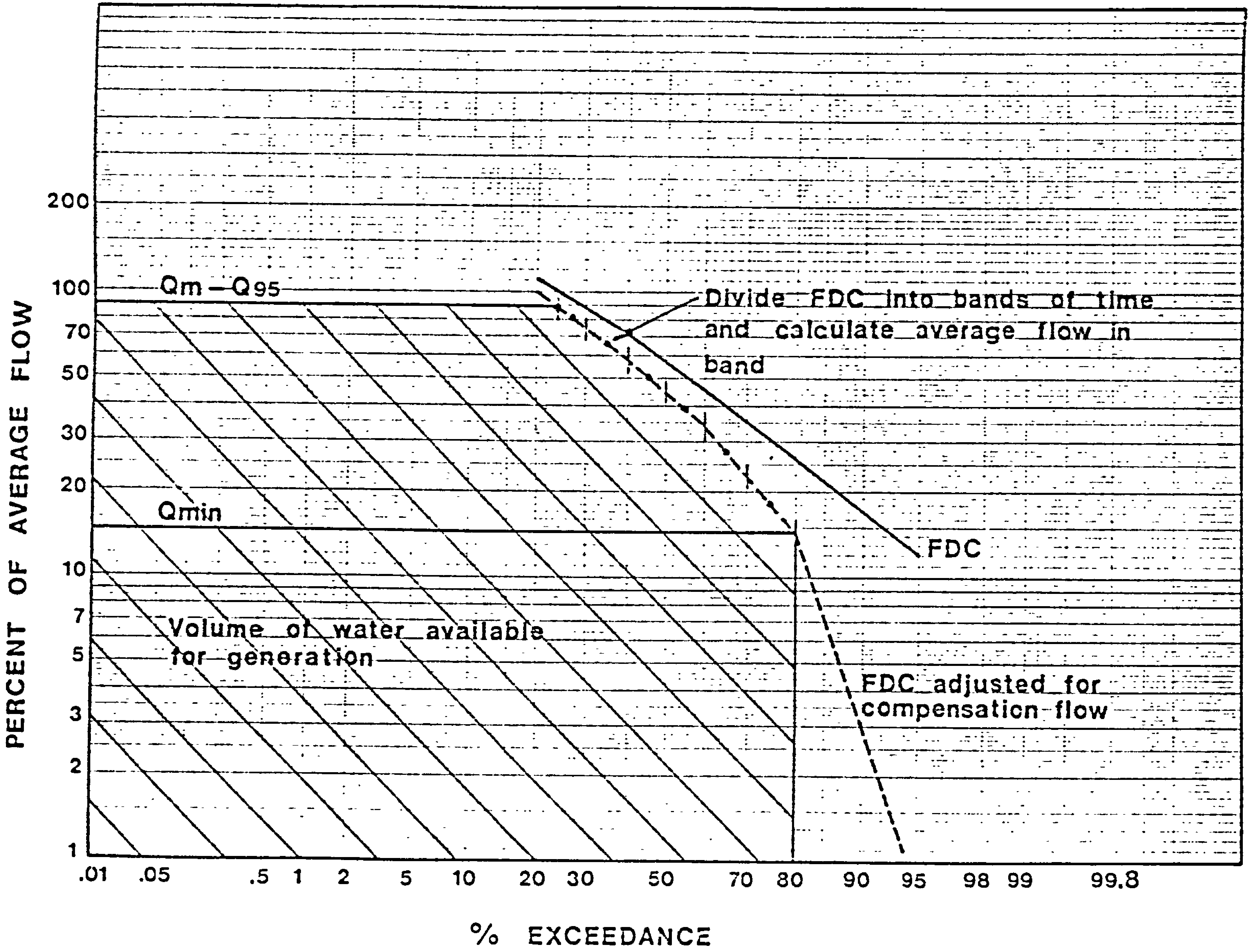
[1] FDVB - fixed distributor variable blade



ELECTRICAL GENERATOR EFFICIENCY CURVES

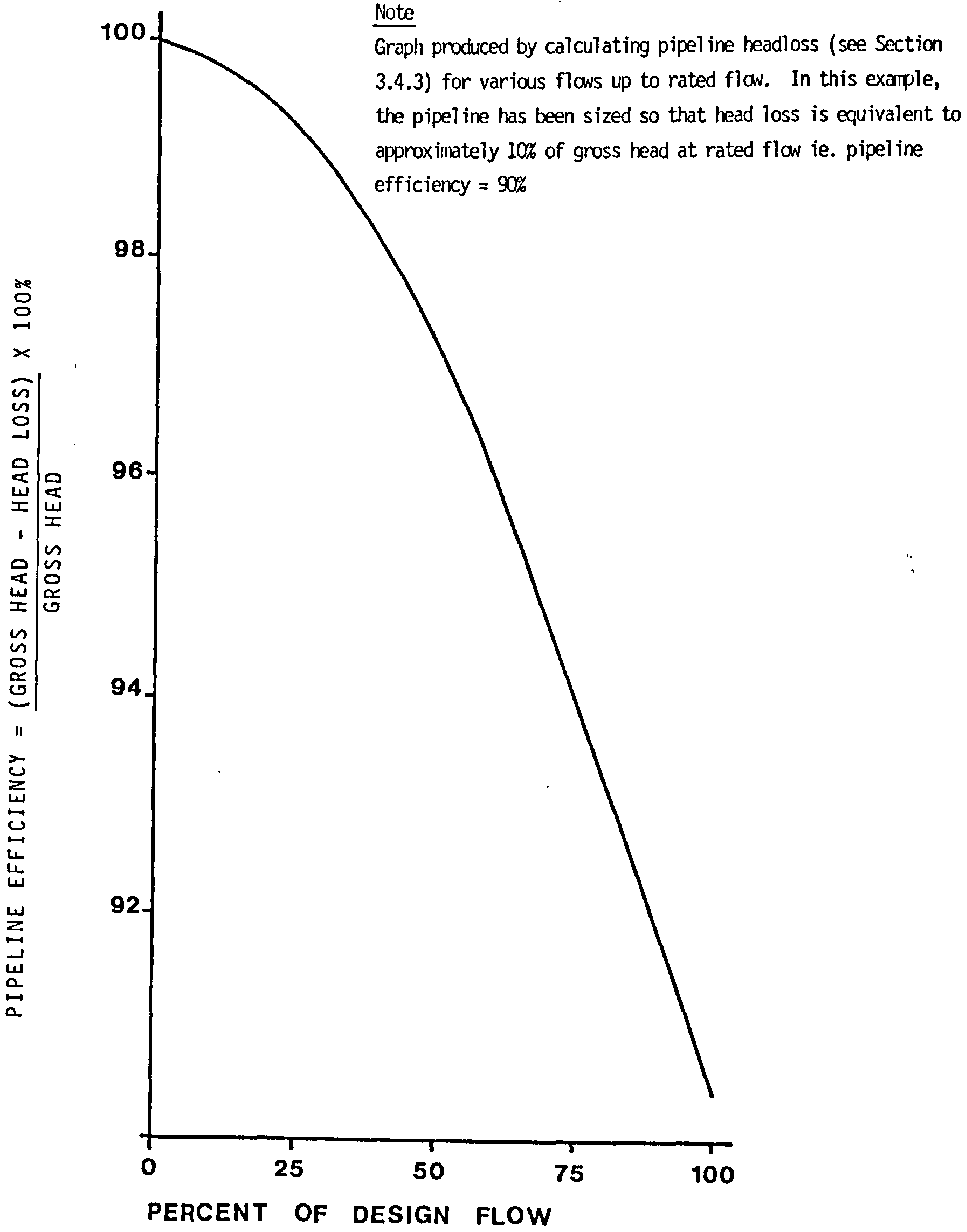
MANUFACTURER'S DATA

FIG 2.6



CALCULATION OF ENERGY YIELD FOR CROSSFLOW & IMPULSE TURBINES

FIG 2.7



ESTIMATION OF NET TURBINE HEAD

FIG 2.8

CHAPTER 3

3.0 Scheme Components

This section describes the various components which make up a small hydro-electric scheme, and considers their application and design.

3.1 Weirs and Dams

The costs involved in the construction of large impounding dams are such that the majority of small hydropower schemes are of the run-of-river type and as such do not have storage. Low weirs are used therefore, their primary function being to divert water into the intake works, providing adequate water depth to ensure submergence of the pipeline or adequate depth in the leat so that it can carry its design flow.

Weirs can be constructed of a variety of materials including masonry, concrete, steel, timber and composites. The simplest type of weir, often found in developing countries, is simply formed by placing boulders across the flow to divert water. This is a temporary structure often being swept away during large floods which are common in the tropics. However, since labour is cheap and the boulders are easily replaced, such a diversion weir is often adequate.

Weirs of a permanent type are usually constructed to raise the water level slightly, in which case they collect the bed load and debris carried by the river. To alleviate this problem, it is usual to incorporate a sliding gate on the intake side of the weir, this permits sufficiently high velocities near the intake to remove debris.

For low-head, high-flow sites, it is unlikely that a scheme will be economic if a weir to develop all the head has to be constructed. Such sites will only be economic where the weir is an existing feature or where a low weir can be built on top of a natural sill. At such sites, flooding due to increased water levels can also be a problem, and it may be necessary to construct flood relief gates over at least a portion of the weir length.

Dams are seldom used in small hydro, however where they are, careful consideration to their design must be given (Ref. 12 provides guidance on the design of dams).

3.2 Intakes

Intakes have two main functions; to control the quantity and quality of water entering the leat or pipeline. Gates (penstocks) and spillways are the usual means of controlling the amount of water entering the intake, whilst trash screens, skimmers and settling basins are used to control water quality. The design of the intake is dependent upon scheme layout and as such is site specific in nature incorporating some or all of the above features. The location of the intake is of importance since use of local features can simplify intake design. In general however, intakes should be orientated perpendicular to the main direction of river flow so alleviating the problems of debris and bed load entering the intake particularly during flood conditions.

3.2.1 Medium/High Head Intakes

Two main types of scheme are encountered here; those schemes which use a leat to supply water to the turbine forebay, and those which pass water directly to the pipeline.

3.2.1.1 Leated Schemes

In the simplest form no penstocks, screens or settling basin will be incorporated at the upper end of the leat, however a diversion wall can be used to deflect debris and restrict flow during floods (Figure 3.1). However, when floods significantly raise water levels, the effectiveness of the wall in reducing flows entering the leat is limited. Accordingly, adequate spillway facilities must be incorporated along the length of the leat to ensure that these flows are dealt with. Further, there is no control of bed load sediment entering the leat, and hence where such bed loads are high, a more sophisticated type of intake must be used which incorporates a settling basin and probably penstocks and coarse screens (see pipeline schemes).

At the downstream end of a leated scheme is the turbine forebay. The forebay will usually incorporate a settling basin, fine screens and spillway arrangements. Stoplog grooves or a penstock will also be included to allow for dewatering the pipeline.

3.2.1.2 Pipeline Schemes

In the case of a pipeline scheme where water is passed directly from the intake to the pipeline, it is necessary to remove all debris and most of the silt from the flow prior to flow entering the pipeline. A typical example of an intake for such a scheme is shown in Figure 3.2. The intake includes coarse screens upstream of the penstock to protect it from damage from large floating material. The penstock gate controls the quantity of water entering the intake, and this is aided by the inclusion of a side spillway to accommodate temporary flow fluctuations. A settling area is used to catch suspended material and fine screens to allow removal of vegetation and other small debris. It should be noted that the screen is placed above the base of the intake chamber on a concrete sill which further helps to trap sediment. Further consideration of screens and settling basins are given in 3.2.3 and 3.2.4 respectively.

Other types of intake can also be considered for high head schemes, eg. stream bed/drop type intakes. An example of one such intake is given in Ref. 13.

3.2.2 Low Head Intakes

A typical sketch for a low-head scheme is shown in Figure 3.3. In this case the weir is the primary settling basin and as previously explained the side sluice allows removal of sediment from the intake area. A surface skimmer at the entrance to the leat prevents large floating material entering the leat. Coarse screens prevent damage to the penstocks and large debris entering the leat. Penstocks control the quantity of water entering the leat and fine screens are included in front of the powerhouse to remove debris. A bypass penstock is also often included for additional flow control and to allow desilting of the leat.

3.2.3 Trash Screens

Trash screens are included in a hydro scheme to intercept all flow being passed to the turbine and remove all debris which cannot safely be passed through the turbine. The screen is made up of a series of parallel metal bars which are raked to remove debris. The spacing of the bars is primarily dependent upon the size of the spacings of the turbine passages and is usually in the range of 1.5-10cm.

The area of screen below the water surface is usually sized such that an approach velocity to the screen is approximately 0.5m/s. Allowing for the bar area, and the build up of some debris, this is often equivalent to a flow velocity through the screen of 1.0m/s.

Trash screens are usually installed at an angle to the horizontal (Figure 3.4) typically 45° to 60°. This aids raking, and also allows a degree of self cleaning since flow velocity through the screen tends to move debris towards the top of the screen. When the quantity of water permits, this action can be used to permit self cleaning by allowing some water to flow over the top of the screen so taking some debris with it into a debris collector.

The headloss through screens can be calculated from the formula (Ref. 14)

$$h = K \left(\frac{t}{b}\right)^{4/3} \frac{v^2}{2g} \operatorname{Sin} \theta$$

where h = head loss through screen (m)
K = trash screen coefficient (see Figure 3.5)
t/b = ratio of bar thickness to bar spacing
v = approach velocity (m/s)
g = gravitational constant ($9.81 m/s^2$)
θ = angle of bars to horizontal

Where schemes are required to operate unattended for long periods, or where flows are so large that manual raking is not possible (say in excess of $10m^3/s$), automatic raking can be incorporated. For small high-head schemes, water can be used to provide the motive power for automatic cleaning; however in general an electrical supply will be required and this adds a margin of complexity in isolated areas. Electrically operated automatic screens are most often employed at low head sites and due to their cost they can only be used for large schemes.

3.2.4 Settling Basins

The design of a stilling basin can be undertaken by the use of the formula (Ref. 15).

$$L = 60 \frac{Q}{VoW}$$

where L = length of settling basin (m)
Q = flow volume (m^3/s)
W = width of chamber (m)
Vo = particle settling velocity (m/minute)

The particle settling velocity is dependent upon particle type and size. However, for small hydro, a typical settling velocity of 2m/minute is often used to remove particles with diameters greater than 0.3mm (Reference 15).

3.3 Leats

Leats (also called 'lades' and 'goits' and tailraces) are open, contour-canals for the conveyance of water. Leats are constructed to carry water from the intake works to the forebay in high-head schemes, or from the intake works directly to the power house in the case of low-head schemes. (Tailraces are constructed to carry water away from the powerhouse back to the watercourse).

Leats are constructed at shallow gradients such that they follow the contours of the land and develop potential head as the river falls. Leats are often preferred to low pressure pipelines and to directly conveying water to the powerhouse by high pressure pipeline, since they can be a more economic solution.

The flow capacity of a leat is dependent upon its gradient, its shape and the material from which it is constructed.

3.3.1 Leat Types

Leats fall into two main categories; unlined and lined. Unlined leats are most commonly employed since they are least expensive, and are easily constructed and maintained by a relatively unskilled labour force. They suffer in that they are subject to leakage through seepage and, that flow velocity must be maintained at a level below that for lined leats, to prevent erosion. A typical flow velocity for an unlined leat is 0.5m/s. Lined leats can be constructed from a variety of materials which include masonry, concrete, clay, geotextile and sheet pile linings. A typical flow velocity for a lined leat is 1.0m/s. An examination of the cost curves in 4.2.4 shows that in the UK. the most appropriate method for lining leats is likely to be geotextile. Small concrete leats are likely to be less economic than low pressure pipelines, whilst large concrete leats face competition from sheet piled leats.

Careful consideration in the design of leats must be given to control of water entering the leat and to spillway arrangements. It is the lack of such flow control and spillway structures, particularly in developing countries that often leads to overtopping and subsequent failures.

3.3.2 Design of Leats

The flow capacity of a leat is governed by the basic equation $Q = AV$

where Q = flow
A = area (m^2)
V = velocity (m/s)

Leats can be designed by use of Manning's equation which can be written as

$$V = \frac{R^{2/3} S^{1/2}}{n}$$

where V = velocity (m/s)
R = hydraulic radius
= Area (m^2)/wetted perimeter (m)
S = slope of leat
n = Manning's roughness coefficient

Typical values for Manning's n are given in Table 3.1. (Ref. 7)

Manning's equation can be used for determining the flow capacity of an existing leat by inputting values for leat area (area of flow only), the wetted perimeter of the leat, and the leat slope, to yield a value of velocity which can then be multiplied by Area to give flow volume. Conversely the slope and shape required for a leat to pass a given flow volume can be determined.

If Manning's equation is used to determine the shape of a leat, characterized by its hydraulic radius R, it is useful to note that given the profile to be used for the leat, there is a specific value for R which provides the most efficient section. The value of R for the most efficient canal section for commonly used profiles (Figure 3.6) is given in Table 3.2, whilst Table 3.3 gives cross-sectional dimensions of the most efficient cross-sections for common profiles (Ref. 15).

3.4 Pipelines

For pipelines it is useful to consider two categories

1) Low pressure pipelines
2) High pressure pipelines

3.4.1 Low Pressure or Gravity Pipelines

Low pressure or gravity pipelines are used instead of leats to convey water from intake works to the powerhouse or header tank junction with the high pressure pipeline. Pipelines usually run under gravity, however some types can withstand low presures. As such pipelines are usually laid below ground in trenches on a gravel bed surround. Types of material employed are concrete, lower pressure PVC and glass reinforced plastic (GRP). A useful reference for the design of pipelines flowing both full and part full is "Tables for the hydraulic design of pipes and sewers" produced by Hydraulics Research, Wallingford.

3.4.2 High Pressure Pipelines

High pressure pipelines are used to convey water from the intake works, forebay or header tank to the powerhouse. The main types of pipe used are ductile iron, glass reinforced plastic and steel; choice of pipe is dependent upon pressure rating and site conditions.

A summary of the main types, pressure ratings, diameters and advantages and disadvantages are given in Table 3.4. The most commonly employed are ductile iron and glass reinforced plastic, and they can be laid in trenches below ground or on piers above ground.

3.4.3 Pipeline Design

Pipelines must be selected to withstand the normal operating pressure plus occasional surge pressures. The usual process is to select a pipe which has a rated working pressure a little in excess of the static pressure of the system and subsequently to check that this pipe can also withstand the maximum pressure surge within its margins of safety. (Such calculations are complex and should only be undertaken by a competent engineer).

The selection of pipeline diameter is based on the rated discharge and pipe friction losses. Such losses vary with pipeline material, and for a detailed analysis for large schemes where the pipeline cost is a major part of the capital it would be necessary to optimize pipe diameters over the operating range of the installation. In small scale hydro however, pipe diameter is usually selected to give a loss of head along the straight pipe length equivalent to 5% of the gross head. In this way, when a further allowance of say 5% has been made for losses at valves and bends, a net operating head (at design flow) of 90% of gross head is attained.

For a rigorous analysis it is necessary to solve the pipe friction equation

$$hf = \frac{4fLv^2}{2gD}$$

where hf = head loss in m
f = friction factor
L = pipeline length in m
v = flow velocity in m/s
D = pipe diameter in m
g = gravitational constant ($9.81 m/s^2$)

In the above equation, pipeline length and flows are known. Thus by imputting a value for pipeline diameter and frictional factor the value of hf is obtained. Frictional factor is obtained from the Moody diagram (Figure 3.7), which requires a knowledge of the relative roughness of the pipe K. Typical values of K for various pipeline material are shown in Table 3.5 (Ref. 16).

The pipe friction equation relates to losses along straight lengths of pipe, however allowances can also be made for losses at bends, valves and tapers by equating them to equivalent lengths of straight pipe (Figure 3.8) (Ref. 14). These equivalent pipeline lengths should be added to straight pipe length to obtain the overall length in the pipe friction equation.

For a preliminary analysis, by adopting an average roughness figure for commonly used pipeline types, a pipeline design graph (Figure 3.9) can be used for calculating pipeline diameter eg. with a gross head of 50m and a pipeline length of 200m, with allowable head loss of 5%, the loss per 100m of pipe is 1.25m.

3.5 Turbines

A variety of hydraulic turbines has been developed to exploit a range of head and flow conditions. These can be divided into two main groups:-

1) Impulse turbines
2) Reaction turbines

The range of application of turbine types for small hydro-electric generation is shown in Figure 3.10. For some conditions Figure 3.10 shows that more than one type of machine is applicable. Final selection is dependent upon performance (ie. efficiency at various discharges), cost and site layout.

3.5.1 Impulse Turbines

In an impulse turbine, all the available head is converted into kinetic energy by one or more nozzles through which the water is formed into free jets which strike the runner. There are three main types of impulse turbine:-

1) Pelton Wheel
2) Turgo Wheel
3) Crossflow Turbine

Whilst the crossflow is predominately an impulse machine, it can be used with a draft tube and hence as a reaction turbine. Accordingly, in the following sections when the term impulse is used it refers to Pelton and turgo machines only, the crossflow being treated separately.

3.5.1.1 Pelton Wheel

This turbine runner consists of a wheel to which a number of buckets are attached around the perimeter. The jet or jets are directed onto the buckets tangentially in the plane of the wheel. Flow control in larger installations is achieved using adjustable needle valves to change the jet area and thus its discharge. Needle valves and their associated controls are too expensive for very small projects (say less than 50kW) where a more basic approach must be adopted using inexpensive on/off gate valves. In such cases, a twin-jet arrangement equipped with jets of differing sizes can provide sufficient flow variation simply by use of one, or other, or both of the jets. Pelton runners must be located above the maximum tailwater level since operation with the runner immersed is inefficient. The reduction in head caused is usually acceptable as Pelton wheels are generally only applied to heads in excess of 30m.

A Pelton runner and spear valve arrangement is shown in Figure 3.11. Rotational speeds for Pelton wheels vary from 200rpm upwards, depending upon the head and size of wheel used.

3.5.1.2 Turgo Wheel

This machine is similar to a Pelton wheel although the jet is directed through the wheel at an angle of about 20°, and the runner has blades rather than buckets. The action of the water on the Turgo runner is shown in Figure 3.12. Since water enters through one side of the runner, and emerges through the other it is able to pass a greater volume of water for a given size (and operating conditions) than the Pelton wheel where volume is restricted due to bucket interference with the incoming jet. Alternatively, for the same head and flow, a smaller diameter Turgo than Pelton can be used so producing higher runner speeds and a better chance of direct coupling.

Turgo wheels operate in the head range of 30 to 300m.

3.5.1.3 Crossflow Turbine

This machine has a wide range of application for small-scale hydro-electric generation. Heads from 2 to 100m can be accommodated with flows of up to 7m^3/s for low-head applications. The machine is characterized by a wide water stream of rectangular cross-section flowing through the cylindrical runner at right angles to the axis; its operation is shown in Figure 3.13.

Flow is regulated by a subdivided guide blade which directs a jet of water at the runner. This blade, when divided in the ratio 1:2 allows partial flow admission and gives the turbine an extremely favourable operating characteristic - discharges down to 1/6 of rated flow can be accommodated.

Unlike conventional impulse turbines the crossflow turbine can operate efficiently at low heads and in such applications is often equipped with a suction pipe for the runner to operate in a partial vacuum. Use of the suction tube means most of the head can be exploited and allows the runner to be set clear of the tailwater level thus avoiding flood flows and simplifying construction. Operating speeds can range from 200-2000 rpm, although in the medium head range (10-30m) for which it is normally applied, a speed increasing drive is usually required to allow use of a standard generator.

3.5.2 Reaction Turbines

In reaction turbines flow from headwater through to tailwater takes place in an enclosed pressure system. At the entrance to the runner only a part of the available head is converted to kinetic energy, the rest remaining as pressure head which varies throughout the water passage and in the draft tube, producing an effective suction on the downstream side of the turbine runner. The two principal types of reaction turbine in use today are: the Francis turbine and the propeller turbine.

3.5.2.1 Francis Turbine

Flow through a Francis turbine passes inwardly through a circular series of guide vanes, pivotally adjustable for flow regulation and forming contracting passages in which part of the head is converted into kinetic energy. Flow issues from the guide vanes in a direction having both radial and tangential velocity components. Flow then enters the runner passages in which the radial component of motion is turned to an axial direction, whilst the tangential component is deflected by the runner vanes until only a small component remains. Flow passes out axially into a draft tube, which, by means of its gradually increasing cross-sectional area, reduces the flow velocity, thus recovering a large part of the remaining kinetic energy as effective head. This is seen as a reduction in the static pressure against which the runner discharges. With the use of a draft tube, in many applications Francis turbine runners can be located above tailwater. However, manufacturers information should be consulted to determine a suitable setting level with respect to tailwater since too high a setting can reduce pressure within the turbine passages to such an extent that cavitation occurs. Cavitation in a water-turbine is analogous to 'pinking' in a petrol engine. It can rapidly damage runners and reduces efficiency. The operation of a Francis turbine is shown in Figure 3.14.

With the exception of low head applications, (<10 metres) Francis turbines are installed with a spiral-casing of circular section and constructed of iron or steel castings or fabricated steel plate. A typical example of such a layout is shown in Figure 3.15. For low head installations an open-flume arrangement can be used where the guide vanes and runner are installed in open flume into which the headwater extends (Figure 3.16). Flow regulation by adjustment of the guide vane position can be achieved over a reasonable range although efficiency at reduced discharge is not as good as for the crossflow machine, but on the other hand, peak efficiency is usually slightly better.

Of similar form, but lacking adjustable guide vanes, Centrifugal pumps can be used in place of Francis turbines where flow regulation is not required because a steady flow can be utilized. Reverse-running pumps represent a considerably cheaper solution, although again efficiency may be a little lower.

Due to a wide range of application, operating speeds also cover a wide range, some direct drives are possible but at lower heads a speed increaser, either a gearbox or belt, is usually required to drive the generator.

3.5.2.2 Propeller Turbines

Flow through the runner of a propeller turbine is essentially axial as it passes through the annular 'throat' of the water passage formed by the runner hub and discharge ring. The runner has usually 3 to 5 blades with free outer ends revolving within a stationary discharge ring, the clearance between blades and ring being as small as possible. A circlet of guide vanes, either fixed or adjustable, direct flow onto the runner. Similarly the turbine runner blades can be either fixed or adjustable. A conical draft tube of gradually increasing area is used to recover as effective head some of the remaining kinetic head.

For small-scale hydro the common arrangements are either to have both runner and guide vanes fixed or to have only the runner blades adjustable (this gives a wider range of efficient operation than with only variable guide vanes). Propeller turbines with fixed blades and guide vanes can have high efficiency at one particular head and discharge, but no discharge regulation is possible, as this is determined by the head and speed of rotation. This type of machine is commonly installed in multiples of similar machines and the number in operation at any one time is used to control the discharge. When adjustable blades are used an operating mechanism is incorporated within the runner hub to provide remote control, although for some of the very small propeller turbines, adjustments can only be made manually and whilst the machine is stopped.

Propeller turbines are generally suitable for heads up to about 30 metres, and a range of diameters allows their selection for a range of discharges. As for Francis turbines a draft tube is incorporated and the setting level of the runner with respect to tailwater must be carefully chosen to avoid cavitation. In low head applications a centreline setting at or slightly above tailwater can be accepted, but when high heads are exploited the runner must usually be below tailwater. Thus at the upper head limit of their application the civil engineering costs of powerhouse excavation and construction below tailwater tend to support the use of an alternative type of machine, perhaps a crossflow or Francis. Operating speeds are low and a speed increaser is almost invariably required.

For small-scale hydro three arrangements of propeller turbine and generator are available, these are: the tubular (or S-type) turbine, the right-angle drive unit and the bulb turbine shown in Figure 3.17. As can be seen the right-angle drive and bulb units are quite compact compared to the tubular machine: however, the bulb unit is only available as a 'packaged' unit for small outputs (<50kW). The right-angle drive arrangement has the advantage that its speed increaser is incorporated within the bevel gear drive to the generator - a separate gearbox is required for tubular machines. A rim-drive turbine having a belt drive from the runner periphery to the generator is a recent innovation. This has the advantage that the generator can be conveniently located and the necessary step up of speed is incorporated.

Because flow cannot be completely stopped by closing the turbine runner blades or guide vanes, it is usual to locate a butterfly or gate valve immediately upstream of a propeller turbine. Alternatives are closure of a sluice gate at the intake or, where a siphon is used to draw flow over a dam or embankment, admission of air can break the siphonic action. For larger machines, a draft tube gate may be incorporated with the provision of stoplogs at the entrance.

3.6 Speed Increasing Drives

Turbine operating speeds are determined to give optimum efficiency under the site conditions and as described, speeds vary considerably (from 200rpm - 2000 rpm). However, electrical generator operating speeds are fixed by their frequency of output and number of poles, and for economy, high speed generators are preferred (operating speeds of 750, 1000, 1500 and 3000rpm). With large hydropower schemes, where all turbines are custom designed, generators are coupled directly to the turbine. For small schemes however this is not possible and hence a speed increaser is required to couple the turbine to the generator. The most commonly available generator speed being 1500rpm.

Several types of speed increasing drive are available:-

3.6.1 Belt Drives

There are three main types of belt drive available:- they are, flat belts, V-belts and timing belts.

The most commonly employed belt in the past was the flat belt made from cotton or canvas, since it was easy to repair and ran over pulleys simpler to fabricate than with other belt types. Modern flat belts are made of synthetic fibres with special facing, with a typical efficiency of 98%. The main disadvantages of the flat belt are that it must be aligned carefully to ensure that the belt does not run off the pulley, and that it must operate under relatively high tension to prevent slippage, thus placing greater loads on the bearings, shaft and mountings.

V-belts, made of rubber reinforced with cotton cords and fabric, have the advantage when compared with flat belts that they are capable of operating with slightly misaligned pulleys. Efficiencies typically range from 95% to 97% although low belt tension can cause efficiency to fall to 92%. V-belts are available with different cross-sectional areas to suit a range of powers, and several belts can be used together where the power transmitted exceeds the rating of a single belt.

A toothed belt or timing belt can also be used to transmit power. It has the advantage when compared to the flat belt in that it requires low tension since it relies on mechanical coupling rather than friction. However it is noisy and often more expensive than other types of belt.

Information for the design of belt systems is best obtained by reference to manufacturers.

3.6.2 Chain Drives

Chain drives, although used in the past are not now commonly employed in hydro-power generation, although they do have the advantage of high efficiency, typically 98-99%. There main disadvantages are cost and noise when compared to belt driven systems.

3.6.3 Gear Boxes

A number of gear box types are available commercially for use in hydropower generation. They are commonly employed at larger power ratings where direct coupling is not possible. Efficiencies are typically of the order of 98%. Bevel gears can also be used to increase speed as well as connect vertical and horizontal shafts.

3.7 Electrical Equipment

Hydro-electric installations consist of a hydraulic turbine driving a generator which is connected to an electrical supply system. For each specific case the type and size of energy requirement determines the most suitable arrangement of electrical equipment. Several arrangements are possible: these options should be considered in order to maximize the benefits from generation.

Two basic arrangements are considered: either an isolated generating system or a generating system in parallel with the local electricity network. Schemes operated for direct supply to the grid system fall within this category as do schemes operated for supply to local loads in parallel with the grid system.

For plants of output in excess of say 50kW, parallel operation with the grid network is advantageous. For smaller outputs isolated operation is appropriate since the protection equipment necessary for parallel operation becomes disproportionately expensive. Parallel operation is generally advantageous since electrical switching arrangements are simplified and an increased income can be obtained from the sale of excess energy.

When parallel operation is adopted, either a synchronous (alternator) or induction (asynchronous) generator can be used. When an isolated load is fed from a hydro-electric installation, a synchronous generator will invariably be used.

Construction of an electric power transmission line over a distance in excess of (say) 1km is likely to prove expensive. Where it becomes necessary to construct long transmission lines, the power losses along the line should be considered with the plant efficiency when predicting the energy available. For such lines, a transformer would normally be placed at each end of the line so that voltage can be increased and the transmission losses reduced.

3.7.1 Generators

There are two main types of generator, the induction (asynchronous) generator and the synchronous generator (or alternator). Both these types are used for the production of alternating current (A.C.). Direct current (D.C.) machines are available for small ouputs (several kilowatts) where they can be used for battery charging etc.

A.C. frequency is determined by the rotational speed of the generator and the number of poles according to the formula:-

$$f = Np$$

where f = frequency (Hz)
N = rotational speed (revs/sec)
p = number of pairs of poles

In much of the world outside North America the frequency of generation is fixed at 50Hz as all electrical appliances are designed to operate at this frequency. High speed generators are smaller and more economical, and hence the most commonly available generator speeds are 1500 rpm (4 pole) and 1000 rpm (6 pole).

Electrical equipment ratings are specified in kVA corresponding to the product of output voltage and current. Thus the kVA rating makes allowances for power factor which is typically between 0.8 and 1.0 depending upon the type of load connected. The relationship between power and kVA is:-

$$\text{Power (kW)} = \text{kVA} \times \text{power factor}$$

Either single-phase or three-phase generators can be used, the selection depending upon the size and type of loads to be met. Single-phase generators in excess of 100kVA are rarely used because at higher power ratings 3-phase distribution systems are used.

For cost reasons, small generators of less than (say) 20kVA are nearly always single phase. Generators connected for parallel operation are usually in excess of 50kVA and are thus usually 3 phase. For 3-phase generators, the current for each phase is designed to accommodate one-third of the generators rated power output. It is important that the power drawn from each phase is balanced; otherwise excess power may flow through one or two of the circuits, overheating the generator windings and eventually causing the insulation to breakdown and the generator to fail.

Single phase generators are more economic at lower power ratings since they require switchgear, monitoring, control and protection equipment for only one phase rather than three.

Generator overspeed can be a serious problem in small hydro plants since during load rejection the turbine will accelerate to the no-load runaway speed. Runaway speeds are dependent upon the turbine type but are in the range 130-250% of synchronous speed. It is necessary therefore to have generators which can withstand the runaway speed or to ensure that the plant is either shut down or a secondary load applied to the generator in the event of primary load rejection. Most generator manufacturers will offer generators able to withstand 80% overspeed.

3.7.1.1 Synchronous Generators

A synchronous generator is an A.C. machine in which the frequency of the armature current depends on rotor speed. A constant speed of rotation is thus necessary for constant frequency output.

Three main types of synchronous generator (or alternator) are available; rotating armature, rotating field and brushless. The traditional type of alternator is the rotating armature slip-ring machine, where the excitation current is supplied from the transformer to the stator. The output is carried from the armature via the slip rings to the output terminals. Most of these machines are simple, requiring only routine maintenance to the brushes and slip rings. The rotating field machine is similar in construction, but the field rotates and is supplied with current via the slip rings; the main power is taken from the stator. The advantage with this type is that only a relatively small excitation current is carried by the slip rings. The fully brushless alternator consists of two separate units, the excitor and the main generator connected to the same shaft. Power is fed to the excitor stator to induce A.C. in the excitor rotor. A rotating diode assembly rectifies this, and the resulting D.C. current passes through the main rotating field winding on the shaft. The output is taken from the stator and a small amount of power is fed back into the excitor stator, usually via an automatic voltage regulator (AVR). It is this AVR which has caused problems in hydro plant, since its failure means that the generator cannot function (Ref. 17).

3.7.1.2 Induction Generators

An induction or asynchronous generator is essentially an induction motor if the prime mover runs at less than synchronous speed. When an A.C. current is passed through the stator winding a rotating magnetic field is produced and a voltage induced in the rotor windings. Hence, for the preferred squirrel-cage machines no connections are required to the rotor windings. When the rotor speed is below synchronous speed the relative motion of the induced magnetic field and the stator field causes a motoring action and power is drawn from the electricity system. However, when rotor speed rises above synchronous speed, torque is reversed and power is generated.

The induction generator usually relies on the mains supply for excitation, frequency and voltage control, although it can be self excited by using a capacitor bank to supply the magnetizing reactive power; however such an application is uncommon.

The induction generator can have advantages compared to the synchronous generator when used for parallel operation, since a synchronizing unit is not required, and in the event of a mains failure the induction generator ceases to produce power and consequently protection is simplified. The induction generator is most often found to be less expensive than the compariable synchronous machine.

3.8 Operation and Control

Two forms of operation are possible; schemes which are operated in isolation from the local grid system, and schemes which are operated in parallel with the grid system.

3.8.1 Isolated Operation

For this type a hydro scheme is developed to meet isolated loads which could be a factory, house or for rural electrification. Isolated operation would normally be preferred for outputs below 50kW as the cost of protection and metering associated with parallel operation is too large a proportion of overall cost at low outputs. As scheme size increases, parallel operation may be preferred since this simplifies switching and control. However this may not be possible due to a variety of causes eg. the lack of a grid system, the inability of a system to accept the output, the cost of transmission etc.

When a generator is operating in isolation, the generator power output and the electrical load must be balanced to maintain the required constant rotational speed and thus constant frequency A.C. output. There are two ways in which this can be achieved: either by flow control in which the turbine power output is adjusted to match the load, or by load control in which the load on the prime mover is maintained equal to the hydraulic power output.

Flow control is the traditional method of control whereby a governor is used to adjust water flow to the turbine in response to speed changes caused by a change of load on the generator. A hydraulic or electro-mechanical governor is linked to the flow control mechanism on the turbine (either the runner blades, guide vanes or spear valve). Such types of governing system are usually too expensive for use on small isolated schemes and this has led to the development of the significantly cheaper electronic load governor (ELG).

The ELG consists of an electronic circuit which provides a variable dump load, which, added to the real load equals the power being produced from the hydropower set. This is achieved by linking power output to a secondary resistance circuit in response to changes in frequency (or generated voltage). The secondary circuit or ballast load, may be used for low priority energy demands such as an immersion heater or space heaters. The total of ballast load plus the priority load must be equal at all times to the output of the generator, and the ballast load must be large enough to absorb the maximum generator output (Ref. 18).

3.8.2 Parallel Operation

In this system the hydro scheme is operated in parallel with the local electricity grid. The grid system maintains voltage and frequency of generation and hence there is no requirement for separate flow or load governing.

Parallel operation can be undertaken with both induction and synchronous generators, however in the case of the synchronous generator, a synchronizing unit is required to allow connection of the generator to the mains supply. Protection and monitoring equipment in the form of over and under voltage and frequency relays are required so that in the event of a fault on either the generator or the mains, the main circuit breaker opens and the scheme is isolated.

If this happens, the generator will then be in a no-load situation and will accelerate to runaway speed. The usual means of dealing with this situation is to initiate a controlled shutdown of the turbine, this can be achieved by an automatic self closing butterfly valve or by closing the vanes on the turbine (Francis or Crossflow runner blades, or propeller guide vanes) or using a jet deflector (turgo or Pelton).

In the case of a synchronous generator, an alternative is to provide a back up load-governor and ballast system which can be used to control the load. This will also allow the turbine to generate in the isolated situation during a mains failure, but such an arrangement is complex.

3.8.3 Automatic flow/level control

In the case of small plants, turbine flow adjustment would normally be undertaken manually. However in larger plants which are mains-connected or where there is a requirement to operate for long periods unattended, an automatic flow/level control system is often incorporated. In this case, the flow reaching the turbine is continually adjusted to ensure a particular level is maintained, either an upstream reservoir/headpond or a downstream tailwater. In this way the maximum generation from the scheme is achieved (Ref. 19).

Material type	n
Smooth timber	0.011
Cement-asbestos pipes, welded steel	0.012
Concrete-lined (high-quality formwork)	0.013
Brickwork well-laid and flush-jointed	0.014
Concrete and cast iron pipes	0.015
Rolled earth: brickwork in poor condition	0.018
Rough-dressed-stone paved, without sharp bends	0.021
Natural stream channel, flowing smoothly in clean conditions	0.030
Standard natural stream or river in stable condition	0.035
River with shallows and meanders and noticeable aquatic growth	0.045
River or stream with rocks and stones, shallow and weedy	0.060
Slow flowing meandering river with pools, slight rapids, very weedy and overgrown	0.100

Table 3.1 Values of Manning's roughness coefficient n for straight, uniform channels

Profile	Hydraulic radius R (m)
Semi circular	$0.4\sqrt{A}$
Trapezoidal	$0.5\ \dfrac{\sin\theta}{2-\cos\theta}\sqrt{A}$
Rectangular or Triangular	$0.35\sqrt{A}$

Table 3.2 Hydraulic radius for most efficient leat sections

Profile	Dimensions
Semi circular	diameter, $d = 4R$
Rectangular	depth, $d = 2R$ width, $w = 4R$
Triangular	depth, $d = 2.8R$ width, $w = 5.7R$
Trapezoidal	depth, $d = 2R$ width, $w = \dfrac{4R}{\sin\theta}$

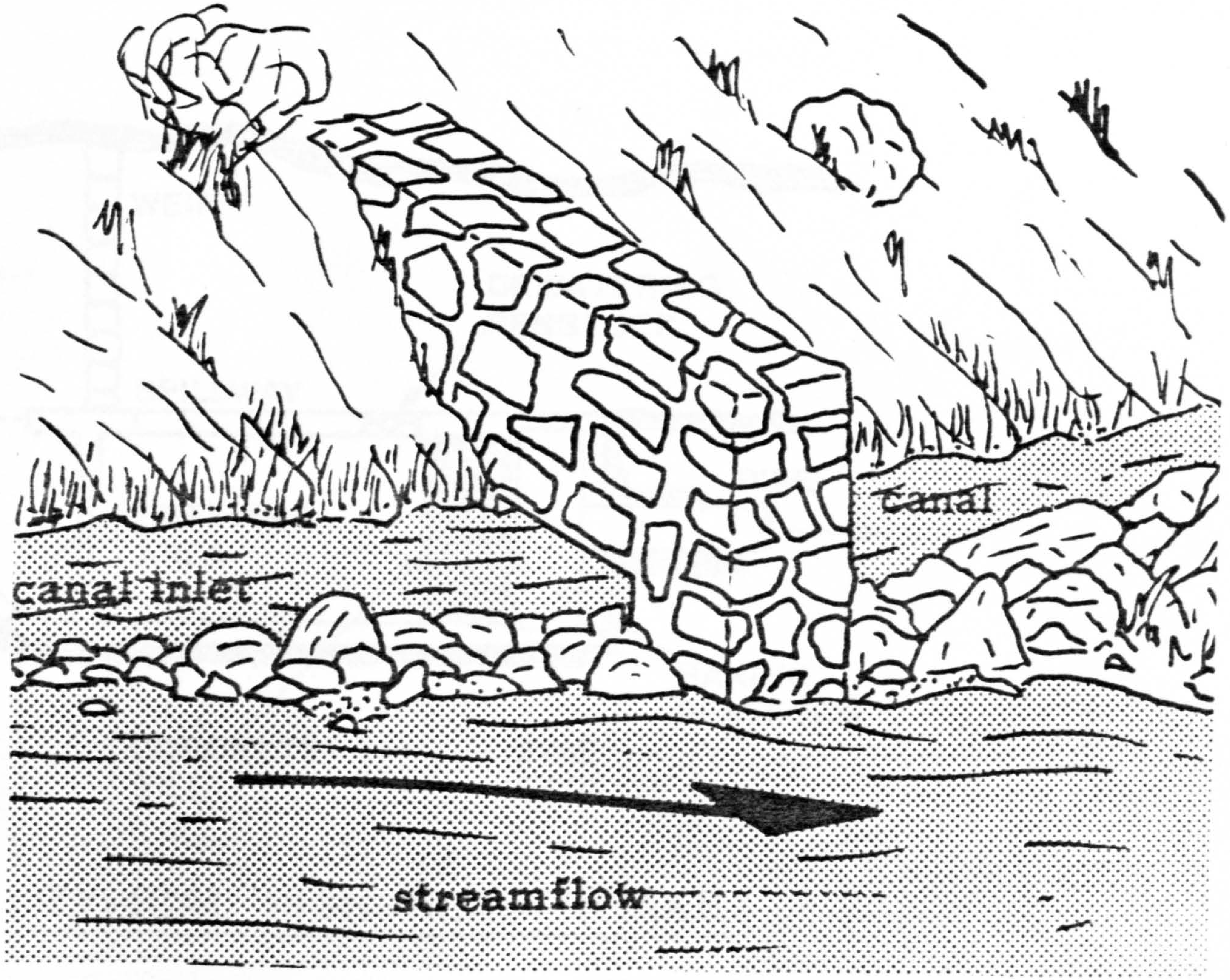
Table 3.3 Dimensions for most efficient leat sections

Pipe Type	Size range (mm)	Pressure rating (m of water)	Comments
Ductile iron	80 - 1600	250 - 400	Cost effective and durable when laid above ground. In trenches do not require a gravel surround but must be wrapped to prevent corrosion. Cement mortar lining reduces internal corrosion. Disadvantage is weight.
Steel tube (seamless)	80 - 400	160 - 4000	Main advantages are high pressure rating and strength. Disadvantages are weight, and requires coating for protection against corrosion. Pipes are joined by on-site welding which can be expensive.
uPVC	80 - 600	60 - 150	Main advantage is light weight, hence easy to install. Small range of sizes only, and uPVC deteriorates due to U.V. light.
Glass reinforced plastic (GRP)	900 - 2500 200 - 1000 200 - 2500	60 - 160 60 - 240 Gravity	Light weight, easy to install and cost effective. Main disadvantage when laying below ground is requirement for prepared bed or granular surround.
Concrete	300 - 2100	Gravity <10m	Useful for gravity or low pressure application, but are heavy compared to GRP.

Table 3.4 Characteristics of commonly available pipe types.

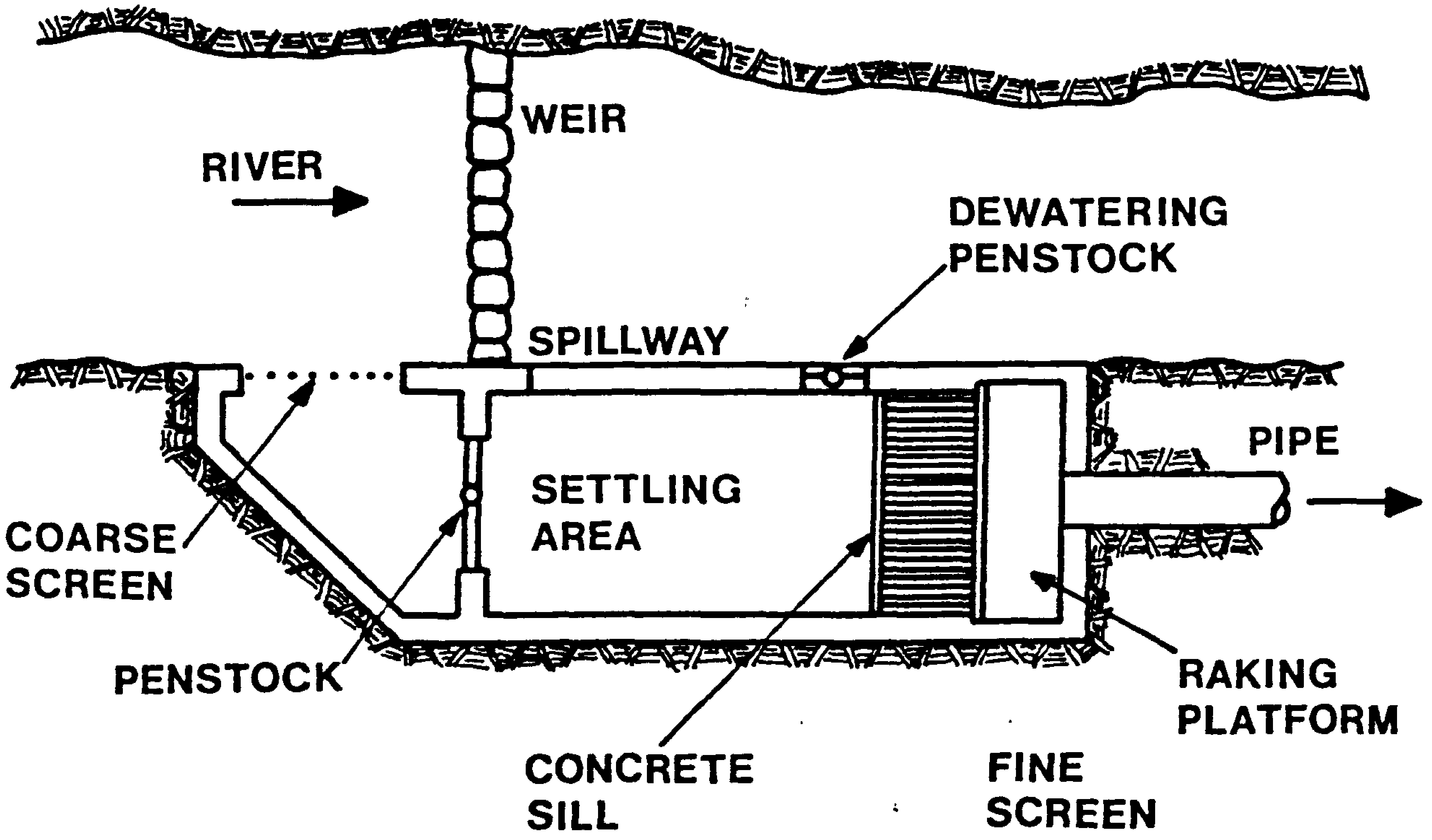
Pipeline material	Relative roughness K (mm)
Riveted steel	1.0 - 10
Concrete	0.3 - 3
Wood stave	0.2 - 1
Cast iron	0.25
Galvanized steel	0.15
Asphalted cast iron	0.12
Commercial steel	0.045
Plastic and GRP	0.003

Table 3.5 Relative Roughness



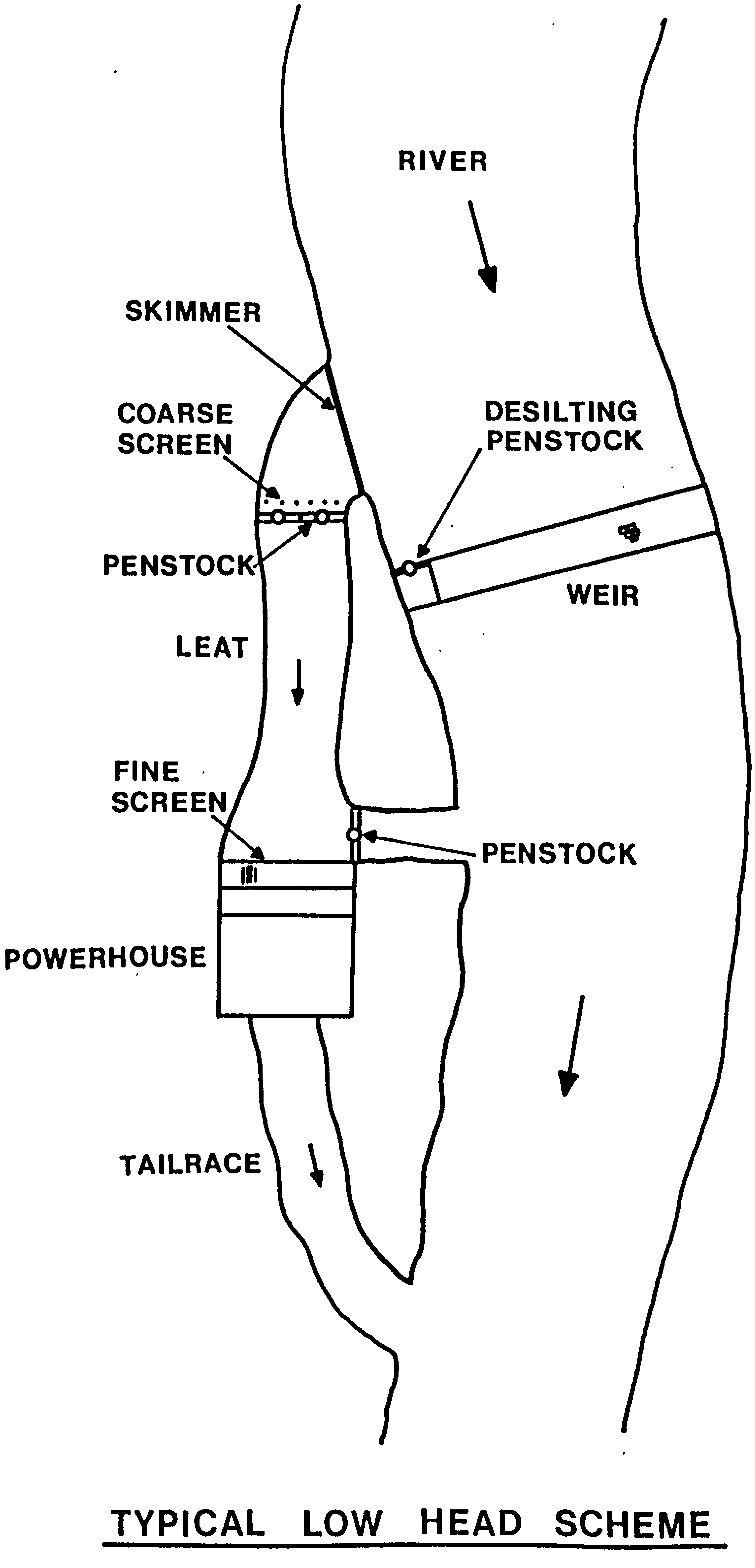
SIMPLE DIVERSION WALL FORMS INTAKE

FIG 3.1



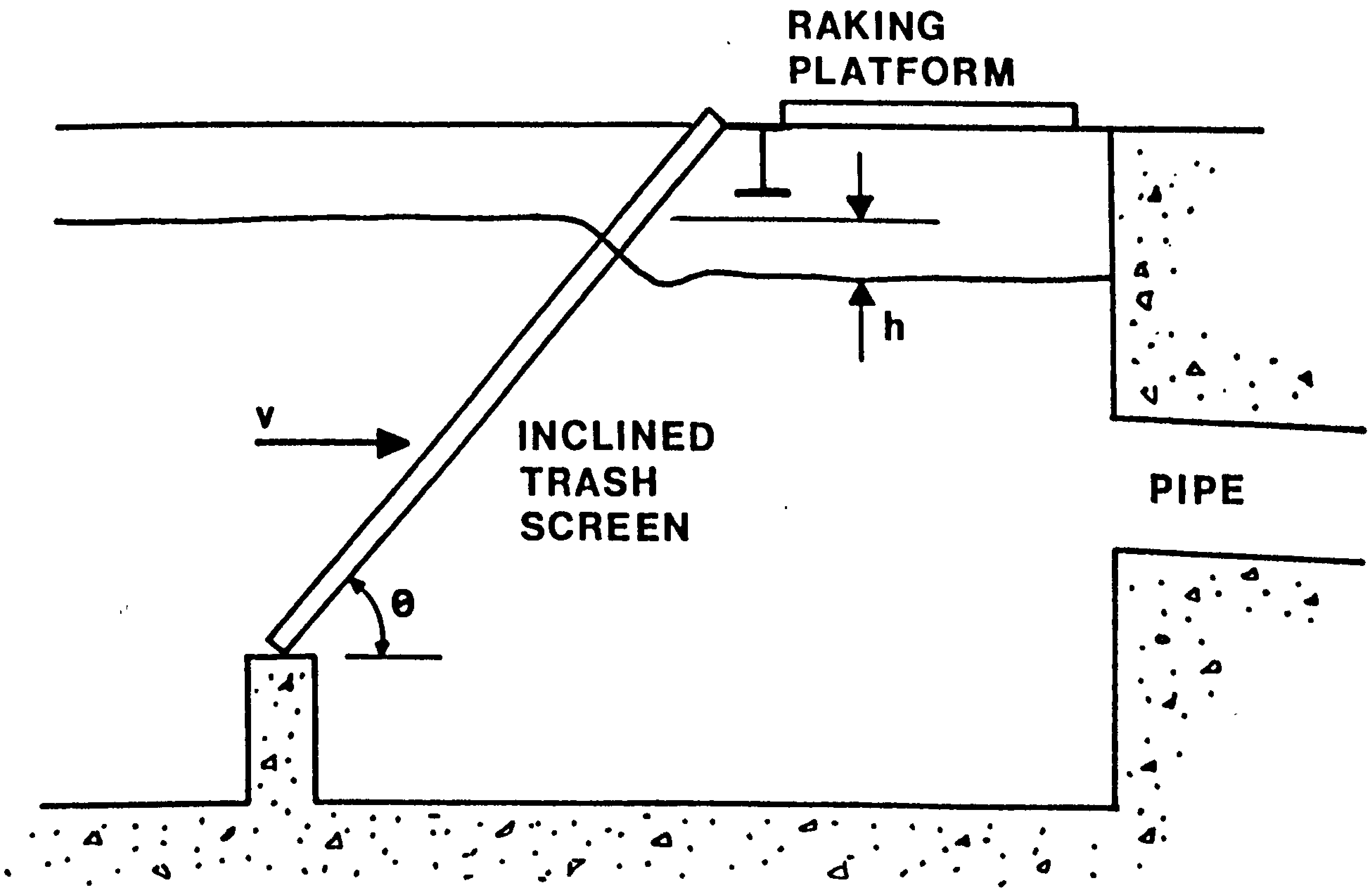
TYPICAL HIGH HEAD INTAKE

FIG 3.2



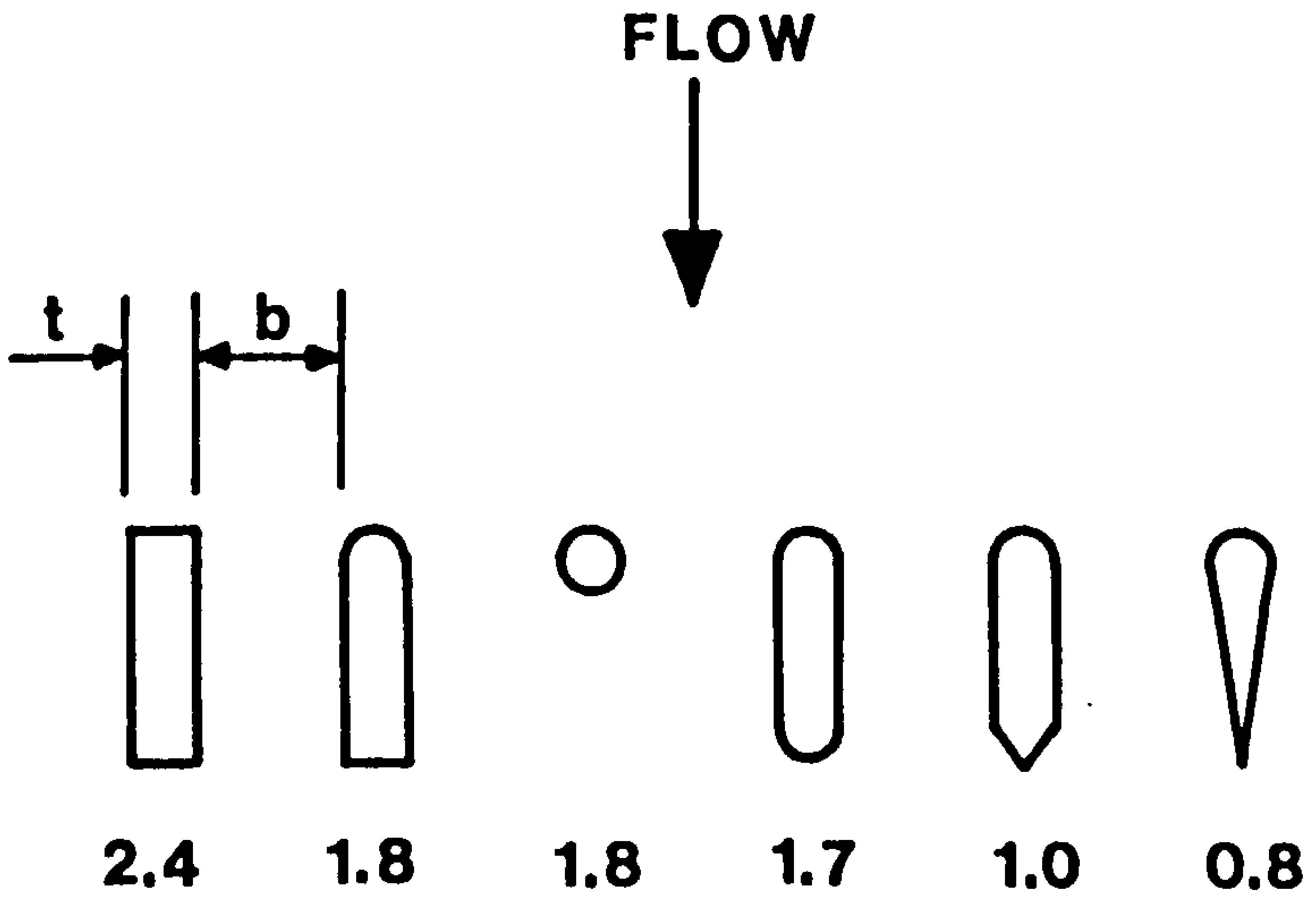
TYPICAL LOW HEAD SCHEME

FIG 3.3



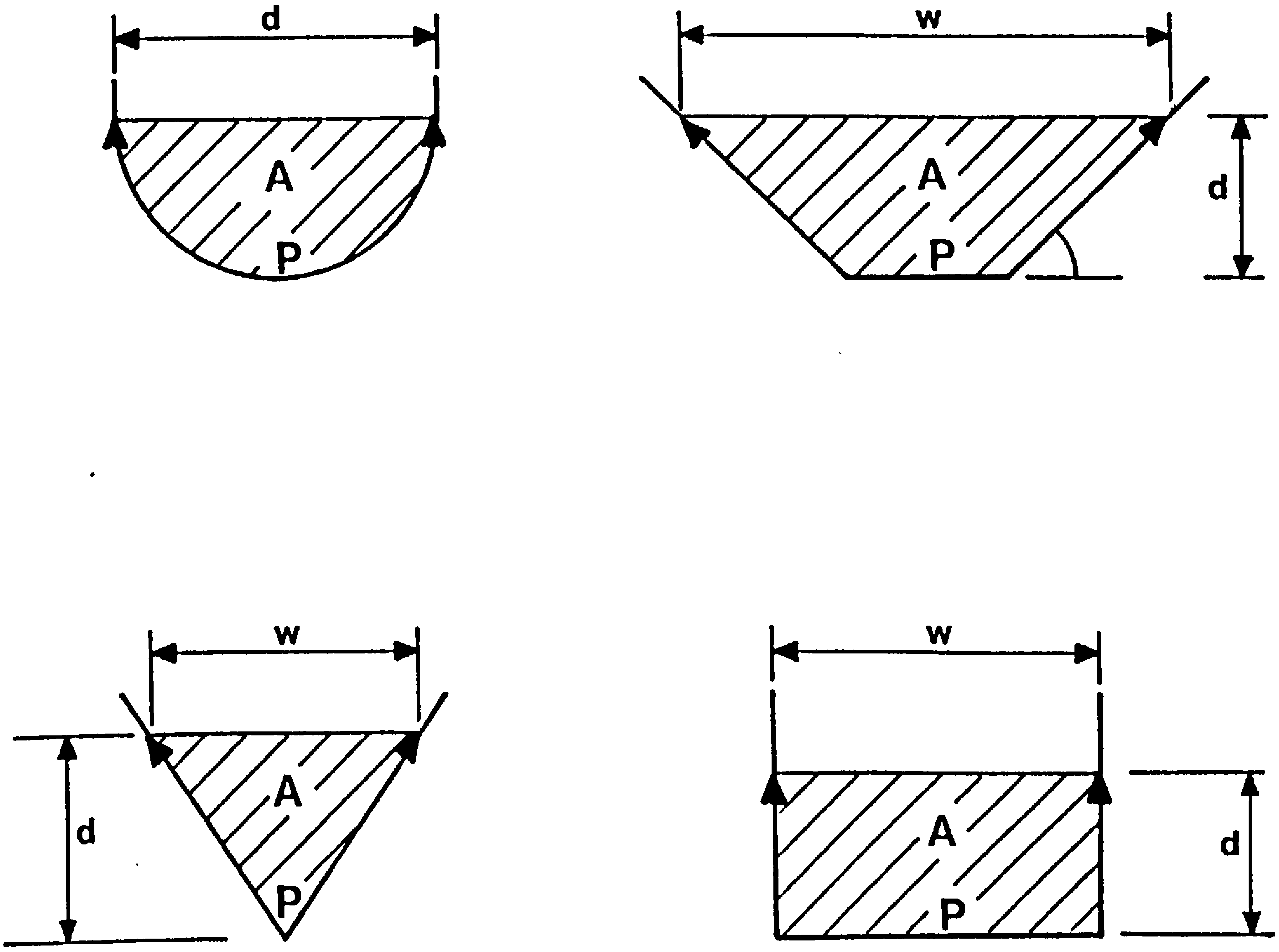
HEADLOSS THROUGH TRASH SCREEN

FIG 3.4



TRASH SCREEN HEADLOSS COEFFICIENTS K

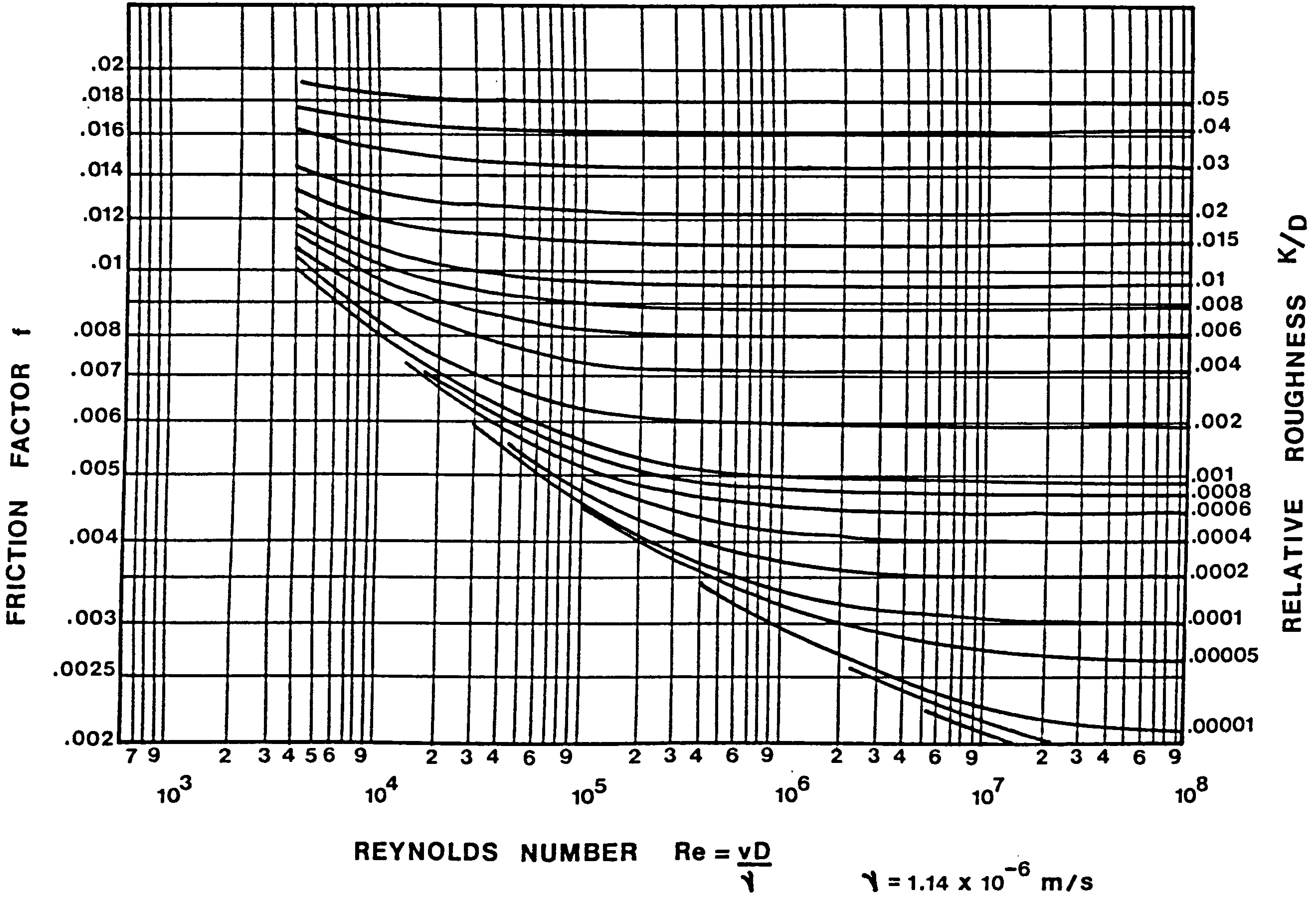
FIG 3.5



COMMON LEAT PROFILES

FOR MOST EFFICIENT SECTION SEE TABLE 3.3

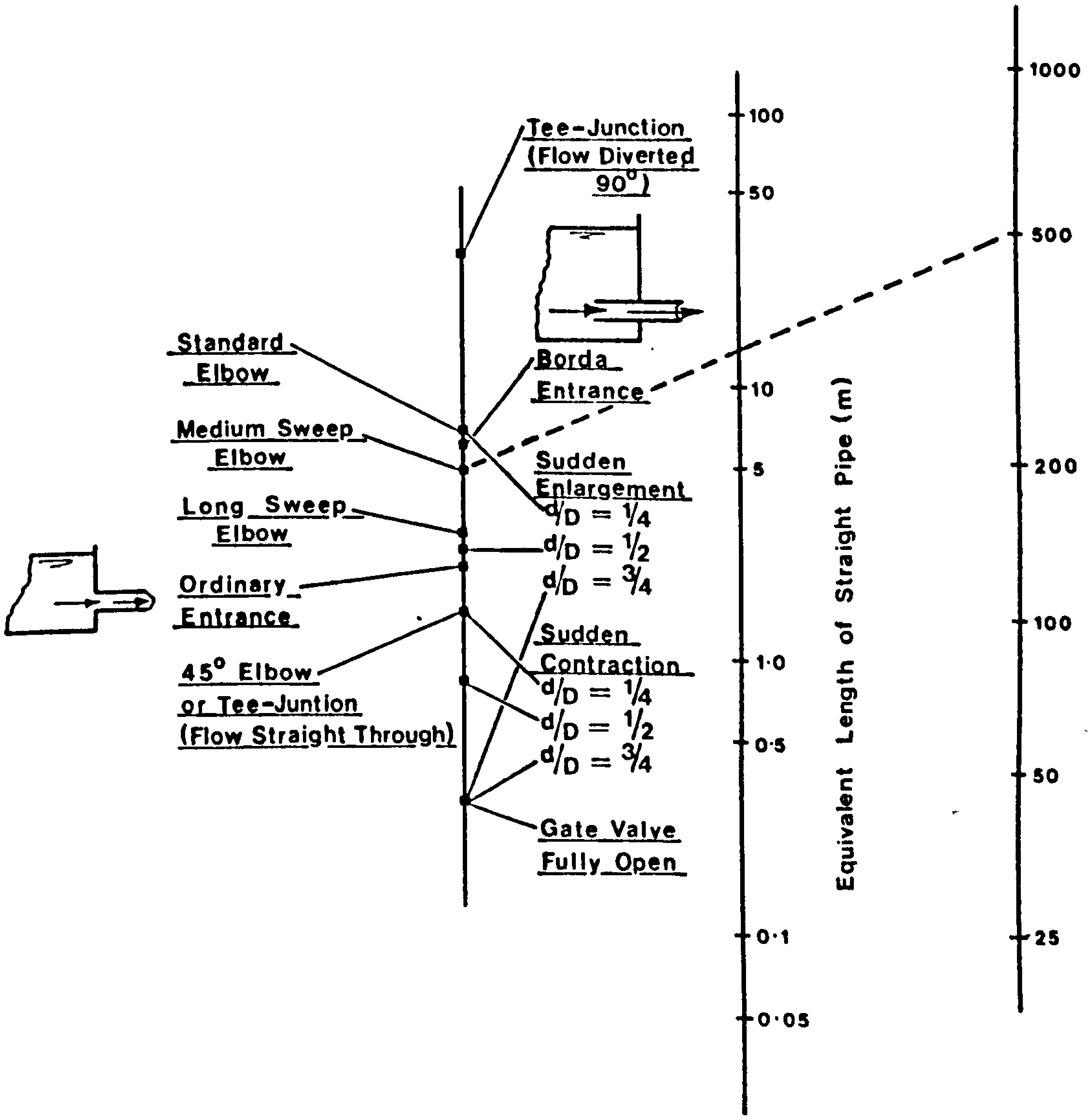
FIG 3.6



MOODY DIAGRAM

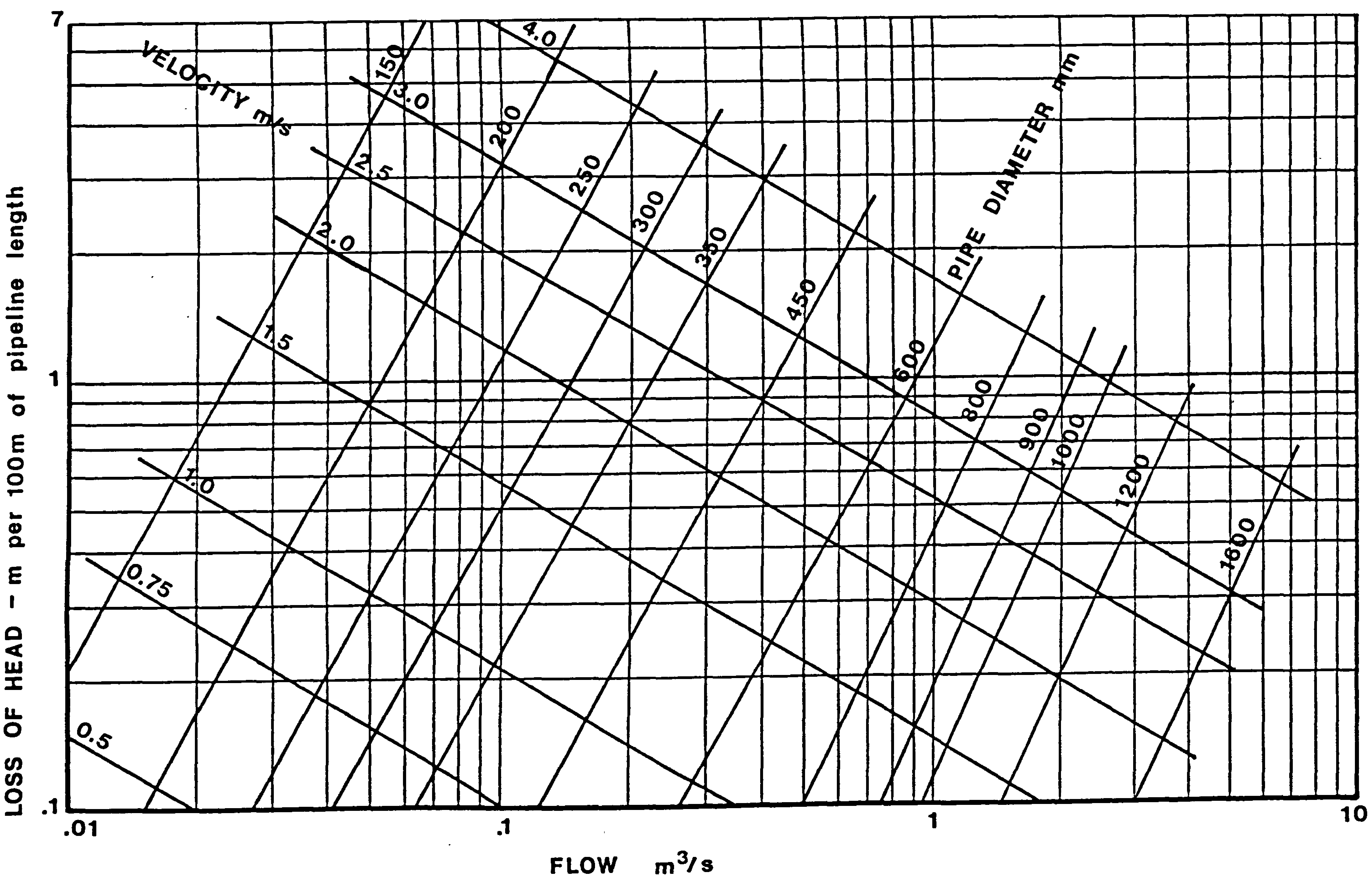
FIG 3.7

Example; For a medium sweep elbow of 500 mm dia., the head loss
is equivalent to that of 15 m of additional pipe



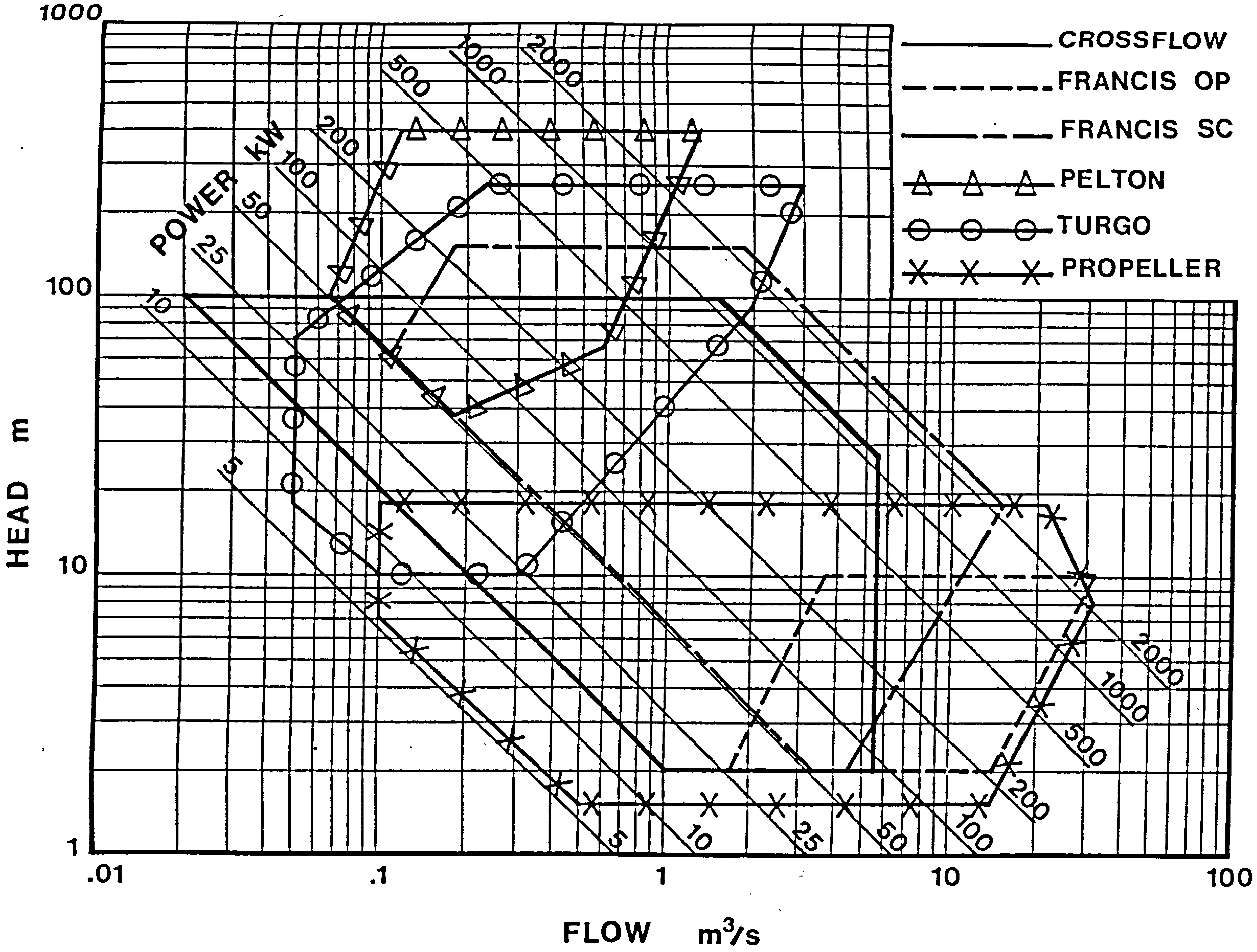
RESISTANCE OF PIPE FITTINGS TO FLOW OF FLUID

FIG 3.8



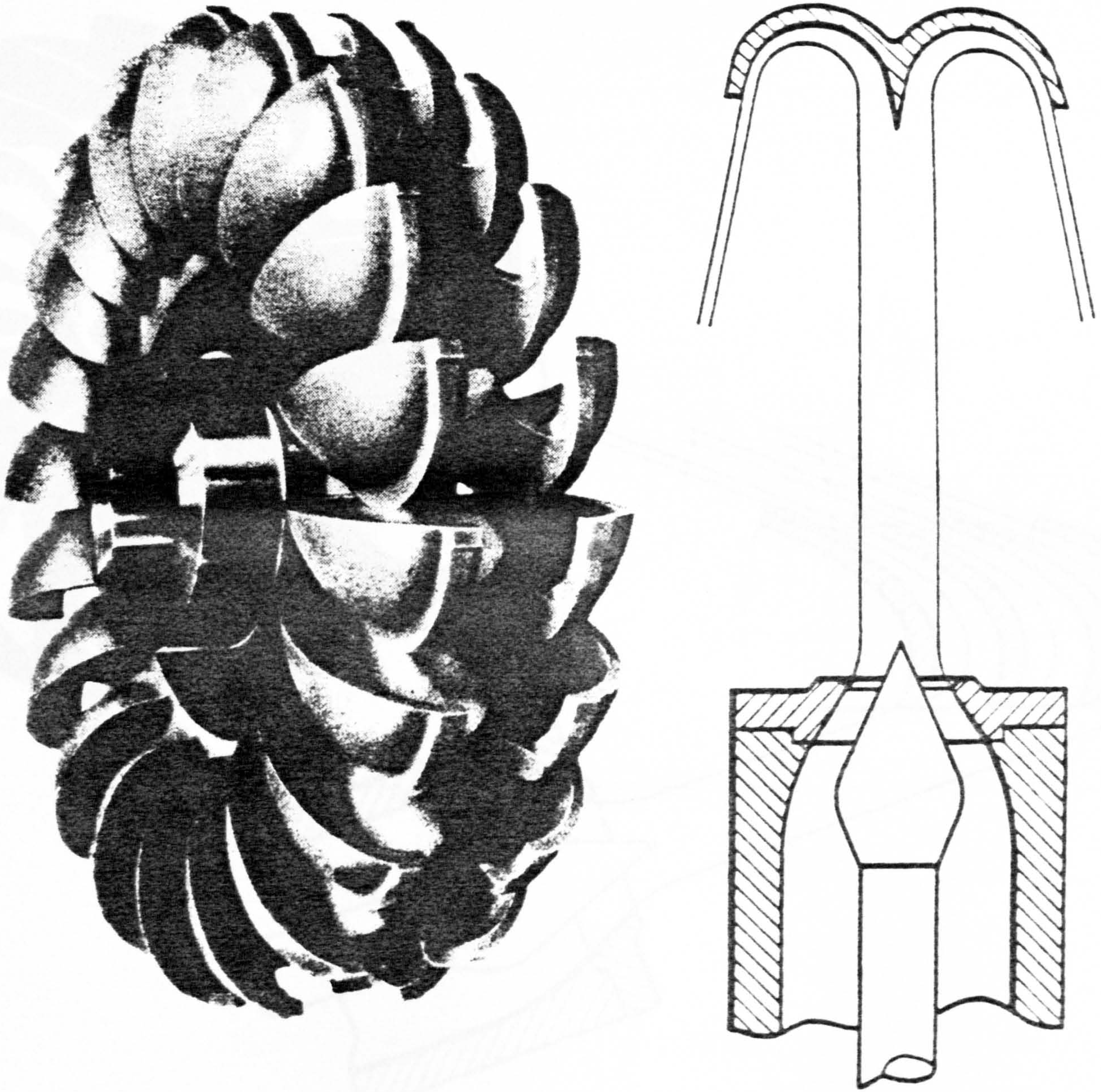
APPROXIMATE PIPELINE DESIGN CHART

FIG 3.9



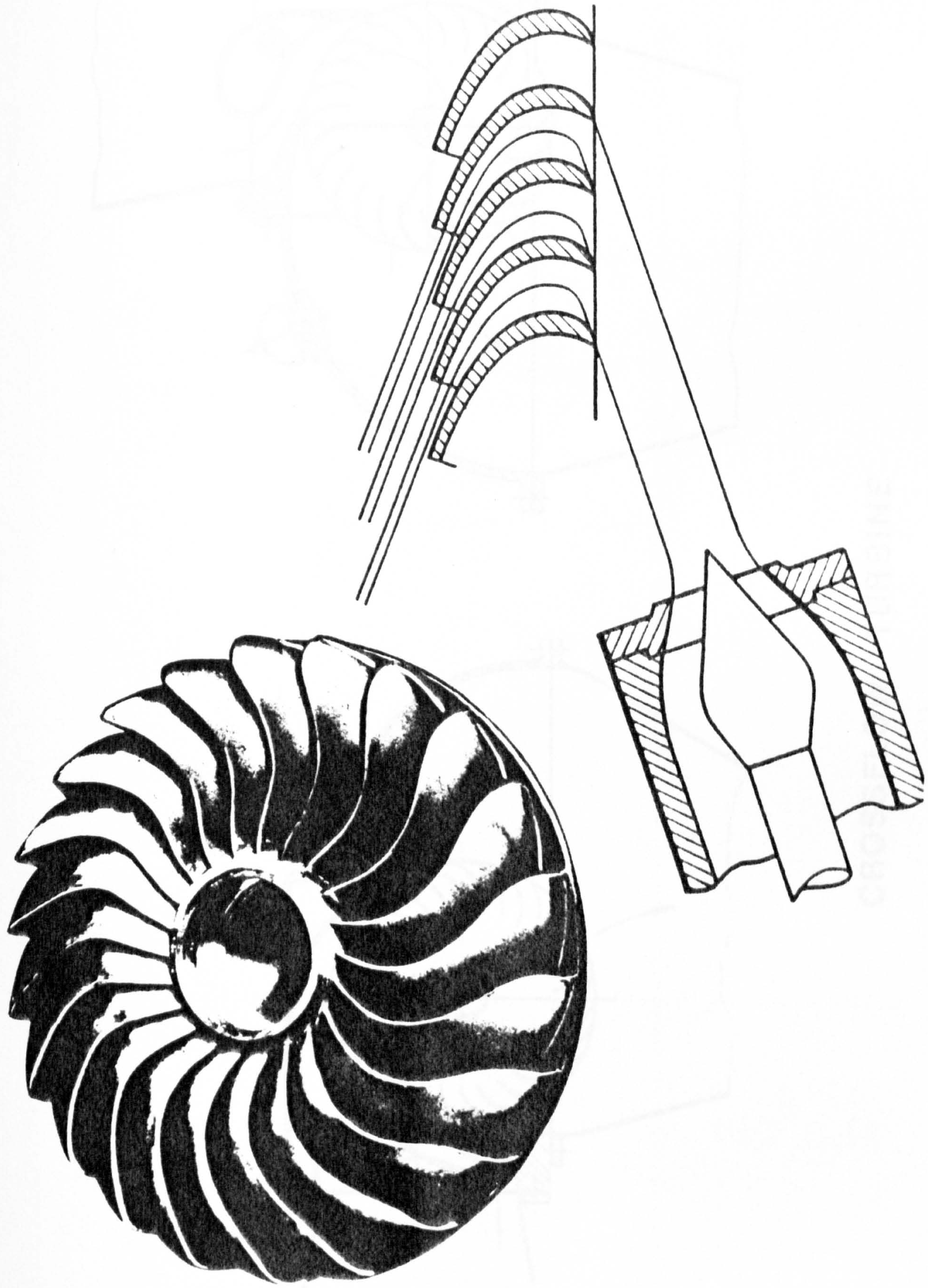
RANGE OF APPLICATION FOR TURBINE TYPES

FIG 3.10



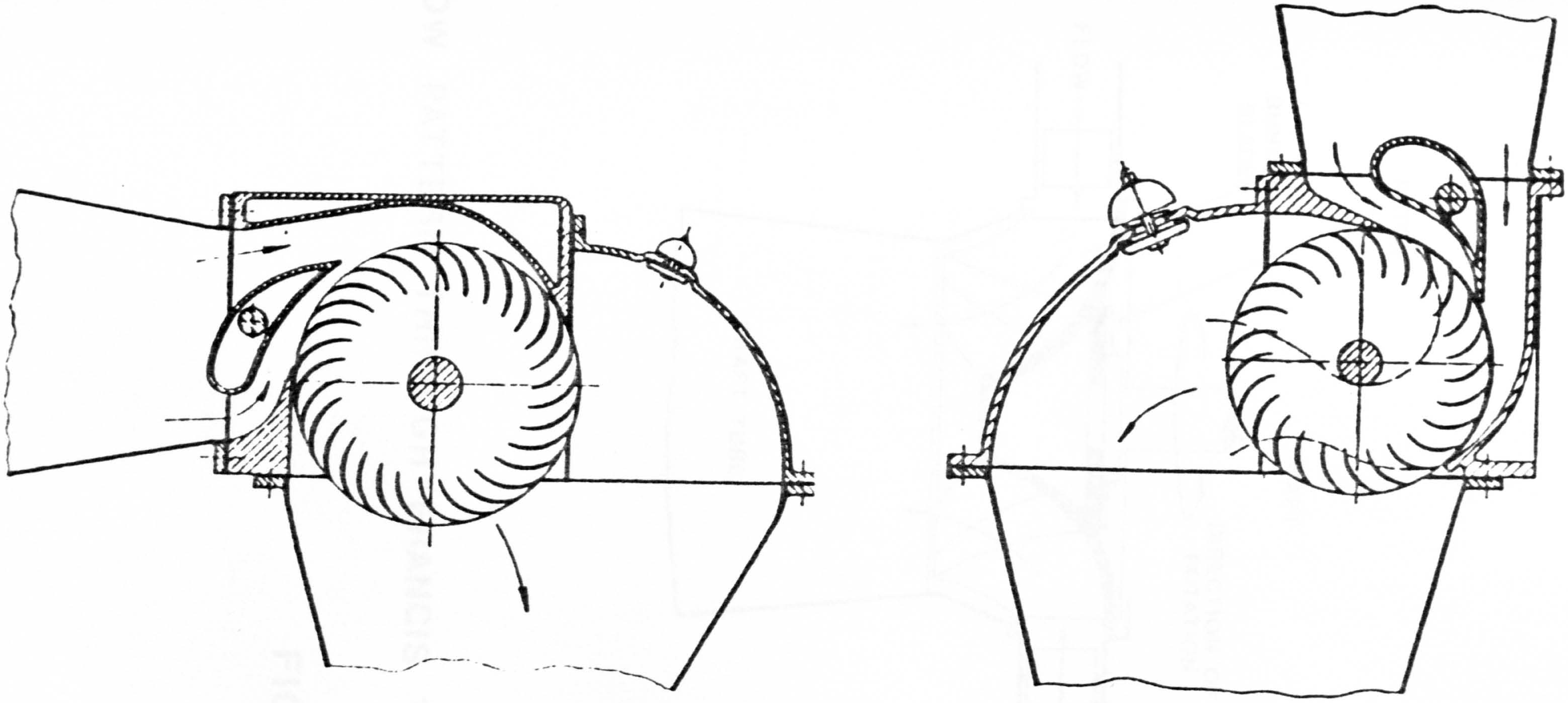
PELTON RUNNER AND SPEAR VALVE

FIG 3.11



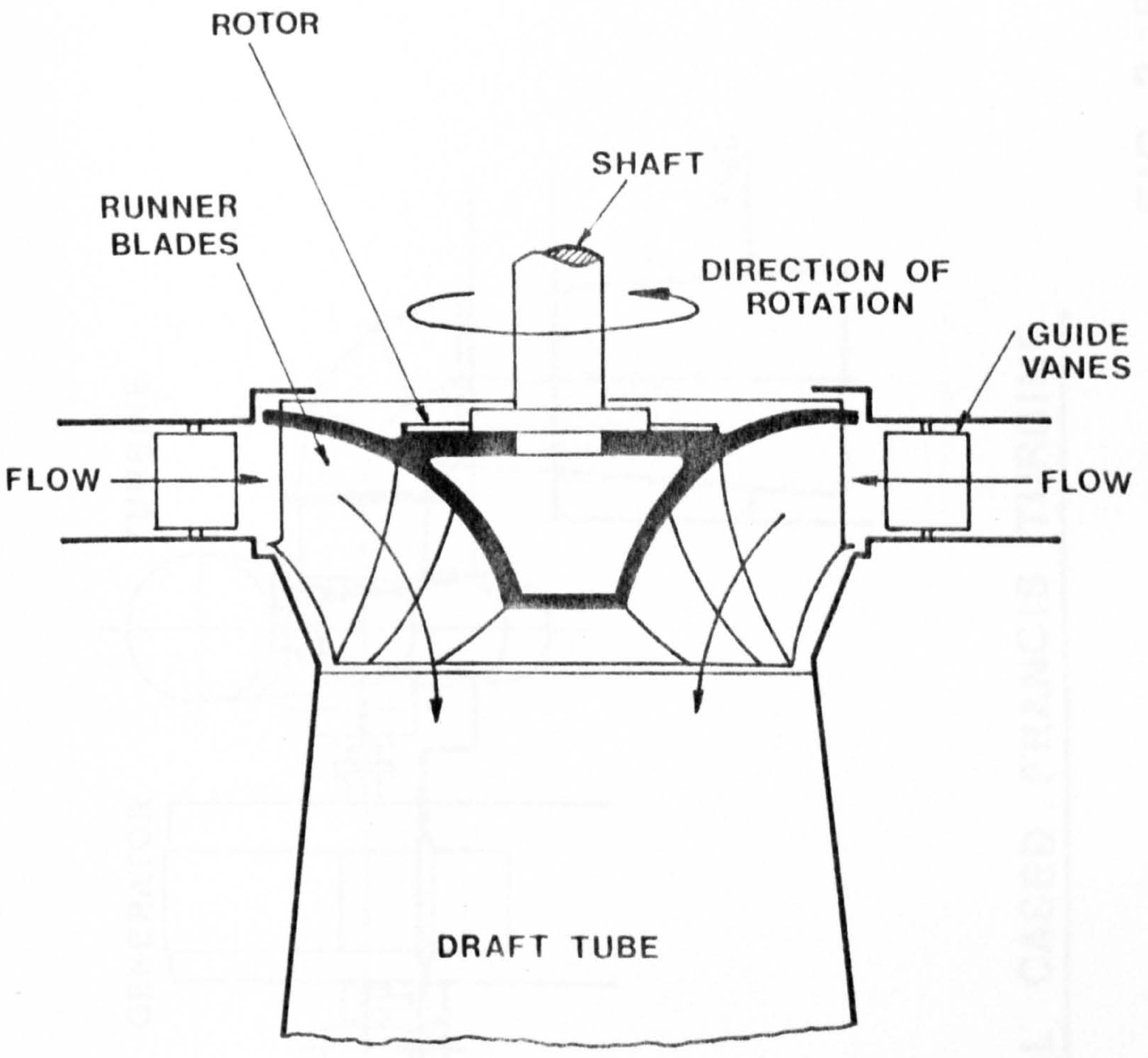
TURGO RUNNER AND SPEAR VALVE

FIG 3.12



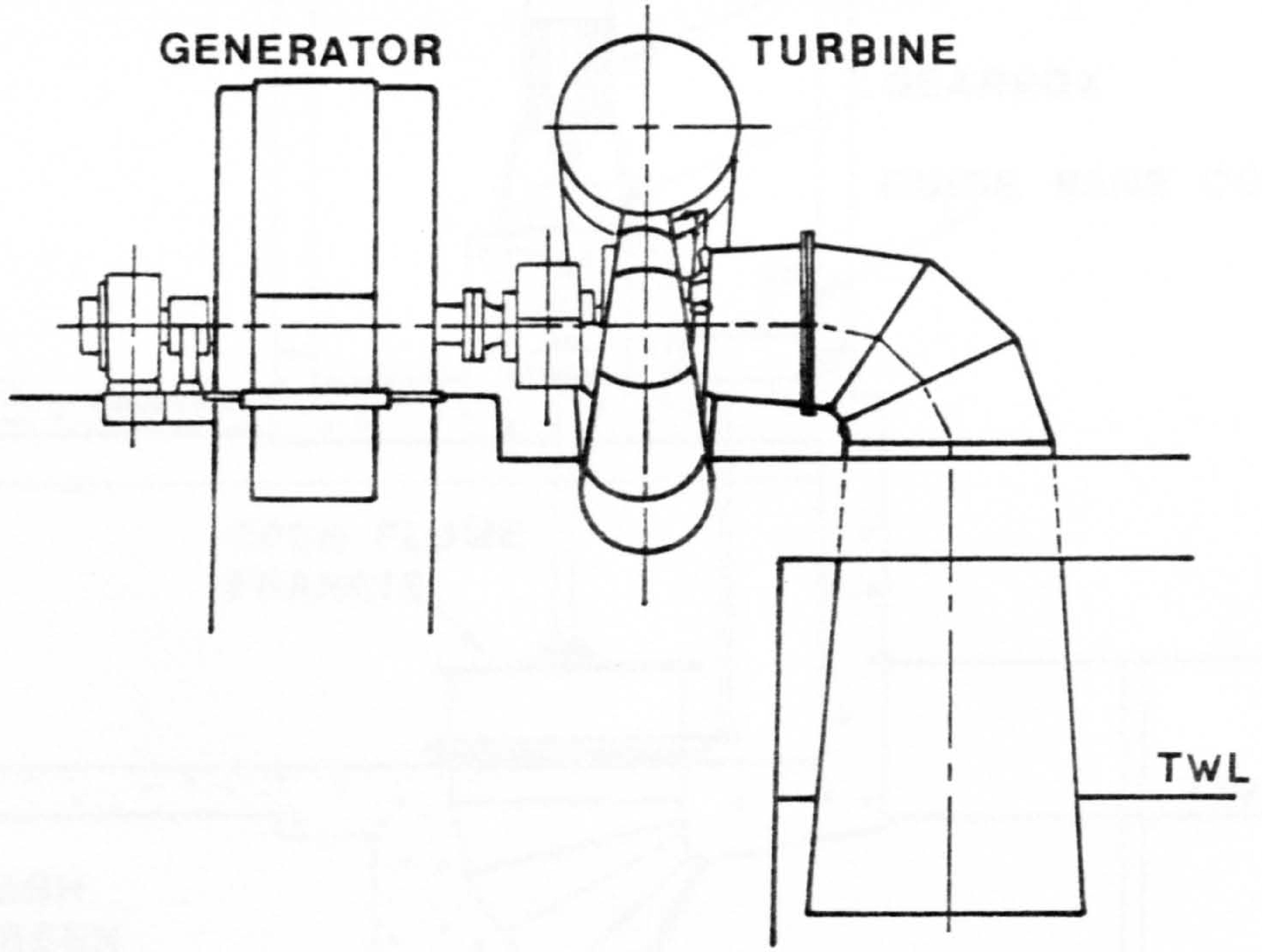
CROSSFLOW TURBINE

FIG 3.13



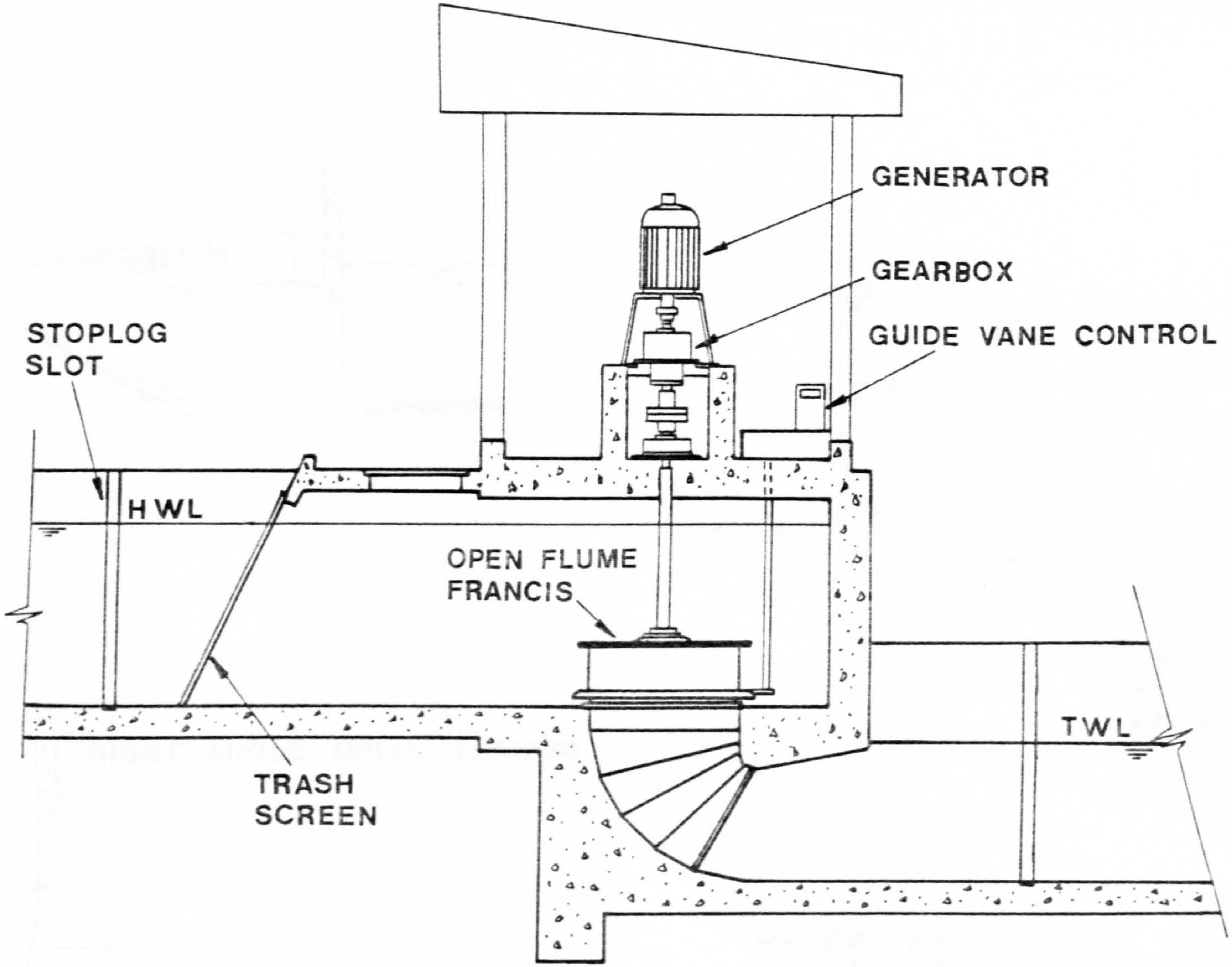
FLOW PATTERN THROUGH FRANCIS TURBINE

FIG 3.14



SPIRAL CASED FRANCIS TURBINE

FIG 3.15



TYPICAL LAYOUT FOR OPEN FLUME FRANCIS TURBINE

FIG 3.16

TUBE TURBINE

BULB TURBINE

RIGHT-ANGLE DRIVE TURBINE

PROPELLER TURBINE ARRANGEMENTS

FIG 3.17

CHAPTER 4

4.0 Cost Estimating and Economics for Small Hydro Schemes

4.1 Introduction

From the previous sections it has been shown that small hydro-schemes can be considered as a number of discrete components. It is possible therefore to produce an estimating package which allows a potential developer to build up a provisional estimate of scheme cost from the various scheme components and thence to consider the economics of generation.

Due to the nature of the basic data, the package is most easily used on a micro computer, and has in fact been developed by the writer and his colleagues to run on a Reflex data base on IBM compatible micros.

4.2 Scheme Components

Scheme costs are built up from the following components:-

1) Dewatering and diversion works
2) Intake structures
3) Automatic screen cleaning
4) Leats and tailraces
5) Header tanks
6) Pipelines - low and high pressure
7) Turbo generators
8) Powerhouses
9) Electrical protection and switchgear
10) Automatic flow/level control
11) Transformers
12) Transmission
13) Access roads

14) Installation and commissioning of turbo-generators
15) Additional works - bank protection and excavation
16) Engineering fees
17) Contingencies
18) Operation and maintenance

All costs are based at April 1987.

4.2.1 Dewatering and Diversion Works

A provisional sum is allowed for diverting the river flow and maintaining a dry environment for construction of the civils works. The sum allowed can range from hundreds to thousands of pounds depending on scheme type. Where construction will involve use of cofferdams, as in the case of some low-head high-flow sites, additional work for sheet piling is allowed for in 4.2.15.

4.2.2 Intake Structures

The intake structure is defined here as the portion of the civils works which house the screens and the penstocks or sluice gates. The package allows for the costing of both the installation of new screens and/or penstocks into existing civils works and for the construction of new intakes. In all cases the estimates made are dependent on the design flow.

4.2.2.1 Existing Civils Works

Coarse screen cost = (£) 66 Q installed
(where Q installed = maximum turbine flow)
Fine screen cost = 280 Q installed
Penstock cost from Figure 4.1

4.2.2.2 New Civils Works

New intake structures are divided into two main types; medium to high head and, low to medium head. In the case of medium to high head intakes, a separate structure is used to house both the screens and the penstocks. This structure will also usually have a desilting function. The cost curve is shown in Figure 4.2.

For the low-medium head scheme, a leat may well be included and as such the screens will usually be distant from the penstocks, ie. the penstocks will be at the upper end of the leat and the screens at the lower. Figure 4.3 therefore allows for costing of screens and penstocks within their own separate concrete structures.

4.2.3 Automatic Screen Cleaning

For large high flow schemes removal of debris from screens by hand will be impractical and hence mechanical raking is required. Figure 4.4 provides a cost curve for mechanical screen cleaning equipment.

4.2.4 Leats and Tailraces

Three main leat/tailrace types are allowed for; unlined, geotextile lined and reinforced concrete. Cost curves for the various types of construction are shown in Figure 4.5.

4.2.5 Header Tanks

Header tanks are required at the junction of low pressure and high pressure pipelines to prevent transmission of surge pressure to the lower pressure pipeline. A cost curve for typical reinforced concrete header tanks is shown in Figure 4.6.

4.2.6 Pipelines

The method of selection of the required pipe diameter is detailed in 3.4. The cost of the pipeline is then obtained by multiplying the pipeline length by the cost from Table 4.1. These pipe costs include either laying in trenches or on mass concrete piers.

4.2.7 Turbo-Generators

The turbine application chart of Figure 3.11 is used to select the appropriate turbine type for the head and flow conditions. The curves of Figures 4.7 to 4.10 can then be used to obtain an estimate of combined turbine and generator cost. It should be noted that more than one turbine type may be applicable in each case, and a consideration of the costs will generally indicate the appropriate type of turbine.

4.2.8 Powerhouses

The costs for powerhouses for the selected turbine type may be determined from Figure 4.11.

4.2.9 Electrical Protection and Switchgear

The costs of protection and switchgear equipment are not easily defined, however typical values are:-

1) Isolated operation, 25-50kW = £5,000
2) Parallel operation, >50kW = £10,000

4.2.10 Automatic Flow/level Control

The cost for automatic flow/level control depends on it's degree of sophistication; however an estimate is £5,000 per turbine/generator set.

4.2.11 Transformers

Costs for 3 phase, 433V to 11kV distribution transformers are given in Figure 4.12.

4.2.12 Transmission

The costs of transmission at both low voltage and high voltage (11kV) do not vary greatly with rated capacity over the range 25kW to 1.5MW. This is because the cable has to be of a certain size to have the required strength, and poles likewise have to be a certain size to carry the cable loads. An analysis undertaken by the Electricity Council shows the cost for 11kV transmission lines to be approximately £11/m.

4.2.13 Access Roads

Access roads are allowed for at a cost of £35.35/m length, for 4.5m road width based on use of hardcore and a geotextile.

4.2.14 Installation and Commissioning of Turbo-generators

The costs for installation and commissioning of turbo generators depends to some degree upon the size of the set, however the complexity of the machine has the greater effect.

The following costs are reasonable first estimates of the costs for installation and commissioning:-

1) For isolated schemes cost = £4,030
2) For parallel schemes <1MW cost = £6,770
3) For parallel schemes at 1MW cost = £6,770 rising to £9,025 at 5MW

4.2.15 Additional Works - Bank Protection and Excavation

Costing of additional works allow for excavation, ground clearance and bank protection.

Excavation for construction of leats, powerhouses etc has previously been allowed for in the costing of the specific works. However, in certain circumstances additional excavation and site clearance may be required and this has been allowed for as follows:-

Desilting (eg. weirs) = £0.54/m^3
Rock Excavation = £52.4/m^3
Soft Excavation = £1.87/m^3
Clearance = £0.10/m^2

River bank protection is priced for sheetpiling, gabions and geotextiles. The costs for such protection are calculated as follows:-

Sheet piling cost (£)
= 1.1 [Length x (Bank height + 0.45) 2 + 22.5 length]

Gabion cost (£)
= 1.1 [(11.4.x length) + (21.3 x length x height)]

Geotextile cost (£)
= 1.1 [(2.2 x length x width) + (3.2 x length)]

4.2.16 Engineering Fees and Supervision

Due to the site specific nature of small-scale hydro-electric generation and the scale of the works involved, the costs for engineering fees and for supervision are generally a greater proportion of the cost of the works than would be anticipated for large scale civil work. Figure 4.13 provides estimates for engineering fees and supervision as a proportion of the total scheme cost.

4.2.17 Contingencies

Contingencies are allowed for at 10% of the total scheme cost inclusive of engineering fees.

4.2.18 Operation and Maintenance

The costs associated with the operation and maintenance of hydro-electric plant are low. An appropriate value for small-hydro is 2% of the total scheme cost per annum.

4.3 Scheme Charges

The costs for the running of a small hydro-electric plant in terms of operation and maintenance have been considered above. However, in the U.K., there are two other types of charge which can apply to small hydro plants, these are abstraction charges, and local authority rates.

4.3.1 Abstraction charges

The Water Authorities in England and Wales are empowered to levy abstraction charges for use of water. The charges applicable to hydro power generation are shown in Table 4.2. It can be seen that there is considerable variation of abstraction charges from one Water Authority to another. The effect that these charges can have on potential schemes is considered in section 5. However, the question of abstraction charges is not straightforward since the 1983 Energy Act gives Water Authorities the power to abate abstraction charges where their imposition is deemed to make a scheme uneconomic. Unfortunately, the term uneconomic is not defined and hence a potential developer is faced with an unknown charge against a scheme. This tends to dissuade some developers from proceeding.

Recently, W. Fernehough Limited, the operators of a small hydro plant, have challenged the Severn Trent Water Authority over proposed abstraction charges. This has led the Secretary of State to rule that the Water Authority must reduce charges to the level of the administration cost associated with the issue of an abstraction licence. This ruling is being seen by Severn Trent Water Authority as setting a precedent, and in future, it anticipates that it will levy a charge to meet the administration charges only and not impose abstraction charges. It is yet to be seen whether other Water Authorities adopt the same line as Severn Trent.

4.3.2 Local Authority Rates

Private generators of electricity are liable for local taxation unless, under the terms of the General Rating Act 1967 the generated power is used purely for their own agricultural or domestic purposes.

An act has been passed to introduce a community charge in Scotland and it is the intention of the Government that a similar charge be legislated in England and Wales, though not in Northern Ireland. The consequences of changes on the rating position for public and private generators in Great Britain are not yet clear.

The current position is that all rating is based on notional rent and, since this is not directly calculable, it is based on the so called "contractors test". This is calculated as follows:-

1) Calculate the value of the plant and land; in the case of small hydro this is probably best interpreted as the total capital cost including consultancy fees.

2) Derive the value at the "Tone Date", ie. that at the last general rating. This is 1973 for England and Wales and 1976 for Scotland; the GDP deflators to correct prices for the first quarter of 1987 are 423 and 252 respectively ie. multiply by 0.23 and 0.4.

3) Calculate the notional rent applying a decapitalization rate; 5% per annum for England and Wales, 8% per annum for Scotland to the Tone Data Value.

4) The annual rate bill is the notional rent multiplied by the non-domestic poundage, the mean value of which in England and Wales is 224.1p/£ rating.

In the future it appears possible that small hydro schemes will come under the "formula' rating as is applied to the generating boards in Great Britain. This "formula" rating is based on energy production and is equivalent to the following average unit rates:-

CEGB	(Generation and transmission)	0.08p/kWh
SSEB	(Generation, transmission and distribution)	0.18p/kWh
NSHEB	(Generation, transmission and distribution)	0.26p/kWh

The effects of both types of rating on potential schemes is considered in section 5.

4.4 Energy Value

The method for calculating the annual energy yield from a hydro power scheme has been detailed in section 2. However, in order to estimate the economics of generation at a potential site, it is necessary to calculate the value of the energy generated. This requires a consideration of the end use for the energy and the value of any energy replaced.

In general there are three types of scheme which can be considered:-

1) Schemes for export only - schemes developed solely for the supply of energy to local Electricity Board grid systems

2) Schemes for isolated operation developed for supply to loads such as factories, farms or domestic households

3) Schemes for parallel supply - schemes developed for parallel supply of loads as in (2) above with sale of surplus energy to local Electricity Boards.

4.4.1 Schemes for Export Only

The electricity utilities in the U.K. publish tariffs for the purchase and sale of electricity from and to their systems. The tariff applicable to England and Wales is shown in Table 4.3. It includes charges which are levied for allowing connection to the transmission system. From this tariff it is possible to produce average monthly unit rates which will be paid for the supply of energy to the utility. Those unit rates are shown in Table 4.4. The method for calculating the annual energy value is therefore to determine the monthly energy yields from monthly flow duration curves as outlined in section 2. This annual value must then be reduced by subtracting the charges for capacity and standby to give the net annual energy value.

For a simplified analysis the annual flow duration curve can be used to estimate the annual energy value. The time-based average unit rate is 2.635p/kWh for England and Wales allowing for fuel price adjustment. However, proportionally more energy is produced during the higher-tariff winter months than from the lower-tariff summer months. An analysis of the effect on the average tariff for rivers with different values of BFI has been undertaken for schemes installed at mean flow minus compensation flow; the results are shown in Table 4.5. This shows that the average unit rate to be applied is probably of the order of 2.745p/kWh.

An analysis of the effects on yield of installing at other exceedence points compared to the mean flow - compensation flow has also been undertaken. The results of this together with the effect on average unit rate are shown in Table 4.6.

It can be seen from this analysis that although there are slight increases in average unit value when capacity is increased, due to production of proportionally more energy during the higher tariff winter months, increase in scheme revenue will be predominately due to increased energy production rather than increased average unit rate ie. there is little advantage in increasing installed capacity to benefit from higher tariffs in winter months.

The average time based unit rate applying to export of energy in Northern Ireland is 2.3p/kWh.

4.4.2 Schemes for Isolated Operation

In the U.K. schemes falling within this category usually have installed capacities of less than 50kW for supply to loads such as households, farms and factories.

In designing a scheme for isolated operation, it would be usual to size the scheme so that it meets the winter demands. These demands could be in the form of heating, lighting and electrical power supply. In such cases, it is often impracticable to usefully use all the energy generated. It is necessary therefore to apply a utilization factor to the energy yield. The actual value of this factor can be obtained only by a detailed consideration of monthly and daily demand patterns.

This may not be practical for small schemes and in such cases an estimated factor should be used. A typical value for the utilization factor would be 50 to 60% ie. only 50 to 60% of the annual energy generated can be usefully used. In the case of a scheme where capacity is only a minor proportion of the total demand eg. a 40kW scheme supplying a factory where the average demand is 400kW, the utilization factor would rise to (say) 90%.

The unit rate for energy applicable to isolated schemes is obviously dependent upon the type of fuel which is being replaced. Typical values for replaced fuels are:-

1)	Heating oil	3p/kWh (heat)
2)	Mains electricity (domestic)	5.5p/kWh
3)	Mains electricity (industrial)	4.0p/kWh
4)	Natural gas (mains supply)	1.3p/kWh (heat)
5)	Diesel produced electricity	7-14p/kWh

An average value of 4p/kWh may be appropriate for initial consideration of the supply of isolated schemes with mixed fuel sources.

4.4.3 Parallel Operated Schemes

In this case schemes are considered where a local demand is first of all supplied, with the sale of any surplus energy to the local Electricity Board. As in the case of isolated schemes, a detailed analysis is required to determine load/demand patterns and hence obtain a value for annual energy yield.

Detailed consideration of a number of schemes has shown a range of average unit value of 3.0 to 4.5p/kWh.

4.5 Economics

The economics of a scheme can be considered in a number of ways, the most commonly used being internal rate of return, and energy cost.

4.5.1 Internal Rate of Return

The internal rate of return (r) is defined as the discount (or interest) rate which, applied to a constant net annual revenue over a period of n years will result in a present value of the income stream equal to the capital cost.

$$\text{The present value factor (PVF)} = \frac{1 - \left(\frac{1}{1 + r}\right)^{n}}{r}$$

and may be calculated or readily obtained from tables of present value of an Annuity. For 5% and 30 years, PVF = 15.3725.

The equation may be set out as

$$\text{PVF} = \text{Capital cost}/\text{Annual net revenue}$$

If the r.h.s. of this equation is known and n is selected then the value of r is calculable. For hydropower schemes, n is often taken as 30 years, ie. a 30 year plant life. A graphical solution for this equation in terms of r is shown in Figure 4.14.

4.5.2 Energy Cost

Energy cost may be calculated from the formula

$$\text{Energy cost (p/kWh)} = \frac{\text{Capital cost} + (\text{PVF} \times \text{Annual operating cost})}{\text{PVF} \times \text{Annual output}}$$

PVF is dependent upon the rate of return required by the potential developer.

Pipe Diameter	Typical Laid Cost (£/m) Concrete	Low Pressure G.R.P.	High Pressure G.R.P.	Ductile Iron
150				24.2
300	27.3	44.3	49.8	54.4
350	34.5			
400		53.0	57.1	
450	42.9			89.6
600	57.4	88.8	102.8	131.6
800		138.0	155.1	202.3
900	97.6			252.4
1000		198.6	226.6	307.1
1200	144.9	255.5	295.5	407.8
1400		325.1	379.1	
1600		409.9	478.9	648.2
1800	326.3	516.4	605.4	

Table 4.1 Pipe Costs

Area	Rate p/m³
England - Water Authority	
North West	0.00289
Northumbrian	0.0015
Yorkshire	0.0046
Severn Trent	0.00031 - 0.00504
South West	NIL
Wessex	NIL
Southern	0.0146
Thames	0.03567
Anglian	0.0261
Wales	0.0069
Scotland and Northern Ireland	NIL

Table 4.2 U.K. Abstraction Charges

Unit Rates

For each unit supplied by the private generator (all times GMT)

		p/kWh
1)	During the period 00.30 to 07.30	1.64
2)	During the period 07.30 to 20.00 Monday to Friday, November and February	4.25
3)	During the period 07.30 to 20.00 Monday to Friday, December and January	7.25
4)	At all other times	2.66

Fuel Adjustment

The above unit payments are subject to an addition or reduction at the rate of 0.00032p/kWh for each 1p by which the Fuel Price is more or less than £52.00. (For 1987-1988 fuel adjustment is -0.112p/kWh.

Charges

1) A fixed standing charge per month (for low voltage) of £23.00

2) For each kVA of Export Capacity a monthly charge of £0.74.

Table 4.3 Export Tariff For Private Generators

England and Wales

Month	Average Unit rate (p/kWh)	Unit rate with fuel adjustment (p/kWh)
January	4.07	3.958
February	2.954	2.842
March	2.362	2.25
April	2.362	2.25
May	2.362	2.25
June	2.362	2.258
July	2.362	2.25
August	2.362	2.25
September	2.362	2.25
October	2.362	2.25
November	2.954	2.842
December	4.07	3.958
Average	2.747	2.635

Table 4.4 Average Monthly Unit Rates for Supply of Electricity to the Grid England and Wales

River	Gauge Number	BFI	Installed Exceedence at Qm (%)	Q_{95} as % of Qm	Increase in energy value (%)	Equivalent unit rate (p/kWh)
Bottoms Beck	71005	0.21	23	5.9	3.3	2.72
Duddon Beck	74001	0.28	26	9.6	3.6	2.73
Wharfe	27002	0.39	29	13.3	4.5	2.76
Don	27006	0.47	32	16.6	3.7	2.73
Derwent	27041	0.67	30	25.4	4.6	2.76
Great Eau	29002	0.87	31	37.3	3.5	2.73

Table 4.5 Seasonally adjusted average unit rates for schemes installed at mean flow - compensation flow (Qm - Q_{95})

River	Gauge Number	Exceedence at Qm (%)	$Q_{10} - Q_{95}$ (1)	$Q_{10} - Q_{95}$ (2)	$Q_{10} - Q_{95}$ (3)	$Q_{10} - Q_{95}$ (4)	$Q_{20} - Q_{95}$ (1)	$Q_{20} - Q_{95}$ (2)	$Q_{20} - Q_{95}$ (3)	$Q_{20} - Q_{95}$ (4)	$Qm - Q_{95}$ (3)	$Qm - Q_{95}$ (4)	BFI
Bottoms Beck	71005	23	47	97	4.5	2.755					3.3	2.72	0.21
Duddon Beck	74001	26	39	96	5.3	2.770	11	22	4.2	2.746	3.6	2.73	0.28
Wharfe	27002	29	47	113	6.5	2.806	47	49	5.0	2.767	4.5	2.76	0.39
Don	27006	32	50	107	5.1	2.770	23	41	4.4	2.750	3.7	2.73	0.47
Derwent	27041	30	39	82	6.6	2.808	17	31	5.3	2.775	4.6	2.76	0.67
Great Eau	29002	31	31	63	4.3	2.749	18	28	3.9	2.737	3.5	2.73	0.87

Table 4.6 Comparison of Unit Value and Energy Yield with Variation in Installed Flow

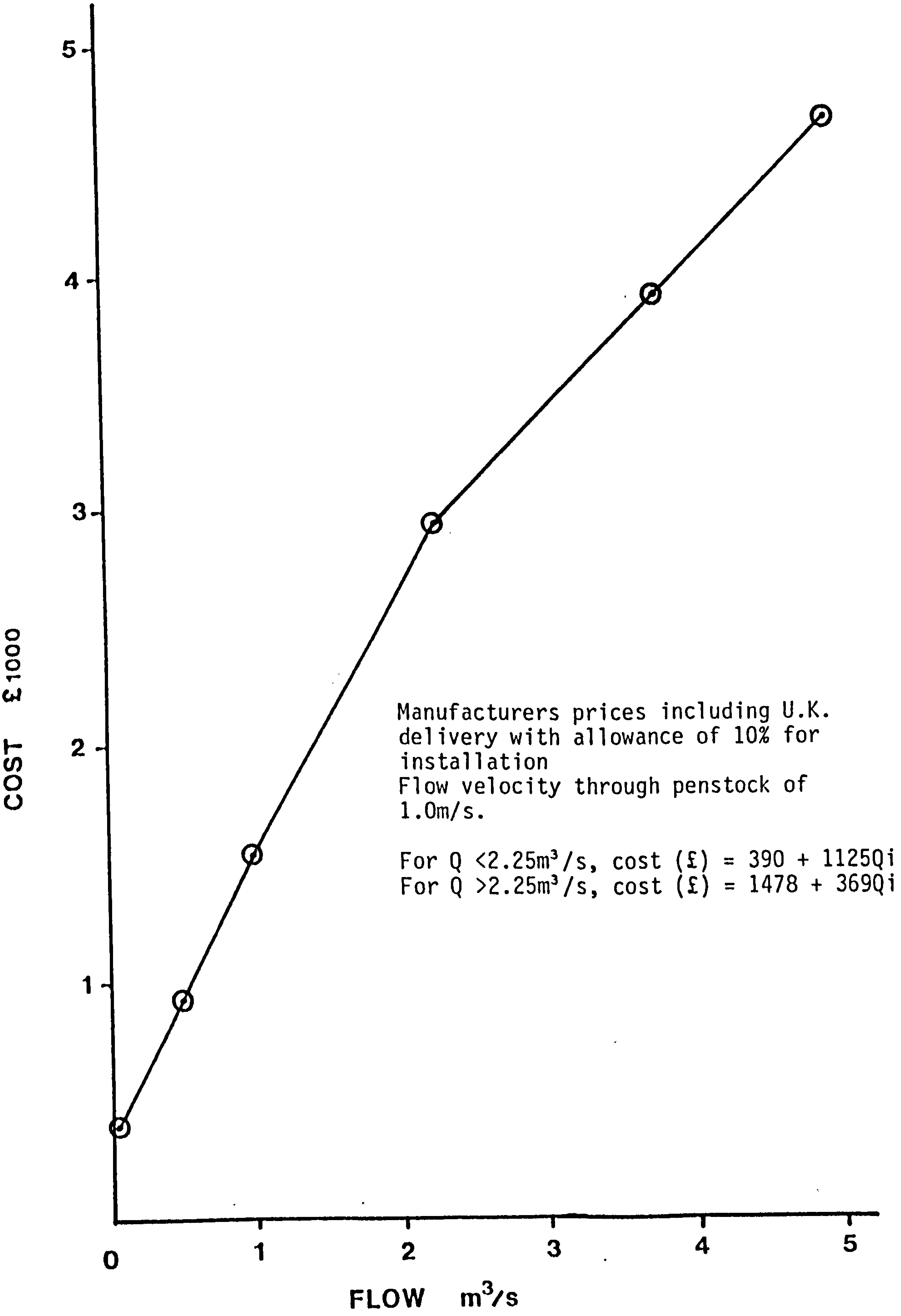
Rates

(1) % increase in energy yield at various installed flows, compared to yield at installed flow of Qm - Q_{95}

(2) % increase in installed capacity at various installed flows, compared to installed capacity at installed flow of Qm - Q_{95}

(3) % increase in unit rate using monthly flow variation compared to average annual unit rate of 2.635 p/kWh

(4) Average unit rate (p/kWh) using monthly flow variation



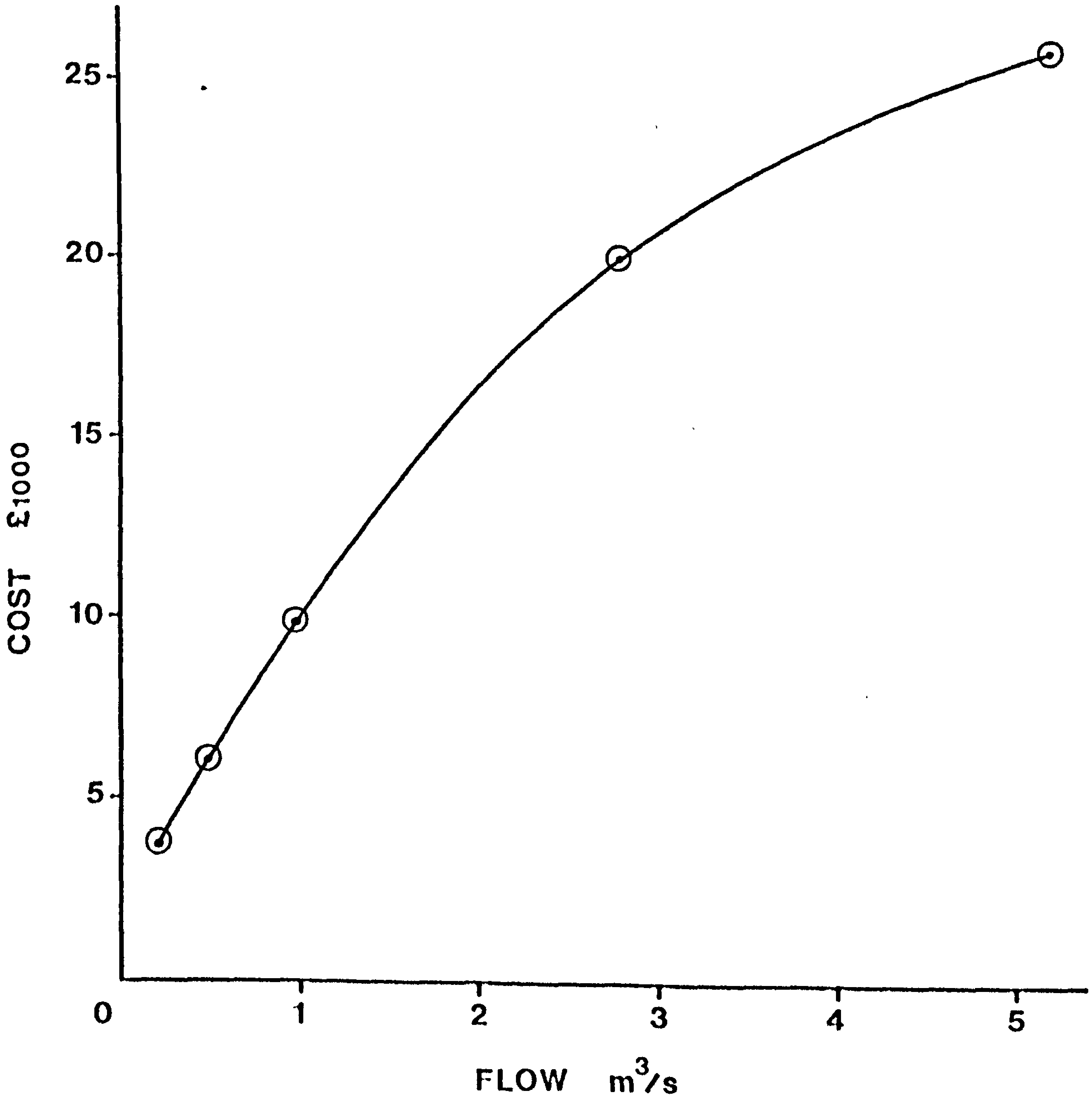
Manufacturers prices including U.K. delivery with allowance of 10% for installation
Flow velocity through penstock of 1.0m/s.

For $Q < 2.25 m^3/s$, cost (£) = $390 + 1125Q_i$
For $Q > 2.25 m^3/s$, cost (£) = $1478 + 369Q_i$

COST CURVE FOR PENSTOCKS IN EXISTING CIVILS

FIG 4 1

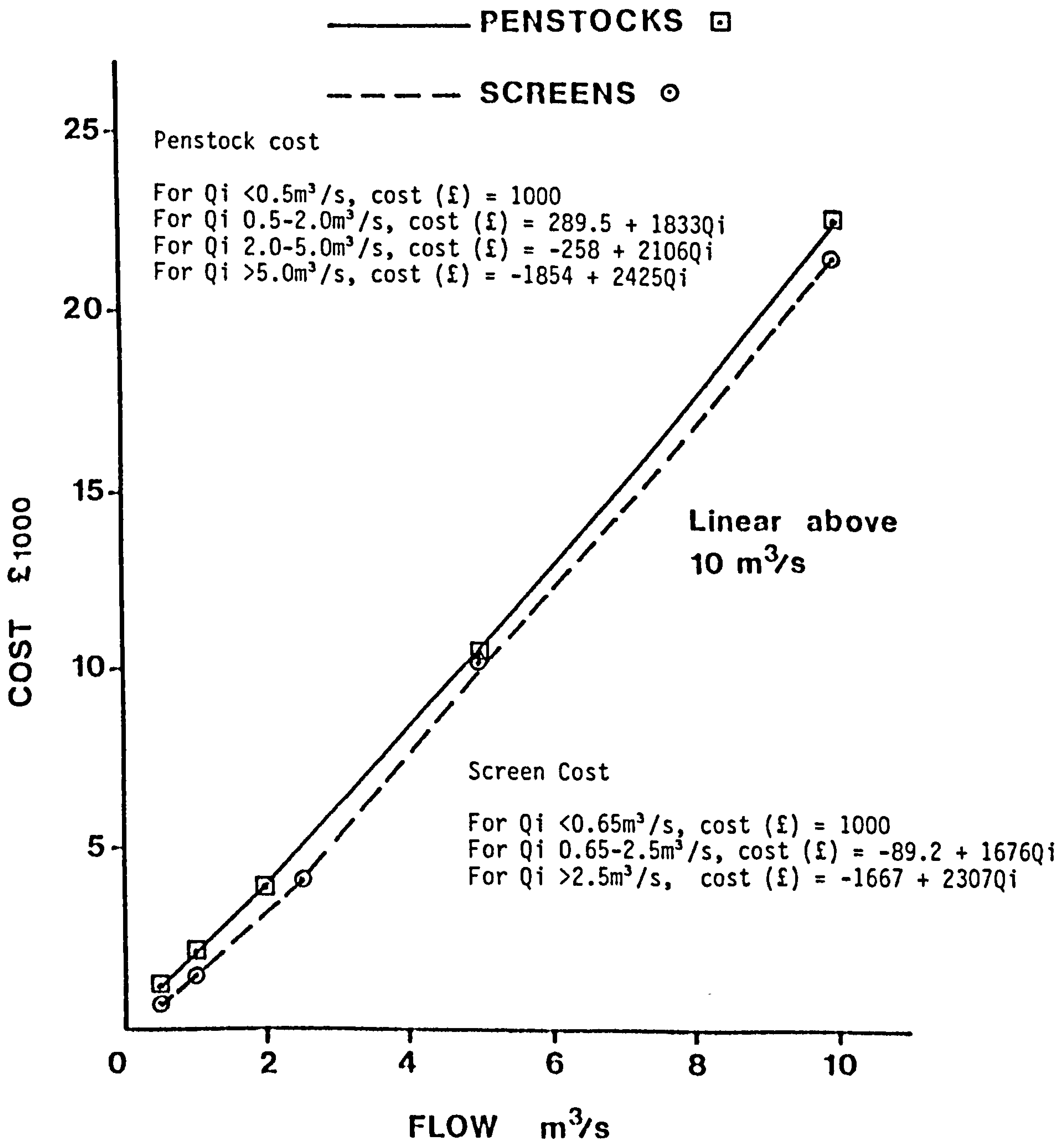
Combined intake and sediment tank (Fig. 3.2)
Cost includes screens and penstocks
Civils cost from Wessex Data Base
Cost (£) = EXP (9.25 + 0.58 ln Qi)



COST CURVE FOR MEDIUM/HIGH HEAD INTAKES

FIG 4.2

Penstock Prices from Manufactures Data
Screen and civils costs from Wessex
Data Base. Flow velocity through penstock
and approach velocity to screen of 1.0m/s.



Penstock cost

For Qi <0.5m^3/s, cost (£) = 1000
For Qi 0.5-2.0m^3/s, cost (£) = 289.5 + 1833Qi
For Qi 2.0-5.0m^3/s, cost (£) = -258 + 2106Qi
For Qi >5.0m^3/s, cost (£) = -1854 + 2425Qi

Screen Cost

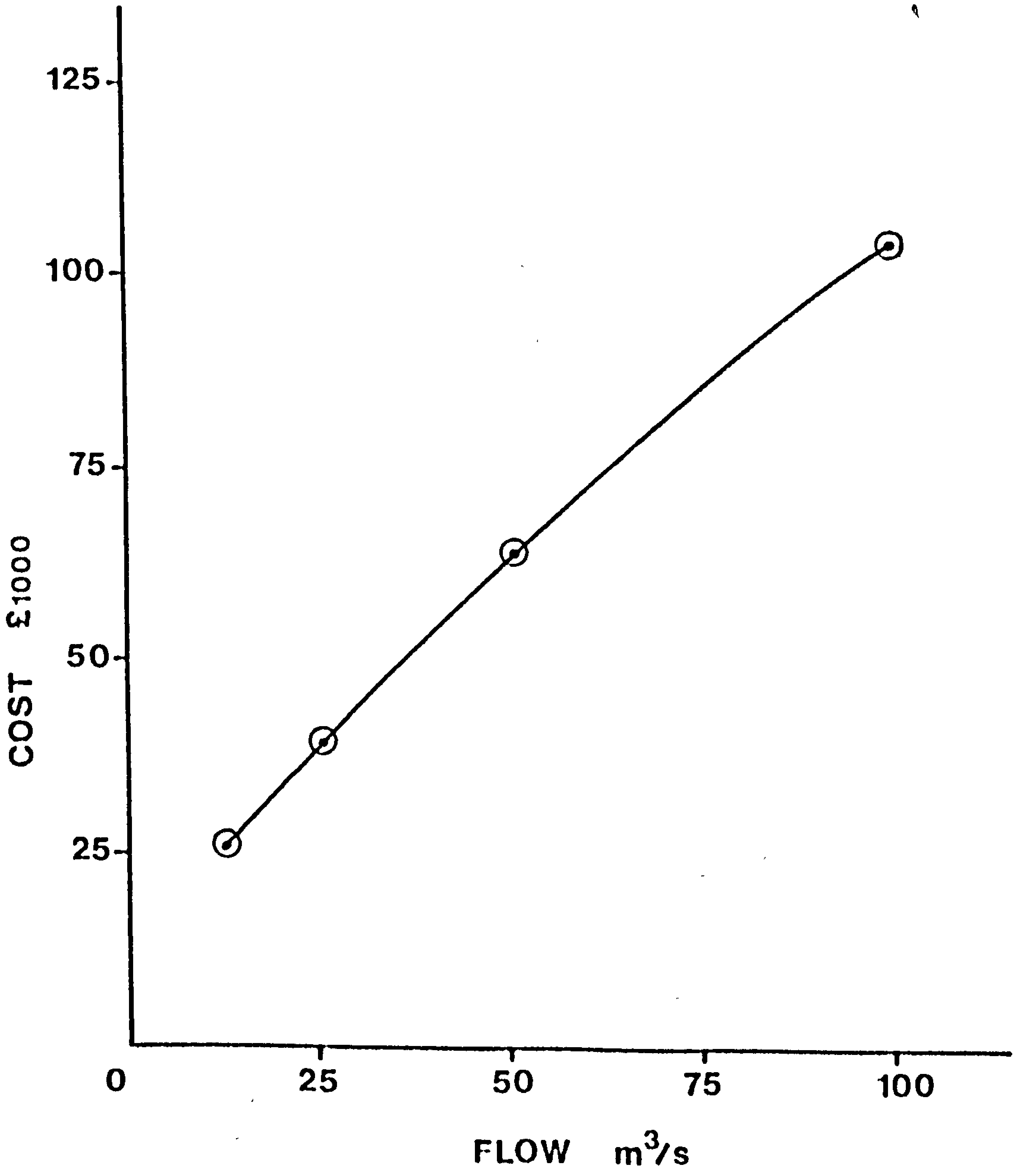
For Qi <0.65m^3/s, cost (£) = 1000
For Qi 0.65-2.5m^3/s, cost (£) = -89.2 + 1676Qi
For Qi >2.5m^3/s, cost (£) = -1667 + 2307Qi

COST CURVES FOR PENSTOCKS AND SCREENS IN NEW CIVIL WORKS

FIG 4.3

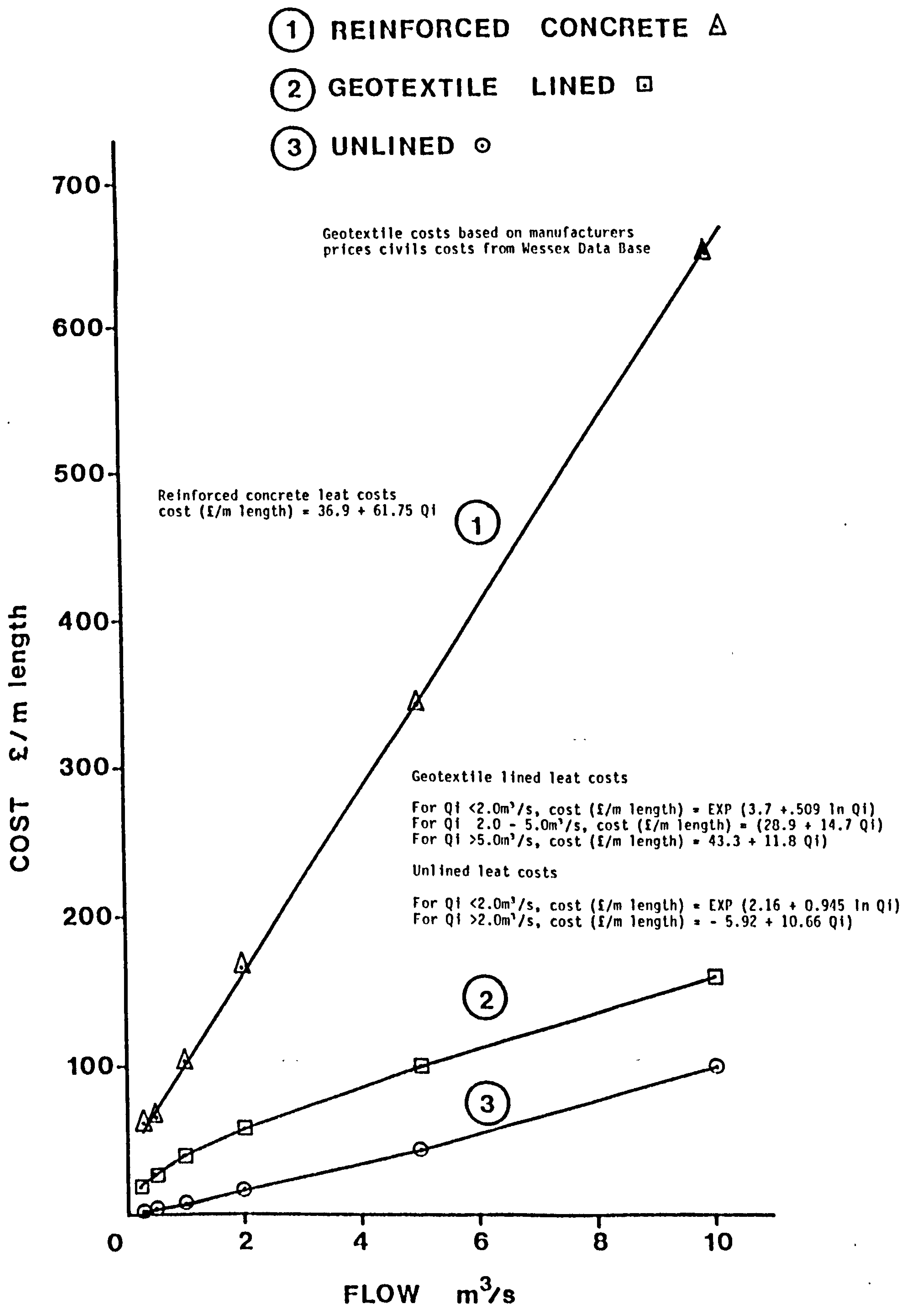
Manufacturers Data

Inclusive of U.K. delivery and installation
Flow approach velocity to screens of 1.0m/s.
Cost (£) = 1000 EXP (1.501 + 0.677 ln Qi)



COST CURVE FOR AUTOMATIC SCREEN CLEANING

FIG 4.4



Geotextile costs based on manufacturers prices civils costs from Wessex Data Base

Reinforced concrete leat costs
cost (£/m length) = 36.9 + 61.75 Qi

Geotextile lined leat costs

For Qi <2.0m^3/s, cost (£/m length) = EXP (3.7 +.509 ln Qi)
For Qi 2.0 - 5.0m^3/s, cost (£/m length) = (28.9 + 14.7 Qi)
For Qi >5.0m^3/s, cost (£/m length) = 43.3 + 11.8 Qi)

Unlined leat costs

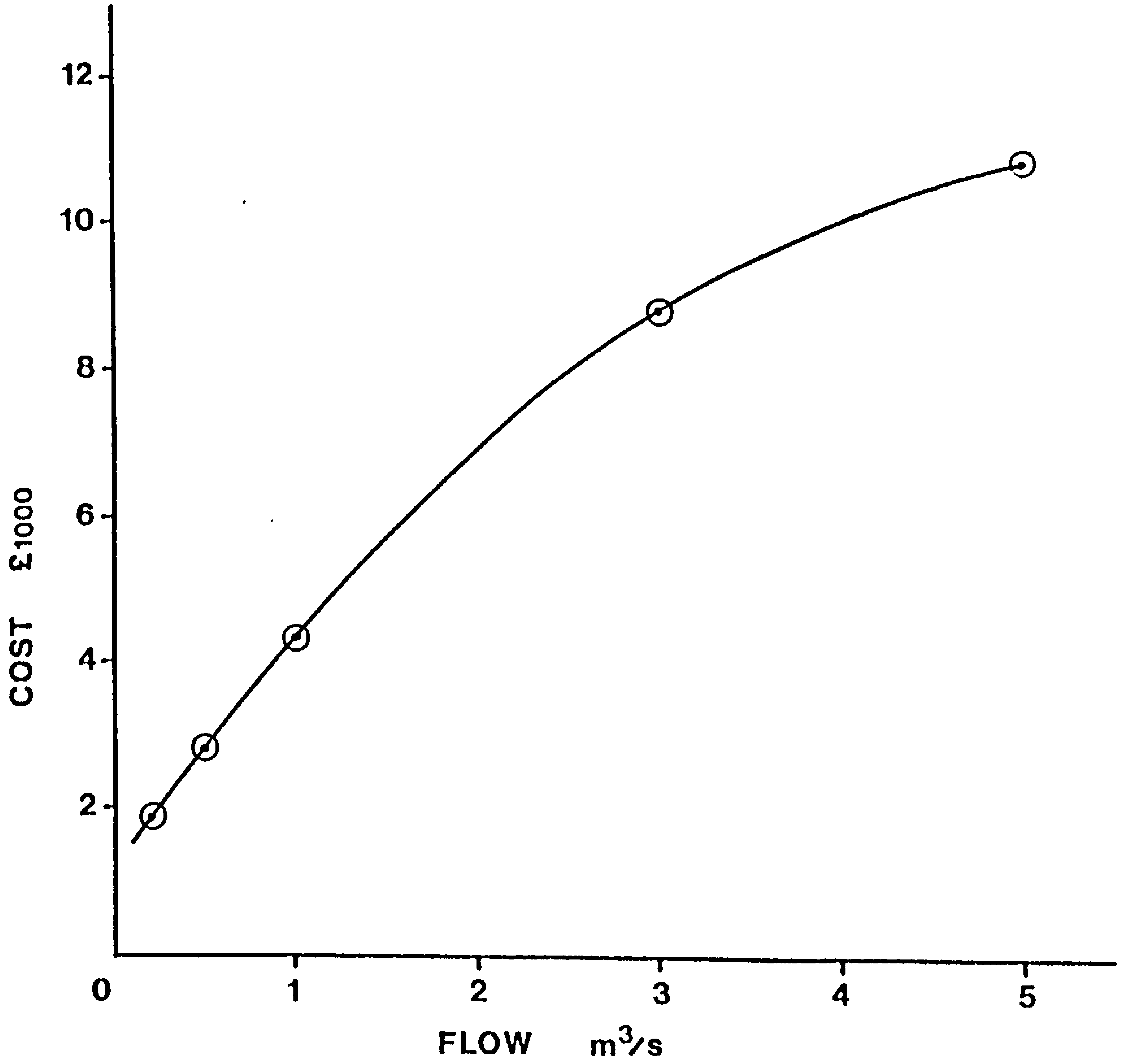
For Qi <2.0m^3/s, cost (£/m length) = EXP (2.16 + 0.945 ln Qi)
For Qi >2.0m^3/s, cost (£/m length) = - 5.92 + 10.66 Qi)

COST CURVE FOR LEATS/TAILRACES

FIG 4.5

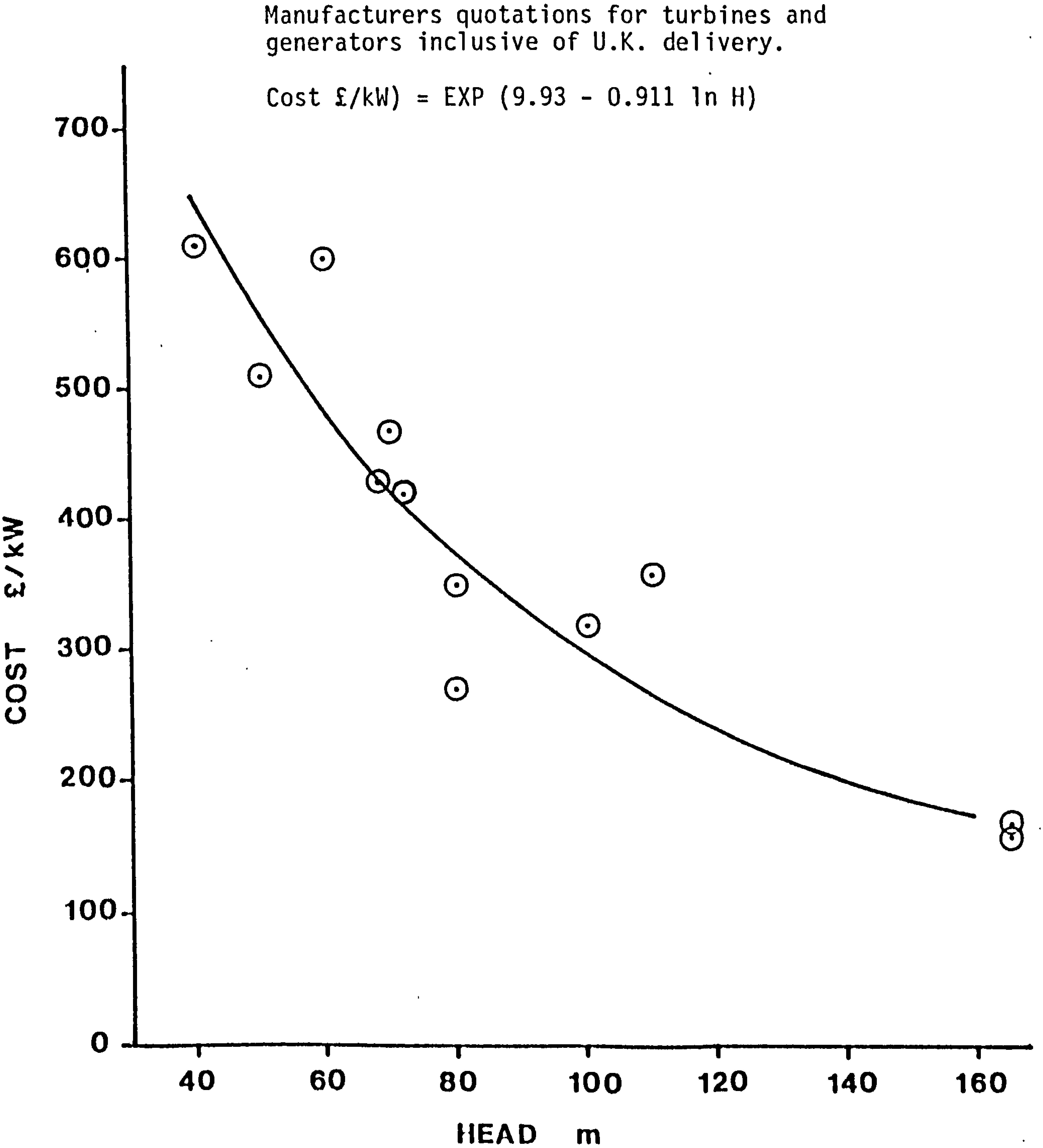
Civils cost from Wessex Data Base header tank cost ≙42% of cost for combined intake and sediment tank.

Cost (£) = 0.42 EXP (9.25 + 0.58) ln Qi)



COST CURVE FOR HEADER TANKS

FIG 4.6



Manufacturers quotations for turbines and generators inclusive of U.K. delivery.

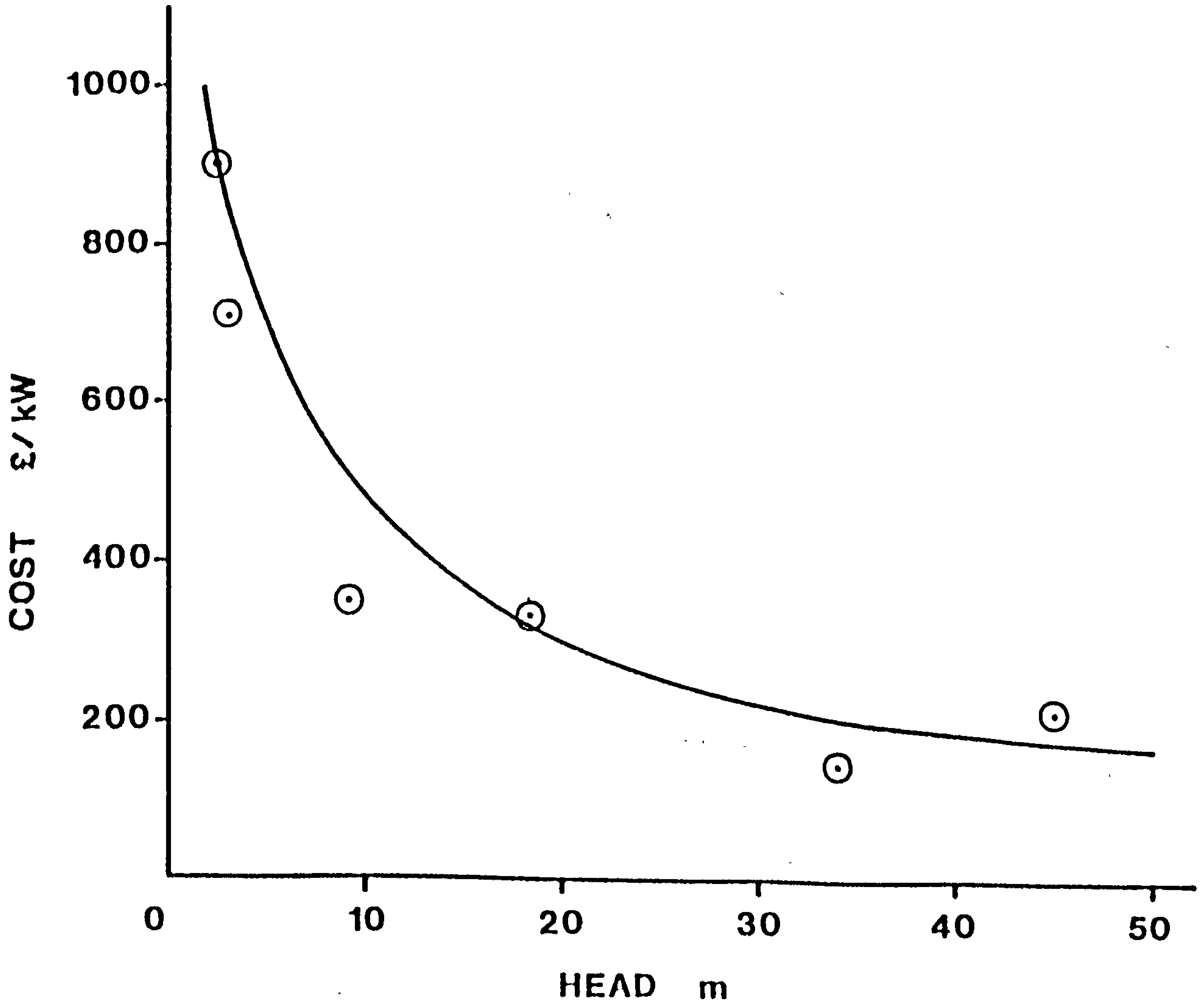
Cost £/kW) = EXP (9.93 - 0.911 ln H)

IMPULSE TURBINE COSTS

FIG 4.7

Manufacturers quotations for turbines and generators inclusive of U.K. delivery.

Cost (£/kW) = EXP (7.237 - 0.554 ln H)

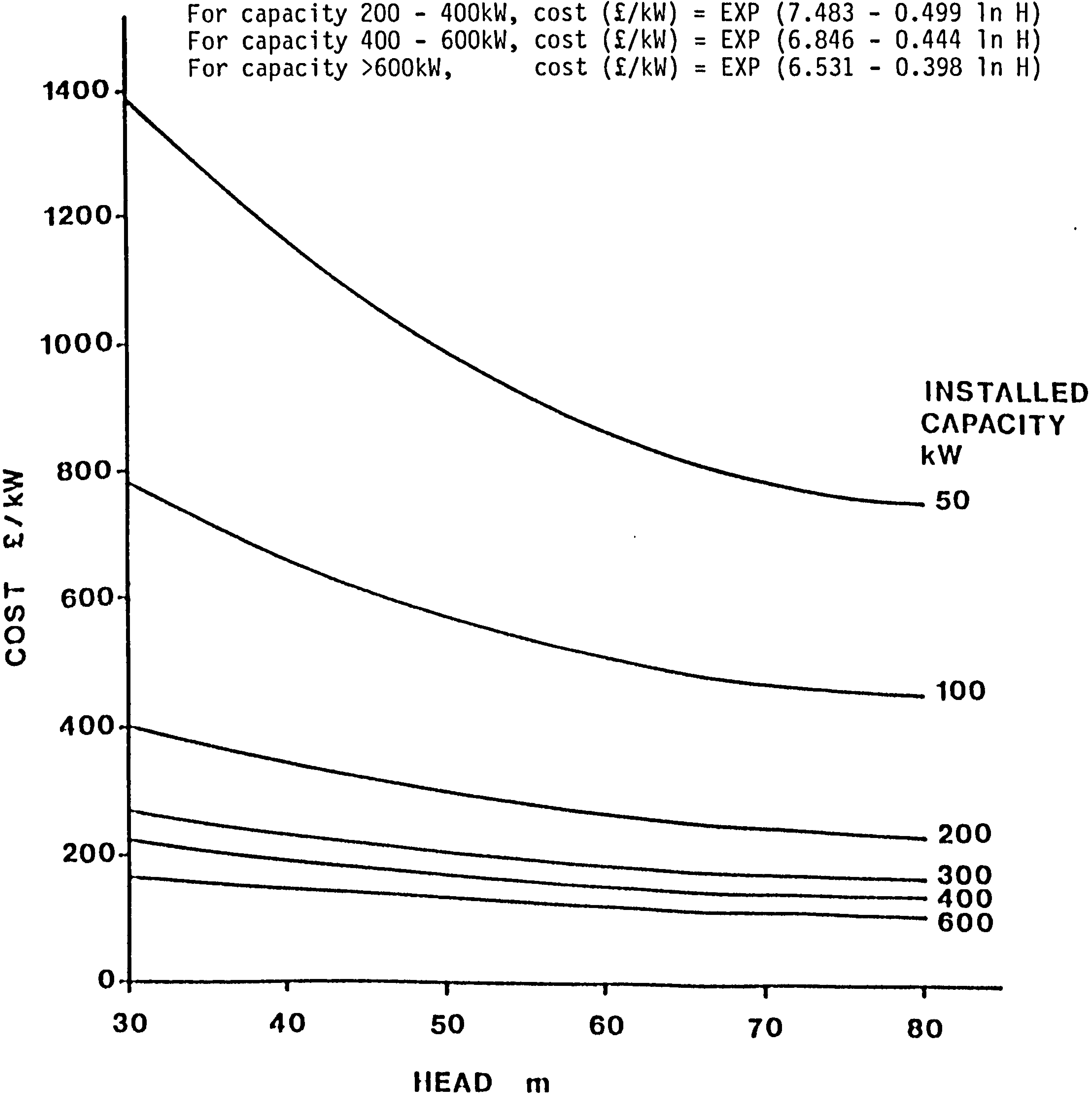


CROSSFLOW TURBINE COSTS

FIG 4.8

Manufactures data for turbines and generators inclusive of U.K. delivery

For capacity 100 - 200kW, cost (£/kW) = EXP (8.225 - 0.536 ln H)
For capacity 200 - 400kW, cost (£/kW) = EXP (7.483 - 0.499 ln H)
For capacity 400 - 600kW, cost (£/kW) = EXP (6.846 - 0.444 ln H)
For capacity >600kW, cost (£/kW) = EXP (6.531 - 0.398 ln H)

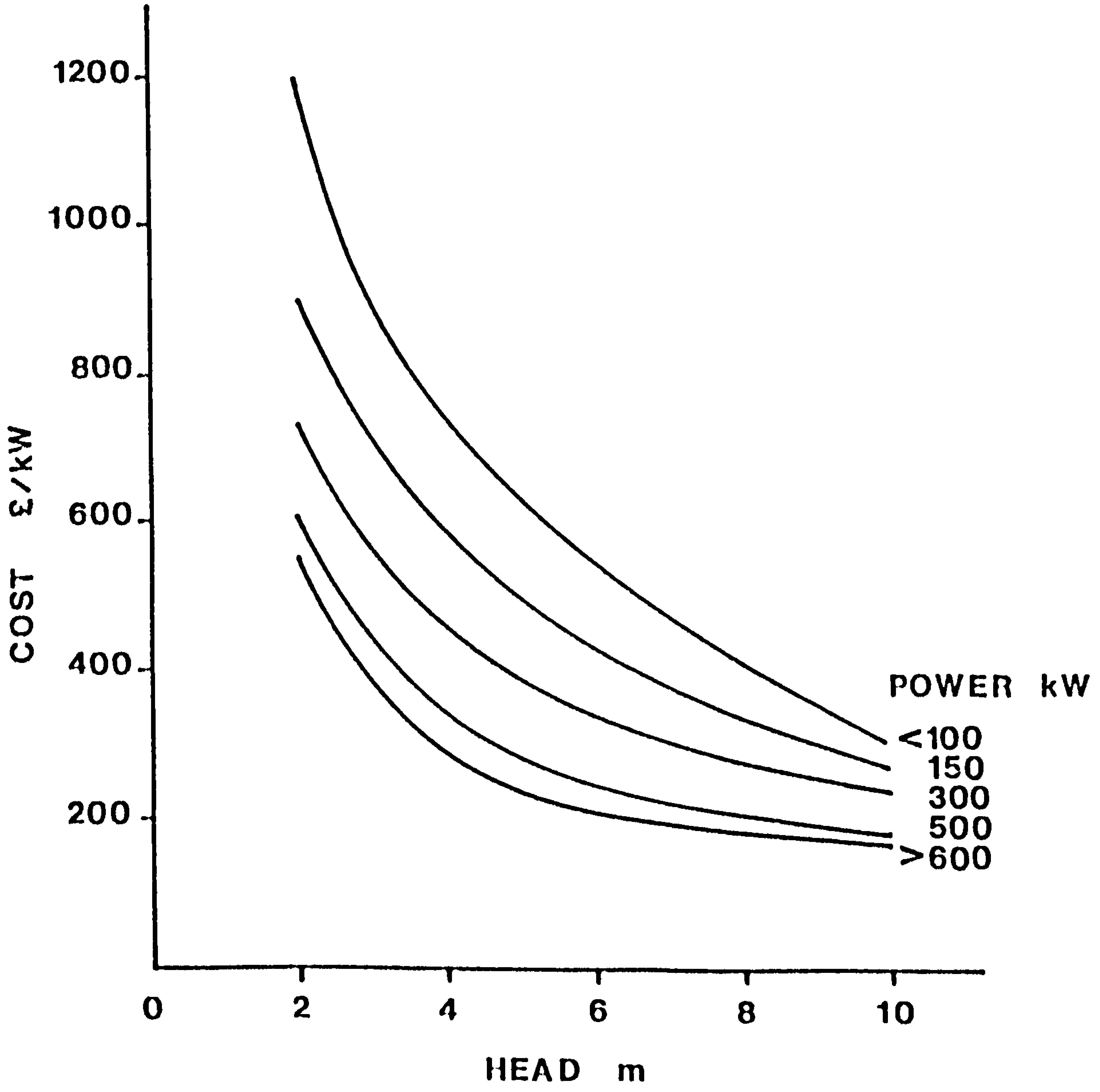


FRANCIS TURBINE COSTS

FIG 4.9

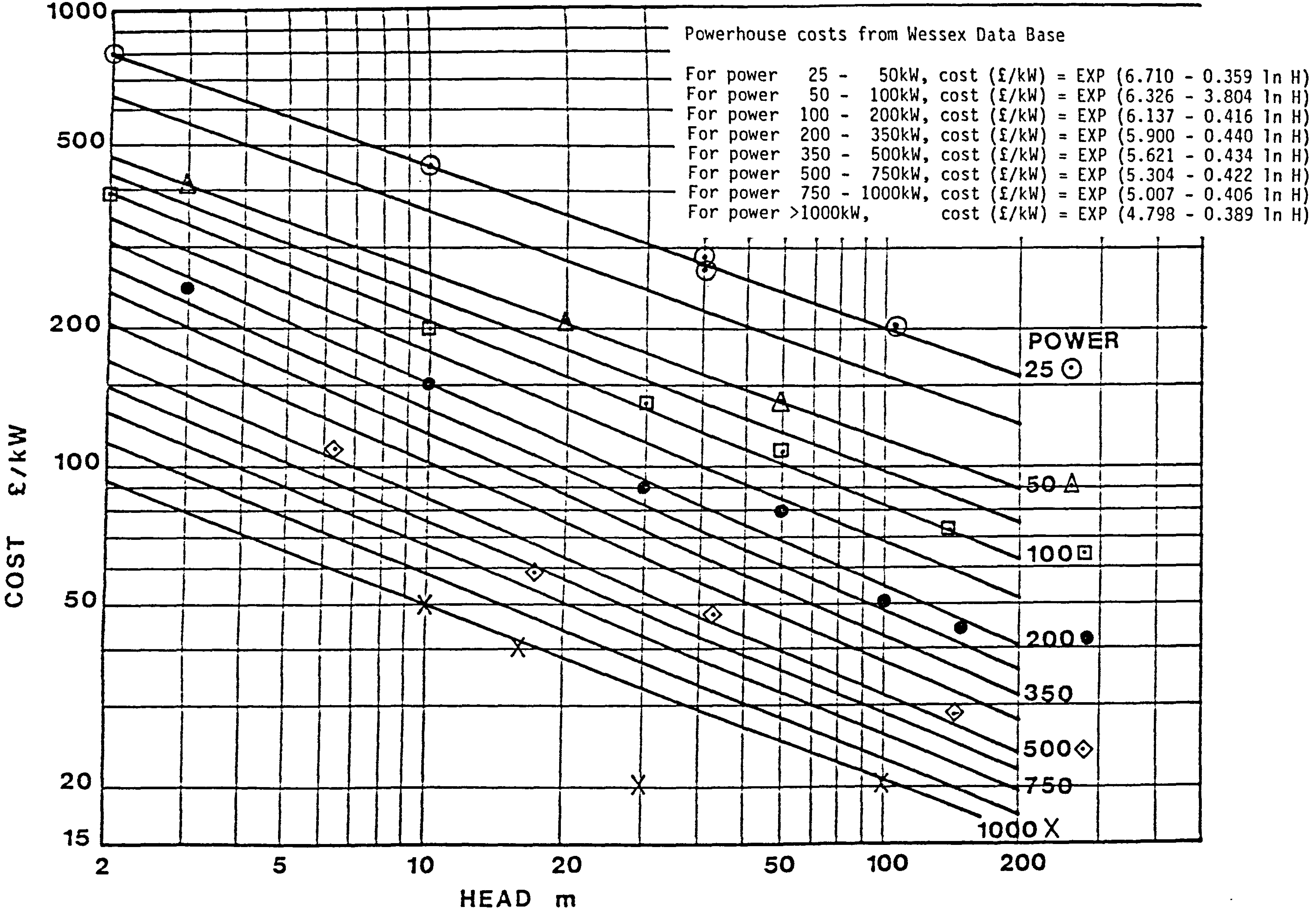
Manufacturers data for turbines and generators inclusive of U.K. delivery

For capacity <100kW, cost (£/kW) = EXP (7.771 - 8.216 ln H)
For capacity 100 - 200kW, cost (£/kW) = EXP (7.316 - 0.717 ln H)
For capacity 200 - 400kW, cost (£/kW) = EXP (7.088 - 0.704 ln H)
For capacity 400 - 600kW, cost (£/kW) = EXP (6.903 - 0.753 ln H)
For capacity >600kW, cost (£/kW) = EXP (6.800 - 0.763 ln H)



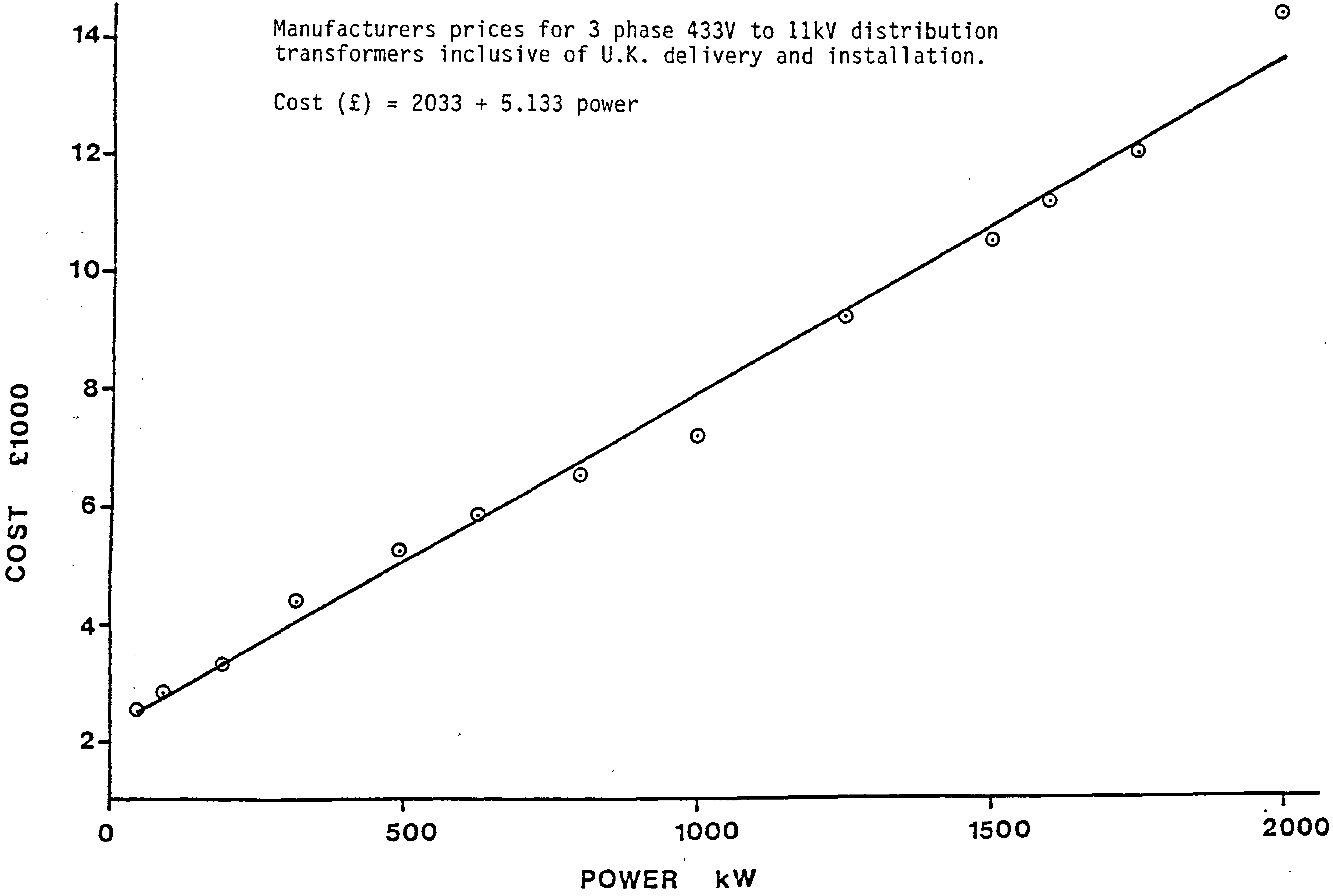
PROPELLER TURBINE COSTS

FIG 4.10



COST CURVES FOR POWERHOUSES

FIG 4.11

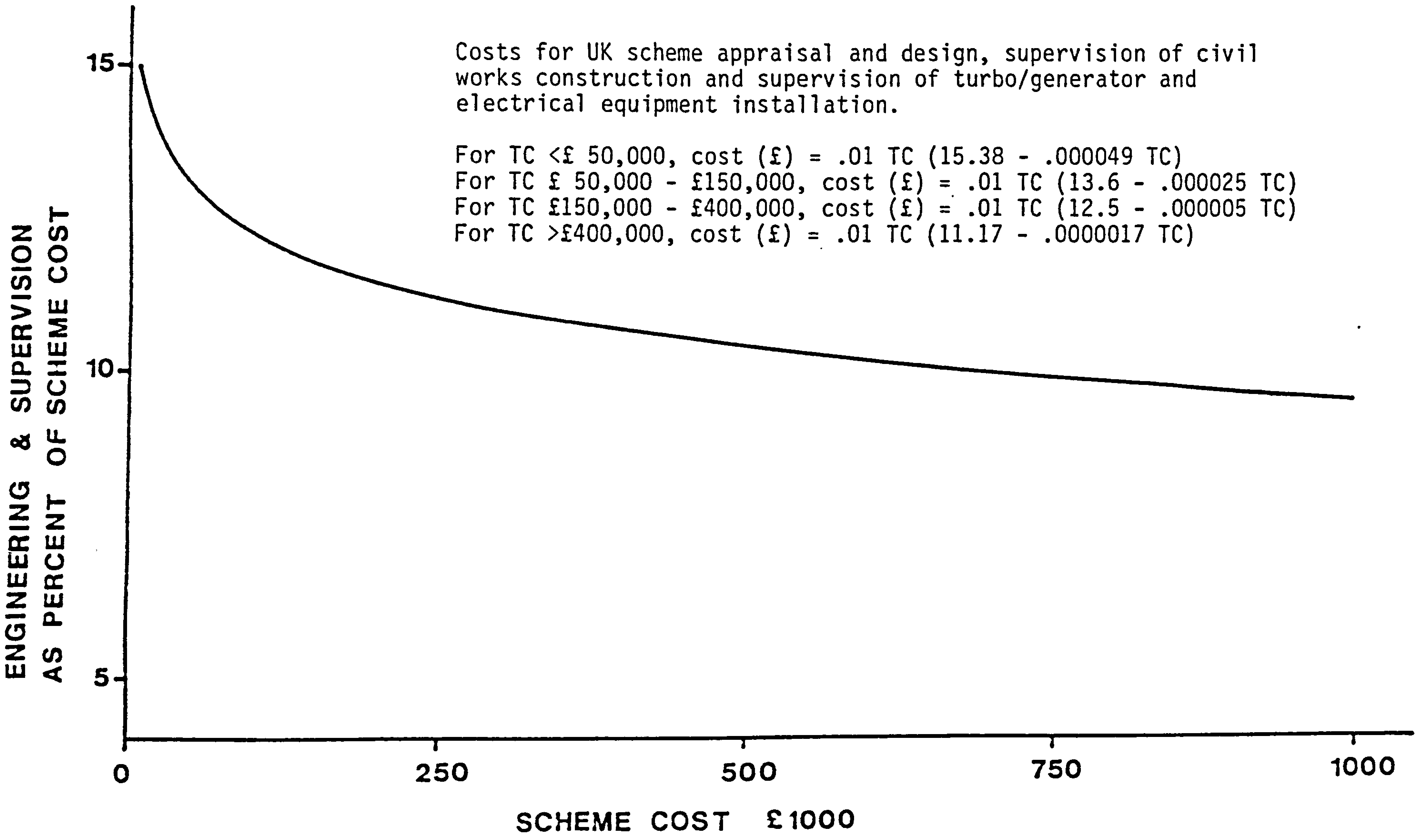


Manufacturers prices for 3 phase 433V to 11kV distribution transformers inclusive of U.K. delivery and installation.

Cost (£) = 2033 + 5.133 power

COST CURVE FOR TRANSFORMERS

FIG 4.12

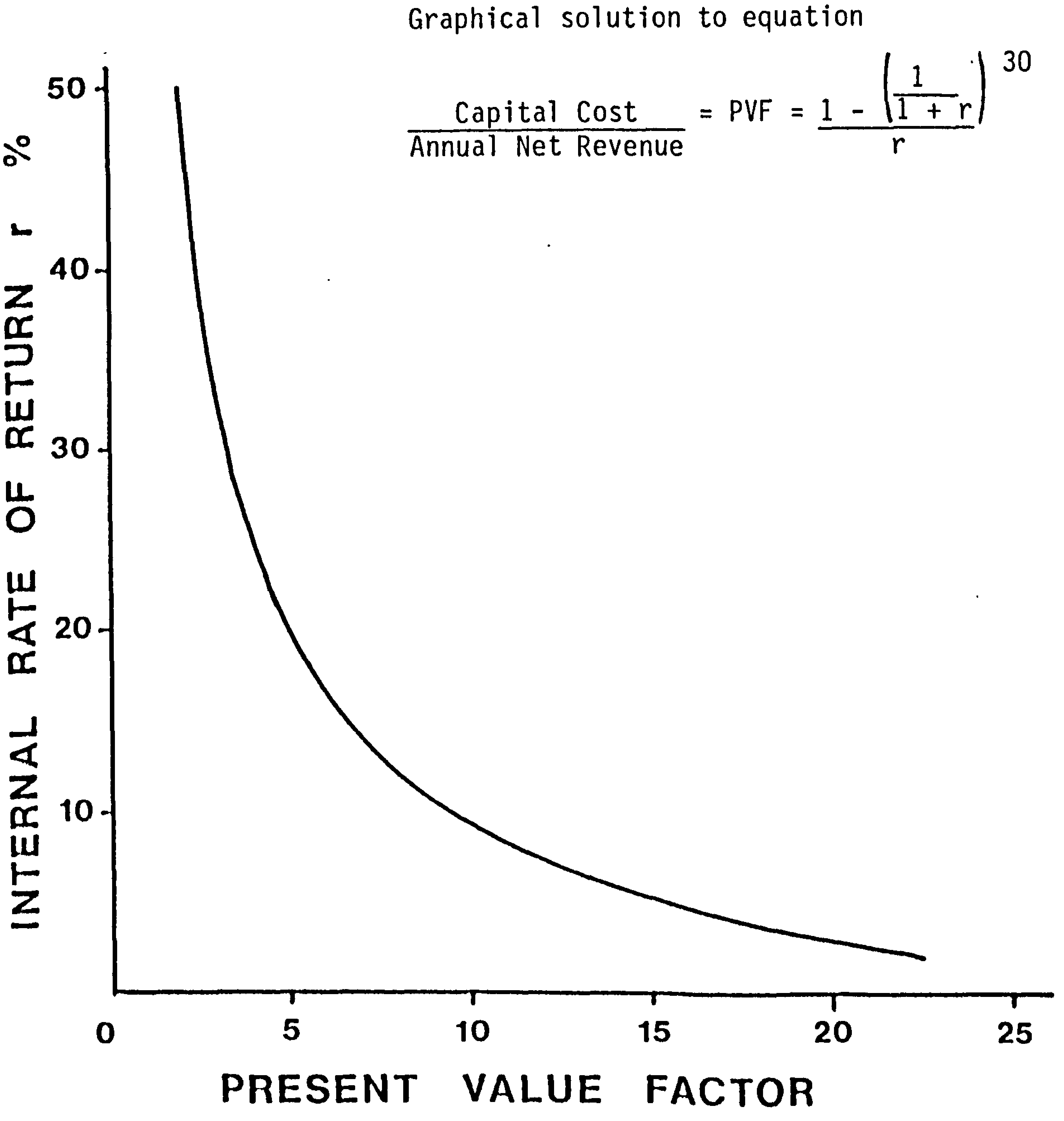


Costs for UK scheme appraisal and design, supervision of civil works construction and supervision of turbo/generator and electrical equipment installation.

For TC <£ 50,000, cost (£) = .01 TC (15.38 - .000049 TC)
For TC £ 50,000 - £150,000, cost (£) = .01 TC (13.6 - .000025 TC)
For TC £150,000 - £400,000, cost (£) = .01 TC (12.5 - .000005 TC)
For TC >£400,000, cost (£) = .01 TC (11.17 - .0000017 TC)

COSTS FOR ENGINEERING AND SUPERVISION

FIG 4.13



Graphical solution to equation

$$\frac{\text{Capital Cost}}{\text{Annual Net Revenue}} = \text{PVF} = \frac{1 - \left(\frac{1}{1 + r}\right)^{30}}{r}$$

IRR AGAINST PVF

FIG 4.14

CHAPTER 5

5.0 Regional Assessment of Small-Scale Hydro-Electric Potential in the U.K.

5.1 Background

There is no comprehensive survey of the small-scale hydro-electric potential of the U.K. although two recent studies have investigated potential for generation at sites with installed capacities of greater than 25kW in Wales (Ref. 20), and within the Water Industry in England (Ref. 21). Both these studies were concerned with assessment of potential only, and did not consider costs of development or the economics of generation at potential sites. In Scotland, some work has been undertaken by the electricity generation boards for assessment of potential at sites with installed capacities of greater than 500kW. However this work (at least in the case of the North of Scotland Hydro Electric Board) is being treated as "commercial in confidence" and therefore not available. In Northern Ireland, work has tended to concentrate on evaluation of individual sites rather than the assessment of total potential.

Due to the obvious gaps in existing knowledge, the Department of Energy as part of its strategic energy review contracted Salford University Civil Engineering Limited in May 1987 to undertake a comprehensive survey of small hydro potential as follows:-

1 England and Northern Ireland - to assess the economic potential at run-of-river sites with installed capacities of greater than 25kW.

2 Wales - to review the Welsh report and bring it in-line with England and Northern Ireland ie. to consider the economics of generation at potential sites.

3 Wales and Northern Ireland, Water Industry - to assess the economic potential.

4 England, Water Industry - to review the previous report by consideration of economic potential.

5 Scotland - a desk survey of run-of-river potential and a preliminary appraisal of sites within the Water Industry.

The remainder of this section is concerned with 1 and 2, the economic assessment of run-of-river potential in England, Wales and Northern Ireland, and is included as an illustration of the methods of assessment previously detailed in sections 1 to 4.

5.2 England and Northern Ireland

5.2.1 Site Identification

The first step in the appraisal was to identify all potential sites from Ordnance Survey 1:50,000 scale maps. The sites fall into two main types, undeveloped or virgin sites, and previously developed sites which have a history of hydropower generation. The former sites are identified as lengths of river where contours are steep, waterfalls, and "forces"; the latter from weirs, leats and mills. Recourse was also made to the eight regional Water Authorities in England and the Department of Environment in Northern Ireland, and to turbine manufacturers, some of whom were able to provide details of previous developments.

Sites were eliminated from the survey where it could be determined from the head and flow that the capacity was less than 25kW, or less than 50kW where there was no prospect of on-site demand. The 50kW criterion was used for remote sites since it was considered that sites with smaller capacities are uneconomic for connection to the grid. This is due to the disproportionately high costs associated with protection and metering equipment required for connection, typically of the order of £10,000 per installation.

A simple graph of the form shown in Figure 5.1 was of use for determining whether sites were likely to make the required minimum installed capacity, in this case for 25kW. It is particularly useful for sites with heads greater than 10m, the contour interval on the O.S. 1:50,000 scale maps. (Methods for obtaining SAAR and Ea are outlined in section 2.3.1).

5.2.2 Site Visits

Having identified all potential sites, site visits were undertaken to determine, heads, and to devise sufficiently detailed scheme layouts for incorporation in the costing package of Section 4. As previously, sites were eliminated where the capacity was less than 25kW or less than 50kW for remote sites. Sites were also eliminated where head was less than 2m or less than 3m for virgin sites, as such sites were considered likely to be uneconomic for development.

5.2.3 Hydrology, Capacity and Yield

A detailed hydrological analysis was undertaken for each of the sites returned from the site visits. Mean flow was calculated from the equation in Section 2.3.1

and a flow duration curve (FDC) for England from the Base Flow Index method of Section 2.3.2.2. The method of implementing this analysis was first to plot the site catchment on a river network map produced by the Institute of Hydrology at scale 1:250,000. This network map contains all the stream data available on the 1:50,000 Ordnance Survey maps but replotted at 1:250,000. Catchment area was now measured from this by planimeter for sites with areas greater than $50km^2$. Where area was less than $50km^2$ catchments were plotted on 1:50,000 O.S. maps making use of topography. The error by use of 1:250,000 network map for sites above $50km^2$ has been assessed to be 1-2% when compared to use of 1:50,000 map and is therefore sufficiently accurate for this type of potential survey.

Catchment average rainfall (SAAR), potential evapotranspiration (Ep) and SOIL were obtained for sites by overlaying the appropriate map onto the catchment plot at scale 1:250,000. This process is illustrated in Figures 5.2 to 5.5. Actual evaportranspiration (Ea) was obtained from Ep using the graph of Figure 5.6.

The method of producing FDC's for Northern Ireland varies from that for England since in Northern Ireland the predominant factor for determining the shape of the FDC is the proportion of drift deposits, particularly sands and gravels, occuring in the catchment (Ref. 22). The recommended equation for Northern Ireland is

$$Q_{95}\ (10) = 0.55\ GL + 7.8$$

The Q_{95} (10) value is directly substituted in the method of (Ref. 6) to determine the shape of the FDC.

Having determined mean flow, the installed flow was calculated for each site using the minimum of

1) Mean flow - compensation flow ($Qm - Q_{95}$)

or

2) The flow capacity determined from the existing civils works where expansion of the scheme was deemed to be uneconomic.

The installed flow, net head and typical turbo-generator efficiency were then used to calculate installed capacity, and the FDC, adjusted for the 95 percentile compensation flow, was used to calculate annual energy production.

5.2.4 Revenue, Costing and Economics

Revenue, costing and economics were determined for each site using the computer-based costing package of Section 4.

5.3 Wales

The method of assessment for Wales differed significantly from England and Northern Ireland since all sites with installed capacity of greater than 25kW had been identified previously in the Welsh report. Further, it was felt that it would be inappropriate to revisit all identified sites, but would be preferable to select, visit and analyse a representative sample of sites. The results obtained from this sample would then be used to predict the total economic potential in Wales.

5.3.1 Site Classification and Sample Selection

An initial screening of sites was undertaken to remove sites as follows:-

1) Operating sites - since these do not form part of the undeveloped potential of Wales.

2) Reservoir sites - such sites are under control of the Welsh Water Authority and were to be included for detailed consideration at a later stage. It is not appropriate to use a sampling technique for water industry sites since their operational requirements and the restrictions imposed by existing civil works require that each site must be considered individually.

3) Sites with heads of less than 2m were considered to be uneconomic for development.

4) Sites with heads in the range 2-3m with no existing civils works were considered to be uneconomic for development; the minimum requirement being the presence of a weir.

5) An average overall conversion efficiency, from water to electrical power output of 85% had been used in the Welsh report. This was now considered to be too high. Further, no allowance had been made for compensation flow. Accordingly, by adoption of more realistic values for the overall efficiency, and by inclusion of a compensation flow of 12% of mean flow, sites were eliminated where capacities were less than 25kW. The Figure of 12% of mean flow was adopted as it is typical of the 95 percentile flow for rivers in Wales.

6) Sites with installed capacities of less than approximately 50kW, where from examination of O.S. 1:50,000 scale maps it could be determined that there was no prospect of on-site energy use ie. remote sites.

Of the 565 potential sites identified in the Welsh report some 353 remained after the screening. These sites were then classified according to head and installed capacity (Table 5.1). A sample of the sites (approximately 1/3) was selected for site visit and detailed appraisal as for England and Northern Ireland. The sample was selected to be as representative as possible by ensuring that sites from each head and capacity group were included, and that the sites selected from each group were geographically spread throughout Wales. There was however, a tendency for sites of the same head and capacity grouping to be located within one area.

5.3.2 Analysis of selected sites

Site visits were undertaken to determine the feasibility of development, and to devise a scheme layout in each case. Some sites were rejected at this stage as inappropriate for development using the criteria of section 5.2.2. Sites returned from the visits were subjected to detailed analysis as follows:-

1) Adjusted scheme capacity

Installed capacity and energy yield were recalculated to take account of revised effiency, the inclusion of 95 percentile compensation flow and restrictions imposed by the existing civils works.

In the case of annual energy yield, this is not straightforward since the effect of compensation flow on energy yield varies with exceedance flow at which the scheme is rated.

To investigate this effect, a typical flow duration curve was selected (Figure 5.7). Energy yield values were computed with and without compensation flow at various exceedance points. The results of this analysis are plotted on Figure 5.8. By establishing the exceedance on the regionalized FDC from the Welsh Report corresponding to the rated (or design) flow, it was then possible to calculate a revised energy yield from the values of the Welsh report.

2) Revenue, Costing and Economics

Revenue costing and economics were determined for each site using the computer based estimating package of section 4.

5.3.3 Total Potential of Wales

The detailed analysis of selected sites and the proportions of selected to rejected sites from the sample were used to predict the gross potential and economics for Wales.

1) The previously calculated Welsh report capacity of sites remaining after the initial screening was known (W).

2) The proportion of sites visited and selected to those visited and rejected was known for each head and capacity range. This "success rate" (R) was then applied to the sites not visited.

3) The previously calculated Welsh Report capacity of selected (visited and included) sites was known (X), and a revised capacity figure was obtained from the detailed analysis (Y).

4) An estimate of the total capacity for Wales was then obtained for each head/capacity range from:-

Capacity = WRX/Y

This calculation is shown in Table 5.2. For consideration of economics, the average values obtained for selected sites were applied to the not-visited sites in each of the head/capacity ranges.

5.4 Results - England, Northern Ireland and Wales

The results of the study for England, Northern Ireland and Wales are shown graphically in Figures 5.9 to 5.11.

In Figure 5.9 cumulative installed capacity is plotted against internal rate of return for schemes with a plant life of 30 years and against which are placed various scheme charges. The measure of a schemes attractiveness from an economic view point is dependent upon the requirements of the potential investor. For nationalized industries such as the Electricity Generating Boards and Water Authorities, the Treasury guideline for economic viability is that a scheme should yield a real internal rate of return of 5%. From Figure 5.9, for the base case of a scheme for which charges of operation and maintenance only are levied, this implies that from a national view point, some 45.5MW of capacity is attractive for development. Presently, however schemes are liable for abstraction charges and for local authority rates based on capital cost, the imposition of which would reduce economic potential to 29MW. If, as appears likely, abstraction charges are no longer applied and formula rating is adopted the economic potential is then 42MW.

The electricity generating boards do not, at this time, appear to be considering small hydro for development. Consequently, if schemes are to be developed it will have to be through private investment. In this case it is likely that investors will require a minimum internal rate of return of 10%. Such a criterion, for schemes charged only with operation, maintenance and 'formula' rating, will reduce the total available capacity for development to about 24.5MW.

In Figure 5.10, cumulative installed capacity is plotted against scheme cost. This graph provides a useful indicator of the cost for which a scheme can be developed in order that it is economically attractive. For national development and private development these indicators are £1580/kW installed and £1100/kW installed respectively, and are equivalent to capital investment sums of £66.4 million and £27 million.

In Figure 5.11 cumulative installed capacity is plotted againt average scheme cost. This plot is of interest from the national view point in particular since it shows that applying the indicator of £1580/kW installed that 64.5MW of capacity is attractive for development ie. the effect of averaging the better schemes with the less good yields a capacity of 64.5MW. By coincidence, this 64.5MW is the total capacity considered appropriate for small hydro development by the writer and his colleagues, and if developed, would be equivalent to a capital investment sum of £102 million.

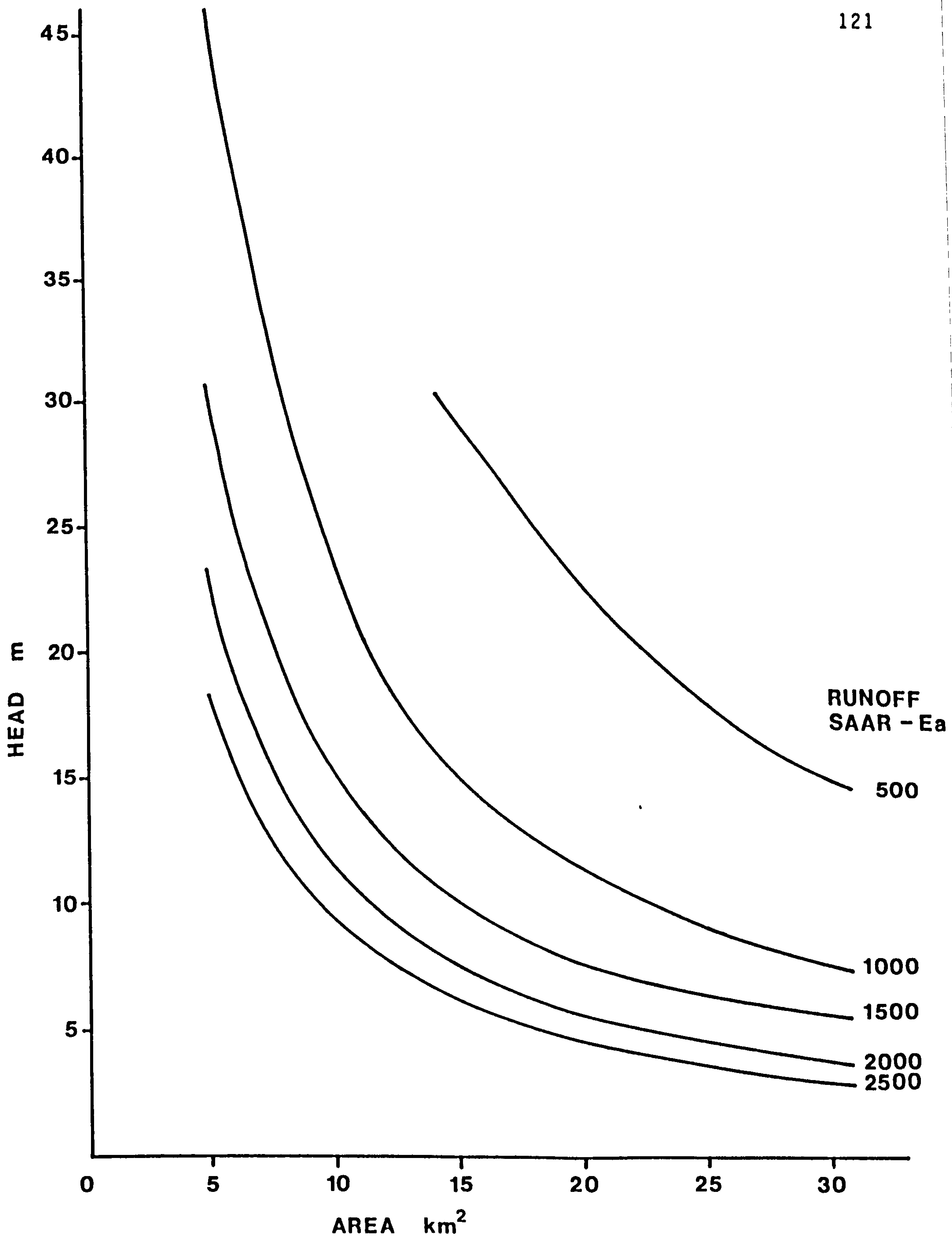
In concluding this section, it is worth noting that the sum required for "large scale" development of small hydro in the U.K. is not large. The impact that such development might have on local economies and for export potential for manufacturers is discussed in section 6.

Head (m)	Capacity (kW) <50	50 - 100	150 - 250	250 - 500	>500
2 - 3	2	3	6	0	4
3 - 5	4	22	17	4	4
5 - 10	19	16	16	1	0
10 - 20	26	29	14	3	1
20 - 30	8	26	12	2	0
30 - 50	8	20	16	5	0
>50					

Table 5.1 Wales - Site Classification by Head and Capacity

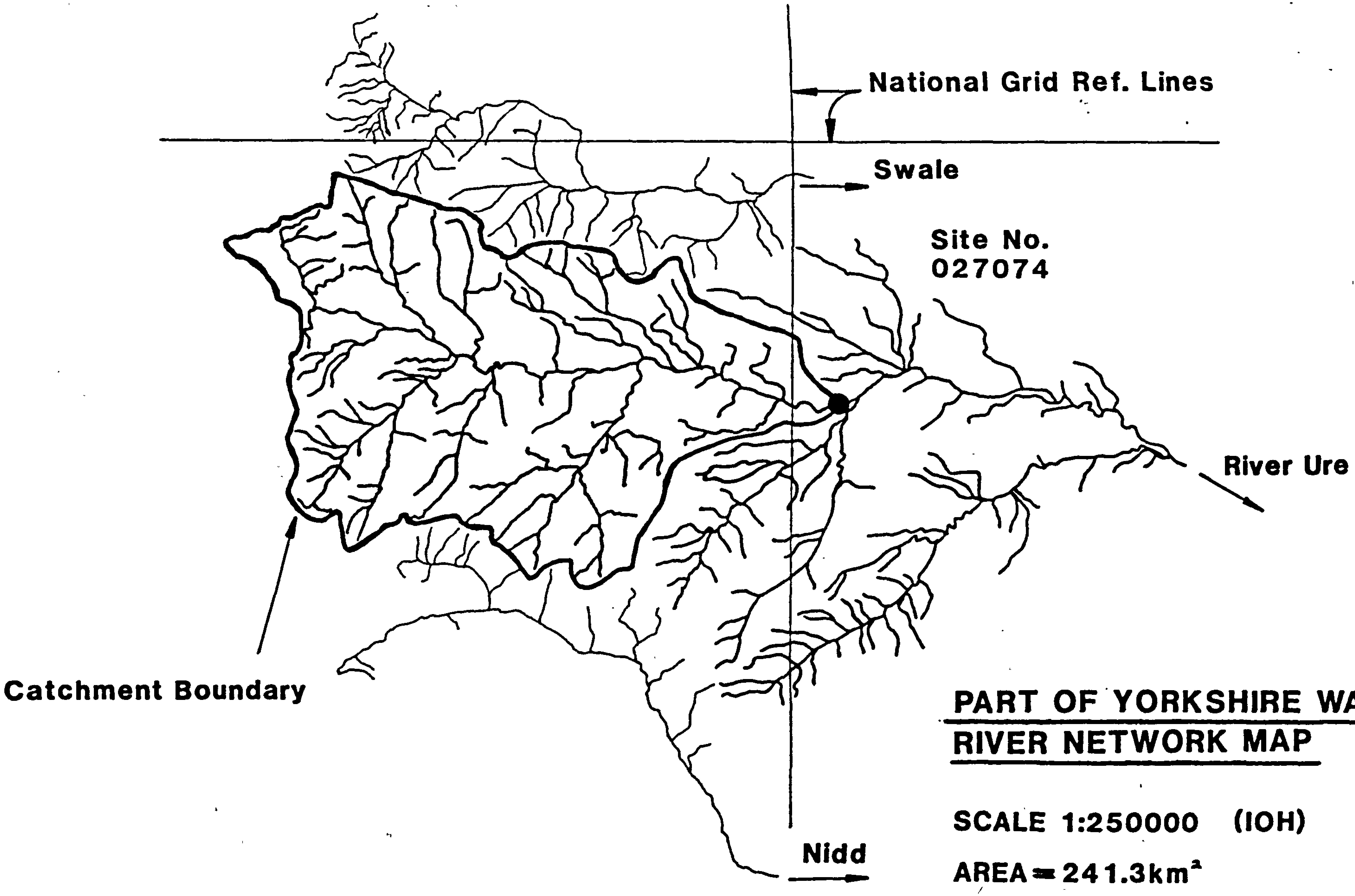
Head	Capacity Range	Welsh Report		Success Rate	Welsh Report Included Sites		Included Sites Revised		Included Sites Revised/Report (%)		Total Welsh	
		Capacity (kW)	Energy (MWh)	(%)	Capacity (kW)	Energy (MWh)	Capacity (kW)	Energy (MWh)	Capacity (kW)	Energy (MWh)	Capacity (kW)	Energy (MWh)
2 - 3	<50	93		--								
	50 - 100	295		NIL								
	100 - 250	969	3620	25.0	103	401	59	293	57.3	73.1	139	662
	250 - 500	467		--								
	>500	3637		NIL								
3 - 5	<50	163	622	100	43	174	44	211	102.3	121.3	167	754
	50 - 100	1413	5445	20	151	557	86	419	57.0	75.2	161	819
	100 - 250	2674	13007	30	501	2801	216	1132	43.1	40.4	346	1576
	250 - 500	1728	9577	66.7	757	4230	307	2207	40.6	52.2	468	3334
	>500	2650	10168	100	800	3087	521	2560	65.1	82.9	1725	843
5 - 10	<50	628		--								
	50 - 100	1194	5336	66.7	409	2034	353	1806	86.3	88.8	687	3160
	100 - 250	2649	12131	37.5	510	2347	337	1939	66.1	82.6	657	3758
	250 - 500	263		--								
	>500	--		--								
10 - 20	<50	961	4942	66.7	167	934	141	669	84.4	71.6	541	2360
	50 - 100	2043	10691	10.0	89	373	57	264	64.0	70.8	163	916
	100 - 250	2432	13143	50.0	964	4698	673	3469	69.7	73.8	941	5383
	250 - 500	815	--	NIL								
	>500	510		--								
20 - 30	<50	213		NIL								
	50 - 100	1797	8276	37.5	234	1123	192	880	82.0	78.4	553	2432
	100 - 250	1806	9562	33.3	290	1593	222	1075	76.5	67.5	460	2149
	250 - 500	625	--	NIL								
	>500	--		--								
30 - 50	<50	328		NIL								
	50 - 100	1511	7112	57.1	300	1331	230	1104	76.7	82.9	661	3368
	100 - 250	2246	10606	50.0	525	2662	361	1692	68.8	63.6	772	3371
	250 - 500	1508	7538	100.0	310	1612	196	906	63.2	56.2	953	4236
	>500	1366		--								
>50	<50	129		NIL								
	50 - 100	1257	6246	50.0	174	932	161	741	92.5	79.5	581	2483
	100 - 250	4422	21757	80.0	1408	7368	1188	5501	84.4	74.7	2985	12995
	250 - 500	3915	20639	66.7	809	2600	510	2522	63.0	97.0	1645	13353
	>500	3584	22404	50.0	750	4320	147	960	19.6	22.2	351	2487
										TOTAL	14956	70469

Table 5.2 Calculation of total potential in Wales



MINIMUM CATCHMENT AREA TO YIELD 25kW

FIG 5.1

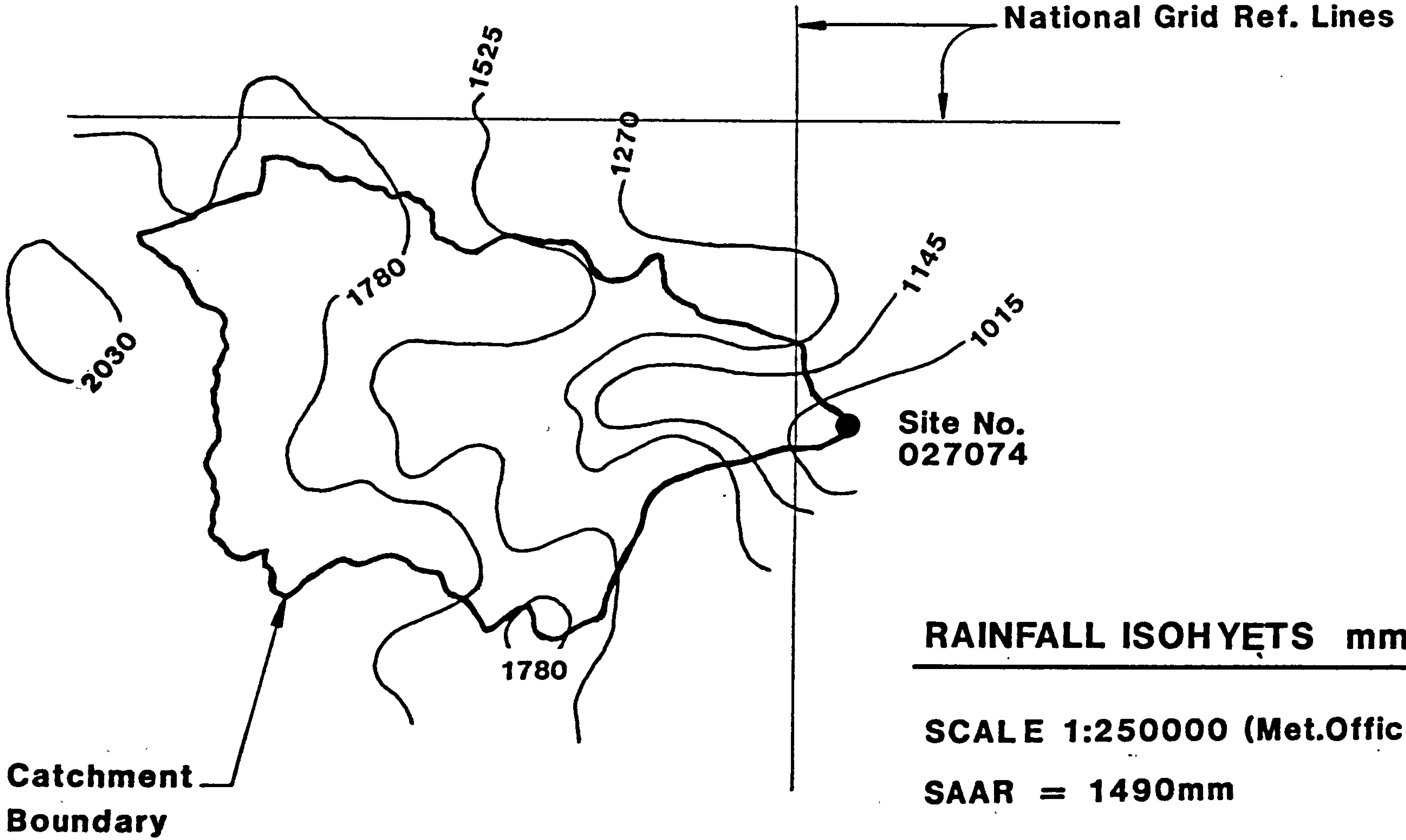


PART OF YORKSHIRE WATER RIVER NETWORK MAP

SCALE 1:250000 (IOH)

AREA = 241.3km^2

FIG 5.2

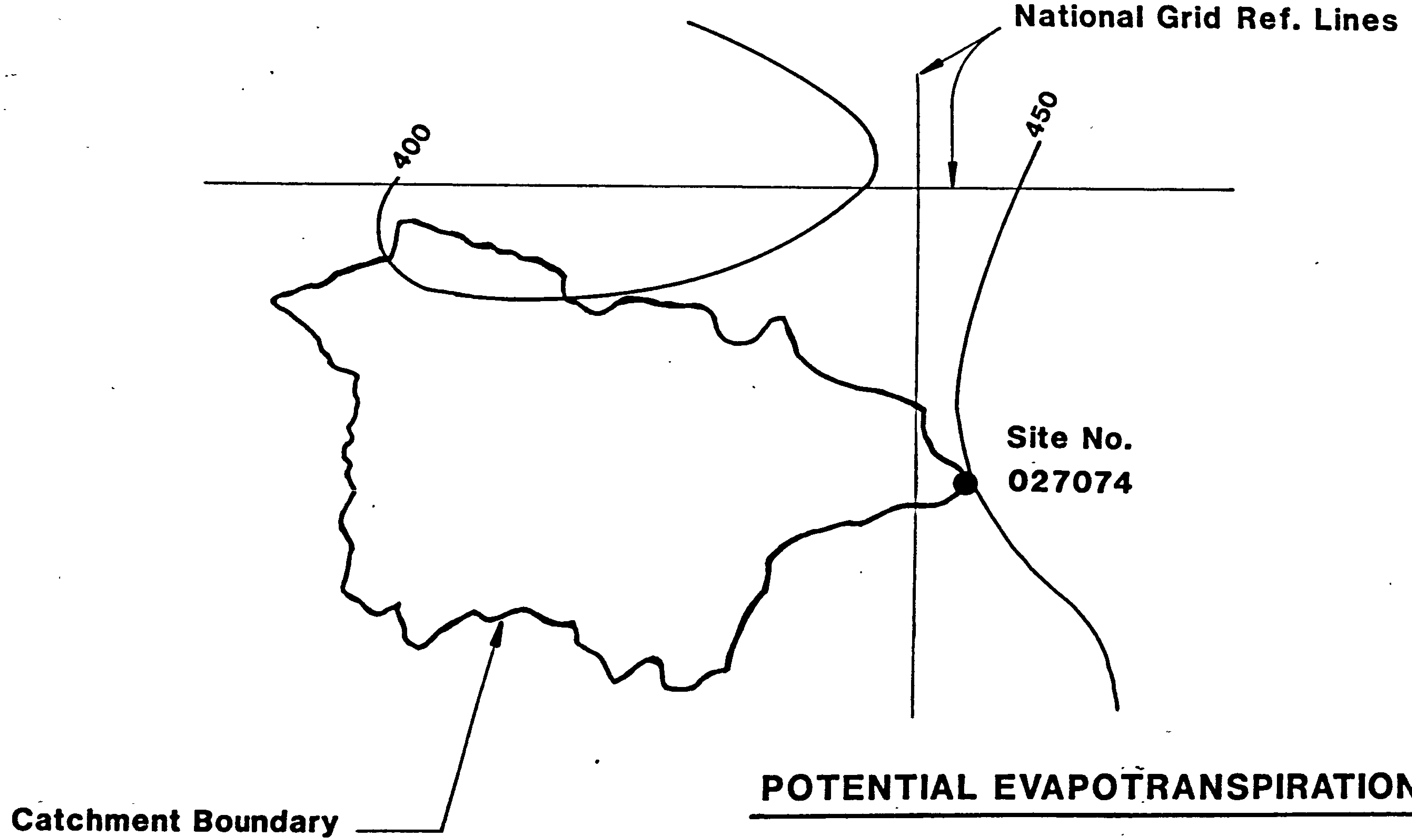


RAINFALL ISOHYETS mm

SCALE 1:250000 (Met.Office)

SAAR = 1490mm

FIG 5.3

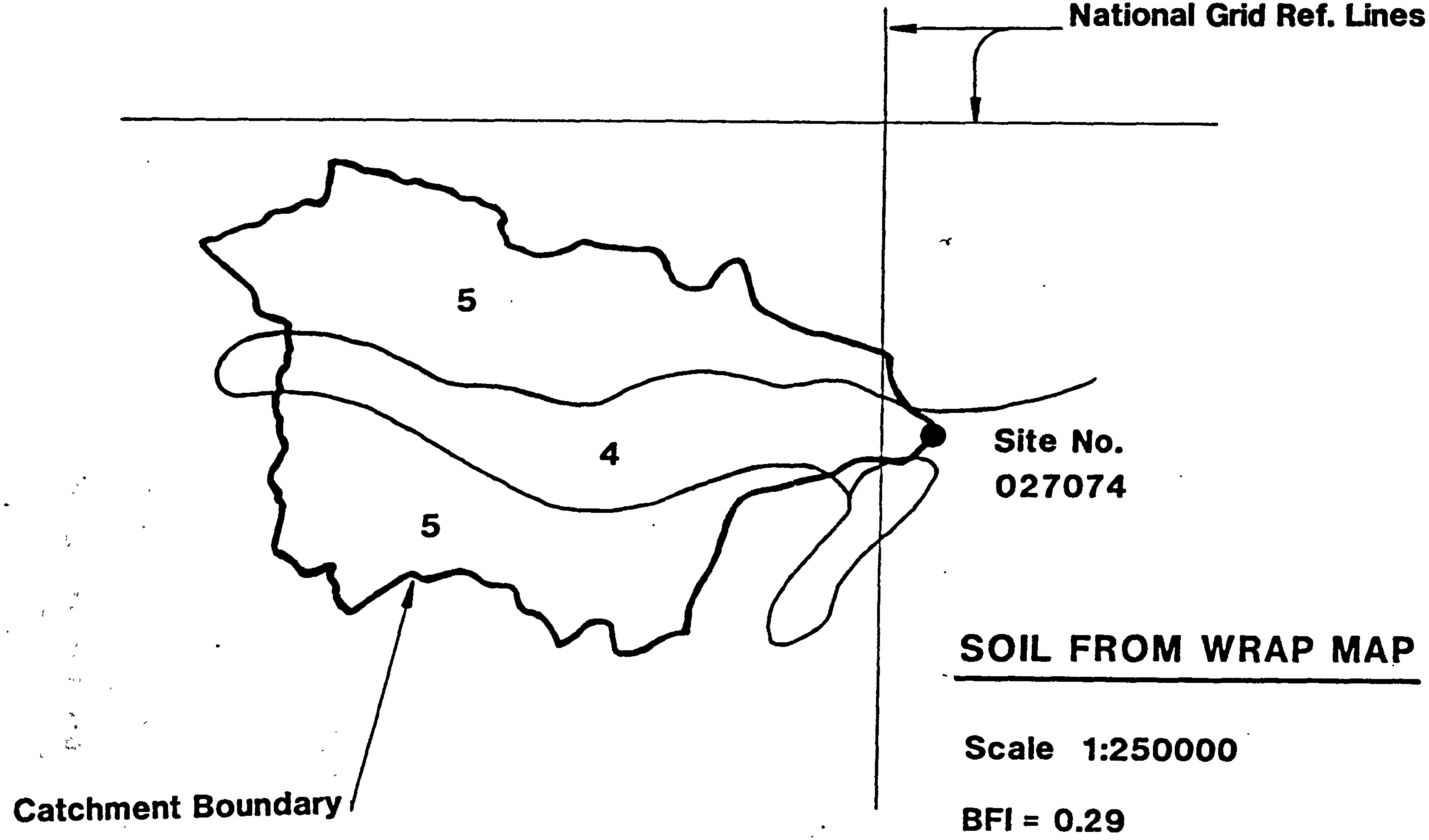


POTENTIAL EVAPOTRANSPIRATION mm

SCALE 1:250000 (Met.Office)

Ep = 410mm

FIG 5.4

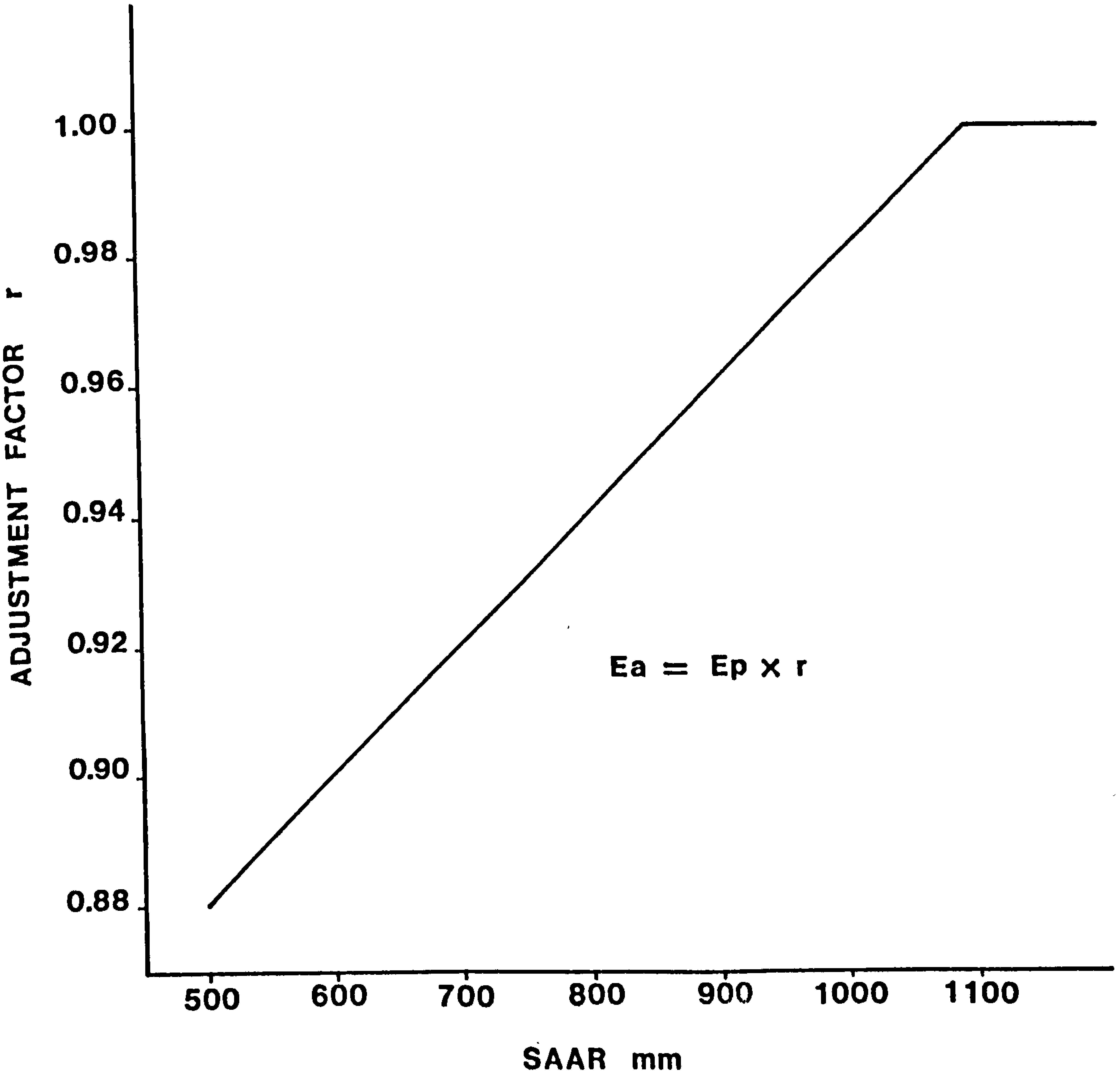


SOIL FROM WRAP MAP

Scale 1:250000

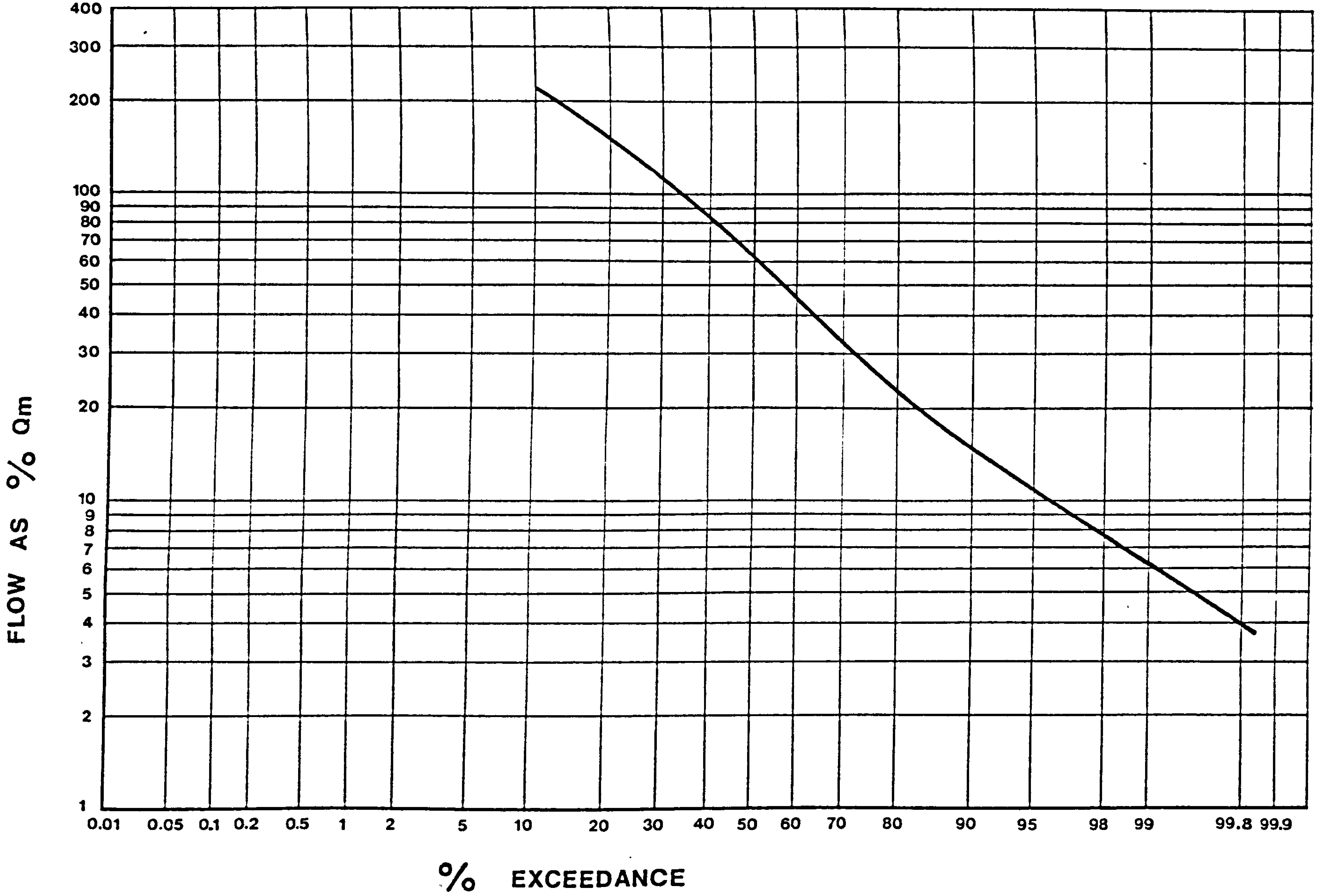
BFI = 0.29

FIG 5.5

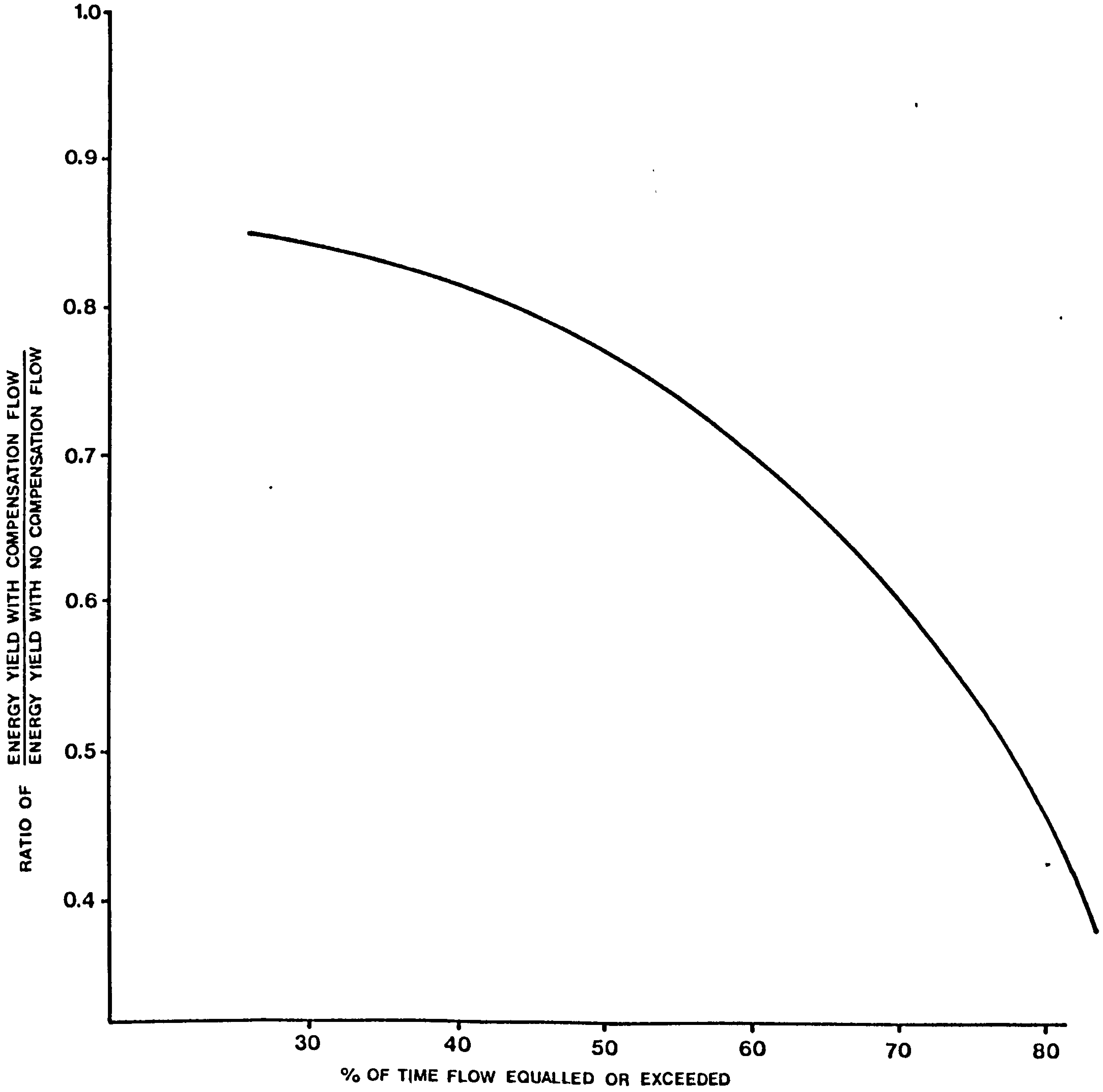


CALCULATION OF ACTUAL EVAPOTRANSPIRATION FROM POTENTIAL EVAPOTRANSPIRATION

FIG 5.6

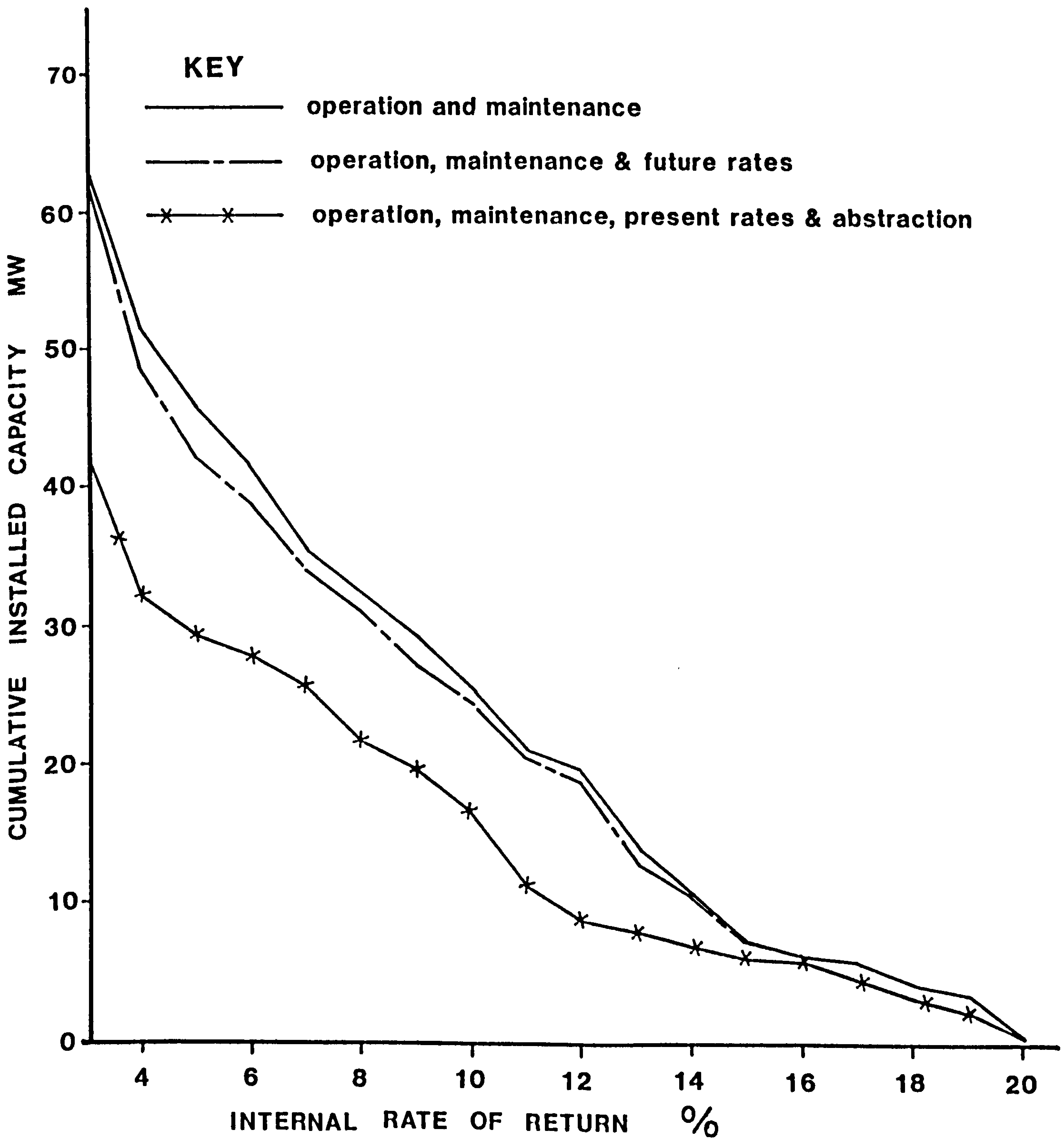


FDC FOR RIVER TAFF AT GAUGE 060003



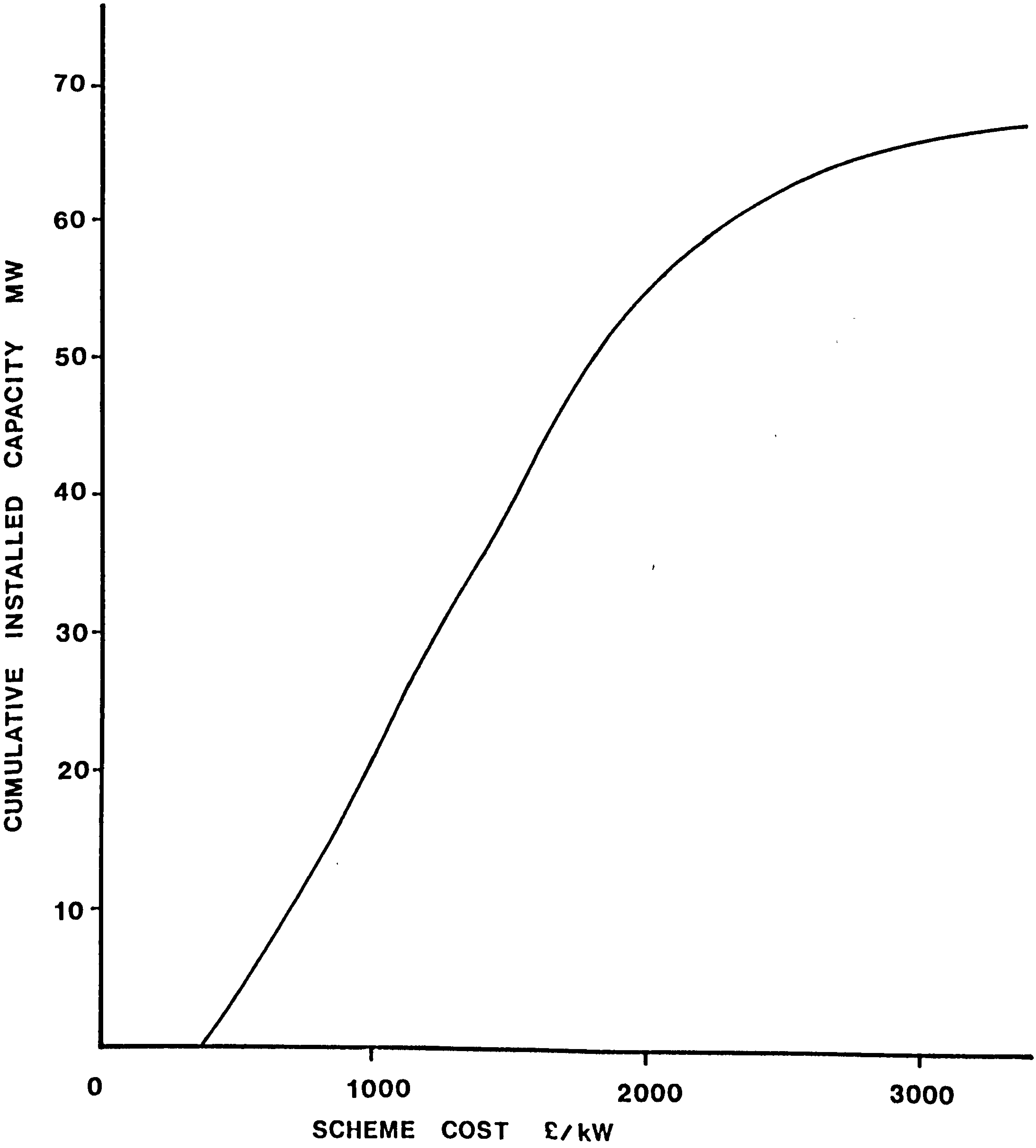
EFFECT OF COMPENSATION FLOW ON ENERGY YIELD

FIG 5.8



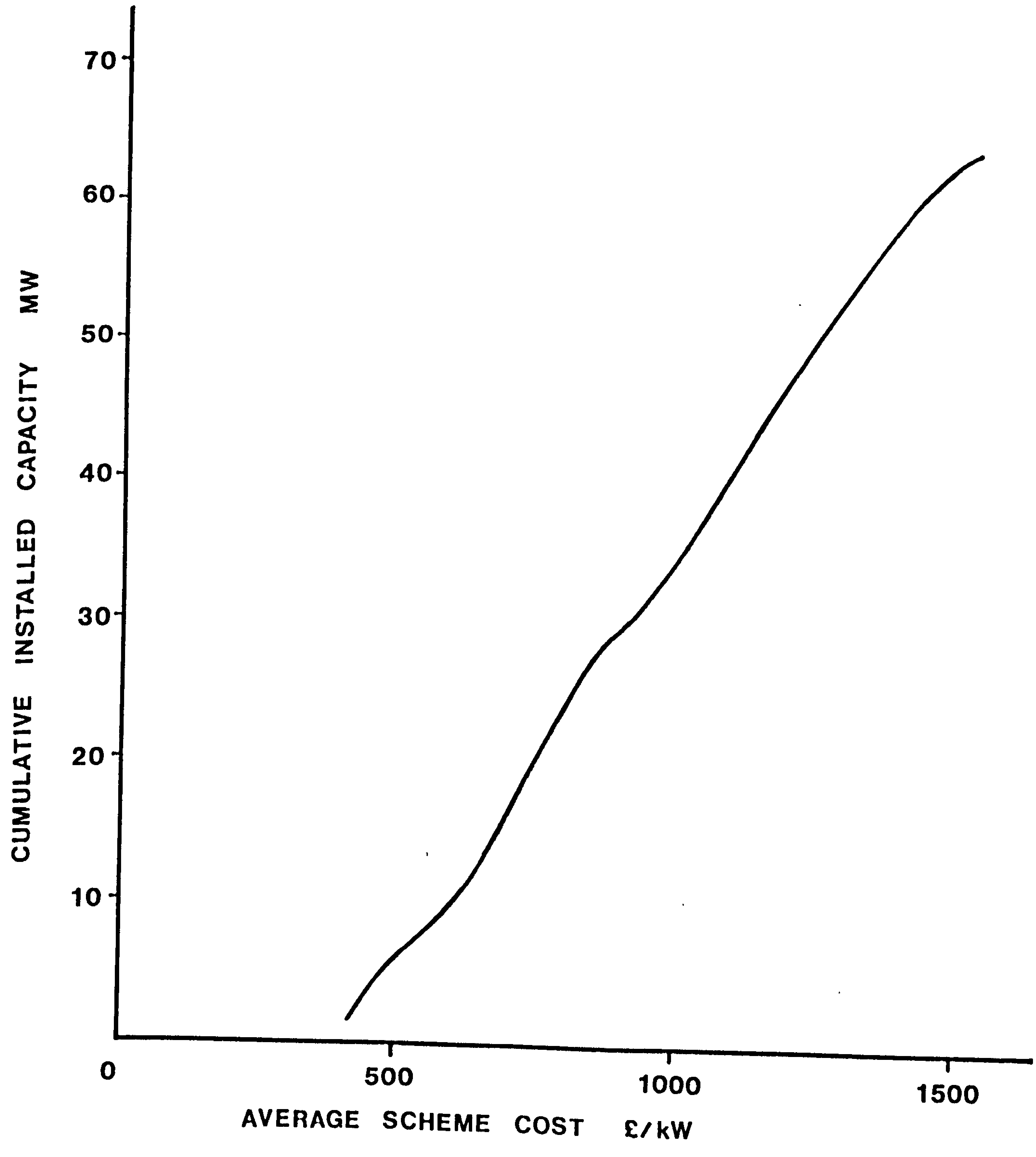
ENGLAND, NORTHERN IRELAND AND WALES

FIG 5.9



ENGLAND, NORTHERN IRELAND AND WALES

FIG 5.10



ENGLAND, NORTHERN IRELAND AND WALES

FIG 5.11

CHAPTER 6

6.0 The Salford Transverse Oscillator

6.1 Introduction

The majority of hydro-electric schemes in operation today have large installed capacities and generate electricity from high heads and relatively small flows. The number of undeveloped sites throughout the world where such schemes can be installed is limited. Further, these undeveloped sites often lie in inaccessible areas away from the main centres of population which makes transmission expensive and usually necessitates a large interconnected grid system to absorb the energy produced. This latter point is of particular significance in undeveloped countries where often, no such systems exist and hence energy produced must be consumed locally. The capital sums involved in large scale developments also have significant effect on investment and aid programmes and the "Third World debt". Focus has turned therefore to developing small, low-head, high flow sites which have a nearby demand for energy of which there are many thousands throughout the world. A study in India has detailed that there is a potential capacity of 97MW for schemes with heads of less than 3m at canal sites in the Punjab alone (Ref. 23).

The problem with low-head hydropower is that to produce worthwhile energy outputs requires the use of large water flows. This makes the use of conventional rotodynamic hydraulic turbines with their small water passages and complex shapes uneconomic, particularly so when the ultra-low-head range of less than 3m is reached. Further, the technology required for the manufacture of conventional low-head turbines precludes local manufacture in undeveloped countries.

The Salford Transverse Oscillator (STO), a new type of positive displacement hydro-electric generator seeks to provide a solution to these fundamental problems by virtue of large water passages and simple design. The concept of the STO is to provide a generator capable of operation in rivers, canals and tidal estuaries (2 way generation) at heads in the range 0.5 - 3m with installed capacities from 10kW to several MW's.

6.2 Concept of the STO

The concept of the STO was first envisaged by Professor E.M. Wilson and Dr G.N. Bullock of Salford University. The patents were subsequently acquired by AUR Hydropower Limited of London, who where responsible for funding development of the STO.

The main features of the STO are shown in Figure 6.1. It consists of a parallel double wall barrage built across the direction of flow in a river, canal or tidal estuary, to make use of or create a hydraulic differential. At regular intervals along the barrage are gaps into which are placed gates, the sections of the barrage between the gates are called cells. The purpose of the gates is to direct water through the cells from the higher level to the lower.

Paddles are placed in the cells to prevent the free passage of water from upstream to downstream. There is thus, a net hydraulic force on a paddle in the direction the water moves causing it to be pushed to the end of the cell. By linking the paddles at the top to a carriage and synchronizing gate action, it is possible to make the carriage and paddles oscillate from end to end of the cells along the barrage. It is this motion transversely to the main direction of water flow which gives the STO its name. The action of the gates and paddles is clearly shown in Figure 6.2

A power take-off rod links the paddles at about one third of their height above the base of the cell. It is located to pass through the centre of pressure of the water acting on the paddles and so keep the bending moments obtained at the carriage to a minimum. The rod, which passes through the centre of the gates but does not impede their motion, is linked to a double acting hydraulic ram. The ram provides resistance to the motion of the paddles causing them to do work by pumping pressurized hydraulic oil.

The STO gates are driven by actuating rams which are supplied by a small proportion of the high pressure oil "bled-off" from the main hydraulic circuit, making the STO self powered.

In most cases the pressurized hydraulic oil would be passed via accumulators, which smooth the flow, to variable displacement hydraulic motors linked to electric generators. However, the oil can be used directly for driving hydraulic machinery, or to produce heat by being "blown" through a restricting valve and heat exchange unit.

6.3 Model Tests

The period of operation, discharge, power output and efficiency of the STO are dependent upon its physical dimensions, the hydraulic head, the upstream and downstream water levels and the force or loading applied to resist the paddle motion at the power take-off rod. In order that the STO could be considerd for application to run-of-river and tidal development it was necessary to produce a STO operating characteristic equivalent to a turbine "hillchart". Accordingly model testing and development were undertaken at Salford

University to determine STO operating characteristics and to dimension a unit which was most likely to produce energy at minimum cost.

Model development concentrated on optimizing gates, paddle/carriage and power take-off systems, and cell dimensions. At all stages of the development due regard was made to the design of full size STO units. The model parameters showing the best results were:-

3 cells
Cell length = 0.88m   Cell depth = 0.88m
Cell width = 0.44m   Gate width = 0.26m
Stroke length = 0.78m

A definitive set of test data was produced for this model configuration and is shown plotted in Figure 6.3. Here power output is plotted against head for different values of operating pressure and downstream depth. The power output plots show a general trend characterised by a peak value for a specific operating pressure.

This characteristic of STO operating curves is of particular significance because it shows that for any particular water levels, it is necessary to place a specific load on the paddles to ensure maximum power output. Further, for given operating levels, pressure controls the speed of carriage operation and hence discharge is specified.

By plotting envelope curves to the maximum output values, it is possible to produce a maximum power operating characteristic for the STO under any occuring condition. This process is shown schematically in Figures 6.4 and 6.5.

A detailed description of model development and performance data is given in Ref. 24.

6.4 Scaling of Results

The results of the model tests allow prediction of STO operating characteristics under any condition. In order to use these characteristics for the specification of full size STO units, it is necessary to scale the model test results by use of Froude Laws. The appropriate scaling factors are given in Table 6.1.

6.5 River Unit Selection

As in the case of a conventional hydro-electric generator the size of the unit selected is dependent upon the operating head, the installed flow and to a lesser degree the flow variation at the site. Figure 6.5 shows the appropriate size of unit to be selected for a variety of head and installed or design flows. The discharge operating range for a particular unit is dependent upon a number of inter-related factors, but typical operating ranges are given in Table 6.2.

In a run-of-river situation the STO barrage would be operated to maintain a constant upstream water level ie. the period of oscillation of the STO would be adjusted to maintain this constant level as the flow arriving at the barrage varies. This would be achieved by altering the swash plate angle on the hydraulic motor in response to changes in upstream water level. Adjustment of swash plate angle varies system operating pressure which in turn varies the load applied to the power take off rod by the hydraulic ram, and consequently adjusts the period of oscillation and discharge. The setting level for the barrage is such that the top of the STO gate is at the normal upstream water level.

In order that the hydraulic motor can effectively control the flow of water through the barrage it must be sized correctly, such that it can accommodate the range of oil flows and pressures pumped to it by the power take off ram whilst continuing to operate at constant speed (1500 rpm for a 4 pole alternator). The hydraulic motor can only be specified correctly when the power take off ram has been sized since this together with the period of oscillation of the carriage determine the volume of oil arriving at the motor. The power take off ram is sized as the minimum necessary to withstand the maximum buckling load transmitted to it by the power take off rod, with a margin of safety. The minimum size should always be selected since this will minimize oil flows and thus hydraulic motor size, with consequent effects on unit costs.

In the model, test results were always quoted in terms of power output measured in the oil. Having correctly specified the hydraulic motor and selected an appropriate electrical generator the performance characteristics of the combined motor/generator unit can be used to calculate the electrical power output and energy yields.

The selection of an appropriate STO unit and calculation of power outputs and energy yield is best illustrated by the example in section 6.6.

6.6 Raowal on the Sidwhan Branch Canal, Punjab, India

6.6.1 Introduction

Typically irrigation canals in India are constructed in such a way that every 2 to 3km along their length there is a drop structure. The heads at these drop structures are usually in the range 1 to 3m with flows of 5 to

$50m^3/s$. As such they are most appropriate for small-scale hydro-electric generation using the STO.

In early 1985, at the request of the State Electricity Board, an appraisal was undertaken for a proposed STO installation at Raowal on the Sidwhan Branch Canal in the Punjab. The project brief was to dimension a STO unit suitable for generation using the existing canal drop structure, to calculate power and energy yields and to produce cost estimates for the manufacture of all mechanical and electrical items. Basic civil engineering layout was also to be determined, but the design and construction of the civil works were to be undertaken by the Punjab State Electricity Board.

6.6.2 Site Parameters

The head at the drop structure is 1.8m at the full supply discharge of $35.4m^3/s$. Although there is less flow variation (and head) than would be experienced in a normal run-of-river situation, monthly mean flows shown a 2 to 1 variation of flow from wet to dry months. This variation of flows causes a reduction of head at high flows and an increase at low flows due to variation in downstream depth. Mean monthly flow figures, stage and head occuring at the drop structure are shown in Table 6.3.

6.6.3 Unit Selection

An examination of the curves of Figure 6.6 suggests that a 3 cell STO unit of basic 5.5m configuration is suitable for the design head of 1.8m and full supply discharge of $35.4m^3/s$. However with a constant upstream level, fixed at the top of the STO gate, a single unit of this size is not capable of operating effectively during low flow months when the head rises to 2.58m and flow falls to $17.7m^3/s$. A more appropriate solution is to use two 3 cell STO units of 4m configuration. This selection also has two advantages when compared to the use of a single 5m unit as follows:-

1) Excavation to obtain the required depth for setting the barrage is minimized.

2) The flow variation required by each of the 4m units is significantly less than that of a single 5m unit; this is reflected in a less onerous pressure variation in the hydraulic circuit and fewer accumulators for smoothing oil flows.

6.6.4 Energy Computation

Once the unit size has been selected the forces in the power take off rams can be calculated and the hydraulic power take off rams specified. Sizing of the power take off rams and calculation of the periods of oscillation that are required to meet the flows arriving at the barrage allows the oil flow arriving at the hydraulic motors to be calculated. Oil flow and power are now used to select the appropriate size of hydraulic motor from manufacturers catalogues. A typical operating characteristic for one such motor is shown in Figure 6.6. This characteristic allows calculation of motor efficiency and shaft output. Applying electrical generator efficiencies to hydraulic motor shaft output then allows calculation of electrical power output and energy yield.

In the case of Raowal the oil flows and operating pressures are such that two motors are required to match STO output. These motors would be mounted each side of a single electrical generator. A 'spragg' type clutch would be incorporated between one of the motors and the generator such that this motor could be isolated when not required.

The calculation of output for the STO installation at Raowal is shown in Table 6.4.

6.7 Tidal Development

In general, conventional turbines are uneconomic for tidal energy generation, the exception to this being at sites with large tidal ranges and enclosed basins eg. Bay of Fundy, Canada and Severn Estuary, England. The number of such locations is limited, however, there are numerous locations throughout the world where a small-scale tidal generator could be usefully employed. This situation is exacerbated by the fact that the large schemes being investigated are for single-effect ebb-generation and as such produce two "slugs" of energy daily. They thus have a requirement for connection to a large grid where diversity of generation capacity can accommodate output of this type. If small remote tidal power stations are to be developed, then a generator is required that is capable of producing worthwhile outputs at low heads by double-effect (two-way) generation. Such a generator would produce four periods of output daily, and as such would increase the proportion of energy which could be usefully employed. Due to its symmetry and range of operation the STO has potential for development at such locations.

6.7.1 STO Tidal Potential

The tidal energy potential of a particular location is dependent upon the size of the tidal ranges and the enclosed basin area. Optimisation of installed capacity and calculation of energy yield is complex and requires use of computational modelling techniques. A suite of computer programs have been developed at Salford University for analysing potential tidal power sites, (Ref. 25), and these have been modified for incorporation of the STO maximum power operating characteristic of Figure 6.4.

The operation of the STO for tidal generation differs from that for run-of-river development in that as the water levels vary at the barrage, the operating pressure can be continually adjusted to ensure that the STO always operates at maximum output. The selection of unit size is such that the cell depth of the STO must be selected to accommodate the maximum variation of water levels occuring at the barrage, and the number of units selected must allow adequate variation of basin level.

6.7.2 Scottish Desk Study

The Scottish coastline offers potential for tidal power development using the STO; the sea lochs are often characterised by narrow necks and shallow entrance sills (Ref. 26) which would make the construction of an impounding barrage a relatively simple matter. Mean tidal ranges around the West Coast and Outer Hebrides are generally in the range 1.5 to 3.5m with variations of extreme water levels of 3 to 6m, which implies operating heads in the range 0.5 - 3m. Accordingly a study of tidal potential around Scotland has been undertaken for the Scottish Development Agency and the Highlands and Islands Development Board (Ref. 27).

Of 127 sites examined in the study some 49 sites were considered to have potential for development using a standard size of STO unit of the following dimensions:

3 cells per unit
Cell depth = 6m
Cell length = 6m
Cell width = 3m
Gate width = 1.8m
Stroke length = 5.3m

The locations and details of these sites are given in Figure 6.7 and Table 6.5.

The selection of an appropriate STO unit and calculation of power and energy for a tidal site is illustrated by example in section 6.8.

6.8 Sponish, North Uist, Outer Hebrides

The Scottish desk study identified Sponish on North Uist in the Outer Hebrides as a possible prototype site for development of a tidal STO. The location of the site is shown in Figure 6.8. The site was selected because it offered potential for demonstration of the STO at full-scale, and for its proximity to a nearby energy demand from Lochmaddy Hospital.

6.8.1 Selection of STO Unit

The size of STO unit required for a particular location is dependent upon a number of factors as follows:-

1) The depth and cross-section at the barrage site (Figure 6.9).

2) The variation in water levels occuring at the barrage.

Admiralty Tide Tables and charts were used to relate sea levels to chart datum (and ordnance datum) as follows:-

Mean High Water Springs = 4.8m
Mean Low Water Springs = 0.7m
Mean High Water Neaps = 3.6m
Mean Low Water Neaps = 1.9m
Highest Astronomical Tide = 5.1m
Lowest Astronomical Tide = 0.0m

In the case of the STO, the unit must be capable of accommodating the maximum variation of water levels occuring at the site.

3) The enclosed basin area. Area obtained from O.S. map by planimeter as follows:

Area at MHWS = $0.506km^2$
Area at MLWS = $0.279km^2$

For double effect generation, the enclosed basin area determines the discharge capacity required by the generator, since adequate capacity must be incorporated to allow adequate variation of basin levels.

In order to satisfy the above, a single STO unit of the following dimensions was selected:

Cell depth = 6m
Cell length = 6m
Cell width = 3m
Gate width = 1.8m
Stroke length = 5.3m

The base of the cell was set at -0.9m Chart datum (Figure 6.10). Due to the size of the basin, independent sluices were also required to allow adequate basin level variation, these were optimized to 2 No. 2.5 x 2.5m. square sluices with their base set at 1.0m above Chart datum.

6.8.2 Energy Computation

Energy computations using the maxmimum power envelope curve were undertaken for various tidal ranges. These were then combined with the tidal histogram for Sponish (Figure 6.11) to obtain the annual energy yield. The results obtained for this analysis are shown as:-

Figure 6.12 Typical operating diagram
Figure 6.13 Variation in basin level with tidal range
Figure 6.14 Variation in energy output with tidal range
Table 6.6 Annual energy yield.

The energy values shown in Figures 6.14 and Table 6.6 are in terms of oil power and energy. As in the case of run-of-river development it is necessary to convert the oil power and energy figures to electrical output by consideration of the hydraulic motor and electrical generator efficiencies. In this case an overall average conversion efficiency of approximately 75% would be expected giving an annual electrical output of 525MWh.

6.9 Economics of Generation

The Scottish study suggested that the Sponish prototype STO would produce energy at a cost of 7.3p/kWh. Whilst this figure appears high, it should be remembered that this would have been the prototype development of an entirely new device. In fact, with further optimisation and economies of scale due to mass production that costs of energy could be expected to fall to approximately 5p/kWh. Typically, a tidal generator has a plant factor of approximately 20%, whereas in a run-of-river development this could be in the range 50-100% depending on the application. Assuming the same project cost for the same size of STO unit in a run-of river situation, with 100% utilization the energy costs would be as follows:

	Head 1m	Head 2m	Head 3m
Installed capacity (kW)	145	280	400
Energy yield (MWh)	1270	2450	3500
Cost per kW installed (£)	3240	1680	1175
Energy cost (p/kWh)	3.1	1.6	1.1

6.10 Conclusions

The Sponish prototype was abandoned in October 1985 due to the high costs associated with the development, particularly the hydraulic power take-off system, and the construction of the civils works in such a remote location. It is worthwhile to note here that at a unit cost for energy of 7.3p/kWh, the STO would have been competitive with supply from the North of Scotland Hydro-Electric Board (NSHEB) in the Hebrides which is in the range of 7-14p/kWh. Unfortunately NSHEB subsidise customers on the Hebrides such that the rates they pay for electricity are in-line with rates on the mainland, which is the cheapest electricity in the U.K. as such NSHEB were prepared to pay for STO output at a rate equivalent only to the marginal cost of electricity on the mainland of 2.1p/kWh. If the rate paid by NSHEB had been more nearly equal to their generation costs it seems likely that STO development would have gone ahead.

With hindsight it could be argued that a less ambitious prototype site would have had a better chance of success than Sponish. However, Sponish was chosen because it offered the opportunity for collection of substantially more performance data than at a run-of-river location. Further, it presented a far more onerous operating regime and this would have led to more rapid development of faults due to fatigue and corrosion, allowing earlier rectification.

Attempts are now being made to reduce STO costs by replacing the hydraulic power take-off system with electro/mechanical conversion. It remains to be seen whether this will prove successful enough for potential investors to reconsider the STO as a viable low-head generator.

Function	Scale factor
Depth	VFACT
Head	VFACT
Volume	$\text{HFACT}^2 \times \text{VFACT}$
Stroke	HFACT
Time	$\text{HFACT} \times (\text{VFACT})^{-\frac{1}{2}}$
Period	$\text{HFACT} \times (\text{VFACT})^{-\frac{1}{2}}$
Flow	$\text{HFACT} \times (\text{VFACT})^{3/2}$
Force	$\text{HFACT} \times (\text{VFACT})^2$
Power	$\text{HFACT} \times (\text{VFACT})^{5/2}$
Energy	$(\text{HFACT})^2 \times (\text{VFACT})^2$

Table 6.1 STO scaling factors

Note: VFACT = Vertical scaling factor
HFACT = Horizontal scaling factor
Where natural scaling applies VFACT = HFACT

Unit Size (m)	No. of cells	Cell length (m)	Cell depth (m)	Cell width (m)	Gate width (m)	Stroke length (m)	Discharge operating range (m^3/s)
6	3	6	6	3	1.8	5.3	20-52
5	3	5	5	2.5	1.5	4.4	13-33
4	3	4	4	2	1.2	3.5	8-20
3	3	3	3	1.5	0.9	2.6	4-10

Table 6.2 STO discharge operating range

Month	Flow (m^3/s)	Head (m)	Downstream depth (m)
January	17.7	2.58	1.12
February 1-10	17.7	2.58	1.12
February 11-28	26.6	2.27	1.43
March	26.6	2.27	1.43
April	17.7	2.58	1.12
May	31.9	2.05	1.65
June	31.9	2.05	1.65
July	28.4	2.31	1.39
August	28.4	2.31	1.39
September	31.9	2.05	1.65
October	31.9	2.05	1.65
November	31.9	2.05	1.65
December 1-10	31.9	2.05	1.65
December 11-31	17.7	2.58	1.12

Table 6.3 Site data for Raowal, Punjab

Note: Tainter type gates at the drop structure are operated to maintain a constant upstream water level.

Month	Discharge (m³/s)	Head (m)	STO Power in oil (kW)	Period (secs)	Oil Flow (l/min)	Motor Efficiency (%)	Generator Efficiency (%)	Electrical Power (kW)	Annual Energy (MWh)
January	17.7	2.58	134	16	385	90	91	109	81.1
February 1-10	17.7	2.58	134	16	385	90	91	109	26.2
February 11-28	26.6	2.27	178	24	513	87	92	142	61.3
March	26.6	2.27	178	24	513	87	92	142	105.6
April	17.7	2.58	134	16	385	90	91	109	78.5
May	31.9	2.05	212	15	821	92	92	179	133.2
June	31.9	2.05	212	15	821	92	92	179	128.9
July	28.4	2.31	193	22	560	88	92	156	116.1
August	28.4	2.31	193	22	560	88	92	156	116.1
September	31.9	2.05	212	15	821	92	92	179	128.9
October	31.9	2.05	212	15	821	92	92	179	133.2
November	31.9	2.05	212	15	821	92	92	179	128.9
December 1-10	31.9	2.05	212	15	821	92	92	179	43.0
December 11-31	17.7	2.58	134	16	385	90	91	109	54.9
								Total	1345.9 MWh

Table 6.4 Annual energy computation, Raowal, Punjab

Site No.	Site	OS 1:50,000 Sheet No.	National Grid Reference	Basin Area at MSL (km²)	Mean Tidal Range (m)	No. of STO units	Installed Capacity (MW)	Annual Energy Production (MWh)
12	Loch Gair	55	NR 931901	0.6	3.0	2	0.5	990
25	Loch Feochan	49	NM 822226	2.7	2.3	12	2.8	4,083
28	Upper Loch Creran	49	NM 980443	2.0	2.5	10	2.5	3,487
31	Upper Loch Leven	41	NM 136613	1.5	2.5	4	0.9	1,484
33	Loch Aline	49	NM 681445	2.0	2.9	10	2.6	4,011
34	Loch Don	49	NM 746315	1.3	2.3	6	1.5	1,940
40	Loch Teacuis	49	NM 623552	2.8	3.1	14	3.7	5,790
41	Upper Loch Sunart	40	NM 745610	6.5	3.1	24	6.4	10,650
43	Loch Ailort	40	NM 725791	5.5	3.2	24	6.5	10,150
44	Upper Loch Nevis	40	NM 801934	4.8	3.2	24	6.6	11,490
47	Loch Long	33	NS 881266	2.2	3.3	6	1.7	2,750
48	Loch Eishort	32	NG 635154	3.0	2.9	18	5.2	6,020
49	Loch Slapin	32	NG 570200	1.4	2.9	8	2.2	2,800
53	Acairseid Mhor (Rona)	24	NG 610564	0.15	3.6	2	0.5	953
54	Loch Sligachan	32	NG 530325	2.1	3.6	12	3.7	5,500
56	Loch Na Cairidh	32	NG 583290	1.8	3.6	10	3.0	4,610
59	Poll Creadha	24	NG 707413	0.5	3.6	2	0.5	1,000
62	Ob Mhellaidh	24	NG 829548	0.4	3.6	2	0.5	992
63	Badachro	19	NG 781745	0.3	3.3	1	0.27	420
67	Loch Roe	15	NC 059241	0.3	3.1	2	0.7	710
68	Loch Nedd	15	NC 130330	0.3	3.2	2	0.7	720
69	Loch Ardbhair	15	NC 163344	0.7	3.2	2	0.5	877
73	Loch a Chad-Fi	9	NC 210507	0.5	3.2	2	0.5	858
79	Loch Fleet	21	NH 805955	4.0	2.6	22	5.5	7,490
85	North Bay (Hoy)	7	HD 305912	3.9	2.3	16	3.8	5,220
87	Bagh Beag	31	NL 656978	0.15	2.5	1	0.3	280
91	Acairseid Mhor	31	NF 798096	0.15	2.5	1	0.3	281
93	Loch Eynort	22	NF 801273	2.5	2.8	9	2.3	3,240
94	Loch Skiport	22	NF 828387	0.4	3.1	2	0.6	780
95	Loch Sheilavaig	22	NF 849406	1.0	2.7	4	1.0	1,315
96	Loch Carnan	22	NF 832444	0.9	2.7	4	1.0	1,390
98	Loch Uiskevagh	22	NF 865510	3.1	2.7	12	3.0	4,352
101	Upper Loch Maddy	18	NF 914679	0.5	3.1	2	0.5	868
102	Loch Houram	18	NF 922694	0.3	3.1	1	0.27	525
103	Loch Portain	18	NF 939715	0.4	3.1	2	0.5	836
106	The Obba	18	NG 013866	0.2	2.9	1	0.27	380
109	Loch Beacravik	14	NG 114900	0.1	3.0	1	0.4	300
110	Loch Stockinish	14	NG 130908	1.0	3.0	4	1.0	1,587
113	Loch Mharabhig	14	NB 418199	0.5	3.0	4	1.4	1,257
114	Loch Erisort	14	NB 377215	7.6	3.0	28	7.4	11,430
115	Loch Leurbost	14	NB 383244	1.6	3.0	6	1.6	2,230
116	Loch Grimshader	14	NB 420258	0.8	3.0	4	1.4	1,238
117	Loch Meavaig	13	NB 092052	0.3	2.5	1	0.25	329
118	Loch Leosavay	13	NB 047076	0.2	2.8	1	0.25	383
122	Miavaig	13	NB 095340	0.14	2.9	1	0.27	354
123	Little Loch Roag	13	NB 130322	2.4	2.9	16	4.2	5,973
124	Loch Barraglom	13	NB 185335	1.6	2.9	6	1.6	2,296
125	Dubh Thob	13	NB 186364	0.2	2.9	1	0.26	362
126	Loch Ceann Hulavig	13	NB 211325	2.7	2.9	12	3.1	4,519

Table 6.5 SITES WITH POTENTIAL FOR DEVELOPMENT IN SCOTLAND USING THE STO

Energy Output at Sponish for a 6m STO Unit with 2 No. 2.5m square sluice gates

Tidal Range (m)	Frequency	Energy Output (kWh)	Annual Output (kWh)
1.3	14		--
1.5	14	190	2660
1.7	39	243	9477
1.9	36	346	12456
2.1	43	452	19436
2.3	50	562	28100
2.5	62	678	42036
2.7	37	788	29156
2.9	37	903	33411
3.1	45	1016	45720
3.3	74	1133	83842
3.5	36	1250	45000
3.7	48	1359	65232
3.9	42	1480	62160
4.1	60	1588	95280
4.3	32	1700	54400
4.5	16	1814	29024
4.7	8	1923	15384
4.9	12	2035	24420
			697194

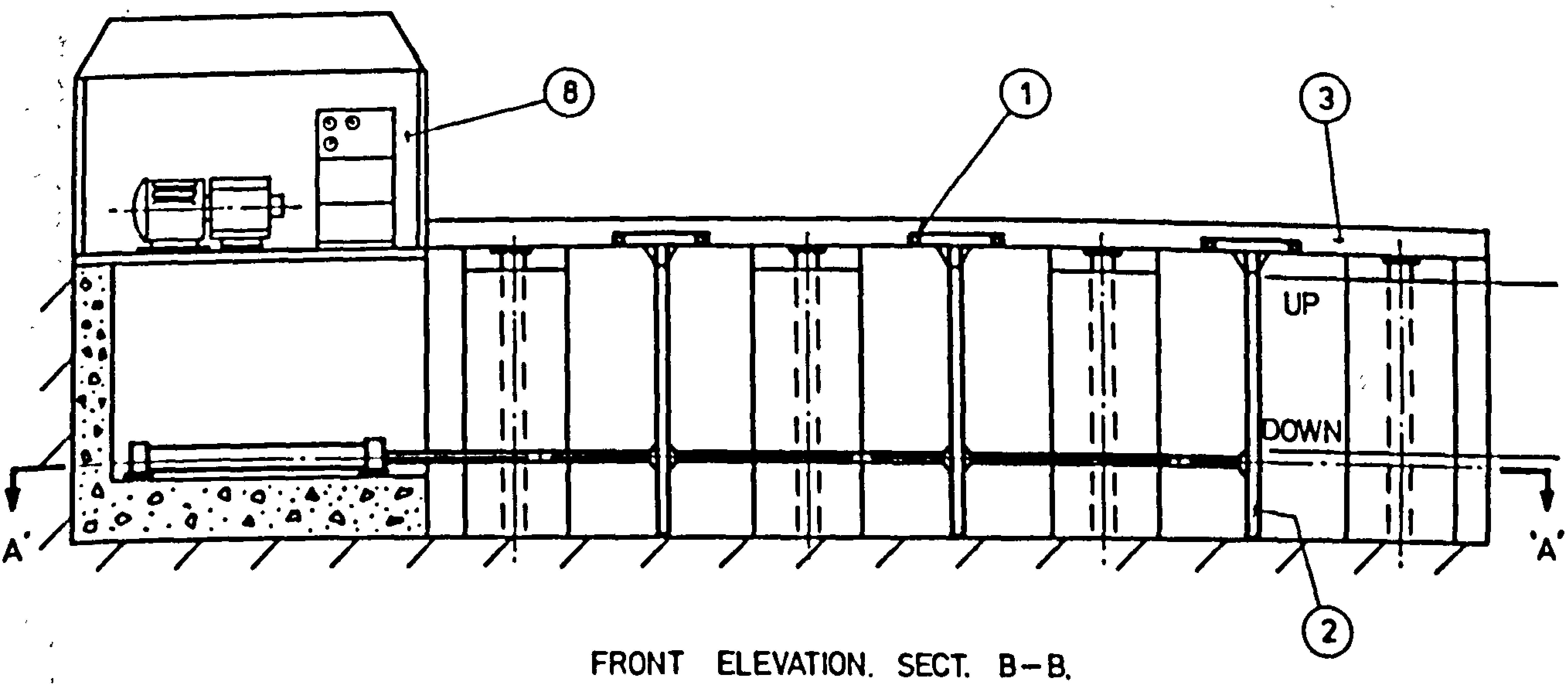
Outputs are based on hydraulic power production. For electrical outputs the numbers should be multiplied by the product of hydraulic motor and generator efficiency. The exact value of these efficiencies can be determined when particular machines are specified, but an average conversion efficiency of 75% appears reasonable giving an annual output of approximately 525 MWh.

Table 6.6 Calculation of Energy Yield at Sponish

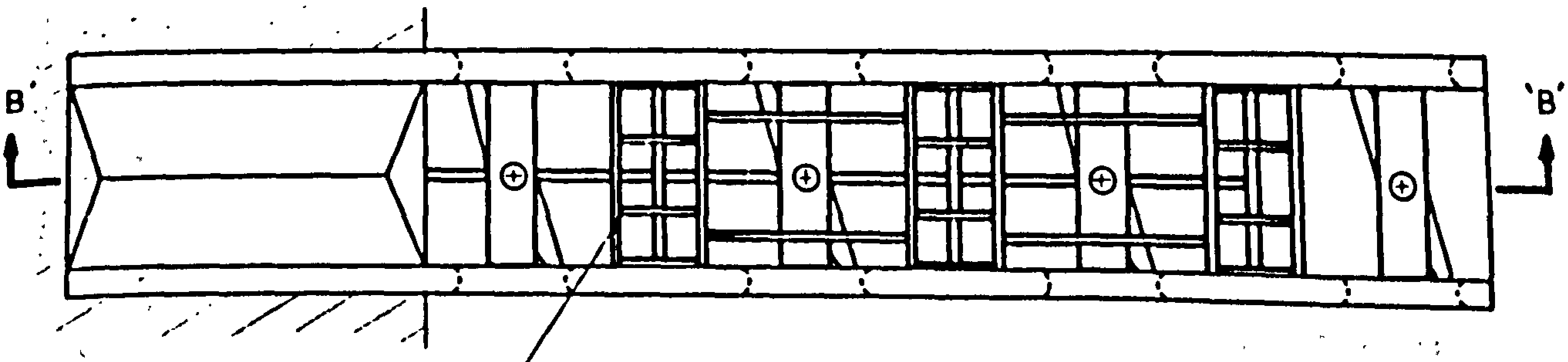
1 — CARRIAGE WHEELS
2 — PADDLE
3 — WALKWAY
4 — GATE
5 — POWER TAKE OFF CYLINDER
6 — BARRAGE WALLS

7 — CARRIAGE FRAME
8 — MACHINERY HOUSE

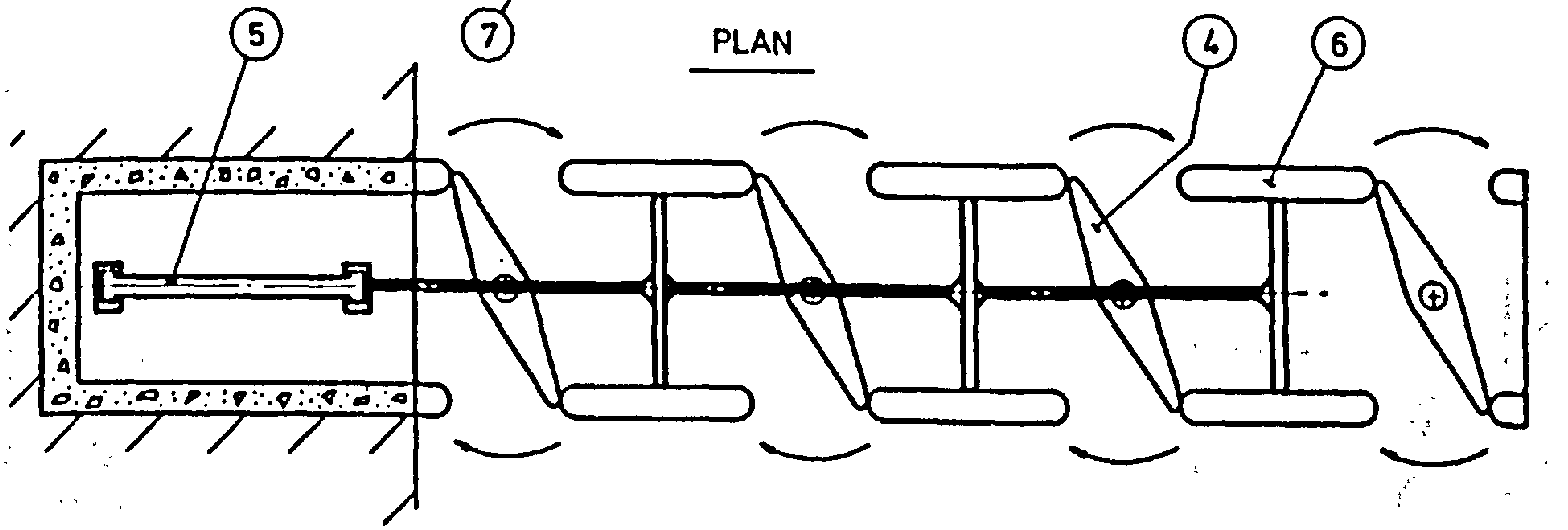
UP — UPSTREAM WATER LEVEL
DOWN — DOWNSTREAM WATER LEVEL



FRONT ELEVATION. SECT. B–B.



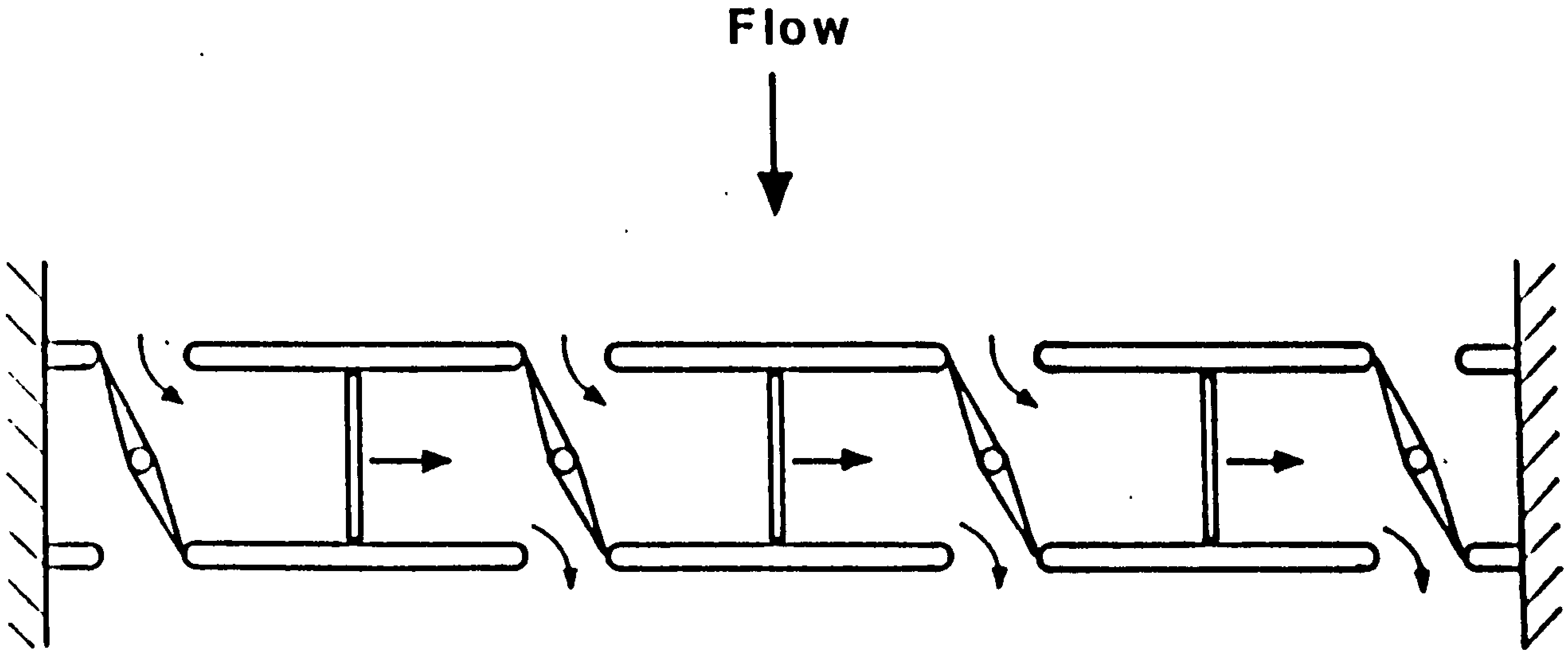
PLAN



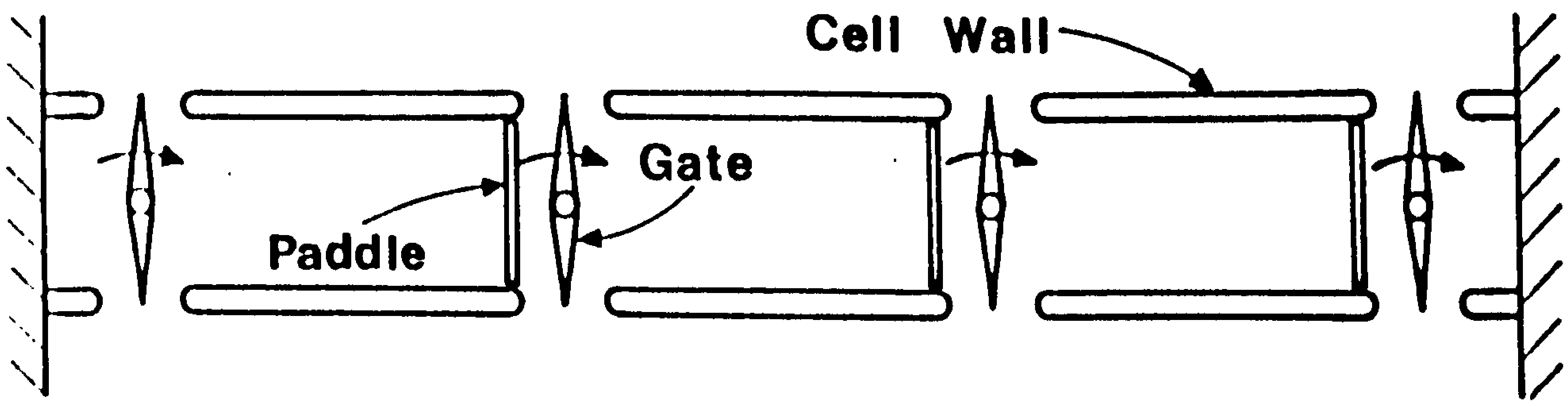
SECTION A–A

SALFORD TRANSVERSE OSCILLATOR

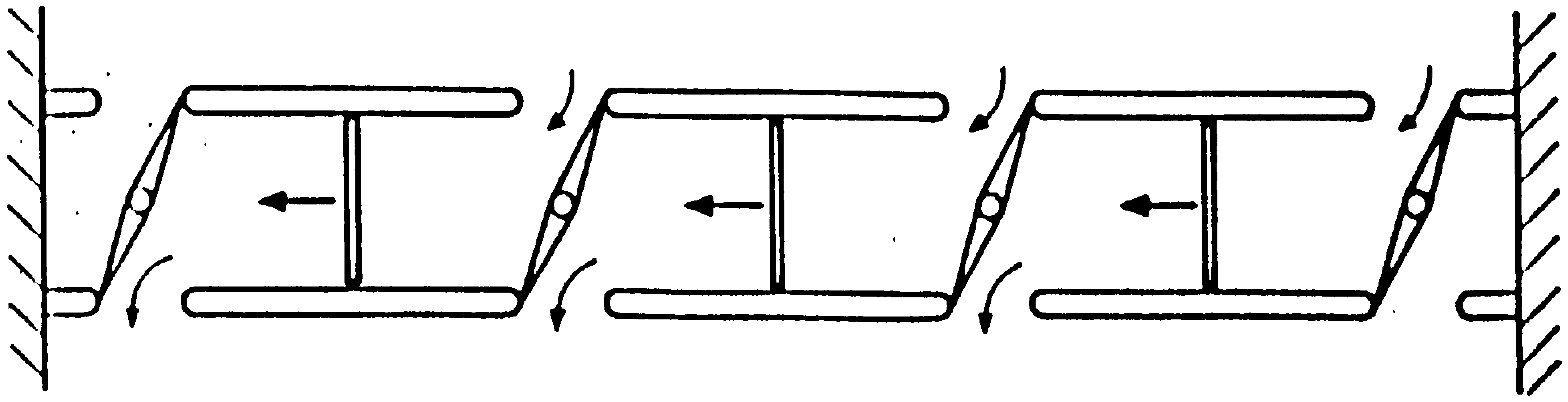
FIG 6.1



1 HYDROSTATIC HEAD FORCES PADDLES TO RIGHT



2 PADDLES REACH END OF TRAVEL , GATE POSITION IS CHANGED



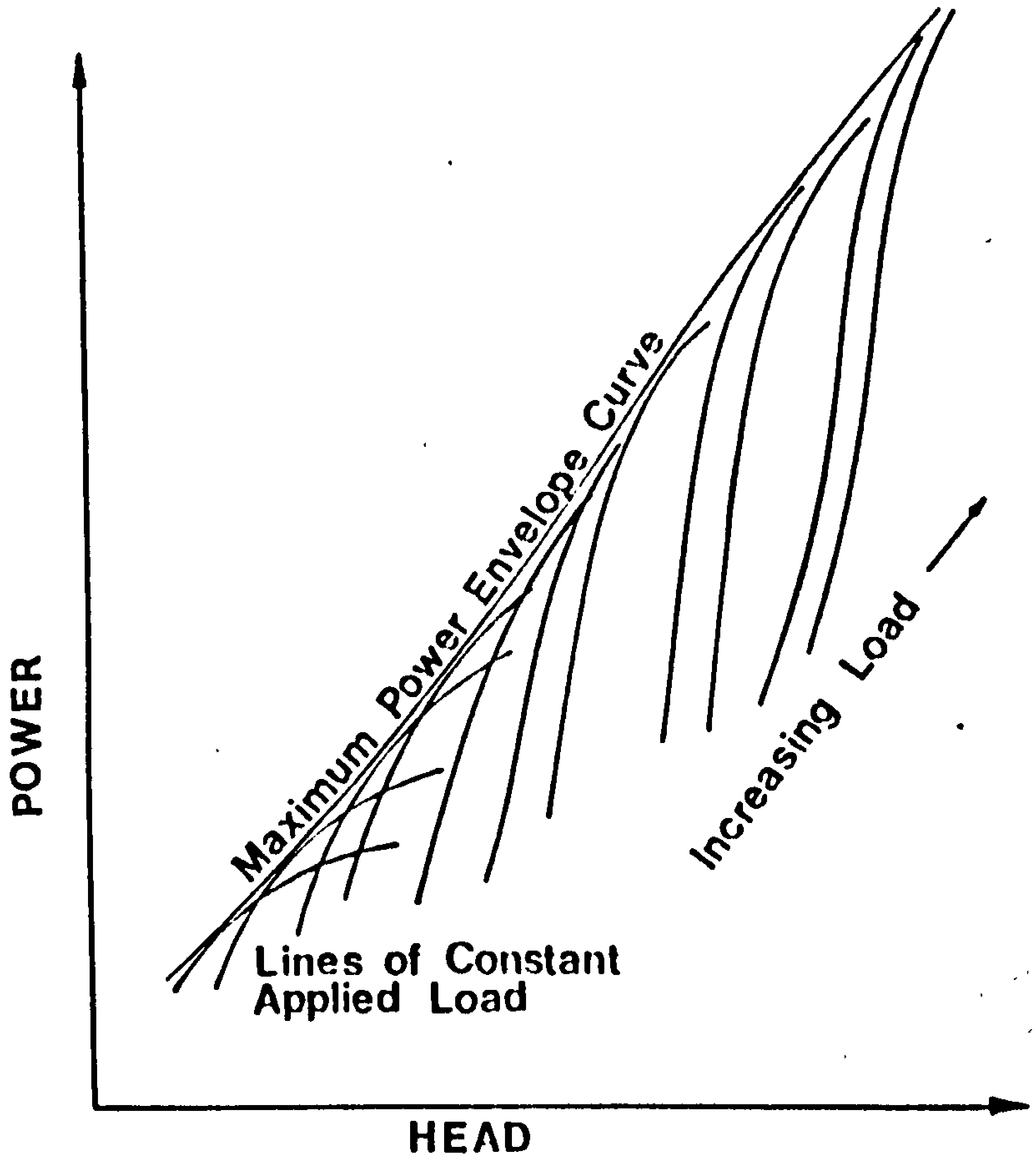
3 PADDLES FORCED TO LEFT

OPERATION OF THE STO

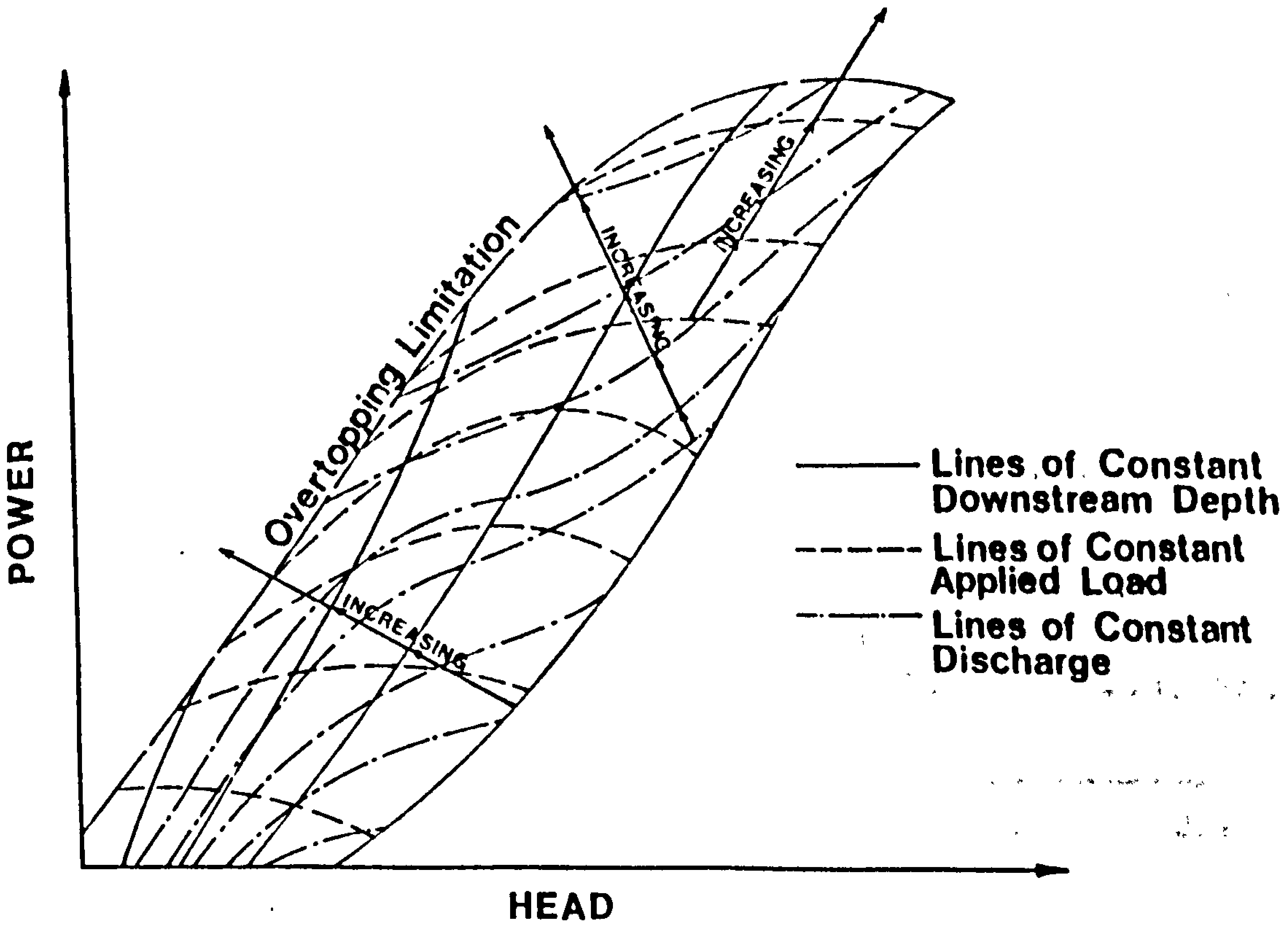
FIG 6.2


POWER VS. HEAD -- D/S = 300,400 & 500
OPERATING PRESSURE
□ 28 BAR
○ 35 BAR
△ 42 BAR
+ 49 BAR
⨯ 56 BAR
◇ 63 BAR
↑ 70 BAR
X 77 BAR
Z 84 BAR
Y 91 BAR
⌘ 98 BAR
✡ 105 BAR
DOWNSTREAM DEPTH
500 MM
400 MM
300 MM
SECOND LABORATORY MODEL RESULTS
STROKE 78 cm
CELL WIDTH 44.5 cm
POWER (W)
50.00
90.00
130.00
170.00
210.00
250.00
290.00
330.00
370.00
410.00
450.00
490.00
HEAD (M)
0.13
0.15
0.17
0.19
0.21
0.23
0.25
0.27
0.29
0.31
0.33
0.35
0.37
0.39
0.41
0.43
0.45
0.47
0.49
0.51

FIG 6.3



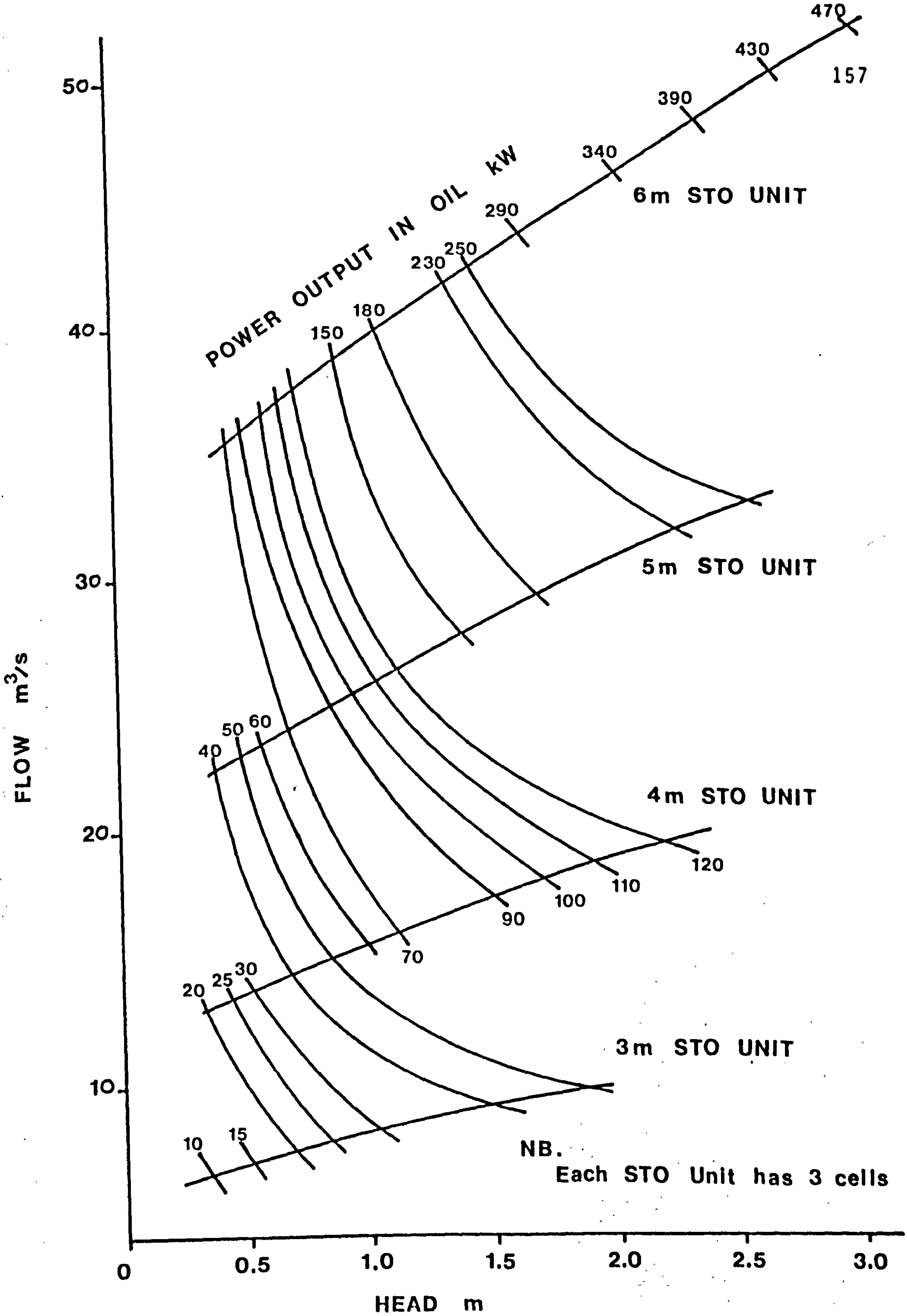
POWER AGAINST HEAD FOR CONSTANT DOWNSTREAM DEPTH AND VARYING APPLIED LOAD



MAXIMUM POWER ENVELOPE CURVE

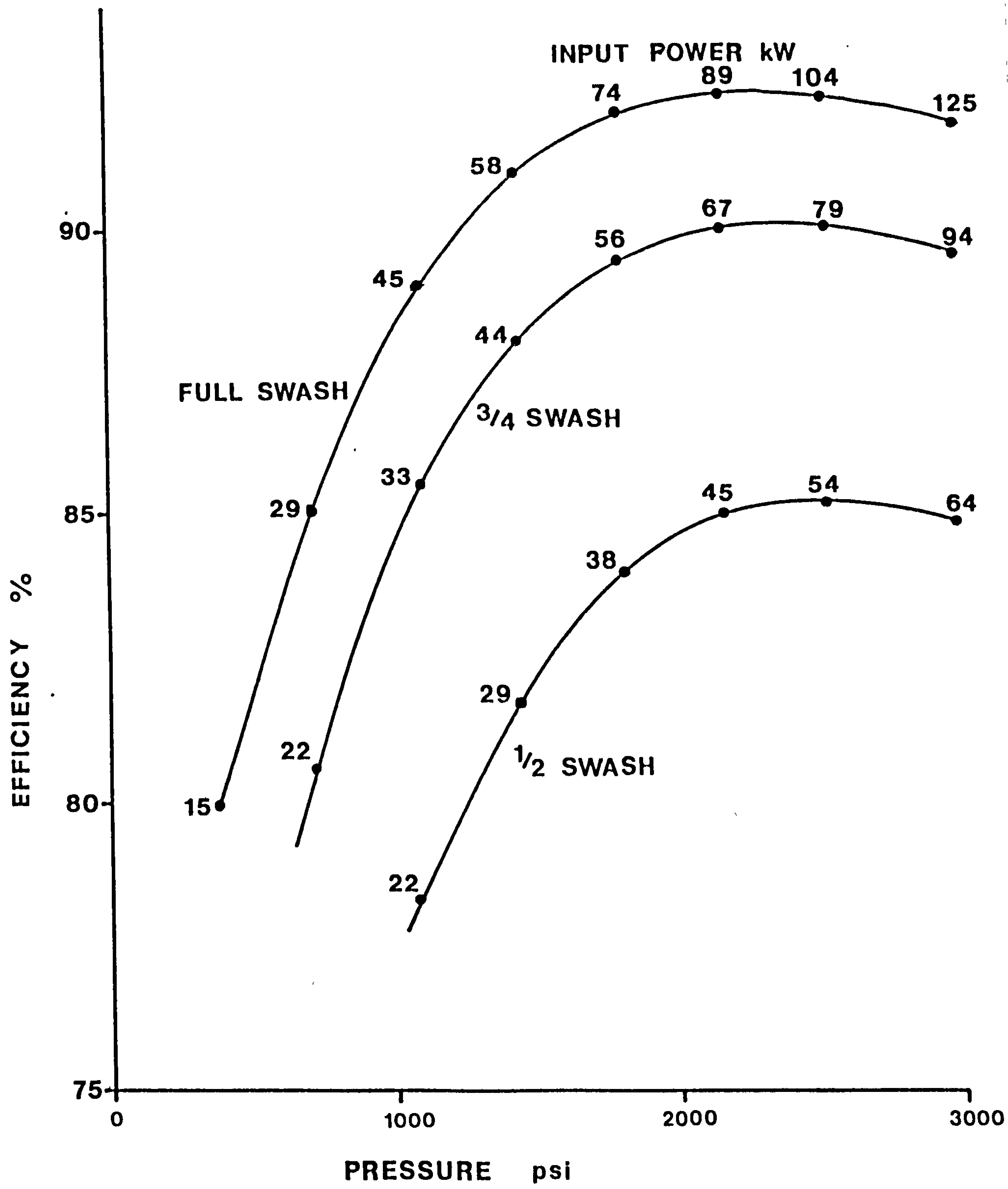
STO CHARACTERISTIC OPERATING CURVES

FIG 6.4



SELECTION OF STO UNITS

FIG 6.5



TYPICAL CHARACTERISTIC FOR SWASH PLATE HYDRAULIC MOTOR

FIG 6.6

LOCATION OF SITES

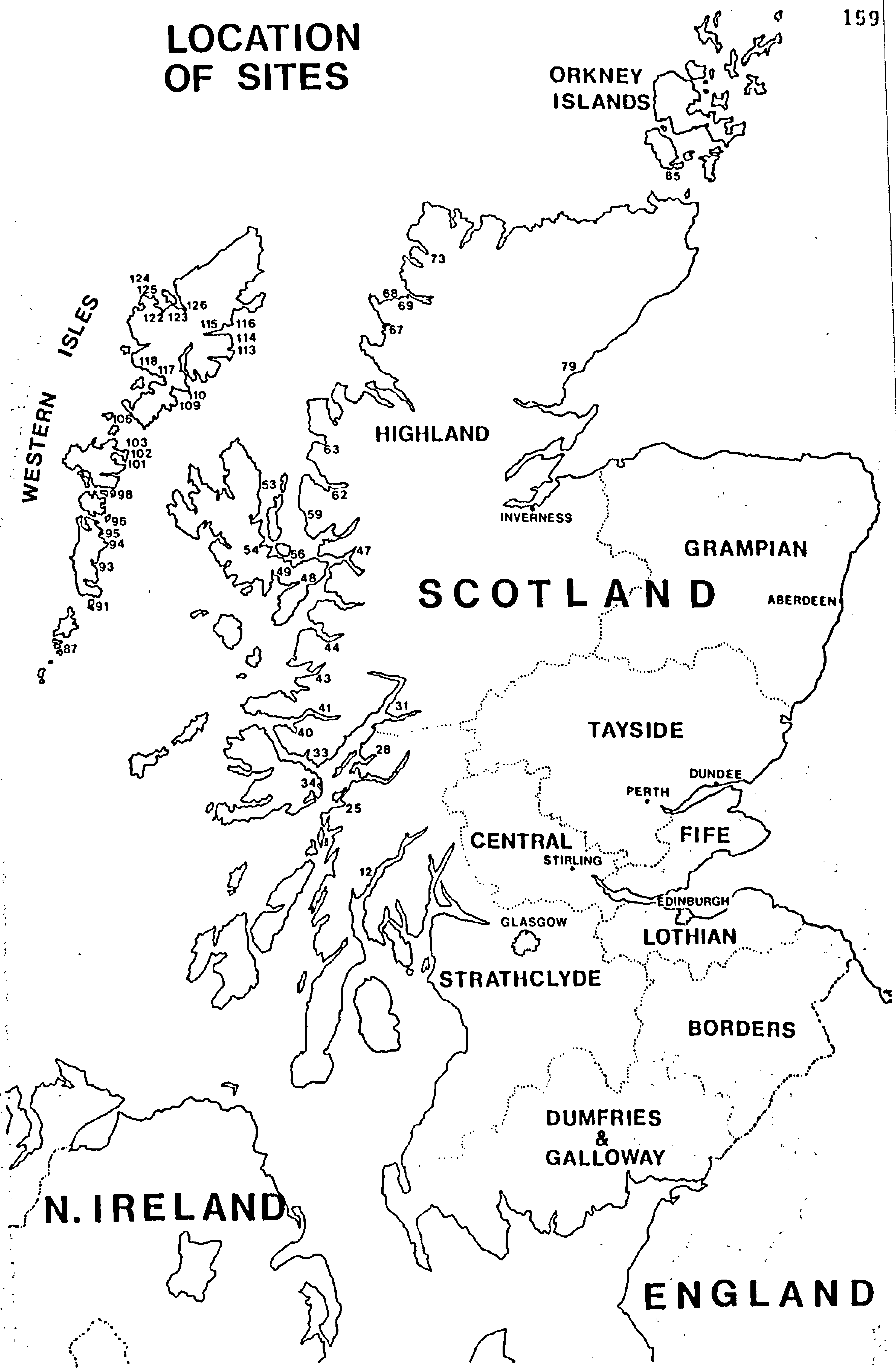


FIG 6.7

LOCATION MAP FOR PROTOTYPE S.T.O. AT SPONISH NORTH UIST

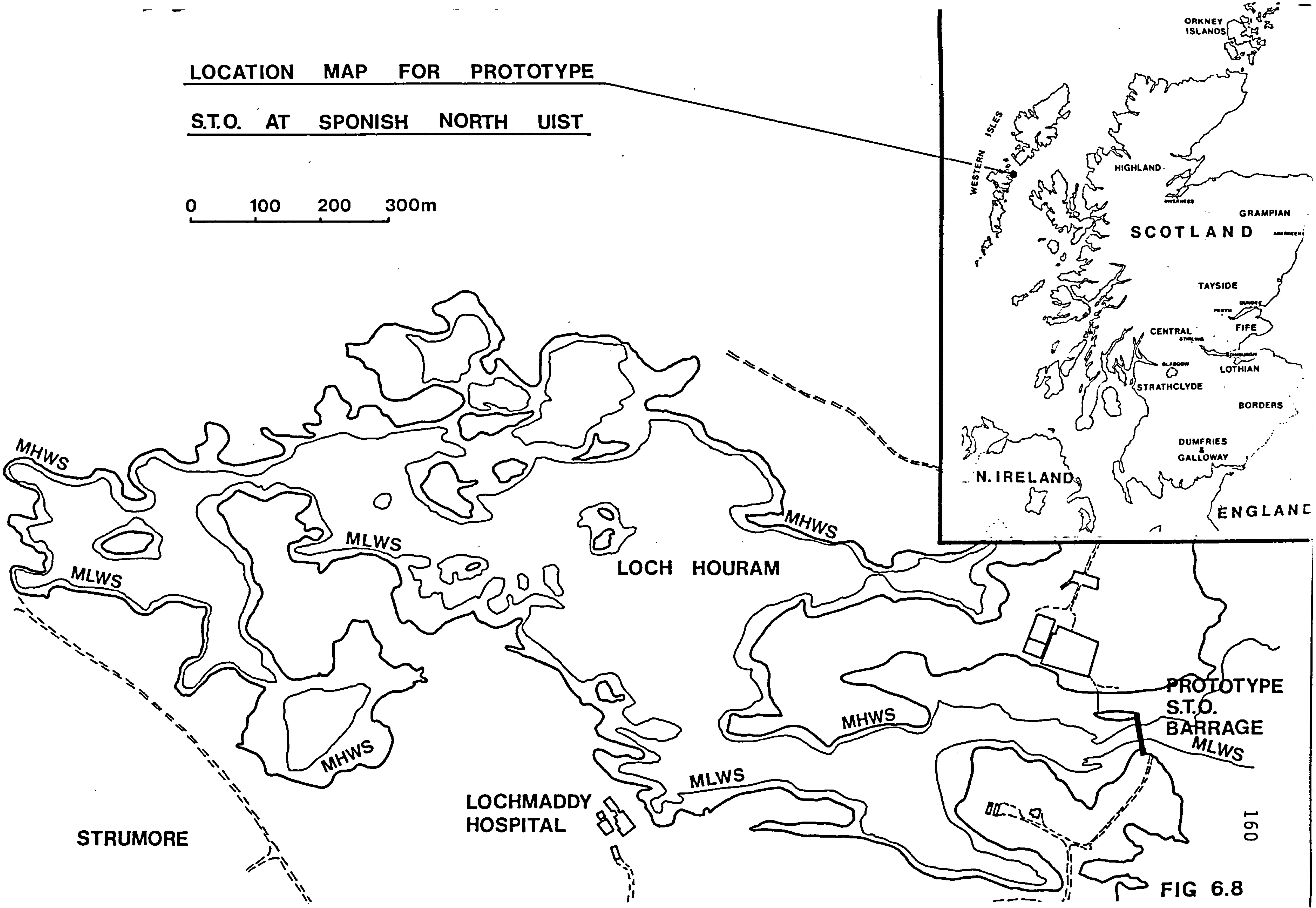
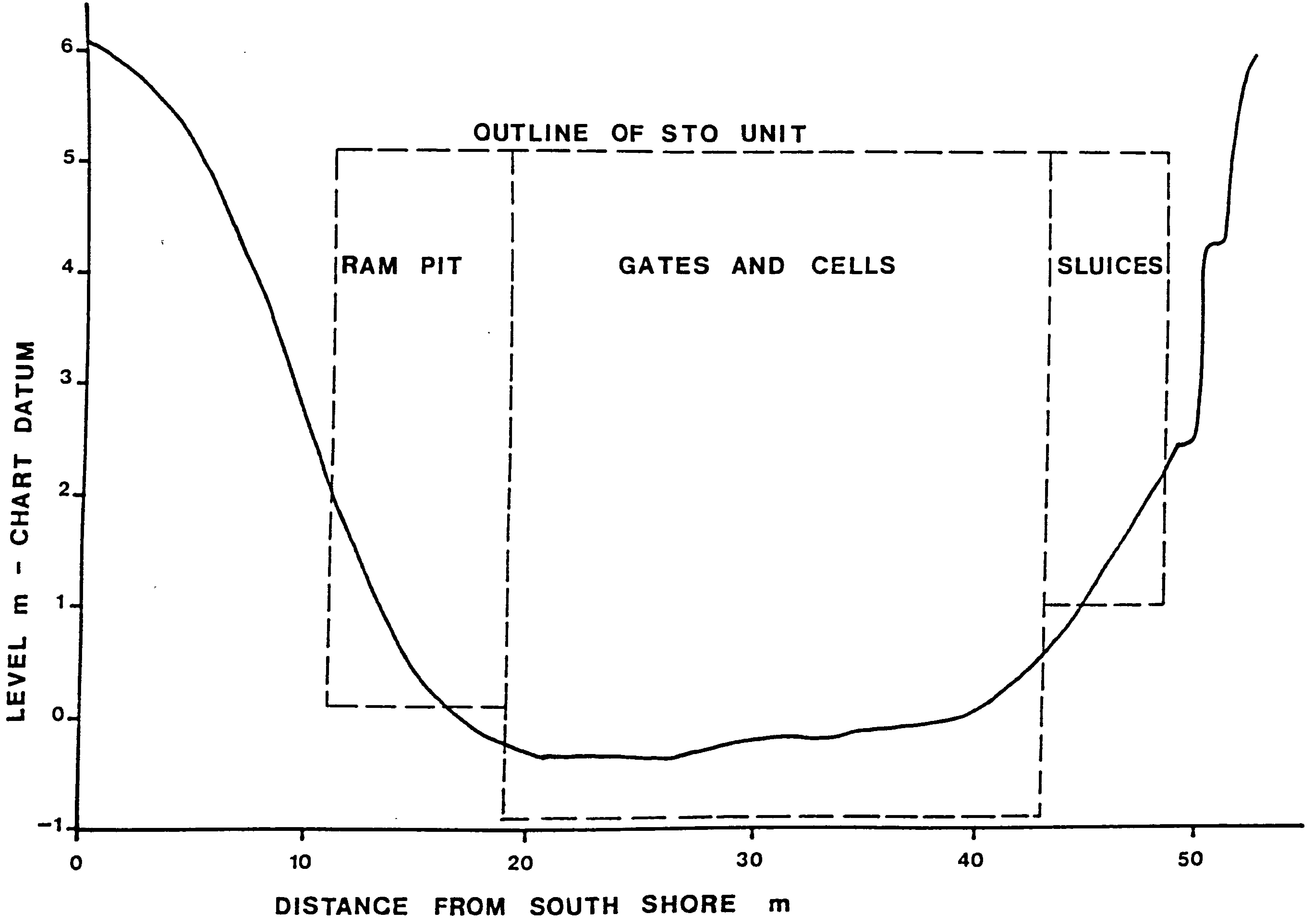
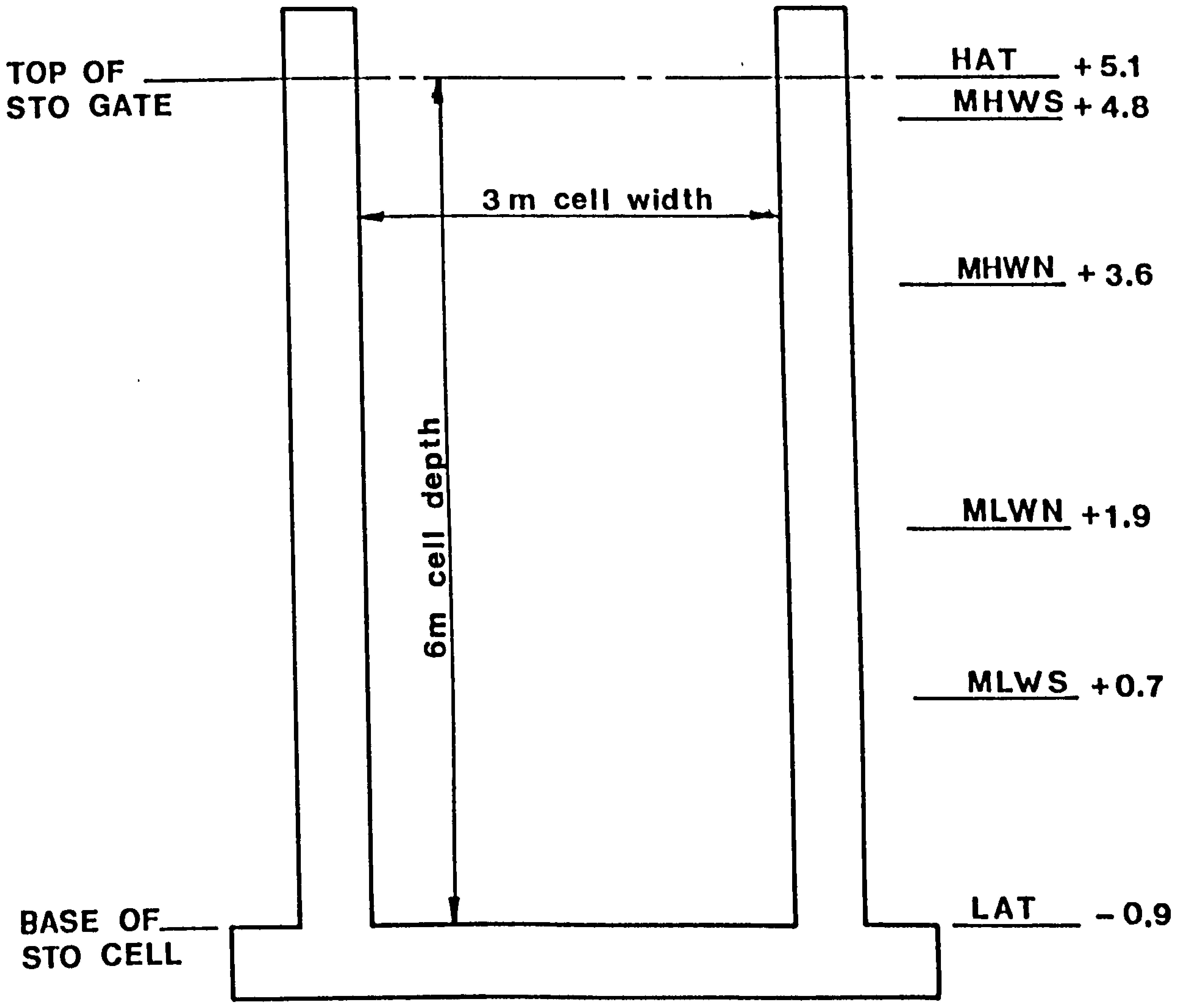


FIG 6.8



CROSS SECTION AT SPONISH

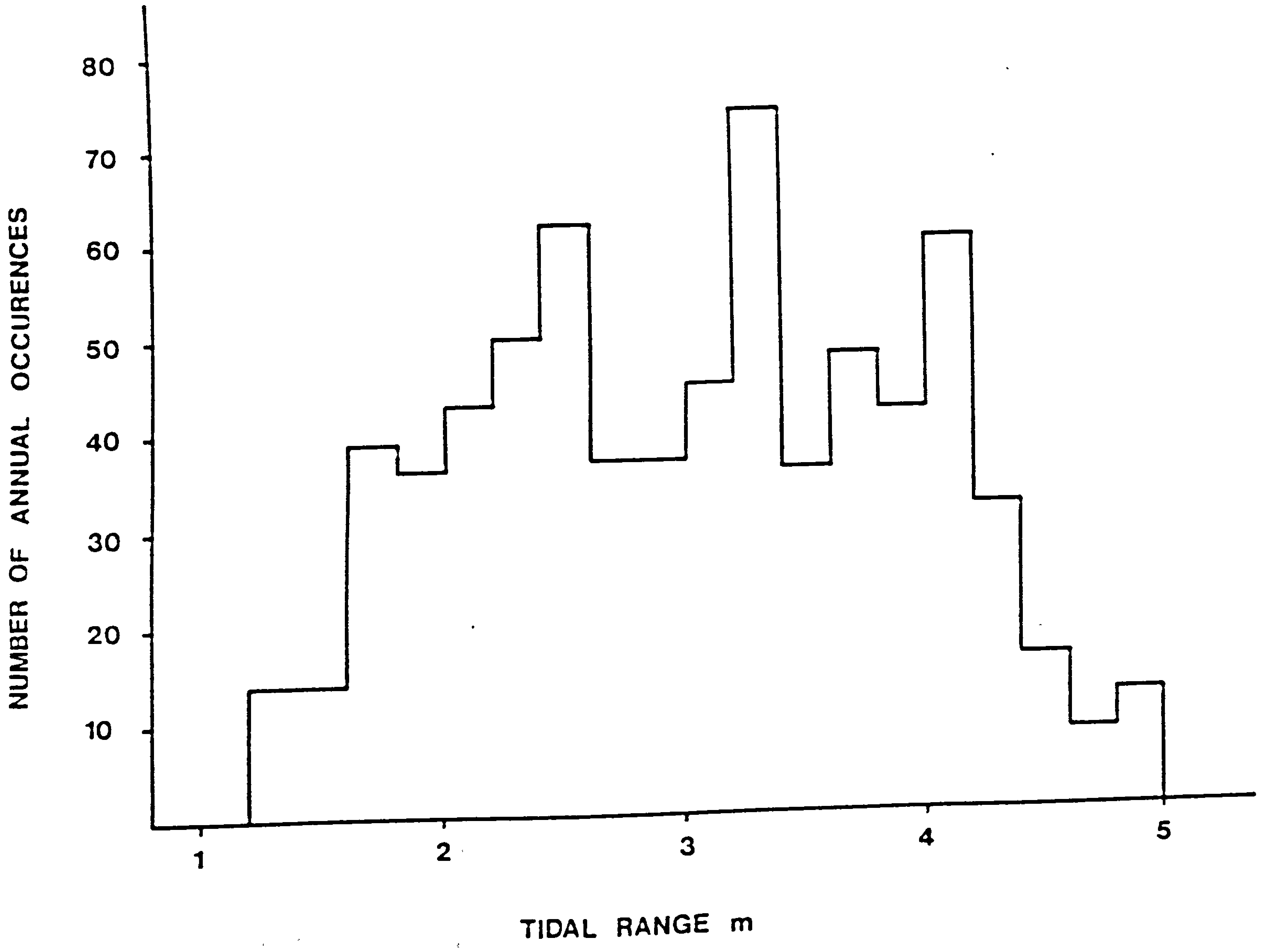
FIG 6.9



All levels refer
to Chart Datum

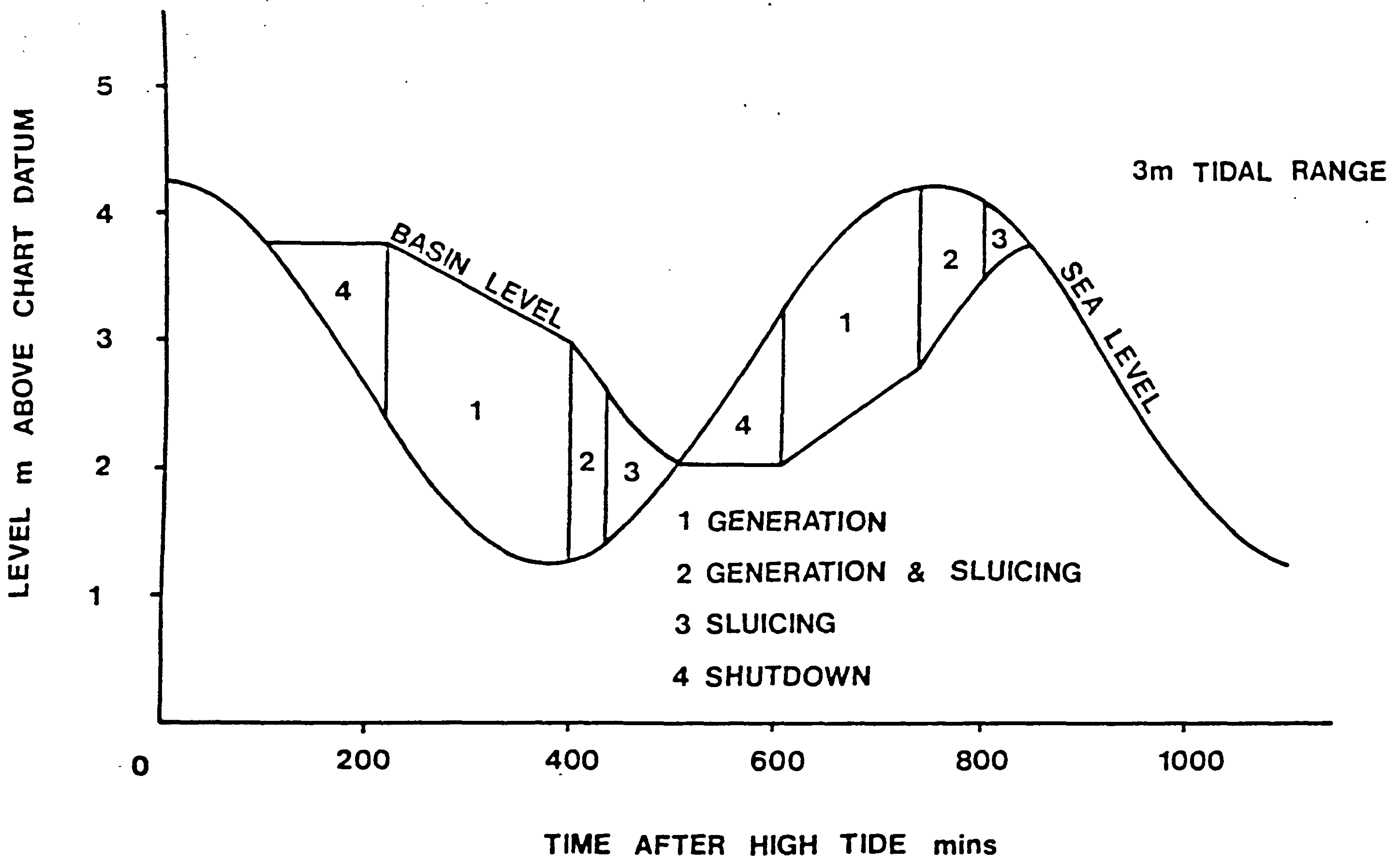
SETTING LEVEL FOR SPONISH STO

FIG 6.10



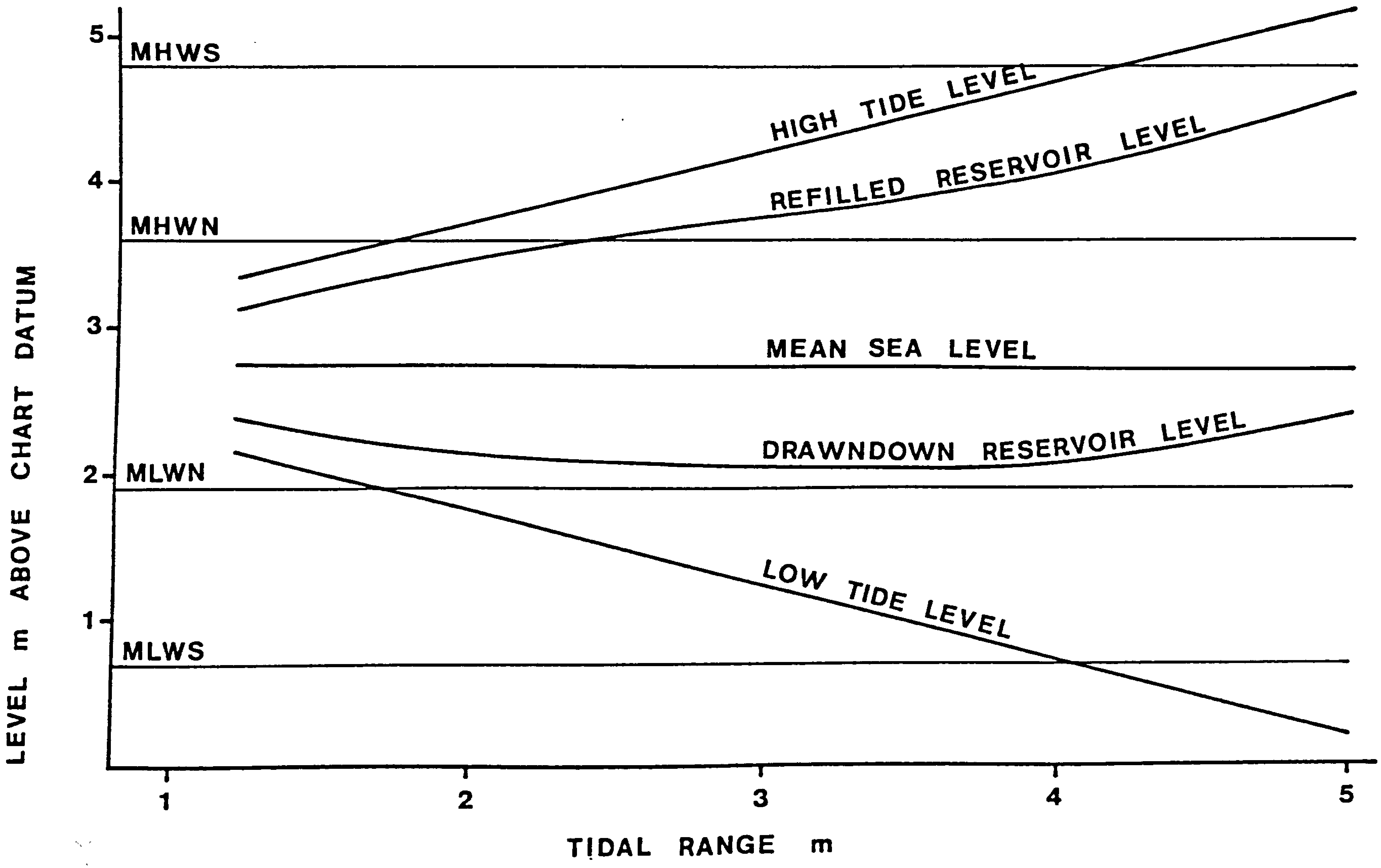
SPONISH TIDAL HISTOGRAM

FIG 6.11



TYPICAL OPERATING DIAGRAM

FIG 6.12



VARIATION IN BASIN LEVEL WITH TIDAL RANGE

FIG 6.13

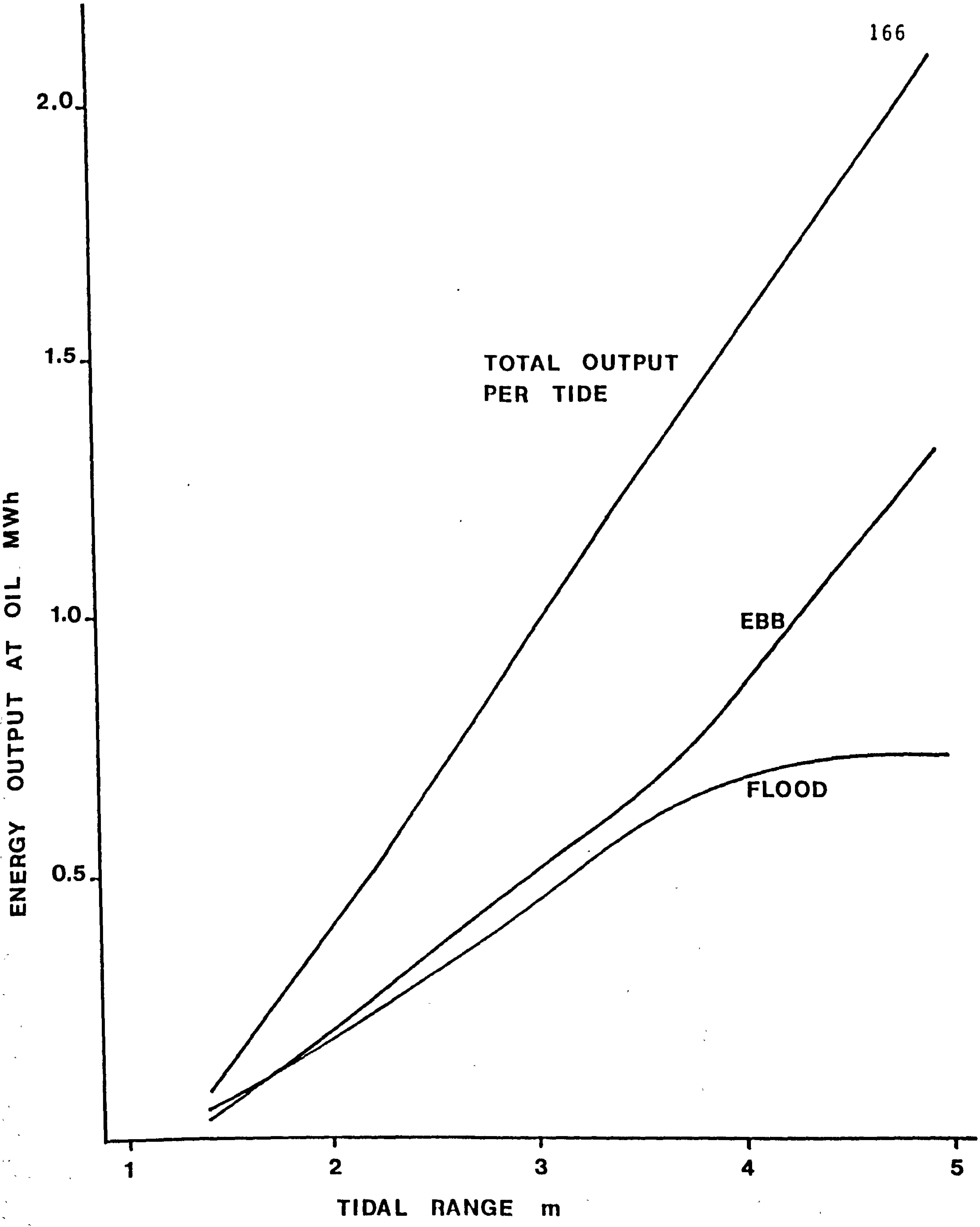

2.0
1.5
1.0
0.5
ENERGY OUTPUT AT OIL MWh
TOTAL OUTPUT PER TIDE
EBB
FLOOD
1
2
3
4
5
TIDAL RANGE m

FIG 6.14

7.0 Overview

7.1 Philosophy of Assessment

A primary consideration in the appraisal of a small-scale hydro-electric scheme is that design effort should be commensurate with the scale of the development and hence the level of investment. There is little merit in adopting a rigorous "engineering" approach where this would prejudice scheme development. Accordingly, it is necessary at the outset to define the elements which are likely to have the major effect on total cost, and to concentrate design effort on them.

The database of scheme information compiled in the analysis of potential sites in England, Northern Ireland and Wales, provides an opportunity to examine in detail the types of schemes which are likely to be economic. Further, a consideration of the cost components which make-up economic schemes will lead to a clearer definition of the methods and procedures to be adopted in the appraisal of potential schemes.

7.1.1 Analysis of sites in England, Northern Ireland and Wales.

Referring to Chapter 5, in the present economic climate, sites will not be worthy of consideration where they show an internal rate of return (IRR) on capital invested of less than 5%. The following analysis has been undertaken therefore on schemes which yield IRR $\geqslant$ 5% for the case where schemes are charged with operation, maintenance and formula rating.

In England, Northern Ireland and Wales, a total of 140 sites yield IRR > 5%. The distribution of these sites by head and capacity is shown in Table 7.1. Also shown for each of the head/capacity groups are the average scheme cost in £/kW installed, the average internal rate of return, and the percentage of sites which have existing civil works. A breakdown of scheme cost into cost elements is shown in Table 7.2.

Table 7.2 shows that the major scheme cost element is for turbo-generators and mechanical installation, amounting on average to some 44% of total scheme cost. Similar cost contributions, from 10.4 to 12.4% are attained for items 4. powerhouse, 5. pipelines, 7. electrical transmission, switchgear, protection and metering, and 8. engineering fees and contractural requirements.

The site specific nature of small hydro is emphasized by the maximum, minimum and standard deviation of the cost elements eg. for turbo-generators and mechanical installation, the maximum, minimum and standard deviation are 73.3%, 16.2% and 12.2% respectively. The maximum figure would perhaps be obtained for a site where the civils works are substantially intact and re-development would involve installation of new turbines and generators into the existing civils. The minimum figure would be obtained either where existing turbines were to be refurbished or for example in the case of a high head scheme where a long pipeline would be required to develop potential.

In table 7.1, it can be seen, that for each head range with a few exceptions, there is a general decrease in scheme cost and an increase in internal rate of return with increasing installed capacity. This trend is predominately due to scale effects since costs for turbines, powerhouses etc fall with increasing installed capacity, and engineering fees, calculated as a proportion of total costs, fall as cost increases. It might also be anticipated that since turbines and generators form a major proportion of total scheme cost, and that turbine cost falls with increasing head, that there would be a trend for scheme cost to fall and internal rate of return to increase with increasing head. However, in general this apparently is not the case, and is probably related to the proportion of existing civils works. For schemes with heads of less than 10m, the proportion of existing civils works is high, whereas for schemes above 30m it is low. To investigate this factor, the analyses of Table 7.1 and 7.2 have been repeated for schemes with pipelines in Tables 7.3 and 7.4 and without pipelines in Tables 7.5 and 7.6.

For the 'with pipeline' case, Table 7.3 shows that less than half of the schemes have existing civils works ie. more than half are previously undeveloped sites. Furthermore, above 30m head, the large majority are previously undeveloped sites. In Table 7.4, it can be seen that turbo-generators and mechanical installation have fallen to 35.0% of scheme cost with a corresponding increase in pipelines to 22.0% of scheme cost when compared to the 'all sites' case. The other cost elements have remained substantially unchanged.

For the 'no pipeline' case, Table 7.5 shows that nearly all sites have existing civils works, and Table 7.6 shows that turbo-generators and mechanical installation. now comprise 51.6% of the total scheme cost on average.

The main conclusion which can be drawn from this analysis is that although small hydro is site-specific in nature, turbo-generators can be expected to make up a significant proportion of the total scheme cost for all sites. As might be anticipated their effect is most marked on sites with existing civils and low heads. As head increases, pipelines become a significant proportion of scheme costs, and for high head sites (above say 50m), pipelines, turbo-generators, and all other costs, would be expected to each make up about 1/3 of the total scheme cost.

7.1.2 Procedure for development

The purpose of developing a hydropower scheme is to exploit economically the resource's potential. To this end, three stages of appraisal and design can be clearly identified: the preliminary appraisal, the feasibility study, and, the detailed design and implementation.

7.1.2.1 The Preliminary Appraisal

The purpose of the preliminary appraisal is to define the resource's potential and economics in sufficient detail to determine whether a feasibility study is justified. A flowchart for preliminary appraisal is shown in Figure 7.1, the steps outlined being essentially the same as those which would also be required for a desk study of regional potential.

The first step is site identification which for a preliminary appraisal is likely to be client led, whereas for a potential study sites have to be identified from a map study. The next step is to devise a scheme layout, so defining head by locating the intake and powerhouse positions and the means of supplying water between the two. The accuracy of the appraisal will be determined to a large extent by the quality of the site information available at this stage. Obviously a walkover survey would be desirable, although financial limitations may preclude this. Where a client is proposing a scheme, use can be made of large scale maps, sketches and photographs to define the scheme layout. For a desk study of potential, the investigator will be limited by the information available on maps eg. in the U.K. 1:50,000 scale maps are available with a contour interval of 10m. Accordingly the desk study could only reliably be applied to sites with heads of 10m or more. Furthermore, it will be necessary to assume that the intake is linked to the powerhouse by a pressure pipeline, where no other data is available.

Having determined the intake positions, a hydrological analysis is undertaken to determine mean flow and the shape of the flow duration curve. An installed flow is selected and power and energy yield are calculated. The installed flow will be selected as either the mean flow minus the compensation flow, or by consideration of the client's end use for energy, or existing civil works restrictions. The proportion of energy used on-site to that sold should be determined and a revenue calculation performed.

Next a scheme cost estimate must be made and economic analysis undertaken. The cost curves of Chapter 5 may be used to calculate scheme cost, although, due to the influence of turbo-generator cost on total cost, a budget price estimate from a manufacturer for a specific machine would be advisable. Finally a brief report will be made to the client who will then decide whether to proceed with commissioning a feasibility study.

7.1.2.2 The Feasibility Study

The purpose of the feasibility study is to define scheme potential and economics in sufficient detail to allow an investment decision to be made. A flowchart for the feasibility study is shown in Figure 7.2.

Data from the preliminary appraisal together with consideration of the clients requirements will provide the investigator with an indication of the likely scheme type and permissible design input for the level of investment. The scheme will be developed for either local supply, parallel supply or grid supply. Parallel and grid supply would normally be considered only where scheme potential is greater than 50kW, with schemes below 50kW being developed to meet local demands.

With data from the preliminary appraisal providing background information only, the first stage is to devise a scheme layout by site survey and then to accurately define resource potential. The site survey will not only define the physical parameters of the scheme but also involve collection of information on the end user demand patterns. These patterns will then be related to the hydrological characteristics of the site invariably by the use of monthly flow duration curves (ie. mean daily FDC's produced for specific months of the year).

During the survey and resource appraisal stage, several scheme options may become apparent. For each of these options, it will be necessary to consult with manufacturers to assess the availability of turbo-generator equipment. This process will involve providing the manufacturer with net head, flow-variability information and perhaps 2 or 3 required installed-flow values. (Mean flow minus compensation flow may provide a base case, however it would be usual also to select installed flows greater and less than this value and to select the most economic solution by analysis). The turbine manufacturer will then attempt to match the site conditions with his machinery and will provide performance data and price quotations. The turbine performance data, making necessary allowance for headloss etc. will then be used to compute power and energy outputs. The energy output will in turn be related to the end user demands and revenue calculated. At this stage it may be possible to determine that some of the scheme and installed-flow options are uneconomic and can be disregarded.

For the remaining options, outline design of the civil works and outline specification of all scheme components must be undertaken and cost estimates produced. An indication of the degree of importance to be attached to each of the scheme components can be obtained from section 7.1.1. The final stage of the feasibility study is to conduct an economic appraisal for the scheme options and then to report the results to the client together with recommendations for the preferred option. Subject to the client's approval a decision to proceed to the detailed design and implementation phase will then be made.

7.1.2.3 Detailed Design and Implementation

A flowchart for the implementation phase is included as Figure 7.3. The first step in implementation is the detailed design of civil works and the specification of electro-mechanical equipment, leading to the production of contract documents. This involves selecting the method to be adopted for implementing the contract. Several options may be considered, including turnkey, separate civil and electro-mechanical contracts or perhaps a direct-labour approach to part of the works. In order to determine the most economical method of implementing the contract, it may be necessary to discuss the various options with interested parties, including the client, Engineer, contractors and equipment manufacturers. Next, the contract will be offered for tender, the tenders appraised and subject to the client's decision to proceed, contracts will be signed.

During the construction phase and commissioning, it will be the Engineer's duty to monitor the progress of the contract and to satisfy himself that the contractors' performance meets the specification. When this has been done, the scheme will be handed over to the client. Usually it will be the client who has the responsibility for operating the scheme, however maintenance may well be contracted-out to the turbine manufacturer or to another suitably-qualified contractor. In any case, the maintenance of the scheme should not be overlooked since failure to undertake necessary routine maintenance may well lead to early failure of components and to subsequent loss of revenue.

7.1.2.4 Comments on Procedure

The three stage approach to development offers the proposer the opportunity to review his committment at several stages, each stage requiring a greater investment on his part.

The procedural flowcharts emphasize the importance of correctly assessing the resource potential. Experience in Sri Lanka has shown that many schemes fell into disuse not because of mechanical failure, but because they were oversized and as such they failed to meet the expectations of their owners and were abandoned.

Section 7.1.1 has shown that the most important cost component is for turbo-generators; consequently the flow charts reflect the need to consult manufacturers at every stage of development. In so doing, considerable design effort may be saved by not pursuing scheme options which are likely to be uneconomic.

7.2 Development in the U.K

The small hydro potential of the U.K. (except Scotland) although not large could if developed have significant implications, particularly at a local level. Furthermore, small hydro offers opportunity for long term investment and continues to attract the interest of groups such as pension fund managers. Schemes are likely to be attractive to entrepreneurs where they show internal rates of return on capital invested of 10-15% particularly where use can be made of attractive taxation benefits as, for example in the "Business Expansion Scheme". A handful of groups are looking at hydro in this way, although presently their effort is being concentrated at sites which have a history of generation where capital requirement is lowest. The planned privatization of the Water Authorities is leading some of them to reconsider the opportunities for investment in small hydro at sites within their systems eg. impounding reservoirs, break-pressure valves on supply mains etc. Such sites are likely to be some of the most attractive for development in the U.K. since opportunities exist for schemes with large capacities and the requirement for new civil construction is minimized.

Presently there is virtually no development of new sites in the U.K. This may be due in part to the costs of development but also in no small measure, to institutional problems. Leglislation is required which removes the threat of abstraction charges from hydro power generation, and links local authority rates to production rather than capital cost. Small hydro also poses environmental problems and is usually in conflict with fishery interests. Development is often precluded in areas run as national parks with the best sites attracting visitors due to their spectacular nature. In this context it is worth noting that it was the development of hydro schemes in the North of Scotland which served to make the Highlands more accessible to visitors. These problems are not insurmountable however, and developments can be undertaken in such a way that they will attract tourists by forming centres of interest at particular locations. An example of such developments can be found at Lynton in Devon where a scheme has been installed around a scenic walk. The visual impact of this scheme is minimal and the powerhouse is open to the public.

The local impact of development should not be overlooked, particularly the implications for employment. Jobs might be created, not only during the construction phase, which would almost invariably mean the use of locally-based contractors, but also long-term, for the operation and maintenance of schemes.

It seems likey that the next 5-10 years will prove an interesting period for small hydro development in the U.K. As experience is gained by Water Authorities and entrepreneurs in the operation of small hydro and the realization of its benefits, then attention will be turned to more ambitious development of virgin sites.

7.3 Ultra Low-head Development

There is a requirement for generators capable of economic development at hydraulic heads of less than 3m. Research and development is being concentrated at this end of the market. However it is the opinion of the writer that none of the systems currently under development in the U.K. offer a better chance of being economic than conventional rotodynamic turbines. The answer may lie in the standardization of components and use of mass production techniques. For example, all sites on the Punjab canal system (140MW) could be developed with 2 or 3 different sizes of fixed blade propeller turbines used in multiple units. This would also have implications for reducing maintenance costs due to the simplified nature of the machinery and the number of spare parts which would have to be kept.

7.4 Development in the Third World

From a national economic view point the development of small hydro can help to reduce imported fuel costs with consequent effect on reducing debt and foreign exchange requirements. There is more chance of a government being able to fund and produce the equipment required for small schemes, and once an initial batch of schemes has been developed, future developments might be self financing (Ref. 28).

At the local level, scheme development can transform living standards and the earning ability of village inhabitants. In the word of the late Mrs Indira Gandhi "all life is sustained by water and progress depends on power".

Local employment opportunities will be increased both during the construction phase and for operation and maintenance. Provision of power will help to reduce illness through refrigeration of food and the ability to store medical supplies, the provision of hot water to creches etc. Power supply to community buildings will help to increase literacy through radio and television for educational purposes. In this way it can help form a central interest in the village, giving inhabitants a sense of identity and hope for improving their standard of living. Accordingly rural electrification will tend to reduce exodus to often already-chronically-overcrowded cities. Provision of local energy supply will have environmental consequences by reducing deforestation and consequent soil loss. Opportunities for local processing of crops, materials and clothing will tend to increase self sufficiency and regeneration of rural communities.

It should be realised that the benefits of local power stations need not be measured solely in economic terms, as account should be taken of environmental and sociological benefits. Many governments, with the help of aid agencies, are developing coherent energy strategies, but the implementation of these will be dependent upon technical assistance from developed countries such as the U.K. In the provision of this technical assistance it is of paramount importance to ensure the transfer of technology and the training of operatives (Ref. 29).

7.5 The Future

Small hydro is an expanding market with a large potential still to be tapped in many areas of the world, but particularly in Asia. It is likely that the next 10-20 years will see major development of this potential for rural electrification. If British manufacturers, and to a lesser degree, consultants, are to play a significant role in developoment, they require a healthy home base for their products. the privatization of the Electricity Boards and the Water Authorities may go some way to creating a home market, but further action by central government is required to overcome institutional problems, and real or imagined environmental prejudices.

One way forward might be for the government to fund or part fund a number of schemes as demonstration projects. These schemes would be selected to exhibit a range of site types and investigate the various problems posed by hydro development. In so doing valuable experience would be gained which could be passed on to other potential developers.

Head (m)		INSTALLED CAPACITY (kW)				
		<50	50-100	100-250	250-500	>500
2-3	No. of sites	1	1	10	7	7
	Average scheme cost (£/kW)	978	2387	1564	1240	1089
	Average IRR (%)	10.4	5.1	7.4	10.1	9.3
	Percent of sites with existing civils	100	100	100	85.7	100
3-5	No. of sites		4	12	5	6
	Average scheme cost (£/kW)		1680	1249	1014	848
	Average IRR (%)		6.5	11.8	11.6	14.6
	Percent of sites with existing civils		100	100	100	100
5-10	No. of sites	8	5	15	3	
	Average scheme cost (£/kW)	1593	1431	1210	832	
	Average IRR (%)	7.2	7.9	10.1	9.7	
	Percent of sites with existing civils	66.7	100	80.0	66.7	
10-30	No. of sites		5	14	1	2
	Average scheme cost (£/kW)		1292	1008	731	918
	Average IRR (%)		9.8	10.8	12.2	9.1
	Percent of sites with existing civils		80.0	35.7	0	0
30-50	No. of sites		1	5	2	
	Average scheme cost (£/kW)		1609	989	999	
	Average IRR (%)		6.5	12.4	9.5	
	Percent of sites with existing civils		0	40.0	0	
>50	No. of sites		1	18	11	1
	Average scheme cost (£/kW)		1789	1125	950	473
	Average IRR (%)		6.4	9.4	10.5	24.5
	Percent of sites with existing civils		0	27.8	0	0

Table 7.1 Distribution of Sites by Head and Capacity for All Run-of-River Schemes in England, Northern Ireland and Wales with IRR >= 5%

Total number of sites = 140

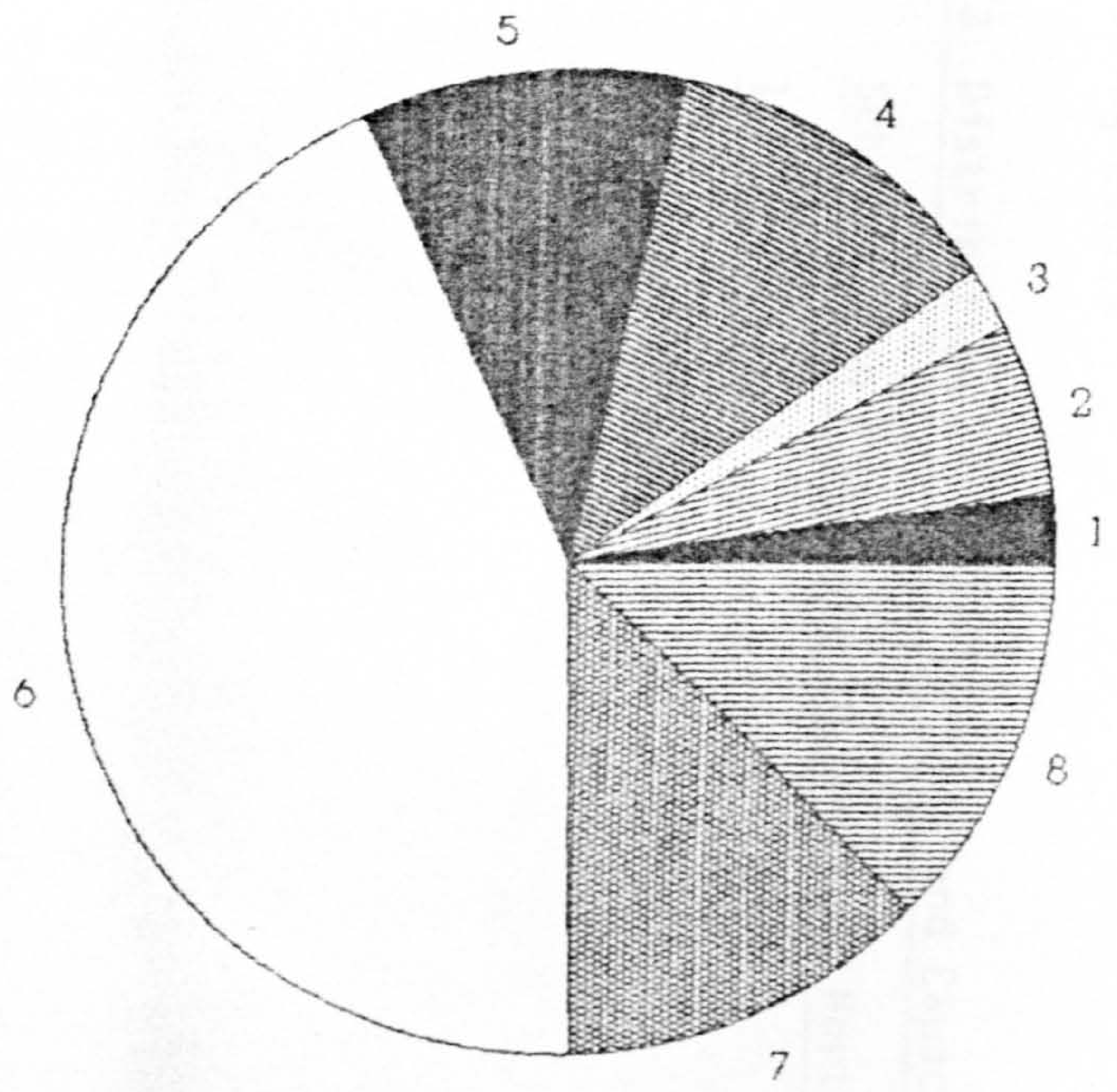


Table 7.2 PIE CHART FOR ALL SCHEMES

KEY

1. Weirs, diversion works, excavation, access road & bank protection.
2. Intakes.
3. Leats.
4. Powerhouses.
5. Pipelines.
6. Turbo-generators & mechanical installation.
7. Electrical transmission, switchgear, protection & metering.
8. Engineering fees & contractural requirements.

Item

	1	2	3	4	5	6	7	8
Average of total costs (%)	2.2	5.8	2.1	11.6	10.4	43.8	12.4	12.4
Maximum 16.0 (%)	17.3	35.1	33.4	25.6	52.9	73.3	40.3	15.9
Minimum (%)	0	0	0	0	0	16.2	3.0	9.4
Stand. Dev (%)	3.4	5.5	5.3	5.8	14.5	12.2	6.0	1.1
Average of total costs (£/kW)	23.5	60.5	22.2	123.5	110.7	467.7	132.9	132.9

Average total cost (£/kW) = 1068.2

Analysis of results for all schemes.

		INSTALLED CAPACITY (kW)				
Head (m)		<50	50-100	100-250	250-500	>500
5-10	No. of sites		3	6		
	Average scheme cost (£/kW)		1471	1326		
	Average IRR (%)		6.8	9.5		
	Percent of sites with existing civils		100	50		
10-30	No. of sites		3	13		2
	Average scheme cost (£/kW)		1420	1026		918
	Average IRR (%)		7.5	11.0		9.1
	Percent of sites with existing civils		66.7	38.5		0
30-50	No. of sites		1	5	2	
	Average scheme cost (£/kW)		1609	989	999	
	Average IRR (%)		6.5	12.4	9.5	
	Percent of sites with existing civils		0	40.0	0	
>50	No. of sites		1	18	11	1
	Average scheme cost (£/kW)		1789	1125	951	473
	Average IRR (%)		6.5	9.4	10.5	24.5
	Percent of sites with existing civils		0	27.8	0	0

Table 7.3 Distribution of Sites by Head and Capacity for Run-of river Schemes with Pipelines in England, Northern Ireland and Wales with IRR > = 5%

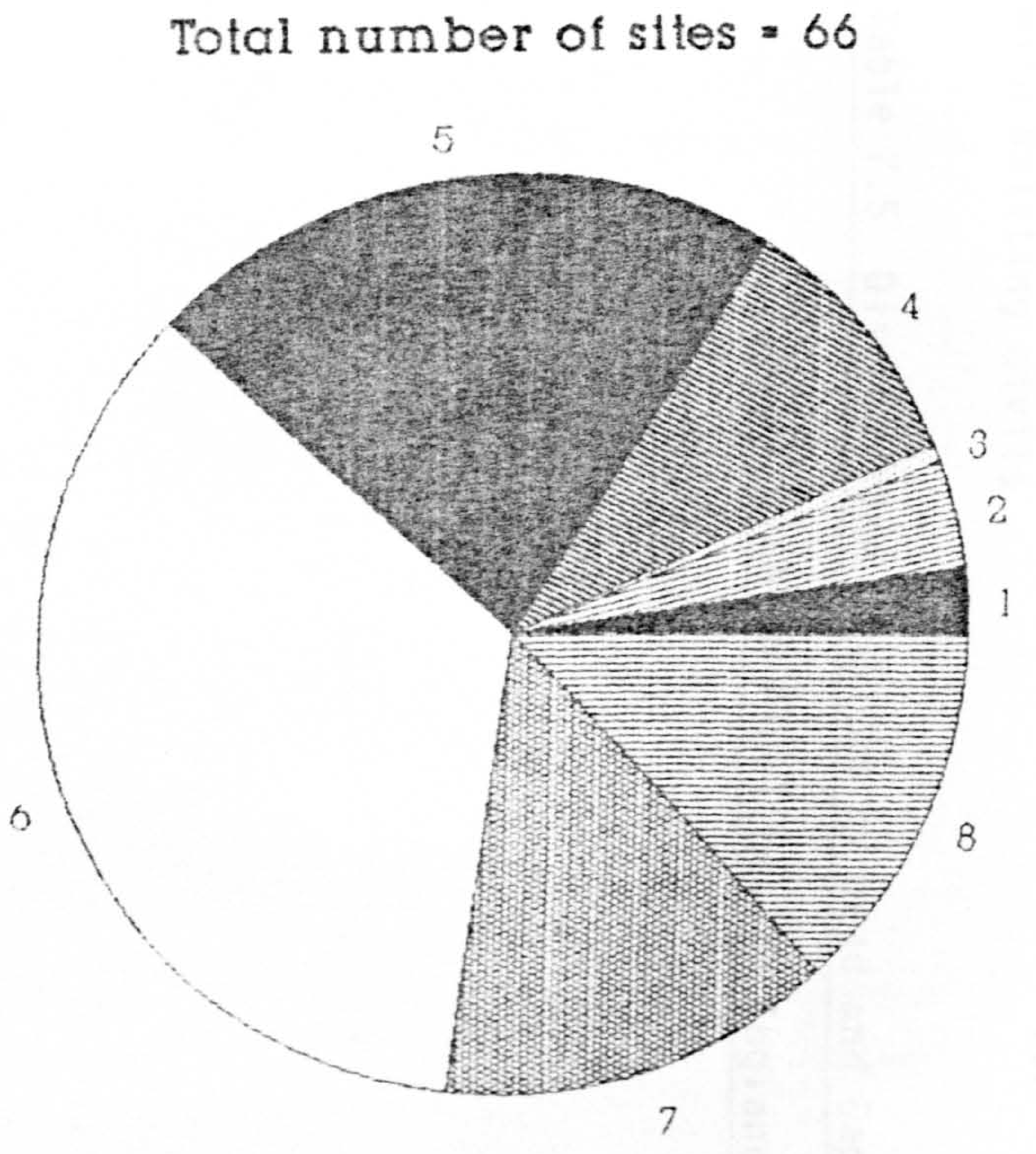


Table 7.4 PIE CHART FOR SCHEMES WITH PIPELINES

KEY

1. Weirs, diversion works, excavation, access road & bank protection.
2. Intakes.
3. Leats.
4. Powerhouses.
5. Pipelines.
6. Turbo-generators & mechanical installation.
7. Electrical transmission, switchgear, protection & metering.
8. Engineering fees & contractural requirements.

	Item							
	1	2	3	4	5	6	7	8
Average of total costs (%)	2.3	3.8	0.6	9.4	22.0	35.0	13.9	13.0
Maximum 15.9 (%)	17.2	8.5	19.7	25.3	52.9	61.5	40.3	15.9
Minimum 10.8 (%)	0	0	0	2.1	1.1	16.2	4.5	10.8
Stand. Dev (%)	3.5	2.1	2.6	5.0	13.9	9.3	5.6	1.0
Average of total costs (£/kW)	21.5	36.4	5.7	89.5	209.2	332.6	131.8	123.4

Average total cost (£/kW) = 951.6

Analysis of results for schemes with pipelines

Head (m)		INSTALLED CAPACITY (kW)				
		<50	50-100	100-250	250-500	>500
2-3	No. of sites	1	1	10	7	7
	Average scheme cost (£/kW)	978	2387	1564	1240	1089
	Average IRR (%)	10.4	5.1	7.4	10.1	9.3
	Percent of sites with existing civils	100	100	100	85.7	100
3-5	No. of sites		4	12	5	6
	Average scheme cost (£/kW)		1680	1249	1014	848
	Average IRR (%)		6.5	11.8	11.6	14.6
	Percent of sites with existing civils		100	100	100	100
5-10	No. of sites	3	2	9	3	
	Average scheme cost (£/kW)	1593	1371	1133	832	
	Average IRR (%)	7.2	9.6	10.5	9.7	
	Percent of sites with existing civils	66.7	100	100	66.7	
10-30	No. of sites		2	1	1	
	Average scheme cost (£/kW)		1100	878	731	
	Average IRR (%)		13.3	7.9	12.2	
	Percent of sites with existing civils		100	50	0	

Table 7.5 Distribution of Sites by Head and Capacity for Run-of-River Schemes with No Pipelines in England, Northern Ireland and Wales with IRR >=5%

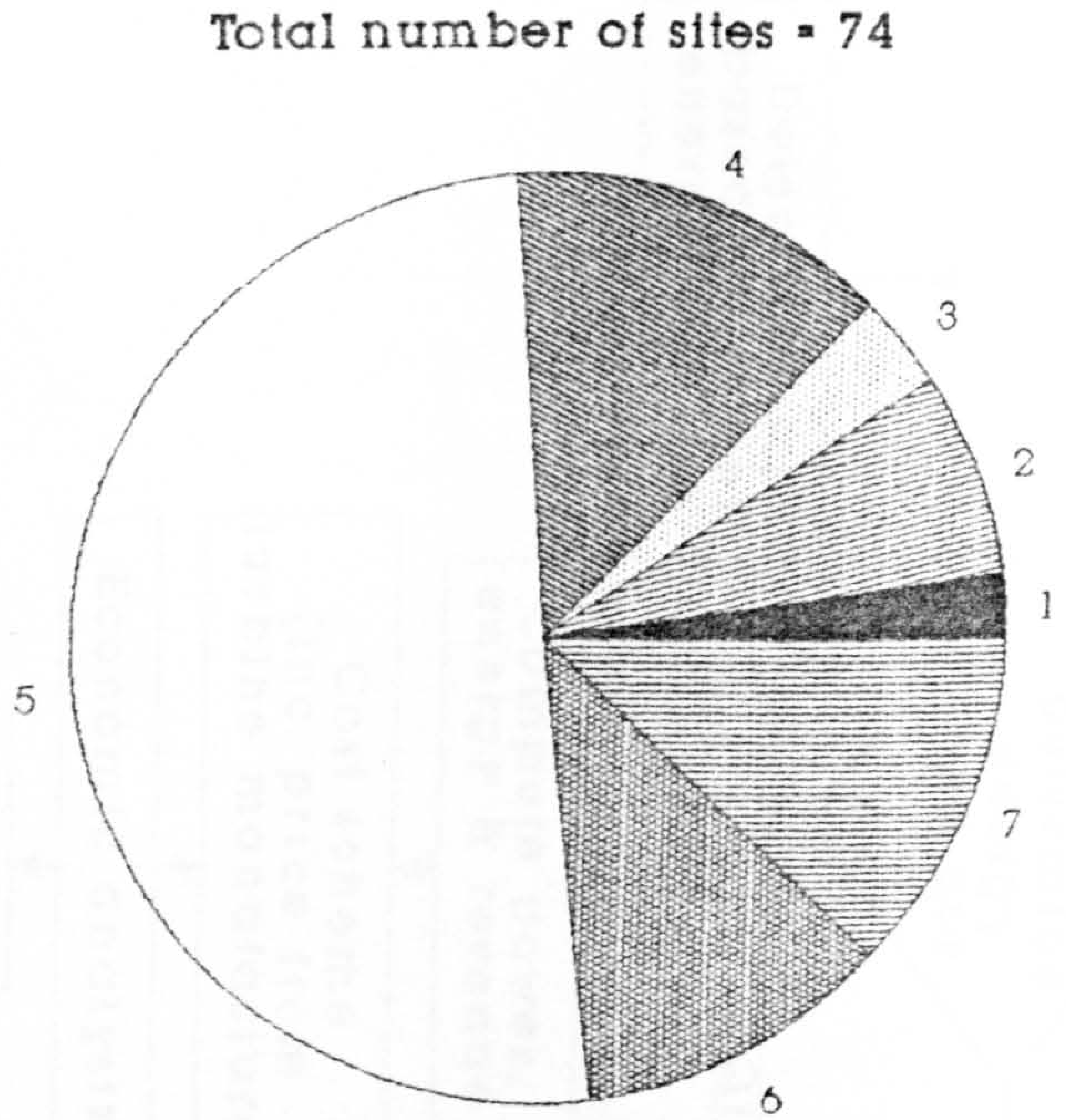


Table 7.6 PIE CHART FOR SCHEMES WITH NO PIPELINES

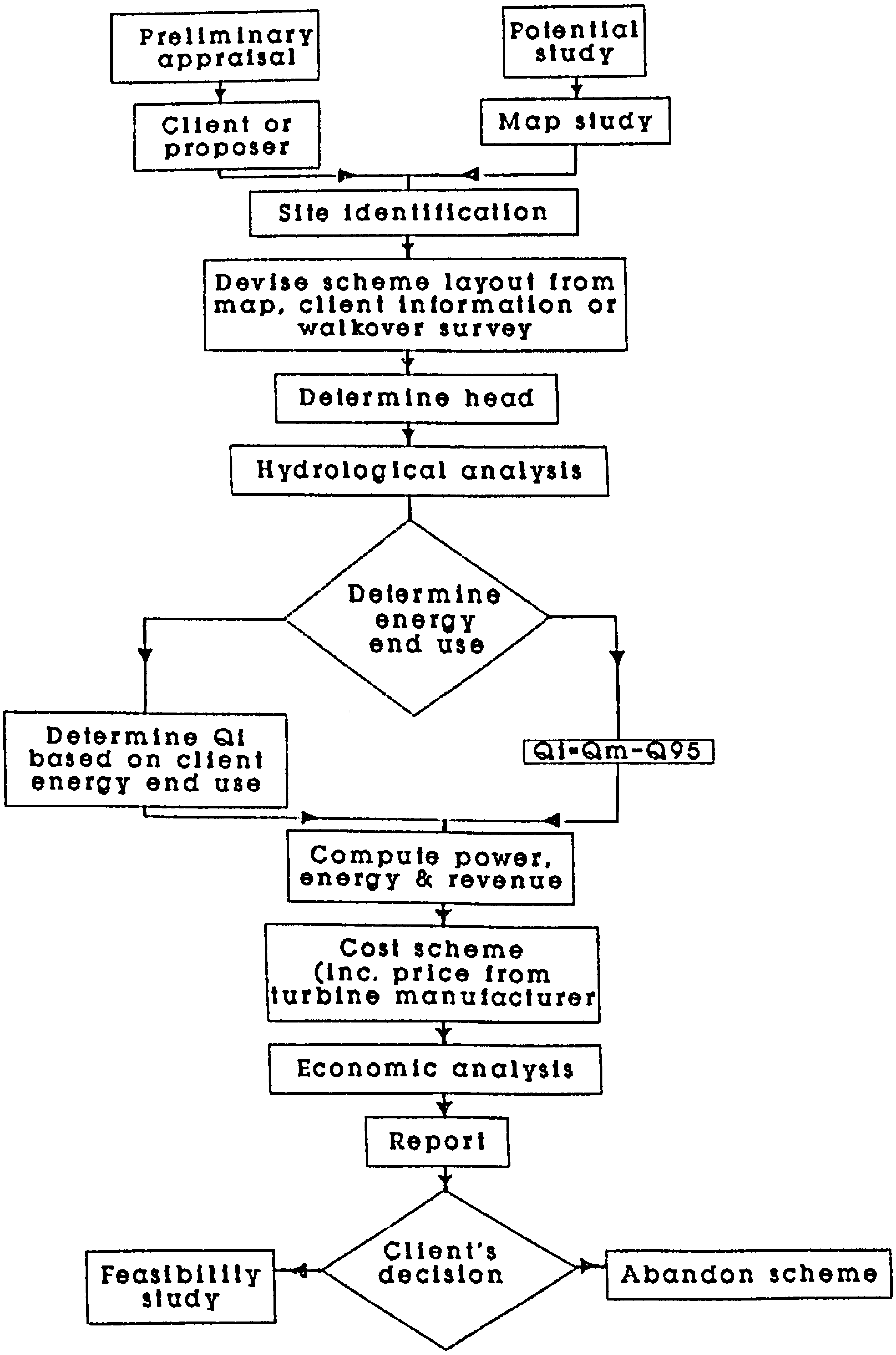
KEY

1. Weirs, diversion works, excavation, access road & bank protection.
2. Intakes.
3. Leats.
4. Powerhouses.
5. Turbo-generators & mechanical installation.
6. Electrical transmission, switchgear, protection & metering.
7. Engineering fees & contractural requirements.

	Item						
	1	2	3	4	5	6	7
Average of total costs (%)	2.2	7.3	3.4	13.5	51.6	11.2	12.0
Maximum (%)	14.8	35.1	33.4	25.6	73.3	34.3	14.4
Minimum (%)	0	0	0	0	21.1	3.0	9.4
Stand. Dev (%)	3.4	6.9	6.6	5.8	8.7	6.2	0.9
Average of total costs (£/kW)	24.1	81.9	38.1	151.1	579.2	125.4	134.1

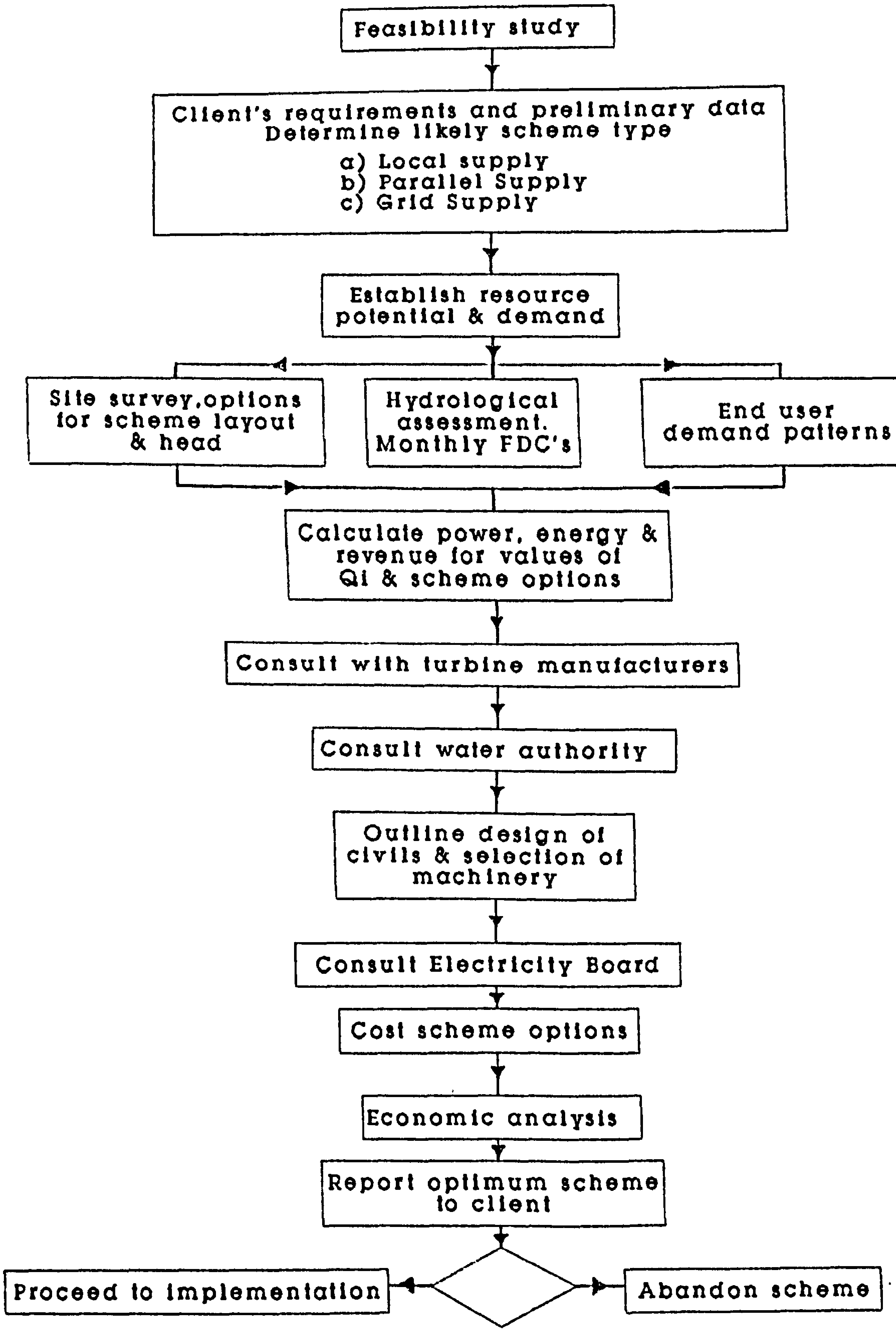
Average total cost (£/kW) = 1121.5

Analysis of results for schemes with no pipeline



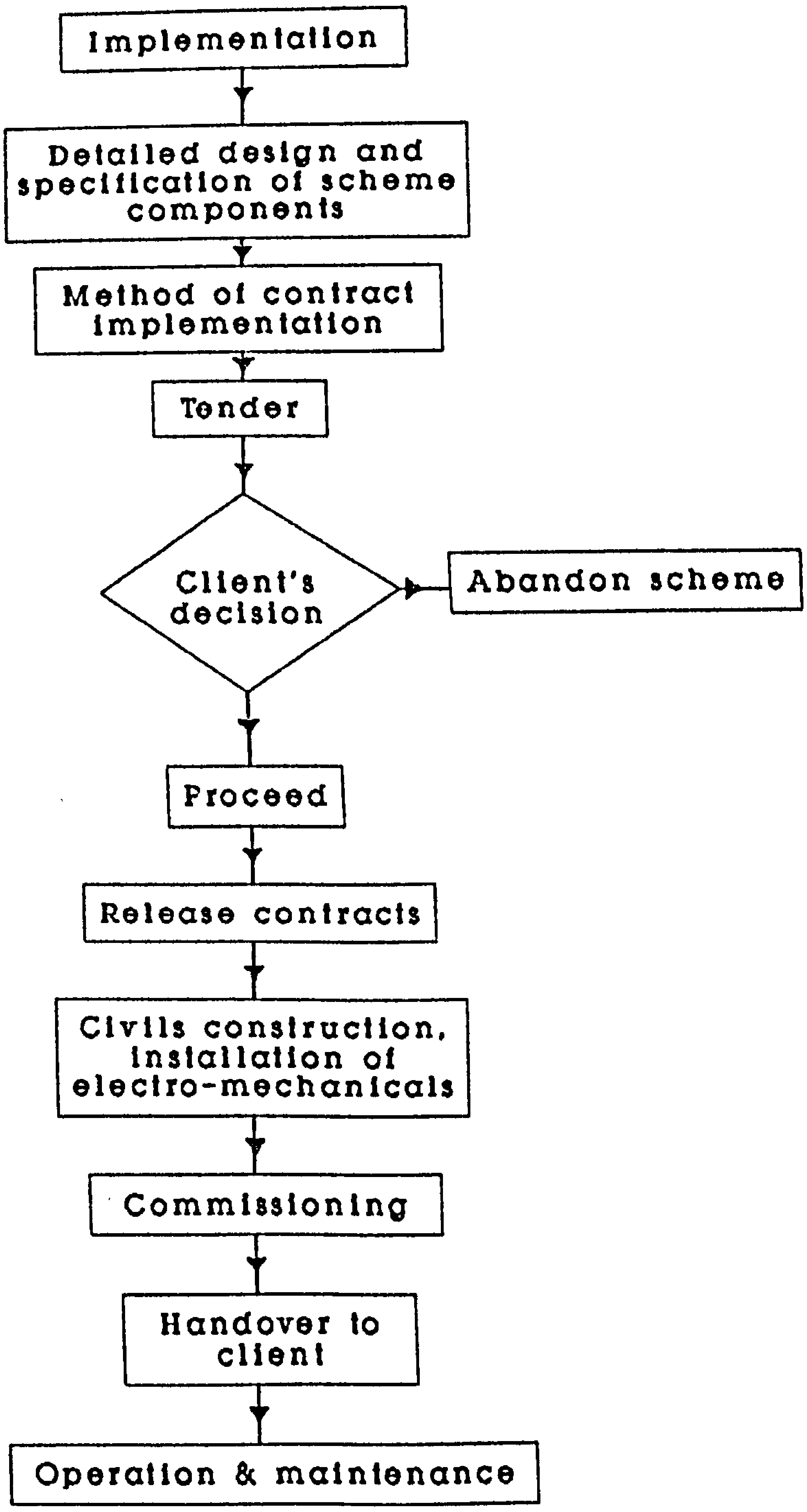
Flowchart for preliminary appraisal or potential study

FIG 7.1



<u>Flowchart for feasibility study</u>

FIG 7.2



Flowchart for implementation

FIG 7.3

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APPENDIX A

Installed Flow Sensitivity Analysis

A. Installed Flow Sensitivity Analysis

A1. Introduction

The selection of installed or rated flow (maximum turbine flow) is of importance since the sizing of all equipment and structures are dependent upon this parameter. Selection of optimum rated flow is dependent upon the hydrological characteristics of catchment, the prevailing site conditions and the optimum sizing of turbo-generator equipment and civil works in relation to the load to be met. For a detailed analysis the procedure to optimize rated flow would be select several flows and thence to conduct economic analyses for each thus allowing determination of the flow which maximizes economic benefit. However, for a preliminary appraisal, or a potential study, the engineering input allowable precludes such a rigorous analysis, and therefore an estimate of rated flow is required which is likely in the majority of cases to yield optimum benefit.

The following analysis has been undertaken to investigate the effect of rated flow on internal rate of return.

A2. Method

A number of sites was selected to exhibit a range of head, flow, BFI, turbo-generator equipment and scheme type. A brief description of the sites is given in Tables A2.1.1 and A2.1.2 and basic site data in Table A2.2.

For each of the schemes, a range of installed flows was selected, power and energy computed, and cost estimates and economic analyses undertaken using the costing package of Chapter 4. Installed flow was selected as multiples of mean annual flow minus Q_{95} compensation flow, this parameter essentially being the mean flow available for generation. For each of the schemes it was assumed that energy would be produced for direct supply to the grid with no local demand for output.

This assumption helps to ensure that the schemes are representative of the majority of sites in the U.K. since investigation has shown that for schemes in England, Wales and Northern Ireland which yield internal rates of return of greater than 5% (the minimum demand acceptable) some 66 percent would be developed for supply to the grid.

A3. Results and Conclusions

Installed flow, power, energy yield and selected turbine type are shown in Tables A3.1.1 and A3.1.2. The results of the economic analyses are plotted on Figures A3.1.1 to A3.1.3. The results indicate that maximum economic benefit occurs between rated flows of 0.75 ($Qm - Q_{95}$) and 1.0 ($Qm - Q_{95}$). Site 025002 provides an exception to this rule which is probably due to its large installed capacity and steep flow duration curve.

Generally, it can be concluded that adopting a rated flow equal to the mean available flow ($Qm - Q_{95}$) is likely to yield an economic return near to optimum and as such, provides a useful first estimate for selecting installed flow for preliminary analyses and potential studies.

Site Number	Description
025002	High Force, new scheme developed around a natural waterfall. Main scheme components: weir 35m long x 2m high, intake works and settling basin, 200m of pressure pipeline, powerhouse, turbo-generators, 1000m of transmission, and 500m of access road.
027072	Linton-on-Ouse, previously developed site for electricity supply to grid. Powerhouse and leat in poor state of repair. Main scheme components: concrete leat 25m long, screens, penstocks and automatic rakes, powerhouse, turbo-generators, 150m of transmission.
027074	Aysgarth falls, new scheme developed around a natural waterfall. Main scheme components: weir 25m long x 1.5m high, intake works and settling basin, 600m of pressure pipeline, powerhouse, turbo-generators, 1000m of transmission and 200m of access road.
028019	Litton Mill, previously developed for on-site use. Main scheme components: intake works, 50m of unlined leat, powerhouse, turbogenerator, repair tailrace 200m long under mill.
046001	Chagford Hotel, although previously developed for local supply, with exception of weir, scheme requires a complete rebuild. Main scheme components: screens and penstocks, 150m of low pressure pipe, 30m of pressure pipe, header tank, powerhouse, turbo-generator, 80m of transmission.
047001	Trebartha Estates, some evidence of previous scheme. Main scheme components: intake works, 800m of unlined leat, header tank, 450m of pressure pipeline, powerhouse, turbo-generator, 500m of transmission and 100m of access road.

Table A2.1.1. Main Scheme Components

Site Number	Description
051001	Watersmeet, new scheme around rapid section of river. Main scheme components: weir 15m long x 0.6m high, intake works settling basin, 680m of pressure pipeline, powerhouse, turbo-generators, 300m of transmission.
069006	Radcliffe Bleach Mill, previously developed site for supply to mill, scheme developed around existing weir. Main scheme components: 2000m^3 of desilting to weir, screens and penstocks, powerhouse, turbo-generator, 1000m of transmission.
069008	Castle Hill, evidence of previous scheme now derelict except for weir. Main scheme components: penstocks and screens, 500m of unlined leat, powerhouse, turbo-generator, 300m of transmission.
069011	Compstall, previously developed but only weir re-usable. Main scheme components, intake works, 50m of pressure pipeline, powerhouse, turbo-generator, 200m of transmission.
073007	Rydal Beck, new scheme around rapid section of river with waterfalls. Main scheme components: weir 5m long x 1m high, intake works and settling basin, 750m of high pressure pipeline, powerhouse, turbo-generator, 300m of transmission.

Table A2.1.2. Main Scheme Components

Site Number	BFI	Qm (m^3/s)	Q_{95} (m^3/s)	$\frac{Q_{95}}{Qm}$ (%)	Head (m)
025002	0.20	7.72	0.35	4.5	21.3
027072	0.53	37.35	6.16	16	3.60
027074	0.29	8.26	0.64	8	15.0
028019	0.73	2.83	0.91	32	9.0
046001	0.41	1.04	0.11	11	20.0
047001	0.41	0.59	0.07	12	75.0
051001	0.74	3.13	0.79	25	70.0
069006	0.39	8.56	0.96	11	3.30
069008	0.55	2.93	0.53	18	6.2
069011	0.47	4.08	0.60	15	6.5
073007	0.39	0.43	0.05	12	100.0

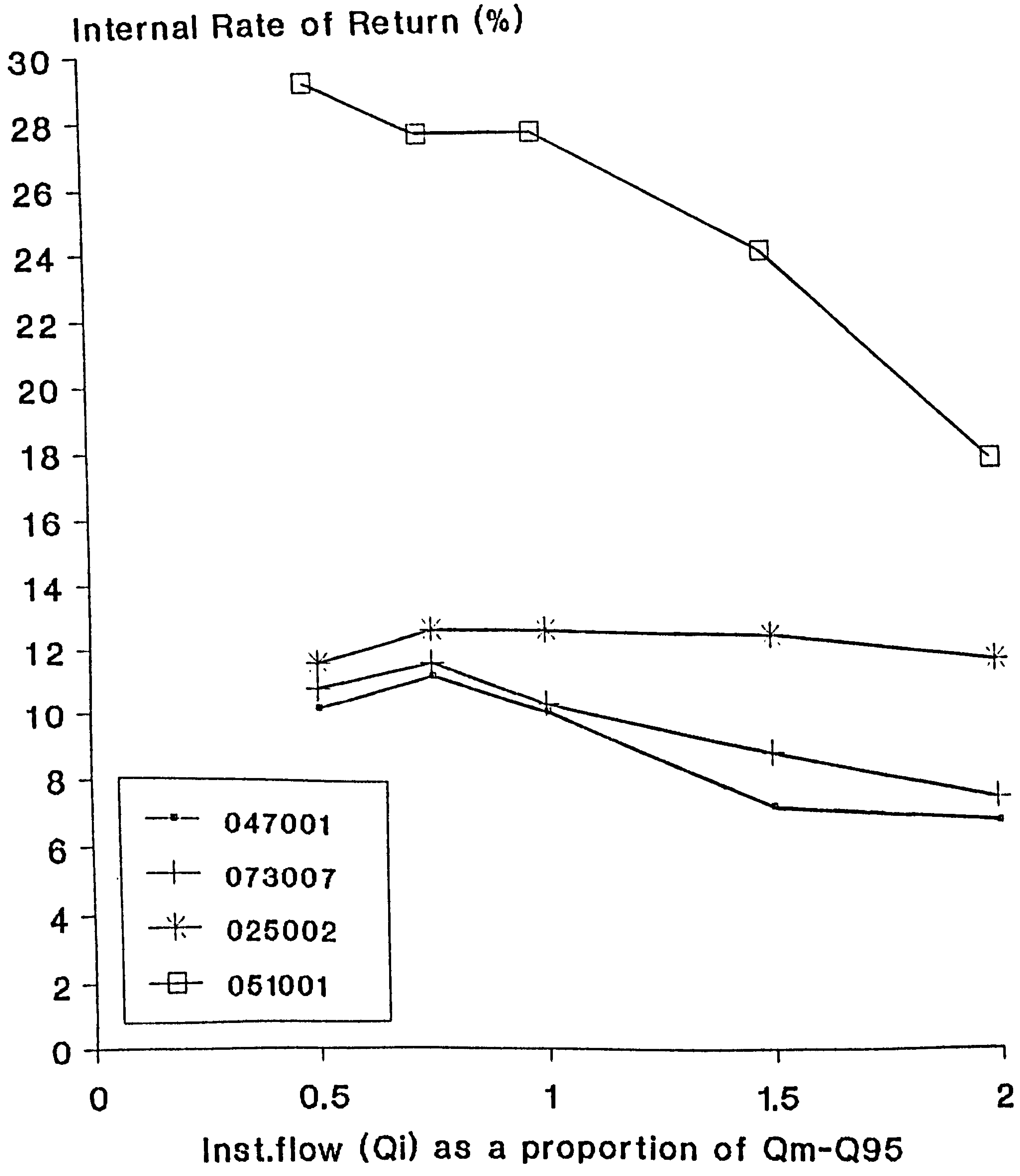
Table A2.2 Basic Site Data

Site Number	Installed Flow Qi (m^3/s)	% Exceedance at installed flow	Power (kW)	Energy Yield (MWh)	$\frac{Q_i}{Q_m - Q_{95}}$	Turbine Type	No. of Turbines
025002	7.37	23.5	1140	4670	1.0	Francis	2
	14.74	7.5	2293	5750	2.0	Francis	2
	11.05	13.1	1719	5394	1.5	Francis	2
	5.53	32.2	852	4045	0.75	Francis	2
	3.68	43.0	549	3084	0.5	Francis	2
027072	31.2	26.1	903	4399	1.0	Propeller	2
	62.4	6.5	1817	5328	2.0	Propeller	3
	46.8	12.7	1362	5023	1.5	Propeller	2
	23.4	36.2	662	3744	0.75	Propeller	2
	15.6	53.7	425	2811	0.5	Propeller	2
027074	7.62	26.5	825	3675	1.0	Crossflow	1
	15.24	6.0	1670	4933	2.0	Crossflow	2
	11.43	13.1	1252	4540	1.5	Crossflow	2
	5.71	35.0	605	3104	0.75	Crossflow	1
	3.81	46.3	388	2336	0.5	Crossflow	1
028019	1.92	30.0	120	649	1.0	Crossflow	1
	3.84	2.0	251	742	2.0	Crossflow	1
	2.88	9.0	184	735	1.5	Crossflow	1
	1.44	40.8	89	552	0.75	Crossflow	1
	0.96	62.1	58	413	0.56	Crossflow	1
046001	0.93	28.6	116	571	1.0	Crossflow	1
	1.86	8.0	243	768	2.0	Crossflow	1
	1.40	14.8	179	677	1.5	Crossflow	1
	0.70	38.4	86	485	0.75	Crossflow	1
	0.47	53.4	57	371	0.5	Crossflow	1
047001	0.52	27.8	256	1268	1.0	Turgo	1
	1.04	8.0	546	1702	2.0	Turgo	1
	0.78	14.5	402	1536	1.5	Turgo	1
	0.39	38.1	188	1062	0.75	Turgo	1
	0.26	53.3	122	795	0.5	Turgo	1

Table A3.1.1 Energy Computation

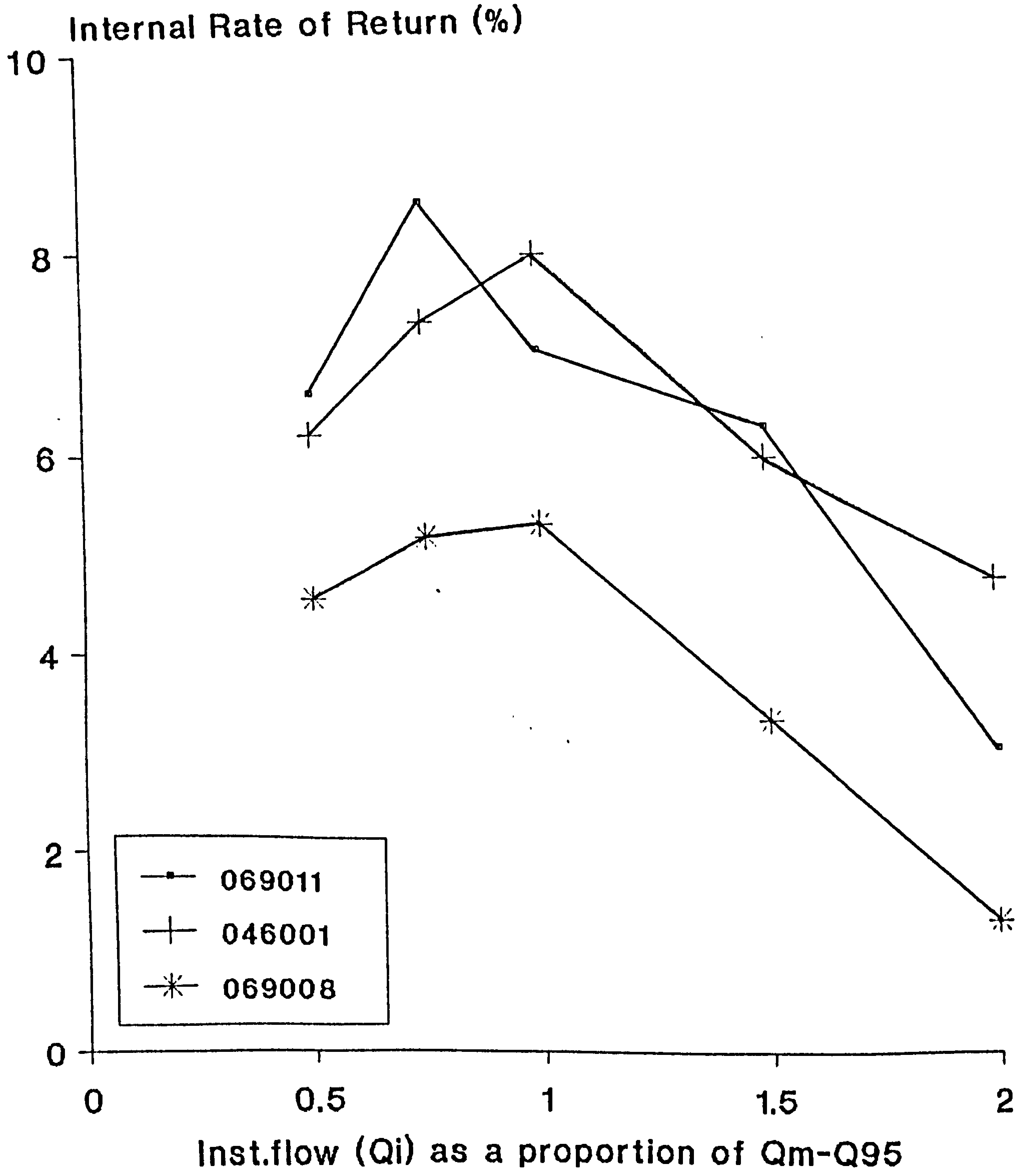
Site Number	Installed Flow Qi (m^3/s)	% Exceedance at installed flow	Power (kW)	Energy Yield (MWh)	$\frac{Q_i}{Q_m - Q_{95}}$	Turbine Type	No. of Turbines
051001	2.34	25.9	1196	6140	1.0	Francis	2
	4.68	5.0	2393	7402	2.0	Francis	2
	3.51	11.2	1795	6909	1.5	Francis	2
	1.76	38.4	893	5131	0.75	Francis	1
	1.17	58.3	576	3895	0.5	Francis	1
069006	7.60	30.9	178	843	1.0	Propeller	1
	15.20	9.0	376	1189	2.0	Propeller	2
	11.40	16.9	275	978	1.5	Propeller	1
	5.7	40.9	131	724	0.75	Propeller	1
	3.8	56.3	86	554	0.50	Propeller	1
069008	2.40	30.3	102	499	1.0	Propeller	1
	4.8	8.5	213	554	2.0	Propeller	1
	3.6	15.5	157	565	1.5	Propeller	1
	1.8	39.6	76	453	0.75	Crossflow	1
	1.2	59.2	49	342	0.50	Crossflow	1
069011	3.48	31.7	159	791	1.0	Propeller	1
	6.96	10.7	336	985	2.0	Propeller	1
	5.22	17.5	246	921	1.5	Propeller	1
	2.61	42.9	118	681	0.75	Propeller	1
	1.74	60.1	77	524	0.50	Propeller	1
073007	0.38	25.3	249	1221	1.0	Turgo	1
	0.76	7.5	531	1593	2.0	Turgo	1
	0.57	13.3	388	1471	1.5	Turgo	1
	0.28	36.1	183	1034	0.75	Turgo	1
	0.19	53.3	119	780	0.50	Turgo	1

Table A3.1.2 Energy Computation



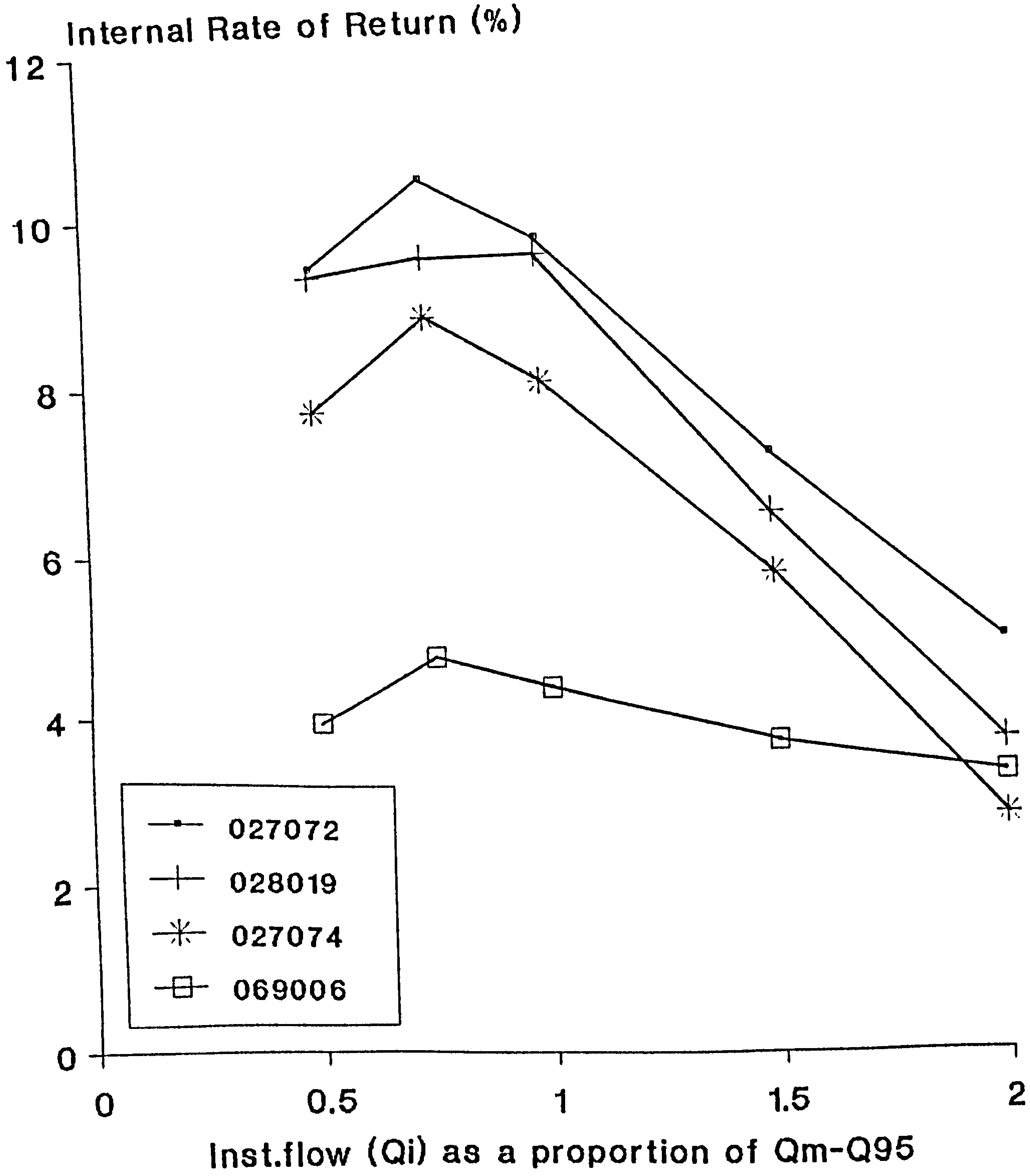
Economic Evaluation of sites

FIG. A3.1.1



Economic Evaluation of sites

FIG. A3.1.2



Economic Evaluation of sites

FIG. A3.1.3