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The Optimal Selection of Turbine-Generators for Tidal Power Projects and the Optimization of their Operation

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by
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ABSTRACT

The Optimal Selection of Turbine-Generators for Tidal Power Projects and the Optimization of their Operation

This thesis describes the development of a suite of computer programs designed to evaluate the optimum operating strategy for turbine-generators installed in a proposed tidal power barrage. The computer models are of the single-tide type but have been extended to incorporate detailed models of the turbine performance characteristics and operating constraints.

The computer programs have been extensively used for studies of the Severn and Mersey barrage proposals in the UK, for one of the proposed barrage schemes in the Bay of Fundy, Canada and for the now-operating scheme at Annapolis Royal, Canada.

One of the most important features of these programs is their ability to simulate, using appropriate characteristics, all the different turbine types suitable for tidal power generation. Results are presented of particular studies showing in each case the conclusions reached.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

In 1978 the Author began working at the University of Salford under the direction of Professor E M Wilson. The work was to form part of the preliminary studies of what is now referred to as the Severn Barrage Committee report (Ref. 1) or Bondi report after the then committee chairman Sir Herman Bondi. These studies were aimed at establishing the technical and economic factors influencing the construction of a tidal power generating barrage across the Severn Estuary in the UK.

The writer joined a team of engineers investigating the tidal energy outputs achievable from six different sites for barrages located across the estuary from Avonmouth seaward to Lynmouth (Ref. 2). The long term objective was to determine the most favourable location for the construction of such a barrage. The Department of Civil Engineering at Salford University was contracted to examine energy yield using the ebb-generation mode of operation, this being both the simplest mode to analyse and the mode believed to produce energy at lowest unit cost.

In the course of his duties the writer was required to use existing computer programs for tidal energy evaluation. These programs, developed by Gibson (Ref. 3) were of the single-tide optimisation type whereby, instead of evaluating a naturally occuring tidal series, a number of sample tides of varying range are evaluated in isolation from one another. Subsequently, the total annual energy yield was evaluated by summation of the product of the energy yield from a single tide and its appropriate number of occurrences of that range per annum.

The single-tide method of analysis had been pioneered by Wilson and Swales as an alternative to the evaluation of a full natural sequence of tides with their wide variation of operating conditions. The single-tide method was validated by Gibson by comparison of results from this method with results obtained from a more complex dynamic programming method which optimised operation through a spring-neap tidal cycle.

Set against this background the writer began development of a new single-tide optimisation model which could be used to investigate, in depth, the relative merits of the various different turbine types which could be deployed in a tidal generating barrage. Prior to this time tidal energy analysis had relied upon somewhat simplified turbine performance characteristics, so an important aspect of the new program was the development of numerical models of turbine data so that practical operating constraints could be incorporated and the operation adjusted accordingly.

At the time of these Severn Barrage studies (1978/79) there was a belief that a tidal power barrage should be developed to extract energy at lowest unit cost and the ebb-generation mode of operation was the way to do this. Comparative studies for the Severn Barrage Committee of the alternative forms of development, to which the writer contributed, confirmed this to be so, although it is true to say that more in-depth studies were carried out for the single-effect ebb-generation mode of operation than for double-effect operation or any of the double-basin alternatives proposed which could provide a degree of firm power.

To decide against the development of a double-effect scheme appears to contradict somewhat the experience of the French, who in 1966 completed construction of La Rance tidal barrage in Brittany. La Rance utilises pump-turbines capable of turbine and pump operation in either ebb or flood flow directions. The Severn Barrage Committee did however recognise the potential for pumping in conjunction with ebb-generation operation which is in line with the present view of Electricite de France that should La Rance ever be repeated it would almost certainly be an ebb-generation plant with sea-to-basin pumping at high tide to enhance the value of generation during the subsequent low tide period.

2.0 SIMULATION METHOD

2.1 The Single-tide Method

Tidal energy analysis is one of the fundamental elements of any study of a tidal power scheme. The objective being to determine, through analysis of the expected barrage power and energy production, the economic benefit of the particular investment. Accordingly various computer models have been developed which simulate the operations of the tidal power machinery and the conditions in the sea and enclosed reservoir so that the power and energy developed can be evaluated.

The single-tide and histogram approach has been the most widely used type of model for this work owing its origin to Wilson in 1963. With the single-tide models the barrage conditions are represented on the seaward side by a tidal curve of specific amplitude and on the basin side by a flat-surface reservoir having a specified area/level relationship. Modelling of the generating equipment usually incorporates realistic estimates of hydraulic inlet and outlet losses, turbine hydraulic performance data, assessments of the electrical losses and a number of operating constraints imposed by the equipment or by environmental considerations.

The analysis proceeds by operating the model using a number of representative tidal ranges selected to cover the full range from springs to neaps. Finally the estimate of annual energy yield is made by summation of the products of each of the energy yields and the corresponding number of annual occurrences of that tidal range. For each barrage location, it is important that the natural tide shape is accurately reproduced. This may require use of a different un-symmetrical tide shape (input as a series of levels at fixed time increments) for each of the representative tidal ranges.

It will be obvious from the description above that the single-tide model incorporates a number of simplifying assumptions. These assumptions can be summarised as follows:

(i) the tidal levels to seaward of the barrage will in all probability be modified from the natural tides by the presence and operation of the barrage. The modification could result in either an enhanced tidal range or as is more often the case a reduction of the tidal range.

(ii) the water level within the enclosed reservoir is unlikely to vary as a plane surface. Dynamic response of the estuary will establish water surface slopes as the basin fills and empties.

(iii) the analysis of a tide in isolation ignores the benefits or disbenefits arising from operation through a natural series of tides where successive tides are of different tidal range.

The significance of these assumptions and the way in which their influence can be treated is as follows:

(i) modifications of tidal regime seaward of a tidal power scheme have been successfully predicted using 1-dimensional and 2-dimensional mathematical models, Ref. 4. Using these more complex hydrodynamic models into which have been built selected barrage configurations, the estimates of tidal modification can be established by comparison with the natural tide. Tide range modifications in the range +5% to -20% have been reported. Using the tidal range modification it is a simple matter to establish the modified distribution of tidal ranges.

(Insert paragraph immediately before Section 2.2)

An operating constraint which is currently ignored but which it may be necessary to incorporate for future analyses is the permissible rate of change of power generation at the beginning and end of the generating phase. The permissible rate of change could be constrained by:-

i) the ability of the electrical system to "bring on" or "shed" conventional generating plant in response to the availability of tidal power input,

ii) the magnitude of surges set up in the basin in response to a rapid change of discharge through the barrage,

iii) the rate at which turbine-generator sets can be brought up to speed and synchronised with the system frequency.

(ii) the dynamic behaviour of the enclosed reservoir has been studied using 1-dimensional models incorporating simple models of barrage characteristics and energy calculation routines. However with these models although the estuary's behaviour is adequately represented, the optimisation of barrage operation has not yet reached the sophistication of that in the single-tide model

(iii) when justifying the application of the single-tide model Gibson (Ref. 3) demonstrated comparisons with a complex and expensive-to-operate model (OCDPM) which could optimise operation through a natural tidal sequence. The writer has been able to further confirm this comparison, the results being presented in Section 5.1.

The writerhas developed a single-tide optimisation model which in particular incorporates detailed representations of the turbine/generator characteristics so that many if not all of the practical limits and constraints are adhered to. The model initially developed for analysis of the ebb-generation mode of operation has been further developed to allow analysis of each of the operating modes described in Section 2.3.

2.2 The variables to be considered

In his thesis Swales (Ref. 5) describes the variables of a tidal power scheme as follows:

a) Natural variables
b) Main variables
c) Operating variables

These descriptions remain valid and are useful when describing the procedure for optimization of energy yield from a proposed tidal power scheme. Discussion of a method for analysis and parameter selection for a proposed scheme can be found in Section 5.3.

2.3 Natural variables

As the description implies these are the variables which are determined by the physical location of the power plant and obviously include the enclosed basin surface area, its variation with elevation and the tidal regime at the barrage.

Basin surface areas

For the tidal energy models described in this thesis the water-surface elevation is assumed to vary as a plane surface in response to inflow and outflow at the barrage site. This is not strictly representative since with a long and relatively narrow estuary the natural tidal wave propogates up the estuary as a progressive wave. The assumption that the basin water surface is plane is one of the simplifications of the modelling technique, the effect upon energy yield is tested against results obtained from an hydrodynamic model. The simplification is appropriate since to date the writer is not aware of a hydrodynamic model which incorporates optimisation routines and limiting conditions comparable with the single-tide optimisation model.

For the single-tide optimisation model basin surface-area is required at a number of levels. These areas can be measured from navigational charts after suitable contours of constant depths and/or drying heights have been superimposed. Attention should be paid to the variations of Chart Datum which occur in the larger estuaries.

Tidal regime

The tidal regime experienced at any potential tidal power barrage location is a complex interaction between the gravitational influences of the sun and the moon, which generates the modest oceanic tides, and the amplification caused by the geometry and bathymetry of the coastline. In general for sites attractive for the development of tidal power, the tides in addition to their greatly enhanced amplitude, remain regular and semi-diurnal; ie, there are two high waters and two low waters daily, (or more precisely every 24 hours 50 minutes).

The tidal amplitudes experienced at a particular location vary steadily according to the phases of the sun and moon and are predictable. The methods of tidal prediction exploit the astronomical sources of the tides to determine the fundamental periods of oscillation and then by harmonic analysis determine the amplitude and phase angle of these constituents. The method highlights the variability of the tides when one considers the period of the various constituents vary from a few hours to 18.6 years or more.

The major tidal constituents are those reflecting the gravitational effects of the Moon's orbit about the earth and the earth's daily rotation about its polar axis. The periods of these (M2 and S2) constituents are 12.4 hours and 12 hours respectively. Consequently the periods for these two constituents vary from being in phase, through antiphase, back to being in phase in approximately 15 days. This variation produces the prominent springs/neaps cycle. Inclusion of all the significant tidal constituents leads to a variable pattern of tidal levels but one which is predictable from month to month and year to year.

The variability of the tides presents something of a problem when it is required to predict the energy yield or the monetary value of tidal power generation. It is usual to estimate the annual energy yield despite the long period variation. To do this an appropriate average years tides are selected;for which the nodal constituent (of 18.6 year period) is of average value. For this reason tidal predictions for 1974 have been used for many of the proposals studied.

Consideration of the variability of the naturally occuring tidal series has revealed that the selection of an analytical solution which works through, and optimises, the operation of the tidal plant, through a natural tide series raises as many questions as it answers. Because analysis using such a technique is more complicated there is a practical limit to a duration of the tidal series, typically to the spring/neap cycle of approximately 29 tidal cycles. Consequently there is difficulty in selection of a typical tide series from which annual energy yield can be extrapolated. In this respect it is more satisfactory to use a selected number of tidal ranges and a histogram showing the number of occurences of these ranges per annum.

Because the tidal regimes in the estuaries and bays which are of significant tidal energy potential are the result of the magnifying effect of the coastal geometry, it is quite reasonable to expect a modification to the natural tides upon the construction and operation of a tidal power barrage. These effects have been predicted by complex computer models of the hydro-dynamics of the tidal propagation in these estuaries. The magnitude of the tidal modification depends upon the siting of the barrage and the morphology/bathymetry of the natural estuary, which properties establish how nearly resonant it is. Computations for the Severn Barrage along a

Cardiff to Weston-Super-Mare alignment show a reduction in the tidal amplitude of approximately 12% (Ref. 6). However similar work for schemes proposed in the Bay of Fundy, Canada indicate a small increase in the tidal amplitude (Ref. 7).

For the single-tide model these modifications to the tidal regime can be incorporated into the histogram of tidal ranges.

2.4 Main variables

The main variables include all those variables for which a selection must be made in order to begin the analysis, each variable may at a later date be optimised. The main variables include all the physical parameters of a proposed scheme, for example:

- the mode of operation, Section 2.6.
- number of turbine/generator sets
- the type of turbine and its performance characteristics
- the turbine runner diameter
- the turbine rotational speed
- the limiting capacity of the generator
- the degree of submergence afforded to the turbine runner
- number of sluices
- the type of sluices, their size and discharge characteristic

2.5 Operating variables

The operating variables are those parameters which can be varied independently of any of the natural variables or main variables. Manipulation of the operating variables to maximise output will be the preoccupation of operators of a tidal power scheme. The single-tide optimisation model is designed to select the optimum values for the following operating variables.

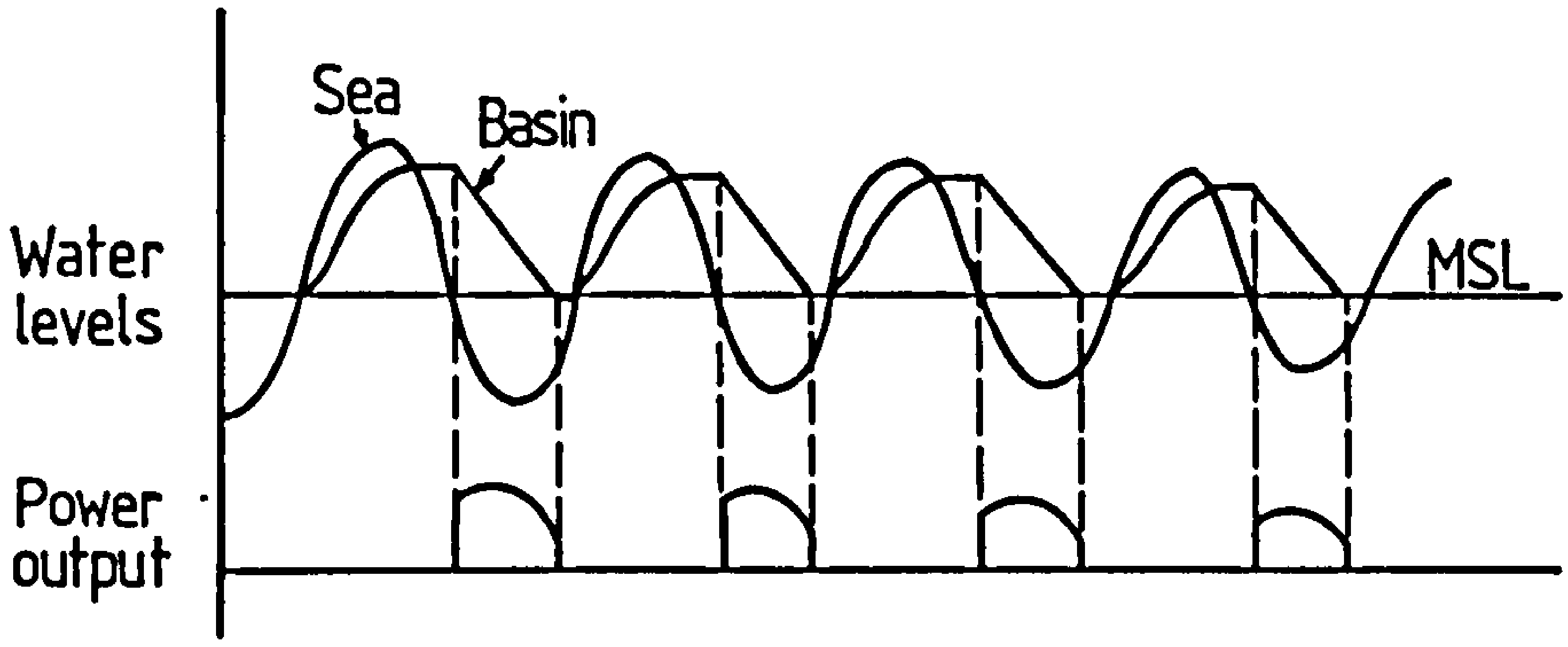
- the reservoir levels
- the time to start generation and the consequent operating head
- the time and head at which generation is to cease
- the turbine discharge at all times during generation
- the timing of pumping operations and the pump discharge
- the timing of opening and closure of sluice gates.

2.6 Principles of Operation

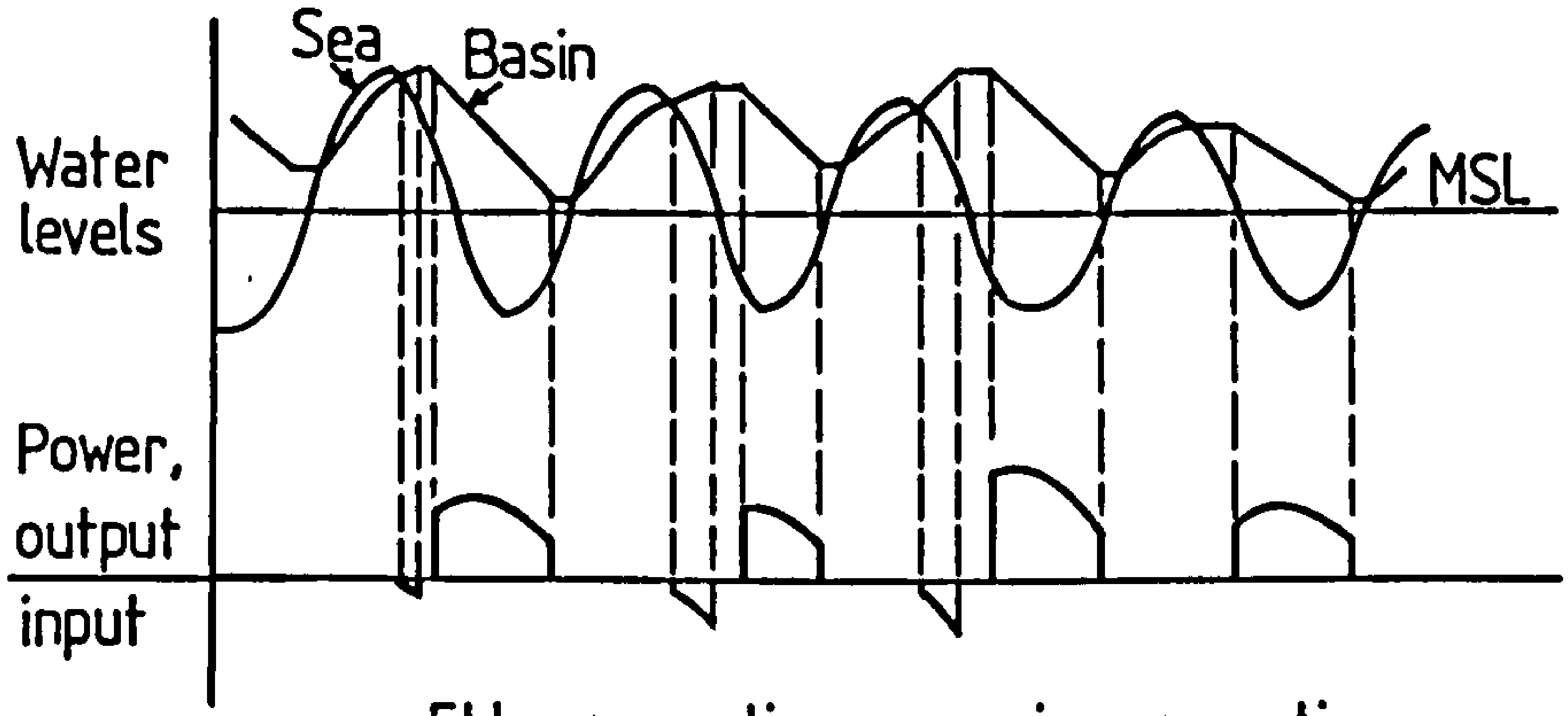
Bernshtein in his book "Tidal Energy for Electric Power Plants" (Ref. 8) describes many of the different modes of operation for tidal power schemes. A considerable number of the options are designed to reschedule tidal power generation away from the lunar period of the tides toward the solar period of electricity-demand. As mentioned in Section 1 the present weight of evidence favours a form of development which can exploit the tidal energy potential at the lowest cost per unit of energy supplied. This philosophy dictates that for a given investment the energy yield should be maximised. The operating mode which establishes this is ebb-generation operation.

However, in order to make the above statement it is necessary to be able to consider what might be achieved using other modes of barrage operation. Accordingly, the writer has developed energy optimisation programs to evaluate ebb-generation with pumping following high tide and double-effect operation. In both cases the programs were written to optimise energy yield but have been subsequently adjusted to examine the effect of value optimisation on operation and energy output.

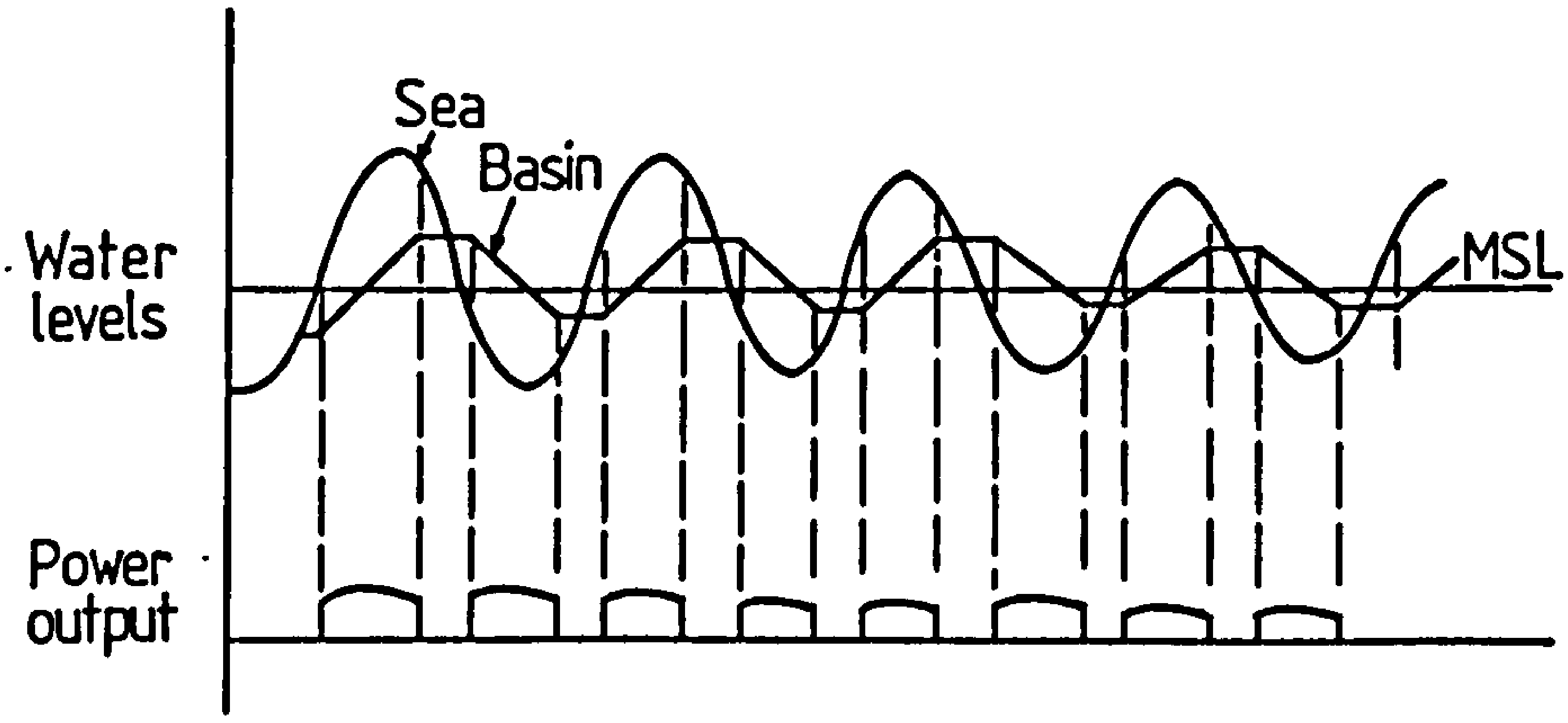
Figure 2.1 shows typical operating patterns for ebb-generation, ebb-generation with pumping and double-effect operation. As well as the total annual energy yield it is important to consider the distribution of power sent out from the tidal power scheme. Figure 2.1 indicates the problem of integration of the blocks of ebb-generation tidal power output, and how this is improved when double-effect operation is adopted because of the reduced peak output and greater duration of the generation.



Ebb-generation operation



Ebb-generation + pumping operation



Double-effect operation.

MODES OF OPERATION

FIG. 2.1

3.0 GENERATING EQUIPMENT

3.1 Operating Conditions

The operating conditions for the turbine-generator sets in a tidal power scheme determine the design and type of machine. Precisely what is required of the machine depends upon the tidal power scheme adopted. It may be only necessary for the turbine to power a generator with flow in one direction. Alternatively the turbine may be required to function as a turbine, a pump and an orifice with flow in either direction. The problem is further complicated by the range of heads at which the turbines are required to operate.

Early proposals for tidal power schemes suggested the use of vertical-axis Kaplan turbines (Ref. 9 & 10). These turbines require a powerhouse construction which incorporates a draft tube curving sharply from the vertical at exit from the runner to discharge in a horizontal direction. This arrangement, in addition to some efficiency loss, requires a considerable depth of excavation and because of the horizontal radial inflow to the runners also requires a considerable spacing between adjacent units to accommodate the water passages. Thus economies were sought in the size and depth of the powerhouse resulting in the development of horizontal axial-flow turbines.

A horizontal-axis axial-flow turbine is ideal for good hydraulic performance and is a compact design; however, location of the generator becomes a problem if these advantages are to be retained. There are three solutions in current practice:

- the S-type turbine
- the bulb-turbine
- the Straflo-turbine

The S-type turbine usually consists of an axial-flow propeller runner connected to an inclined shaft which is brought out of the water passage to drive, via a speed-increasing gearbox, a high speed generator. This arrangement is seldom considered for tidal power applications because the water passage is elongated thereby increasing overall powerhouse dimensions and there is concern over the flexibility of the lengthy shaft required for units with large runner diameter.

3.2 The bulb-turbine

The bulb unit was developed extensively in the period 1952-1964 for tidal power applications by French engineers working on designs for the La Rance scheme (Ref. 10). It is interesting to note that an initial concept for this type of machine consisted of a horizontal axis axial-flow propeller turbine with the generator housed within a metal casing or 'bulb' totally surrounded by the water passages. In addition the inital concept was to locate the 'bulb' in the inlet passage to the turbine, and was termed the upstream bulb turbine.

Ironically, as development for La Rance progressed, specification that turbines should be capable of turbine and pump operation in either direction of flow required an additional downstream 'bulb' arrangement so that bulky runner-blade pitch-control mechanisms could be accommodated in the upstream housing. This arrangement was not entirely satisfactory from an hydraulic view point but was only improved upon by the design of new symmetrical blades with which the angle of pitch variation was substantially reduced, thereby eliminating the requirement for a separate housing for the adjustment mechanism. Had the original turbine specification required only turbine operation in one direction and pump operation in the other, as required for ebb-generation operation with pumping, the development of the modern bulb turbine, Figure 3.1 would have been more straight-forward.

With either an upstream or downstream bulb arrangement generator design was critical to the success of the bulb concept. Hydraulic considerations dictate that the generator to be housed within the 'bulb' should be approximately half the size of a normal generator of the same capacity and synchronous speed. The success of 'bulb' turbines at La Rance and many low-head hydro-electric plants indicates that these constraints can be overcome by careful design but at the cost of additional complexity.

3.3 The Straflo-turbine

The Straflo-turbine, originally patented in 1919, has the generator wrapped around the periphery of the runner blades on a stiff beam so that water flows through the runner, sealed from the generator by special hydrostatic or rim seals, Figure 3.2. The former require a filtered water supply, supplied at a marginally greater pressure than that in the flow so that sand or sediment is excluded. For a tidal power scheme incorporating many turbines, and hence requiring a substantial volume of this water, sea water would be used.

With the Straflo concept, because of the external location of the generator its cooling is not a problem and access is simple. In addition, because the heavy generator is rotating at the periphery of the blades, the inertia of the Straflo turbine is much greater than the bulb type. This is a valuable property for synchronous generators subject to short-term variation of hydraulic head, as tidal machines may be, if exposed to the effects of waves.

Other advantages reported for the Straflo turbine over the bulb-turbine include; a more compact powerhouse design, better accessibility and a reduced cranage requirement to the runner and generator components. To maintain the simplicity of the Straflo design the runner generally has fixed blades and is therefore only suitable in this form for ebb-generation tidal power development.

3.4 Turbine Discharge Regulation

Turbine discharge regulation can be achieved by adjustment of the angle of the guide-vanes forming the distributor upstream of the turbine runner and/or adjustment of the pitch of the runner blades. Consequently, for any tidal energy project, the designers have a number of options for the method of turbine discharge regulation from which to choose. If the operating mode is to be ebb-generation without pumping then the turbines may be either single or double-regulated. But if pumping is also envisaged in one direction to achieve a reasonable pump efficiency the runne blades must be of variable pitch. For the same reason, if pumping is required in both directions both the guide vanes and runner blades need to be variable.

From an operational viewpoint, if the guide vanes are fixed then a downstream gate is required to permit flow closure. This gate would be located towards the exit of the draft tube and would also be used for control of the units at start-up.

To complicate the matter further it is possible, although not always desirable, instead of operating conventionally at a fixed synchronous speed, to operate the turbine at varying speed to improve turbine hydraulic efficiency.

The various configurations of turbine regulation may be provided in different combinations as listed below

Option 1 VD FB FS
2 FD VB FS G
3 VD VB FS
4 VD FB VS
5 FD VB VS G
6 FD FB VS G
7 VD VB VS

Where VD/FD indicates either a variable (V) or fixed (F) distributor (D)

VB/FB indicates either variable (V) or fixed (F) runner blades (B)

VS/FS indicates either a variable (V) or fixed (F) rotational speed (S)

G indicates a downstream gate is required.

The eighth combination FD FB FS G is not technically feasible for a tidal power plant with varying hydraulic heads.

Each of these variants has a particular performance diagram and annual energy yield, and each will have cost implications which will directly influence the optimisation of scheme parameters to achieve,for example, minimum energy cost. Combining these variants with the option for either a bulb or Straflo-turbine leads to a total of ten different possibilities (seven bulb and three Straflo with fixed runner blades). In practice however the hydraulic performance of a particular variant whether bulb or Straflo is almost identical; the performance being determined by the hydraulic layout and the runner blading. Consequently analysis of the turbine types can proceed without reference to the particular generator arrangement except for the increasing difficulty of accommodating a high capacity generator within the confines of the bulb-turbine arrangement.

3.5 Performance Characteristics

Efficiency tests on hydraulic models of turbines provide performance data with which to calculate power and energy production of the prototype machine. Performance of the model is usually in the form of dimensionless parameters to enable easy scaling up to prototype conditions. Model tests are required to cover the full range of operating conditions from zero up to the peak efficiency. A number of tests being required to obtain data for each direction of turbine operation and corresponding tests for the pumping modes of operation. Additionally, when a double-regulated turbine (ie. a machine with adjustable blades and distributor) is tested many combinations of guide vane angle and runner blade pitch must be tested for a given operating condition before the combination giving best efficiency is determined. In consequence, quite apart from the manufacture of a high precision model of the turbine and its water passages the testing procedure is lengthy and expensive. As a result and also because of their commercial value, turbine efficiency hillcharts are not freely available. They are however vital in the evaluation of the relative merits of the different turbine variants.

All of the turbine variants for a one-way turbine can be covered by just three hillchart diagrams. The dimensionless parameters of n_{11} and Q_{11} are commonly used, they are:

$$n_{11} = \frac{n\ D}{\sqrt{h}} = \text{Specific rotational speed}$$

$$Q_{11} = \frac{Q}{D^2\ \sqrt{h}} = \text{Specific discharge}$$

where: n = rotational speed (rpm)
D = diameter of turbine runner (m)
Q = discharge (m^3/s)
h = turbine operating head or net head (m)

Typical dimensionless efficiency hillcharts for a one-way turbine are shown in Figures 3.3a, 3.4a and 3.5b for a double-regulated turbine, VD VB, and the two single-regulated variants VD FB and FD VB respectively. Their corresponding prototype performance at a constant rotational speed in terms of the discharge and operating head is shown in Figures 3.3b, 3.4b and 3.5b.

In situations where operation of the tidal power plant requires turbine operation in two directions of flow and/or the turbines are required to pump in one or both directions, the number of hillchart characteristics increases. This is because where more than one duty is required the hydraulic arrangement and turbine blading can be made to favour one duty, say direct turbine operation, at the expense of a poorer performance in the pumping mode.

Since the majority of the work described in this thesis is concerned with ebb-generation operation and ebb-generation plus pumping the discussion on turbine performance will be confined to the specific case of a one-way turbine. The pump characteristic will be that which results with the specified distributor and blade configuration without prejudicing the turbines performance.

Consideration of hillcharts for the two single-regulated turbine types Figures 3.4 and 3.5 shows that the FD VB machine has a considerably wider zone of operation at high efficiency than that for the VD FB type. This is to be expected, since for the VD FB design, at a specific operating head there will be only a very narrow range of distributor vane angle which will impart on the flow the correct angular velocity for shock-free incidence onto the runner blades. If a discharge is required below that for best efficiency a significantly reduced efficiency is obtained because the distributor has to be incorrectly set. For conventional hydro-electric schemes where discharge variation is required to follow river flow conditions or power system demand, the VD FB turbine is unacceptable because of its poor part-load performance. Does the same criteria apply for a tidal power scheme?

The answer is not obvious because the operating conditions are quite different for a tidal turbine. The discharge rate which can be achieved is almost as important as efficiency because if stored volume is not used it becomes valueless with the next flood-tide. For this reason also, it is important to know the turbine performance at maximum power output, when discharge is increased above the maximum efficiency point until the power output is maximised.

Section 6 compares, for ebb-generation operation the main turbine variants for this mode of operation and the differing performance of the same variant from different manufacturers is highlighted. It is the view of Neyrpic of France that the FD VB type with a downstream gate is the cheapest solution and that this type will yield greater energy than the VD FB type. Conversely it is believed by Escher Wyss of Switzerland that the VD FB type will have a comparable energy yield and the overall cost, particularly in the Straflo arrangement will be significantly cheaper than the FD VB bulb type. The experience of 20 years operation of the 24 no. 5.35m diameter VD VB turbines at La Rance and many large hydro bulb turbines (Ref. 11, 12, 13) favours the selection of a bulb turbine arrangement. However the reported success of the 7.6m diameter Straflo turbine at Annapolis Royal in Nova Scotia, Canada (Refs. 14, 15, 16) is beginning to allay fears over the very large diameter seals required to keep the Straflo generator watertight.

Operating experience, generating efficiency, and energy yield are only some of the factors influencing the selection of turbine type. Reference 17 discusses some of the other important factors such as the influence of machine type upon powerhouse design and the manufacture and installation of mechanical and electrical equipment.

3.6 Use of the Turbine Performance Characteristics in the Energy Optimisation Model

The dimensionless efficiency hillcharts described in Section 3.5 are derived from testing of geometrically similar model turbines. These tests are performed by the manufacturers and independent testing organisation according to standards (Ref. 18) so that in theory test results are independent of the particular apparatus which is used. Performance data derived from these tests are based, according to the standard, upon a number of definitions which the tidal application does not exactly match. Accordingly the characteristic should not be applied directly without making adjustment to, in particular, the turbine operating head.

Effective turbine head

Effective turbine head is defined as the difference between the total energy levels at the inlet to, and exit from the turbine passage. For the closed pipe systems used for model testing 'total' energy is the pressure head plus the nominal velocity head at the model limits where the 'nominal' velocity is equal to the discharge divided by the section area. In practice an uneven flow distribution occurs at the draft-tube exit which results in a velocity head greater than the nominal, however this additional energy present at the turbine outlet is incorporated within the model efficiency curves.

In a prototype application, conditions at entry to the turbine passage are quite straight-forward. Flow is gradually accelerated towards the inlet - increasing the velocity head component and producing a localised drawdown of the water surface. Energy losses in this process are minimal. Accordingly for the computer model it is appropriate to use the reservoir level to represent the upstream total energy.

Downstream conditions are more complicated. A simplistic viewpoint may well be that all the nominal exit velocity head would be lost as flow expanded to fill the full estuary cross-section. However consideration of the initial expansion of the discharge jet (when surrounded by other jets) without entrainment using the momentum equation indicates that a downstream rise in water level and reduction in velocity maintains the balance of forces and indicates some energy recovery.

Referring to Figure 3.6 and equating the forces at Section E and Section 2.

$$\tfrac{1}{2}\rho g L(h_E)^2 + \rho Q U_E = \tfrac{1}{2}\rho g L(h_2)^2 + \rho Q U_2$$

where $h_E = d_2 + l_E$ and $h_2 = d_2 + l_2$
ie. d_2 = bed depth below datum of calculation
and L = centre to centre spacing of turbines.

By rearrangement:

$$\tfrac{1}{2}\rho g L(h_2{}^2 - h_E{}^2) = \rho Q(U_E - U_2)$$

$$(h_2 + h_E)(h_2 - h_E) = \frac{2Q}{gL}(U_E - U_2)$$

substituting

$$h_2 = d_2 + l_2\,,\quad h_E = d_2 + l_E \text{ and } U_E = \frac{Q}{A_E}\,,\quad U_2 = \frac{Q}{A_2}$$

where A_E = sectional area of draft-tube exit.

$$(d_2 + l_2 - d_2 - l_E)(d_2 + l_2 + d_2 + l_E) = \frac{2Q^2}{gLA_2}\left(\frac{A_2}{A_E} - 1\right)$$

$$(l_2 - l_E)(2d_2 + l_2 + l_E) \qquad =$$

But $d_2 + l_2 = \dfrac{A_2}{L}$

$$(l_2 - l_E)\left(2\frac{A_2}{L} - 2l_2 + l_2 + l_E\right) \qquad =$$

$$(l_2 - l_E)\left(2\frac{A_2}{L} - (l_2 - l_E)\right) \qquad =$$

$$(l_2 - l_E)^2 - 2\frac{A_2}{L}(l_2 - l_E) + \frac{2Q^2}{gLA_2}\left(\frac{A_2}{A_E} - 1\right) = 0$$

The solution of the above equation is greatly simplified by neglecting the $(l_2 - l_E)^2$ term to leave:

$$l_2 - l_E = \frac{2Q^2}{gA_2^2}\left(\frac{A_2}{A_E} - 1\right)$$

Thus, knowing the tidal level, l_2, some distance downstream the corresponding level l_E, at the barrage can be deduced, and thence the effective turbine head, H where:

$$H = H_I - H_E = H_I - \left(l_E + \frac{U_E^{\,2}}{2g}\right)$$

A subsequent check on the neglect of the $(l_2 - l_E)^2$ term shows for typical values of turbine discharge and sectional areas that the calculated value $l_2 - l_E$ to be in error by approximately 1mm, the simplification being justified.

Combining the latter equations for a direct calculation of the effective turbine head we have:

$$H = H_I - \left[l_2 - \frac{Q^2}{gA_2^2}\left(\frac{A_2}{A_E} - 1\right) + \frac{Q^2}{2gA_E^2} \right]$$

Note that the $\frac{Q^2}{2gA_E^2}$ term represents the velocity head at the draft exit. So the $\frac{Q^2}{gA_2^2}\left(\frac{A_2}{A_E} - 1\right)$ term represents the energy recovery in the initial expansion zone, this amount being determined by the discharge and the sectional areas of flow at the draft-tube exit and some distance downstream.

Simplifying,

$$H = H_I - \left[l_2 + \frac{Q^2}{2gA_2^2} \left[\left(\frac{A_2}{A_E} \right)^2 - 2\frac{A_2}{A_E} + 2 \right] \right]$$

The above formula represents an approximation to the situation since there will be some degree of flow entrainment at each end of the turbine block. This could lead to a variation in operating head for machines along the length of the barrage. Nevertheless the formula is used in the simulation model to determine from the predicted levels and required discharge what the net effective turbine head is and to determine from the turbine performance model the corresponding efficiency.

A similar procedure is adopted for the sluices.

Scaling of model test results

When using results of model efficiency tests to represent prototype performance it is commonly accepted that an increased efficiency should be attained with a larger machine to allow for less frictional losses which do not scale in the same manner as the hydraulic performance. Several majoration formulae have been postulated for a variety of machine types and are based upon comparison of measured prototype efficiencies and those of the model. The Hutton formula is commonly applied to low-head machines as follows:

$$\frac{1 - \eta p}{1 - \eta m} = 0.3 + 0.7 \left[\frac{Dm\,\gamma p}{Dp\,\gamma m} \cdot \left(\frac{Hm}{Hp} \right)^{1/2} \right]^{1/5}$$

Where Dm and Dp are diameters for model and prototype respectively,

ηp and ηm are efficiencies for model and prototype respectively.

Hm and Hp are heads for model and prototype respectively,

$\delta p = 1.35 \text{ x } 10 \text{ m}^2\text{S}$ water at 9°C
$\gamma m = 1.0 \text{ x } 10 \text{ m}^2\text{S}$ water at 20°C

Used in a typical example where tests were performed with a model runner diameter of 0.5 metres at prototype heads, the efficiency majoration or step-up is 3.3% for a prototype diameter of 8.2 metres.

For some time the efficiency step-up was applied uniformly over the whole turbine operating range, however recently it has been argued that when these turbines are operating well away from the point of best efficiency - the 'top of the hill' indicated by the contours on the hillcharts - and efficiency is low, it is the hydraulic losses which are dominant which should scale to the prototype so the application of majoration is inappropriate. This argument is further strengthened by the fact that the majoration formulae are derived from tests on traditional hydro plants for which operating conditions rarely deviate widely from the best efficiency point.

In order to make some estimate of what the majoration effect will be, recent energy yield calculations have applied majoration as calculated by the Hutton formula at the best efficiency point, and at other points the majoration has been varied linearly to zero at zero model efficiency.

Initial application of the performance characteristics

Prior to detailed consideration of both the turbine operating head and majoration to be applied in energy yield calculations these two factors had been deemed to cancel one another out. This approach has been shown to be flawed on two accounts:

- separate explicit consideration of the effect of turbine exit losses on operating head and the application of majoration has indicated an overall energy loss of the order 2% (reference Mersey Barrage studies, Ref. 19).

- without explicit consideration of exit losses a comparison of machine types is not rigorous because of their varying head/discharge curves and the consequent variation of losses.

Numerical modelling of the hillchart characteristics

In the development of the suite of computer programs described in Section 4, and use of the programs for comparisons of energy yield from various turbine types it was realised that a reliable technique was required for numerical modelling of the dimensionless efficiency hillcharts. Early attempts using simple polynomial least squares fitting were thwarted by the bivariate nature of the hillcharts. Eventually a method of bi-cubic spline fitting was established. This method has proved to be reliable, giving accurate representation of the often quite irregular terrain described by the hillcharts.

The bi-cubic spline fitting technique involves initially digitizing a large number of points (100-200) on the contours of constant efficiency. The hillchart is then subdivided into a number of rectangular panels within each of which the method computes a least squares fit linked to the surrounding panels such that a smooth transition is obtained at the panel boundaries. The fitting routines are part of the extensive Numerical Algo rithms Group (NAG) library. The array of coefficients produced is stored for later use in the energy optimisation model where additional NAG routines are used to find the fitted efficiency for given values of n_{11} and Q_{11}.

Accuracy of the hillchart models is difficult to determine because of the variation of fit over the hillchart diagram. An RMS residual value is output from the fitting procedure but is of limited value because in certain circumstances a good RMS value can be obtained even when a poor fit is obtained, say, at the peak of the hillchart. Consequently, the writer has found the best method of judging accuracy of fit is to produce graphical results of the fit for direct comparison with the hillchart. Adjustment of the panel positions, and tolerance level and weighting of individual points, is continued until the accuracy of fit is better than 0.5%. For VD FB hillcharts because of their diagonal nature, Figure 3.4, it is necessary to extrapolate data into the corners of the diagram and to then introduce limits to prevent the optimisation program from searching the extrapolated data.

An alternative method of hillchart modelling could have been the development of a regular grid of efficiencies for interrogation by the energy program with the efficiency at the nearest grid point being adopted. Unfortunately, this method although quick and reasonably accurate, in terms of the efficiency derived, is not suitable because of the requirement for the values of the partial differentials $\frac{\partial N}{\partial H}$ and $\frac{\partial N}{\partial Q}$ (Section 4.3).

3.7 Operating Constraints

Because of the wide variation in operating conditions between the extreme neap tides and extreme spring tides, and the infrequent occurrence of these extreme conditions it is not practical, largely on economic grounds, to install generating equipment capable of optimum operation at all times. Consequently the turbine-generator equipment installed in any tidal power development would incorporate a number of limiting conditions as follows:

- a maximum generator output limit,
- a finite submergence, limiting the cavitation - free operating conditions,
- various other turbine operating constraints, for example, a maximum blade angle, zones of unstable operation or vibration,

The maximum generator output is limited in order to reduce generator and associated transmission system costs, but with the aim of little overall energy loss. Figure 3.7 shows a typical annual power/duration curve indicating the number of hours operation at or above indicated power levels. As drawn the figure illustrates what would be obtained if there were no limit to the power which could be generated and in consequence high power output is attained for only a very short period. Simplistically, if it were assumed that when power output rose above a predetermined limit, then generation would stop until power dropped again to the limit the shaded area - representing an amount of energy - that would be sacrificed. The shaded area on Figure 3.7 is in fact only a very small proportion of the total area under the curve and so only a small energy loss would result. If however operation of the tidal plant is planned around such a constraint the plant can be operated so that a slightly lower maximum head is reached leading to a reduced maximum power output. When power would otherwise exceed the generator limit, discharge is reduced until the power limit is reached. The effect of these two measures is to adjust the power duration curve so that energy loss described above is considerably reduced.

A similar procedure is required when considering the depth below tailwater levels at which the runner should be set. Submergence of the runner is required to avoid the phenomenon of cavitation, occuring when zones of low pressure allow the water to vaporise. It is the collapse of the vapour bubbles in zones of higher pressure downstream which can be highly erosive. Avoidance of cavitation is critical for the large number of turbines of a tidal scheme as the damage to runner blades would be both costly to repair and costly in terms of lost revenue due to poor efficiency or outages. Consequently, when model testing, a series of tests are performed when the tailwater level (or pressure) is progressively reduced whilst maintaining a constant operating head. The results show a varying efficiency as tailwater level falls below a critical value, the fall of efficiency is considered indicative of the onset of cavitation. Results of these tests are presented as values of sigma, where:

σ = ratio of downstream pressure: driving head = $\frac{B^{*} - Hs}{H}$

where B^{*} is the barometric pressure (ie. atmospheric pressure) minus the vapour pressure,

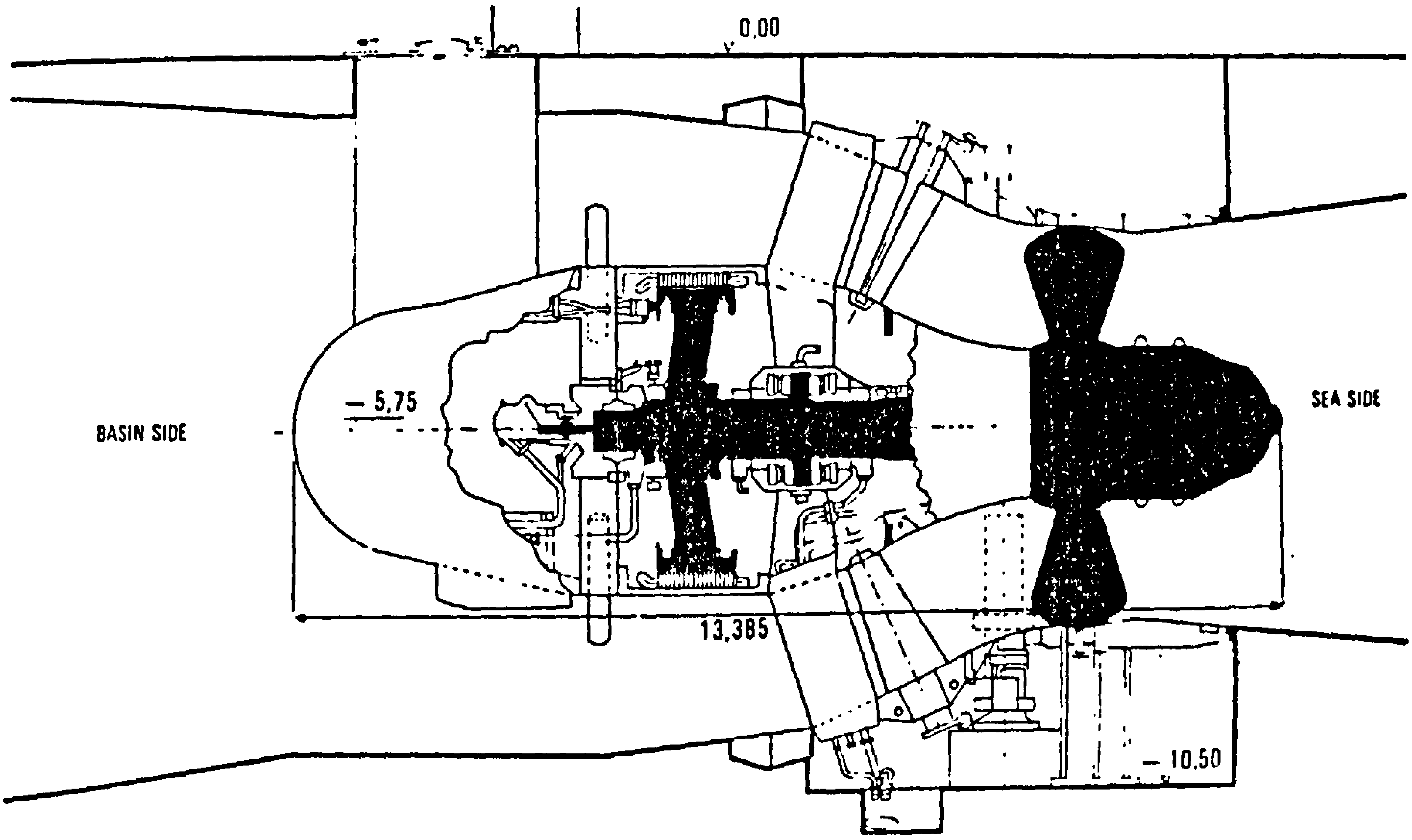
Hs is the distance of the critical plane from tailwater level,

H is the operating head.

A sign convention should be applied since the measurements are relative to the tailwater level, so that in most tidal applications Hs will be negative ie. the critical plane is below the tailwater level. The critical plane is the position for which the values of σ apply and the chosen plane is dependent upon the turbine manufacturers interpretation of the phenomenon. Neyrpic consider, perhaps conservatively, the plane to be the highest point of the turbine runner ie. the blade top at the top of its rotation. Escher Wyss however regard the top of the runner hub to be the critical plane for calculation and checking of values. Figure 3.8 refers.

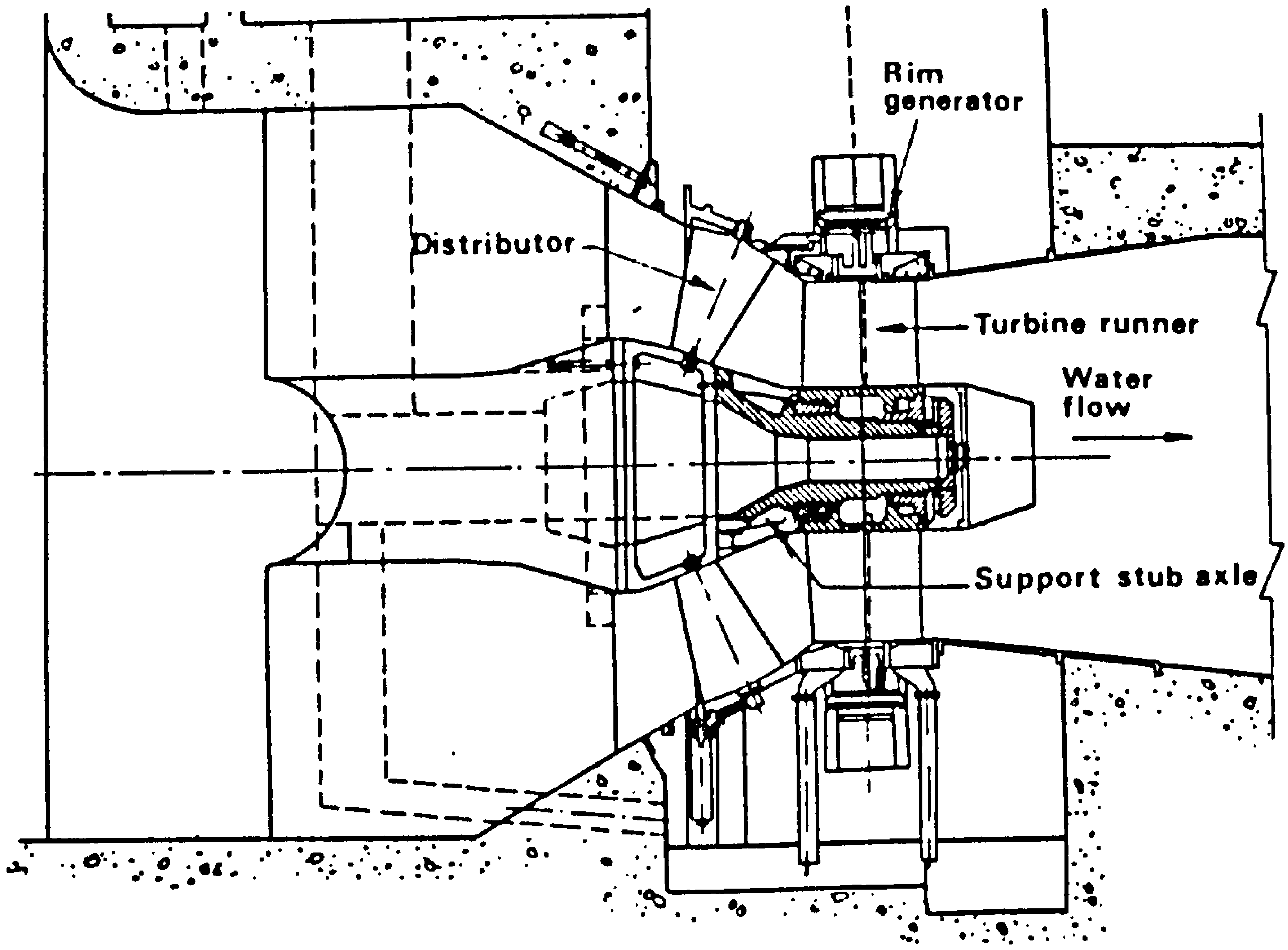
An additional difference of opinion between the principal manufacturers appears in the presentation of limiting values of σ. Neyrpic present σ as a function of both Q_{11} and n_{11} whereas Escher Wyss consider in the limit that σ is dependent only upon Q_{11} the specific discharge, (Figure 3.9). The energy optimisation models incorporate appropriate numerical models of these conditions, checks are made in the calculations that the operating conditions of head, discharge and tailwater level give a value in excess of the limit. If this is not so a reduction in discharge is ordered until operation is just safe from cavitation. Figure 3.10 shows for operating conditions through a spring-tide cycle the limiting discharge imposed by the cavitation limitation. As would be expected, the limitation is only critical when the turbine head is greatest and the tailwater level at its lowest. However, note the short duration over which the limitation applies, hence energy yield is not severely affected.

Reference 20 and 21 discuss in detail the operating constraints and their influence upon turbine operation.



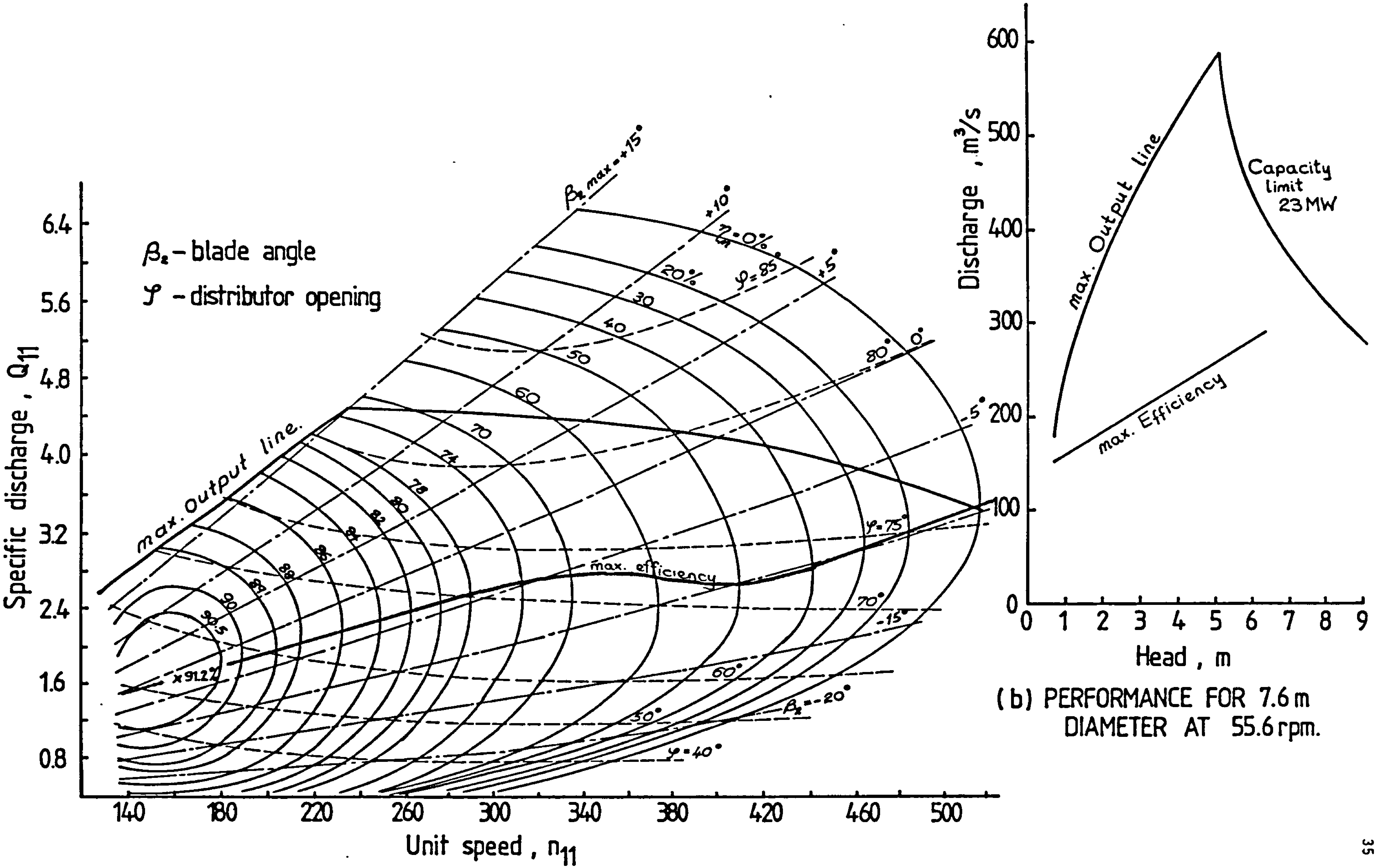
SECTIONAL ELEVATION OF BULB TURBINE.

FIG. 3.1



SECTIONAL ELEVATION OF STRAFLO TURBINE.

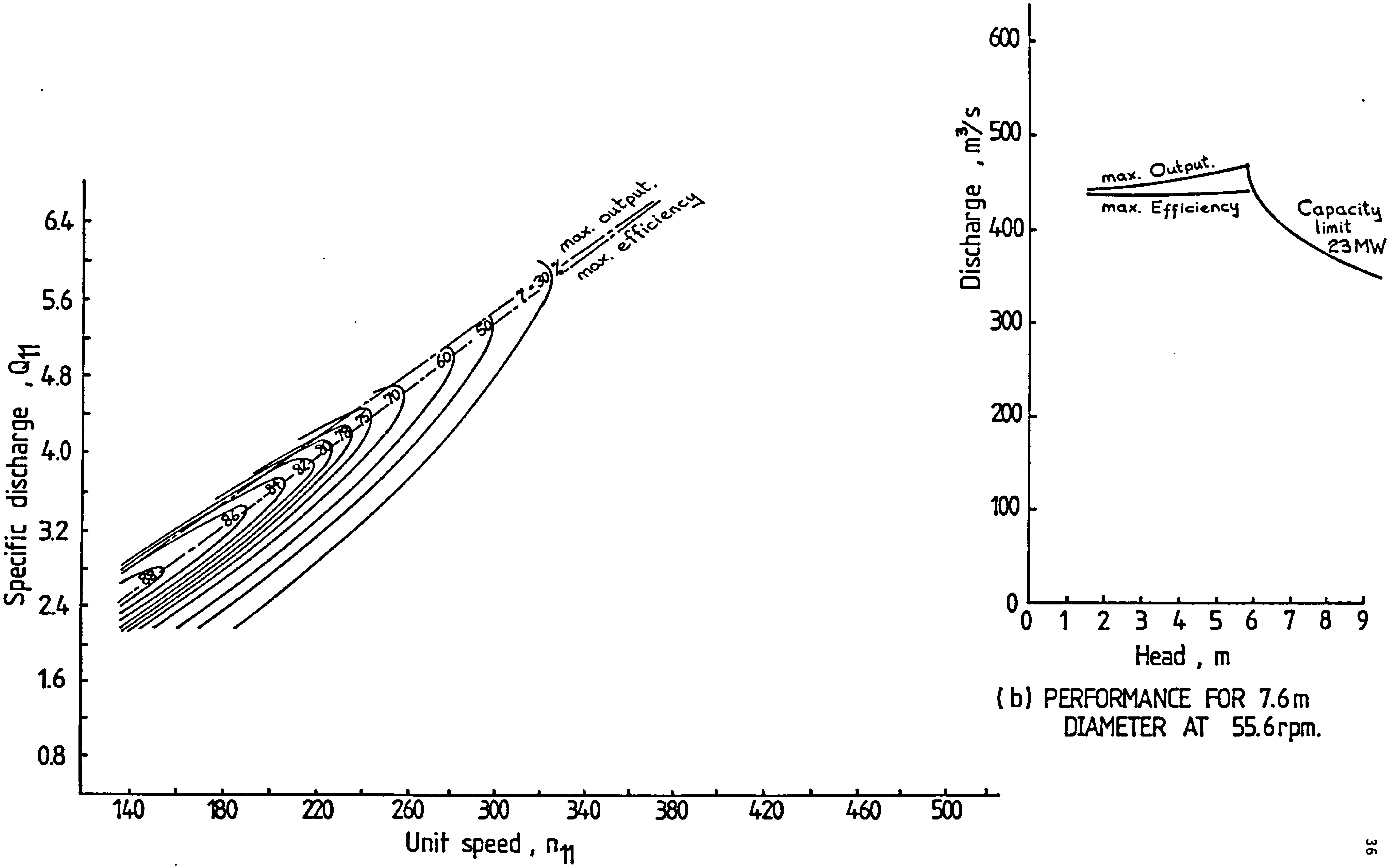
FIG. 3.2



(a) VD VB DIMENSIONLESS CHARACTERISTIC

(b) PERFORMANCE FOR 7.6 m DIAMETER AT 55.6 rpm.

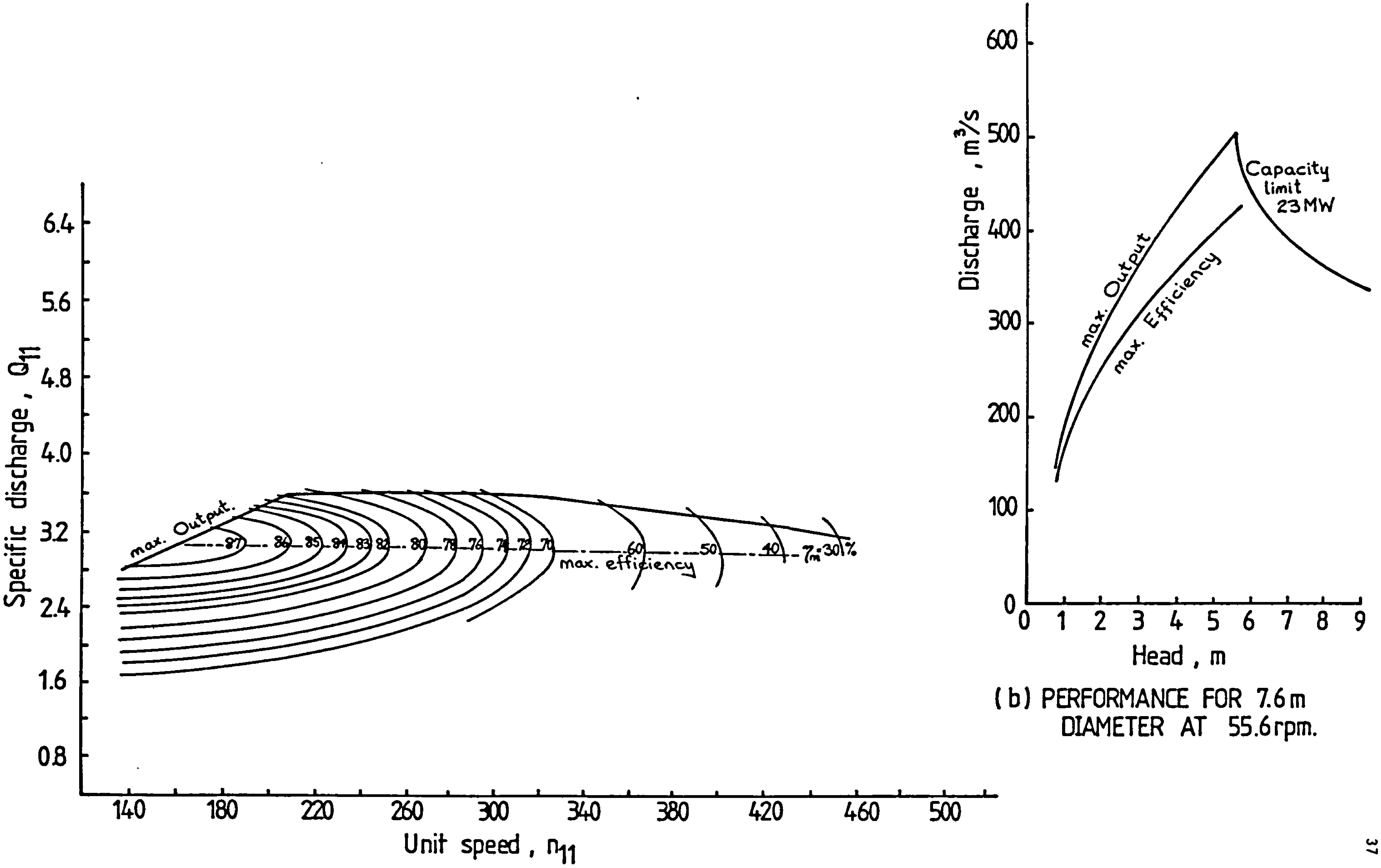
FIG. 3.3



(a) VD FB DIMENSIONLESS CHARACTERISTIC

(b) PERFORMANCE FOR 7.6m DIAMETER AT 55.6rpm.

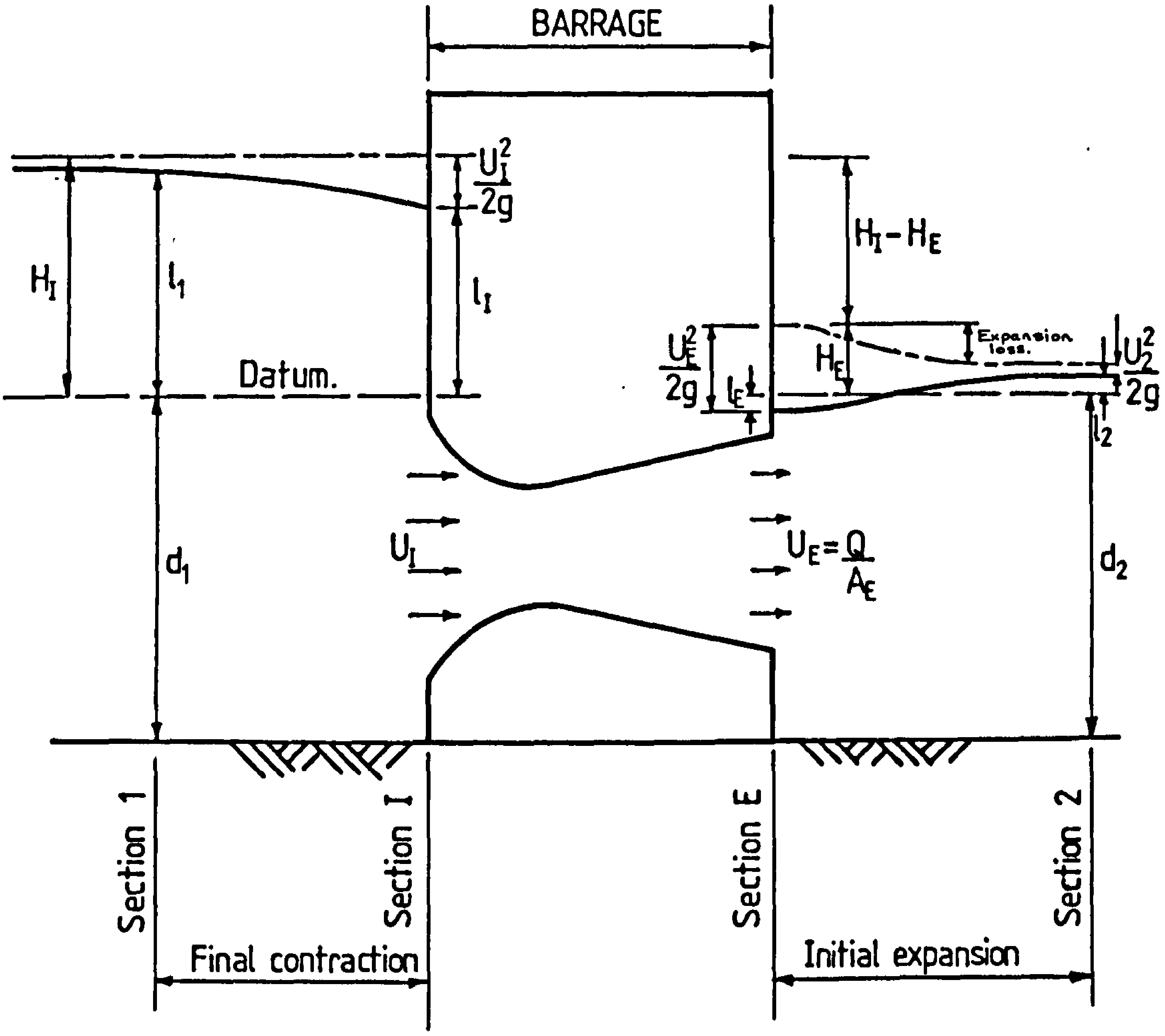
FIG.3.4



(a) FD VB DIMENSIONLESS CHARACTERISTIC

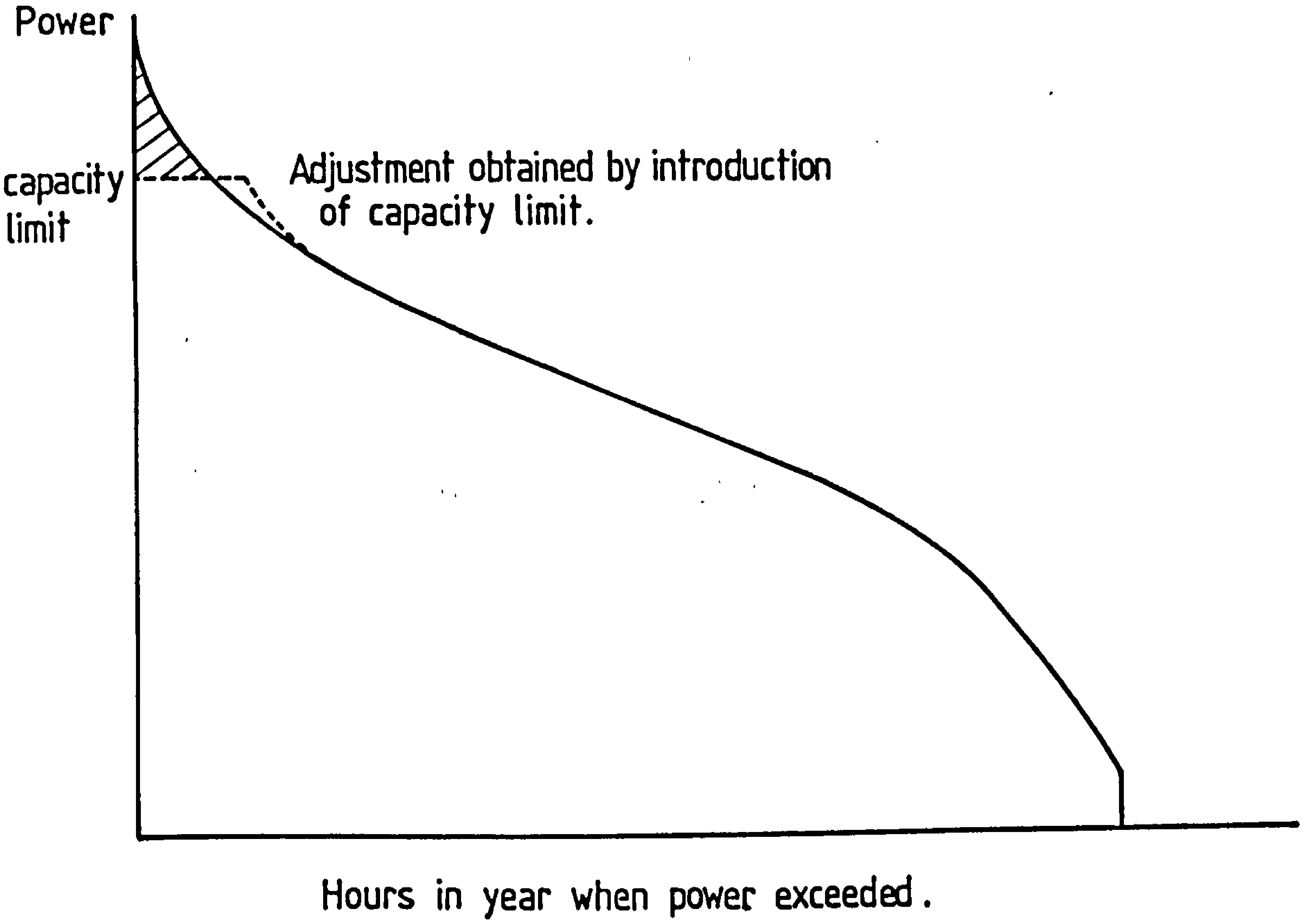
(b) PERFORMANCE FOR 7.6 m DIAMETER AT 55.6 rpm.

FIG. 3.5



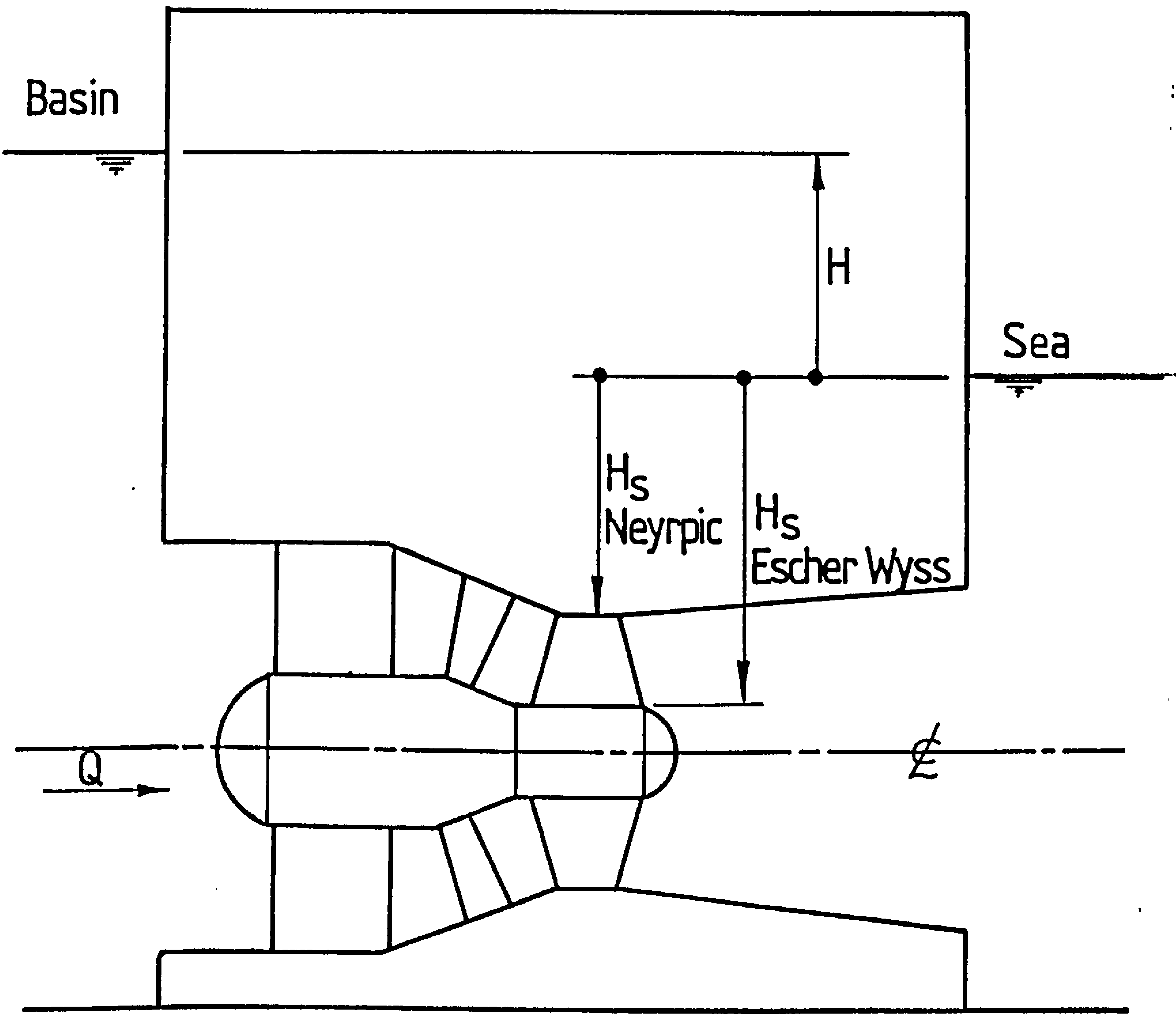
HEAD DEFINITION (taken from Ref. 1)

FIG. 3.6



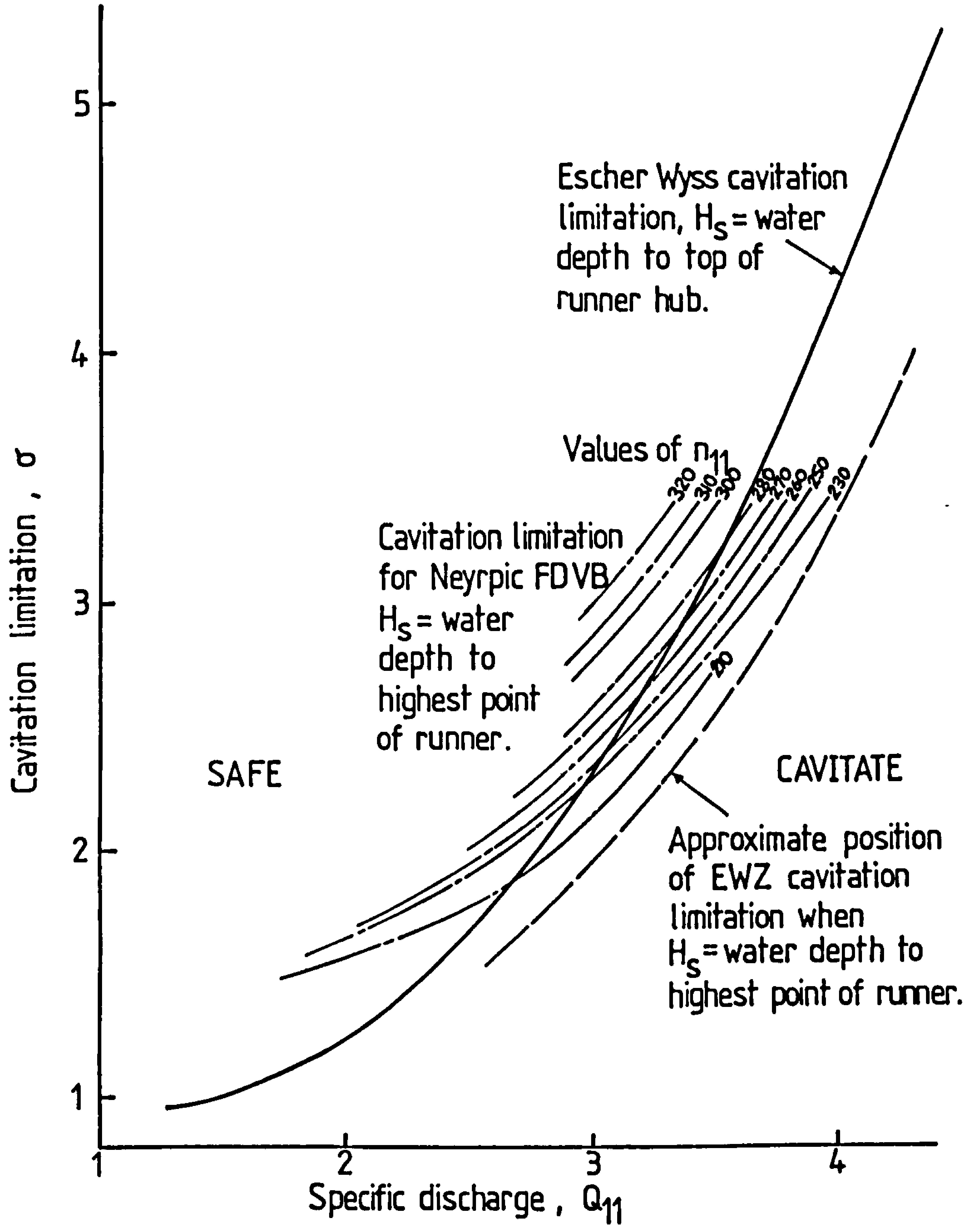
POWER DURATION CURVE - SHOWING INFLUENCE OF CAPACITY LIMIT.

FIG. 3.7



NOMENCLATURE FOR CAVITATION LIMITATION

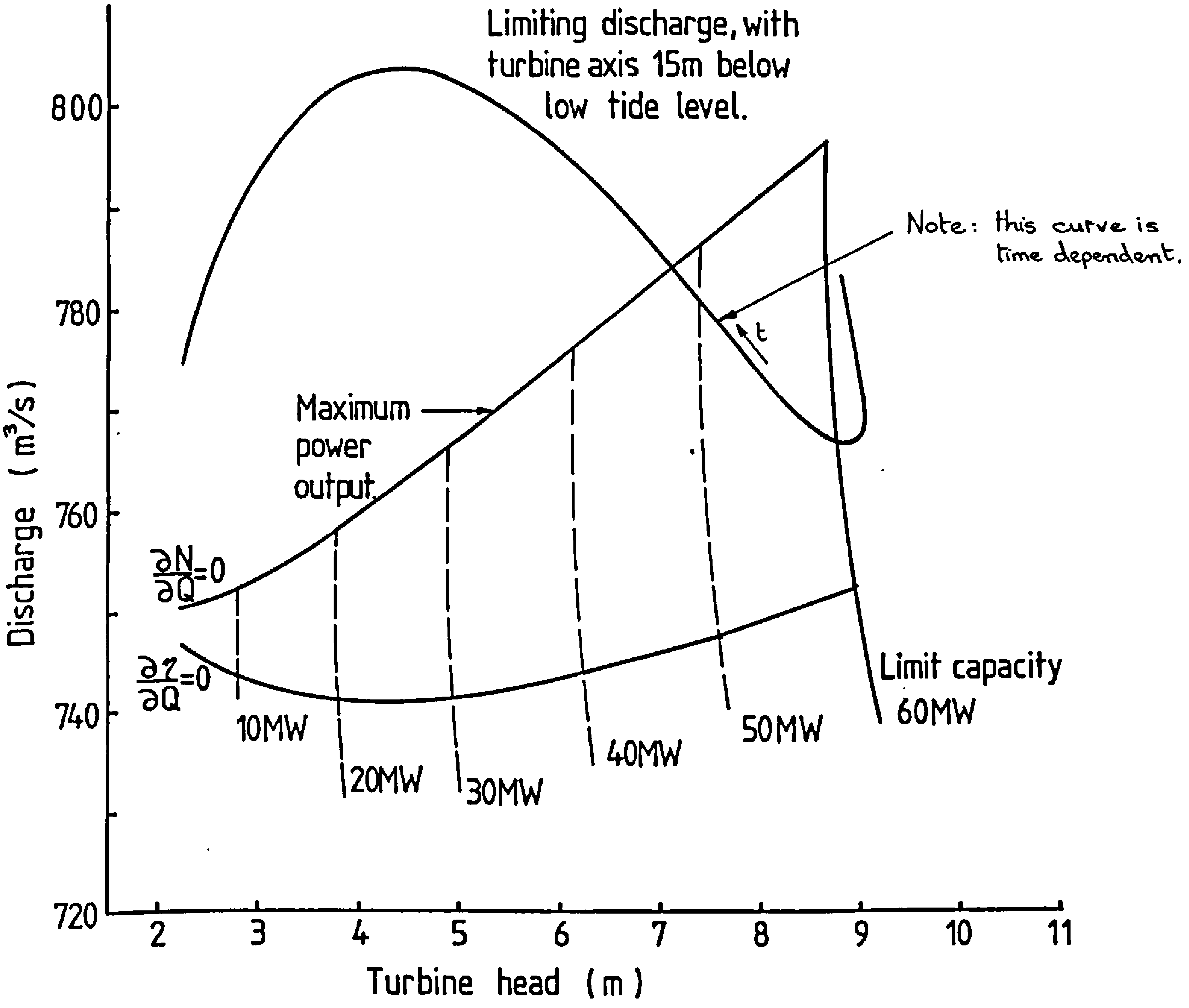
FIG. 3.8



CAVITATION LIMITS

FIG. 3.9

TURBINE : EWZ, VD FB(14°), diameter = 9.0m , 56.6rpm.



CAVITATION LIMITING DISCHARGES - SPRING TIDE.

FIG. 3.10

4.0 DEVELOPMENT OF THE OPTIMISATION PROGRAM

4.1 Introduction

The development of the optimisation program has been based upon the writer's experience gained using a similar model developed by Gibson (Ref. 3). This experience and the need to refine the simulation of turbine-generator operation led to the optimisation procedures adopted for the present model.

The initial versions of the model simulated single-effect ebb-generation operation. Subsequent requirements led to development of new versions to incorporate double-effect operation and pumping. Many routines were written that are common to all versions of the program, however no attempt was made to incorporate both single- and double-effect operation within one program.

Finally the programs were further modified to allow consideration of variable-speed turbine operation, rather than fixed-speed operation which was previously considered the norm.

The basic logic and mathematics employed in each model are followed by modified procedures for the ebb-generation plus pumping and double-effect modes of operation; accordingly the procedures are firstly described in detail for ebb-generation operation. Further documentation in the form of a program description and guide is contained in the Appendices.

4.2 Logic of single-tide optimisation model

The objective of the computer programs was to optimise numerically the energy yield from a single tide cycle from which the annual energy yield could be derived by dividing the annual naturally-occurring tidal ranges into a number of bands of ranges, each band being 0.5m wide. The mean range of each band could then be analysed and its yield considered to be the average of all tidal ranges in the band. Annual yield would then be obtained by summation of the multiples of each band's number of occurrences and its average yield. Based on this approach, the simulation method and the routines developed were to be sufficiently general to achieve reliable optimisation for all conditions of: tidal range, number and type of turbines, number of sluices etc.

To fulfill these requirements the programs search a wide range of operating conditions for the optimal solution. Although from experience the optimal operating conditions can be reasonably estimated such estimates are rejected in favour of using absolute operating constraints such as: maximum and minimum basin levels, to maintain a general solution.

For ebb-generation operation Figure 4.1 shows a typical operating cycle. The program is required to optimise the operating variables to identify the operating strategy leading to maximum energy production. These variables are:

- the basin level prior to generation, RRL
- generation starting head, h_S
- generation finishing head, h_F
- the basin level at end of generation, DDRL

The chosen method of simulation considers the generating and refilling phases separately, optimising the operating variables as follows:

1 A drawn-down reservoir level (DDRL) is selected, this is the level at the end of generation.

2 The refilling phase is computed forwards in time to establish the corresponding refilled reservoir level (RRL). The refilling phase is computed using the discharge capacity of the turbines when idling in reverse and the installed sluice capacity.

3 The generating phase is calculated backwards in time from the DDRL, starting from the time of generation finishing head up to the preceding RRL.

4 Having evaluated energy output for the initally selected DDRL, the program selects a new DDRL and repeats steps 1 - 3 in an iterative search for the DDRL yielding the greatest energy output.

It will be noted that by this method only the DDRL is explicitly optimised. This approach is sufficient because

- With the uncontrolled nature of the refilling phase, selection of a particular DDRL is tantamount to selection of a corresponding RRL.
- Separate optimisation of the generation finishing head is not required; theory (Ref. 22) suggests that this should always be the minimum turbine operating head and it is the writers experience with operating Gibson's simulation model, where this parameter is separately optimised, that this is invariably the case.
- Knowing the generation finishing head, computation from DDRL in reverse time defines the corresponding generation starting head.

The same optimisation procedure is adopted for the rarely-used flood-generation mode of operation. Change of one control character in the program data controls the selection of either ebb- or flood-generation operation.

4.3 Mathematics of the Simulation

4.3.1 The refilling phase

Because of the obvious objective to refill the basin to the highest level possible and the deterministic relationship between head across the barrage and the discharge through the open sluiceways and turbines (idling in reverse) the computation of reservoir level variation is quite straight-forward.

Starting from the point at which the sea level and the basin level at the end of generation (the DDRL) are identical, the sluice and turbine gates would be opened. (depending upon the turbine type, the distributor gates, the turbine blades and/or a draft tube gate would be opened). The unknown function y(t), the variation of basin level with respect to time, t, is defined by three equations:

$$H = h(t) - y(t) \qquad \text{... (1)}$$

$$Q = Q(H) \qquad \text{... (2)}$$

and $$\frac{dy}{dt} = \frac{Q}{A(y)} \quad \text{from continuity} \qquad \text{... (3)}$$

where

h(t) is the sea level
H is the operating head across the barrage
Q(H) is the deterministic discharge characteristic
Q is the discharge rate through the barrage
A(y) is the reservoir surface area as a function of level

Combining the above equations:

$$\frac{dy}{dt} = \frac{Q\ (h(t) - y(t))}{A(y)} = f(t,y) \qquad \ldots (4)$$

The function y(t) is therefore the solution of a first order differential equation. In the program this equation is solved numerically by the Runge-Kutta method. Computation starts at a known point, the drawn down reservoir level, when the level, y_0 and time t_0 are known. The level, y_1 at time $t_1 = t_0 + \Delta t$ is computed using the following standard set of equations:

$K_1 = \Delta t.f\ (t_0, y_0)$
$K_2 = \Delta t.f\ (t_0 + \Delta t/2, y_0 + K_1/2)$
$K_3 = \Delta t.f\ (t_0 + \Delta t/2, y_0 + K_2/2)$
$K_4 = \Delta t.f\ (t_0 + \Delta t, y_0 + K_3)$

$$y_1 = y_0 + (K_1 + 2K_2 + 2K_3 + K_4)/6 \qquad \ldots (5)$$

The resolution is carried out forward in time until operating head, and hence discharge, falls to zero. A time step of 10 minutes has been generally adopted, the background for this is given in Section 5. At the end of the sluicing phase operating head is falling rapidly so that in order to accurately predict the final refilled level the time step has to be progressively reduced.

The deterministic discharge characteristic when refilling is as follows:

$$Q = Q_S(H) + Q_T(H) + Q_R \qquad \ldots (6)$$

where Q_S, Q_T and Q_R are the total sluice flows, the total turbine flow and the net inflow into the basin from river discharges. The standard computer models incorporate sluice discharge functions representative of the submerged Venturi type sluice as follows:

$$Q_S = N_S C_d \; A \; \sqrt{(2gH_S)} \qquad \ldots (7)$$

where N_S is the number of sluices
C_d is the coefficient of discharge
A is the throat area of the sluice openings
g is the acceleration due to gravity
H_S is the sluice operating head

where
H_S = H - (inlet head loss + outlet expansion head loss) (8)

Head loss is calculated according to the method given in Section 3.6.

Turbine discharge during the refilling phase is modelled as follows:

$$Q_T = N_T \; Q_{11} \; D^2 \sqrt{H_T} \qquad \ldots (9)$$

where N_T is the number of turbines
Q_{11} is the turbine specific discharge at runaway in reverse rotation.
D is the turbine runner diameter
H_T is the turbine operating head (as for the sluices)

As for the sluices, the effective turbine operating head is calculated according to the equation given in Section 3.6. Accordingly, a separate calculation of operating head is made for sluices and for turbines.

4.3.2 The Turbining Phase

An elementary examination of the generation problem reveals that to achieve maximum energy production all discharges should be made instantaneously from the basin to the sea when low tide is reached, thereby maximising the generating head. In practice it is not feasible to install sufficient generating capacity to approach this goal. Accordingly with practicable levels of installation a method is required to optimise discharge rates through the barrage during the generation period (Figure 4.1 refers).

During the generation phase regulation of turbine discharge so that energy yield is maximised has been studied by Gibrat (Ref. 23), Godin (Ref. 22) and others. Solutions, derived by the Calculus of Variations have been established which consider the general case where the objective is to maximise the value of generation. For the reasons discussed in section 2 the model developed considers the rather simpler case where energy yield is to be maximised and is thus independent of an energy purchase tariff. In this case, in order to optimise energy yield, E, during a generating period (t_1, t_2), the discharge at each time during that period must be selected such that

$$E = \int_{t_1}^{t_2} N.(Q, H).\ dt \qquad \ldots (10)$$

is a maximum. Where N is the instantaneous scheme power output, varying with Q and H. Power output being defined as:

$$N = w.\eta.Q.H$$

where w = specific weight of sea water

η = combined hydraulic and electrical efficiency

Q = discharge

H = operating head

Using equations (1) and (3) from section 4.3.1

$$E = \int_{t_1}^{t_2} N.[\ A(y).\ y',\ y - h(t)].dt \qquad \ldots (11)$$

or

$$E = \int_{t_1}^{t_2} f(t,\ y,\ y').dt \qquad \ldots (12)$$

where $\frac{dy}{dt}$ is abbreviated to y'.

Using the Calculus of Variations it may be shown that in order to maximise E

$$\frac{\partial N}{\partial H} + A(y).\ \frac{d}{dt}\left(\frac{\partial N}{\partial Q}\right) = 0 \qquad \ldots (13)$$

Additionally, the solution gives information about operation at the end points of the generation phase, that is,

- turbines must commence operation under the condition

$$\frac{\partial \eta}{\partial Q} = 0$$

(ie. operation should be with a discharge giving maximum efficiency, thereby conserving stored volume early on).

- turbines should cease operation under the conditions

$$\frac{\partial N}{\partial Q} = 0$$

(ie. generation should cease with a discharge yielding maximum power output for the available head).

Figure 4.2, a typical turbine operating characteristic, shows the locus of $\frac{\partial \eta}{\partial Q} = 0$ and $\frac{\partial N}{\partial Q} = 0$. The former condition is not directly used in the computer solution; however it is a useful check to see that the optimisation is working correctly. Because the generating phase is to be computed backwards in time, from minimum turbine head at DDRL the latter condition is valuable in determing the starting condition Q_0.

Equation (13) is solved numerically during the generating period. Conditions at the start of the computation (the end of generation) are defined as t_0, y_0 $H_0 = h_{min}$ and Q_0, and new values are computed for time $t_1 = t_0 - \Delta t$ using the finite difference form of equation (13) as follows:

$$\frac{\partial N}{\partial H}\left(\frac{Q_0 + Q_1}{2}, \frac{H_0 + H_1}{2}\right)$$

$$+ A\left(\frac{y_0 + y_1}{2}\right) \cdot \frac{1}{\Delta t}\left[\frac{\partial N}{\partial Q}(Q_1, H_1) - \frac{\partial N}{\partial Q}(Q_0, H_0)\right] = 0 \qquad \ldots (14)$$

Equations (1) and (3) provide the first estimate of y_1 by assuming $Q_1 = Q_0$.

$$y_1 = y_0 - \Delta t. \frac{(Q_0 - Q_R)}{A(y_0)}$$

$$H_1 = y_1 - h(t_1) - h_e \qquad \ldots (15)$$

where h_e = inlet head loss + outlet expansion loss, calculated according to the equation given in Section 3.6.

Having determined a value for y_1 and H_1, by searching, the value of Q_1 giving a solution to equation (14) is found. Improved values of y_1 and H_1 are then obtained by a second use of equation (15) where Q_0 is replaced by $\frac{(Q_0 + Q_1)}{2.}$.

An iterative process is thence initiated to find consistent values of Q_1, y_1 and H_1. The process is not so time consuming because the initial estimate of Q_1 is generally quite good owing to the gradual variation of discharge. A time step, Δt, of ten minutes has been found satisfactory provided end conditions and the times at which operating constraints (refer to 4.3.3) are reached are accurately defined.

In the program N, $\frac{\partial N}{\partial Q}$ and $\frac{\partial N}{\partial H}$ are all evaluated for individual turbines and are subsequently multiplied by the number of operation machines. $\frac{\partial N}{\partial Q}$ and $\frac{\partial N}{\partial H}$ are evaluated numerically from the turbine hillchart model (Section 3.6).

4.3.3 Turbine Operational Constraints

The solution of the finite difference equation (14) is the general solution to the optimisation problem. Figure 4.2 shows for a mean tidal range, that in real time, operation would begin at point A, at H_0 on the line $\frac{\partial \zeta}{\partial Q} = 0$ and progress in a loop, firstly with increasing turbine head and later with head falling to the minimum as the required discharge approaches asymptotically the line $\frac{\partial N}{\partial Q} = 0$ at point B.

Generator Limiting Capacity

Equation (14) is no longer valid when the solution implies operation giving a power output in excess of the prescribed limit. In these circumstances, as explained in section 3.7, the turbine discharge must be throttled to follow the generator limiting capacity curve. Figure 4.2 shows the operational path P, Q, R, S, T followed for a spring tide when the generator limiting capacity curve is reached.

As before, operation would begin at point P on the curve $\frac{\partial \zeta}{\partial Q} = 0$ and progress to point N at the intersection with the limit capacity curve. Once on this curve the discharge becomes deterministic with head and the Runge-Kutta solution as described for the sluicing phase can be applied. The problem at this stage of the simulation is to determine at what point operation should depart from the limit capacity curve. Gibrat (Ref. 23) established that operation should continue along the limit capacity curve until the following is satisfied:

$$\int_{Q}^{S} \frac{\frac{\partial N}{\partial H} + A(y).\frac{d}{dt}\left(\frac{\partial N}{\partial Q}\right)}{A(y).\frac{\partial N}{\partial Q}} \, . dt = 0 \qquad \ldots (16)$$

Accordingly a finite difference form of equation (16) is used to numerically evaluate the integral from the point Q until it is satisfied at point S. Thereafter operation is determined by solution of the general equation (14).

Cavitation Limitation

Section 3.7 describes the conditions leading to the onset of cavitation. The limiting conditions set an upper limit on the specific discharge and hence the actual discharge for the prevailing operating head. In the model at each step of the calculation the limiting discharge with respect to cavitation is evaluated and compared with the discharge prescribed by the optimising routines. If the prescribed discharge is the larger, then operation must diverge from the optimal path in the same way as described for the generator limiting capacity.

4.3.4 Fixed Blade Turbines

Section 3.5 illustrates the typical performance characteristic of a fixed blade propeller turbine. It is evident that the variation of discharge, for a given head, between the line $\frac{\partial \eta}{\partial Q} = 0$ and $\frac{\partial N}{\partial Q} = 0$ is very small.

Using the finite difference method described in the preceding pages it is possible to fully optimise operation of the fixed blade turbine. The resultant energy yield, however, is almost identical to that obtained if a deterministic head/discharge relationship for either $\frac{\partial N}{\partial Q} = 0$ or $\frac{\partial \eta}{\partial Q} = 0$ is followed.

Consequently, because of the savings of computer time when using the latter, the program also incorporates routines to allow computation of the turbining phase using either of these functions.

4.3.5 River Flow into the Reservoir

Fresh water inflows into a tidal estuary suitable for tidal power development are usually very small compared to the tidal flows which occur. Nevertheless provision is made in the program to input a constant river inflow and routines are incorporated to determine its effect upon reservoir levels.

In the routines described which calculate sluicing and turbining operations inclusion of river flow is straightforward. However as Figure 4.1 illustrates, there are significant periods of barrage inactivity, during which impoundment of inflows takes place. At these times reservoir level variation is determined by equation (3):

$$\frac{dy}{dt} = \frac{Q_R}{A(y)} \qquad \ldots (3)$$

where Q_R = constant river inflow.

In the case of inactivity at the end of generation, the program computes reservoir level variation at 10 minute time intervals. The computation proceeds forward in time from the time at which the estimate of DDRL gives the minimum net turbine head, until level equalisation is reached.

For the case when river inflow is solely responsible for reservoir level variation after the refilling phase a different approach is adopted so that as calculation of the generation phase proceeds backwards in time the end condition can be checked following each turbining time increment. However, when river flow is included in the simulation the end condition is now slightly higher than the RRL due to the impounded river flow, Figure 4.3(a) refers. Consequently when backward calculation of the turbining phase produces a reservoir level at or above the RRL the following check on an end condition is made using the modified form of equation (3) as follows:

$$dt = \frac{1}{Q_R} \cdot \int_{Y_0}^{Y_1} A(y).dy \qquad \ldots (17)$$

Considering Figure 4(b) the end condition is checked following each turbining time increment, T0 to T1, during which reservoir level increases from Y0 to Y1. Equation (17) is used to calculate the time increment dt required for the reservoir to rise from RRL to Y0, and again to rise to Y1, and the values added to TRRL to give respectively TRIV0 and TRIV. An end condition is reached if TRIV is greater than T1, and the actual time to start generation, T, is found when the two profiles intersect. For this final calculation a linear reservoir level variation is assumed.

4.3.6 Other End Conditions

The procedure described above forms the basis of a routine used for checking for an end condition as reverse calculation of the turbining phase approaches the refilled reservoir level. Because the optimisation routine iteratively searches for the DDRL giving maximum energy yield there are occasions when the selected DDRL is inappropriate because either,

i) calculation of the turbining phase reaches the minimum turbine head, ie. the RRL cannot be reached or

ii) the reservoir level calculated exceeds a predetermined maximum level.

Accordingly these circumstances form additional end conditions and are included in the general routine ENDCON. See Appendix A. In addition ENDCON also determines the conditions at which to terminate sea-to-basin pumping following high tide as described in section 4.4.

4.4 Optimisation of Ebb-generation + Pumping Operation

For simulation of ebb-generation + pumping additional routines incorporated within the ebb-generation model are used to simulate the operation of the turbines when operated as pumps, for a short period following high tide Figure 4.4. In this period the objective is to raise the retained water level in the basin by pumping against a low head and later generate with this extra volume of water, when the tide has ebbed, using a significantly greater head. In this way the combined efficiency losses of pumping and turbining are offset by the gain in potential energy achieved.

It is normal to use the maximum efficiency pump characteristic which is found to give greatest energy gain when compared to the no-pumping case. However, alternative pumping characteristics giving discharges greater than that for maximum efficiency have been tested in order to confirm that this is so.

The same optimisation procedure as used for ebb-generation operation is adopted. However, when computation of the generating period up to the RRL is complete further generating steps of 2 minutes are calculated. After each turbining step the pumping operation required to raise reservoir level by the corresponding level increment is calculated, and the energy consumed whilst pumping up the level increment compared with the energy generated from the same incremental level. Provided energy output exceeds energy input the calculation proceed to evaluate for another incremental level. Pumping ceases when more energy is required to pump the final incremental level than is recovered by the additional generation, since this would reduce the NETT energy yield from that cycle. As for ebb-generation the optimum strategy is found by optimising DDRL. It has been found that when pumping operations are incorporated the optimum DDRL is slightly higher and that the generating period is extended somewhat to take advantage of the additional stored volume provided by pumping.

Pump performance data input is limited to providing pump specific discharge (Q11) as a function of specific peripheral speed Q11 = f(KU1). When scaled to the appropriate runner diameter and rotational speed this function determines the pump discharge at a particular operating head. A second function linking pump power input to the pump head completes the data required. Use of these deterministic relationships permits computation using the Runge-Kutta method as for the refilling phase, Section 4.3.1 equation (5) although for pumping reservoir level and time are interchanged. (see note opposite)

The question which is sometimes asked is whether, having found the optimum extent of pumping for a particular DDRL, would not the augmented reservoir level be better used with a different generating strategy from that which led to the selected level? This option is implicitly considered by the selection of alternative DDRLs, which each have their own unique generating paths, - one of which would be the result of operating such a different strategy. Accordingly the search for DDRL with maximum nett output defines the optimal solution.

In order to assess the impact of an energy input cost higher (or lower) than the energy output value, an energy cost ratio can be applied to the pump energy requirements so that the optimisation procedure effectively optimises the overall value of generation.

4.5 Optimisation Procedures for Double-effect Operation

Optimisation of the double-effect mode of operation, either with or without pumping has been accomplished using an identical set of routines controlling reservoir level variation as used for the single-effect model. In the double-effect model two different turbine hillcharts are required to represent operation in the direct and reverse turbine quadrants. The turbine hillcharts will almost certainly be representative of the double-regulated turbine type for which discharge regulation must be determined using the Calculus of Variations solution. As with the single-tide model the emptying phase and refilling phase are optimised separately, as follows:

1. A drawn-down reservoir level (DDRL) and a refilled reservoir level (RRL) are selected, refer to Figure 4.5.

2. The emptying phase is computed backwards in time from DDRL using initially the sluices and idling turbines until the turbine head exceeds the

minimum. Thereafter the turbines are operated on the maximum power output curve, $\frac{\partial N}{\partial Q} = 0$, together with the open sluices until the estimate of the sluice opening time TSLUD is reached. From this point until the RRL is reached computation proceeds with only the turbines in operation, their discharge being regulated according to the Calculus of Variation solution as detailed in Section 4.3.2 for single-effect operation.

3. Having evaluated energy output for the initially selected value for TSLUD, the program selects a new value and repeats step 2. in an iterative search for the value of TSLUD which maximises energy yield from the ebb-generation period between the current values of RRL and DDRL.

4. The refilling phase is computed as for steps 2. and 3. above to obtain the maximum energy yield from the flood-generation period between the current values of RRL and DDRL. A total energy yield from the tidal cycle is obtained by summating the results of steps 3 and 4.

5. The program now selects a new DDRL and repeats steps 2 - 4 in an iterative search using the current RRL and the DDRL yielding greatest total energy. This optimum DDRL becomes the 2nd estimate of DDRL and is fixed whilst RRL is varied in a similar way. The procedure, shown graphically in Figure 4.6, progressively 'climbs' to the peak of the total energy contours. Tolerances are inbuilt to stop the iterations once the desired accuracy has been attained.

As will be appreciated from the description of the optimisation procedure the double-effect model is at least an order of magnitude more complex and consuming of computer CPU time than the single-effect model. The writer can see opportunities to enhance the procedure but following use of the program as described above, when program development time was limited, there has been no further requirement for study of the double-effect mode of operation.

4.6 Variable Speed Turbine Operation

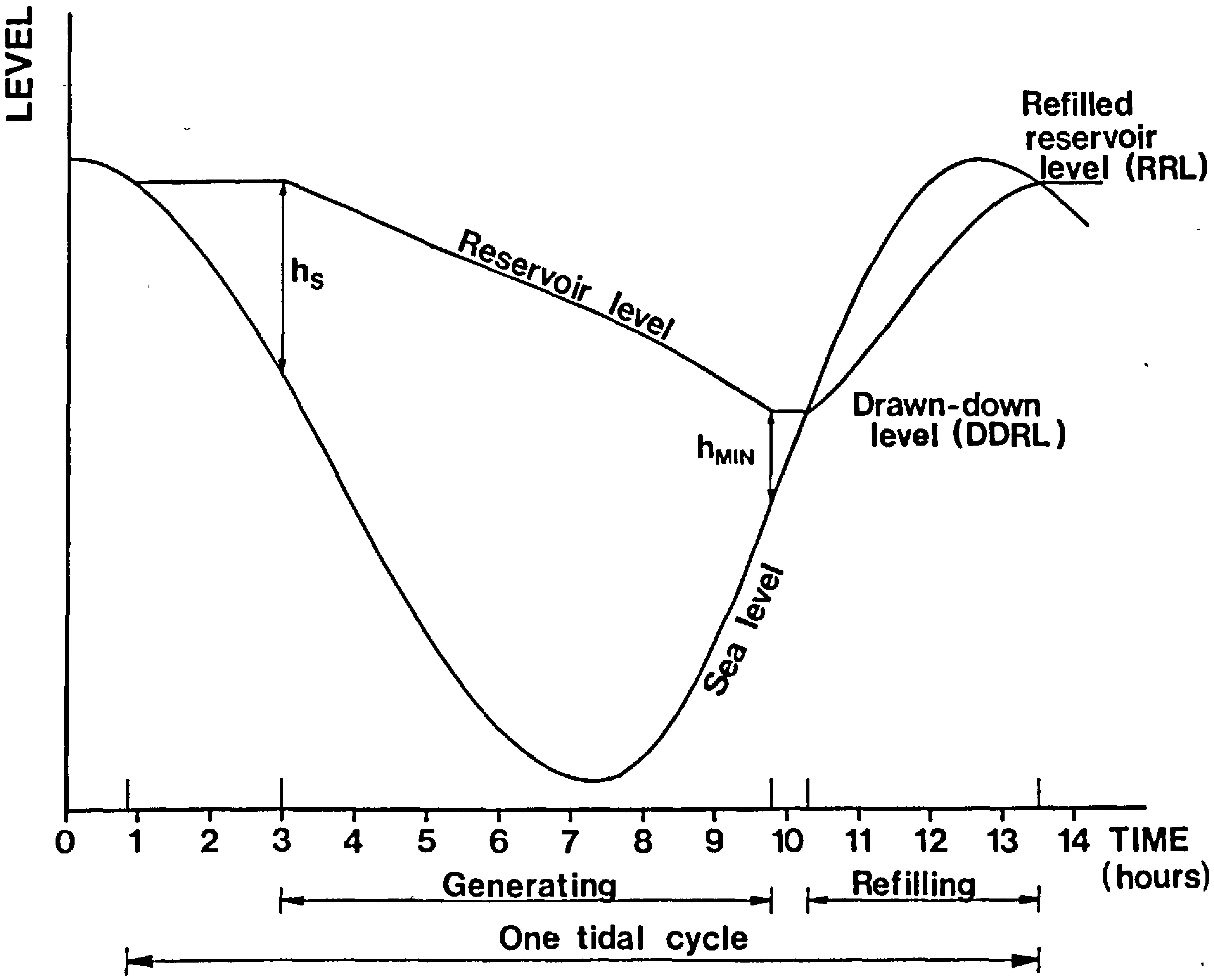
With the wide variation of turbine head experienced by tidal turbines the option of variable rotational speed is an interesting proposition. By constant adjustment and optimisation of rotational speed a high efficiency can be achieved under all operating conditions, thereby increasing energy yield. Alternatively, variable speed operation can be adopted with a simplified, fixed distributor, fixed blade turbine to obtain reasonable energy yield with a machine type of low first cost and low maintenance requirements.

To facilitate variable speed turbine operation electrical power output produced as alternating current at a variable frequency, must be rectified to direct current and subsequently inverted to system frequency. Rectification would take place on or near the barrage but the inverter station could be located, for economy of transmission equipment, near to the load centre. Control of turbine speed would be achieved by control of the electrical load placed on the generator, by adjustment of thyristor firing angle at the inverter station.

The cost of rectification and inverter equipment is not insignificant however and there is a power loss of 1-2% through this process, so the economic case for variable speed operation must be carefully evaluated. A secondary benefit obtained however is elimination of the synchronizing process as units are started up.

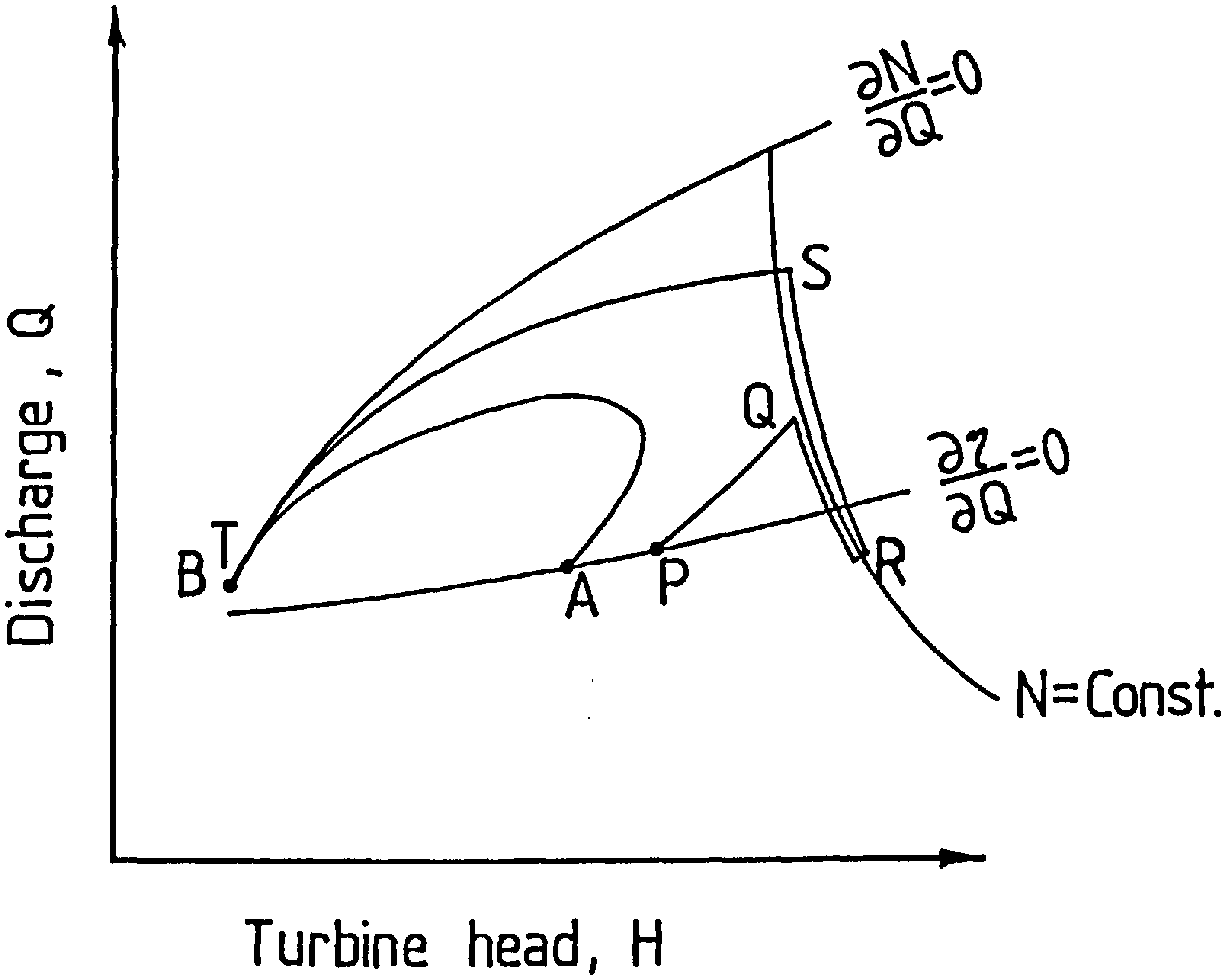
In the optimisation model the problem is to select for the specified head and discharge at each step in the calculation a rotational speed for which efficiency is a maximum. In terms of the dimensionless hill chart characteristic, this means that the program must search the specified Q_{11} , for the value of n_{11} for which efficiency is highest. This is achieved in the model using an additional set of routines.

When operating at variable speed the generator output limit is transformed to a generator torque limit. This limit condition is checked in the speed optimisation routines, if torque at the optimum efficiency exceeds the limit speed is increased until the limit is equalled.



OPERATION DURING ONE TIDAL CYCLE, EBB-GENERATION

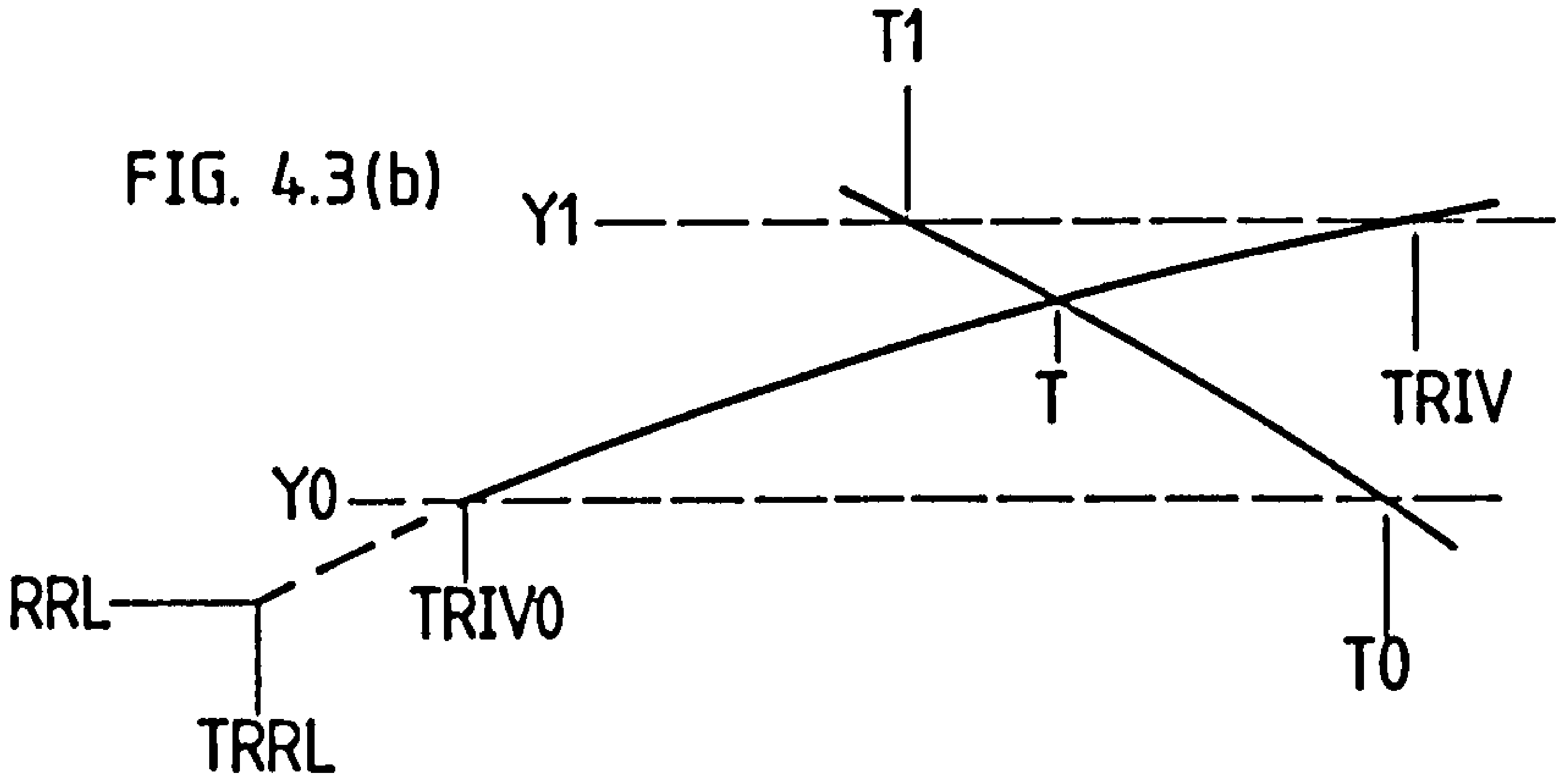
FIG 4.1

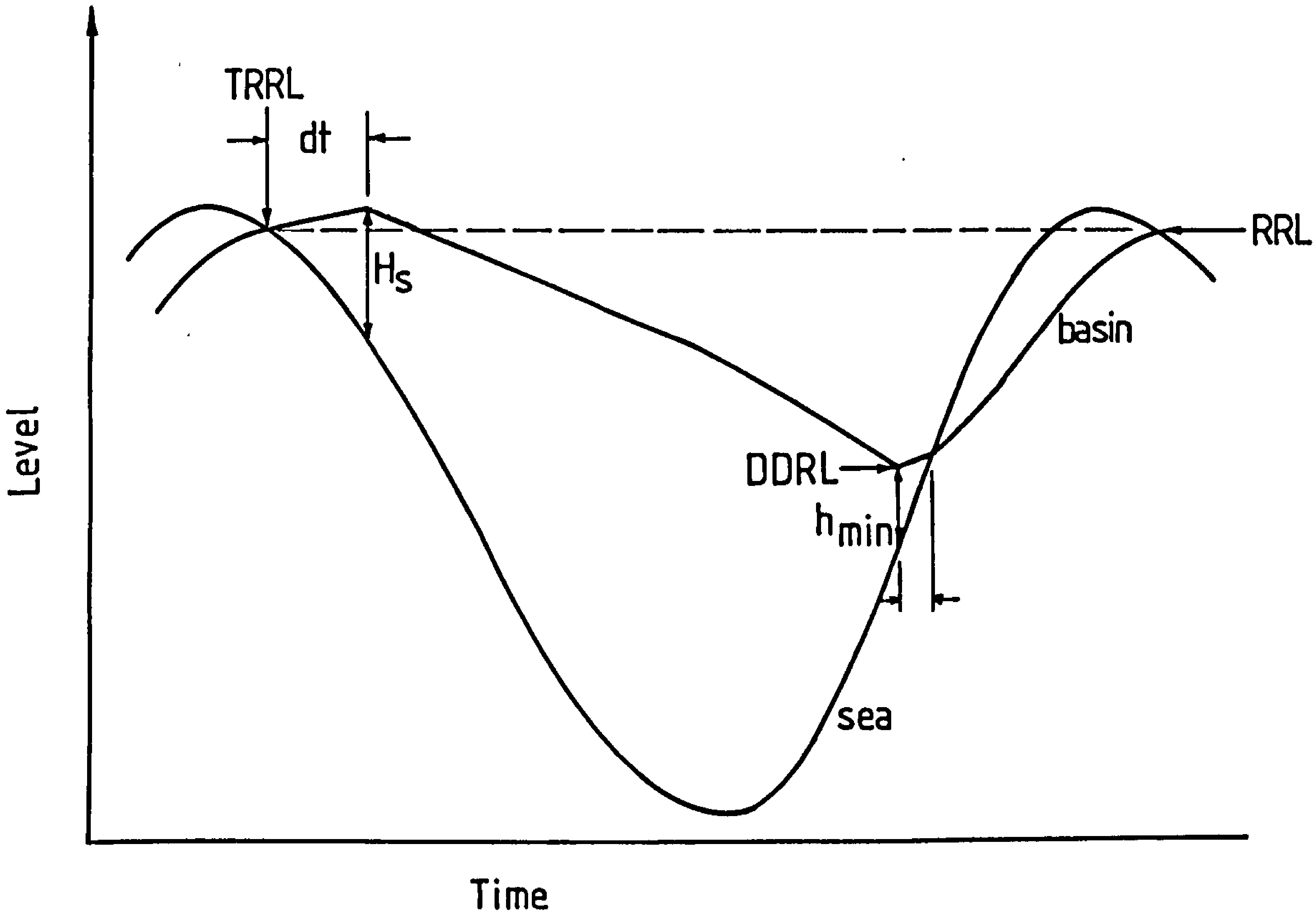


OPTIMUM OPERATIONAL PATHS THROUGH TYPICAL GENERATING CYCLES.

FIG. 4.2

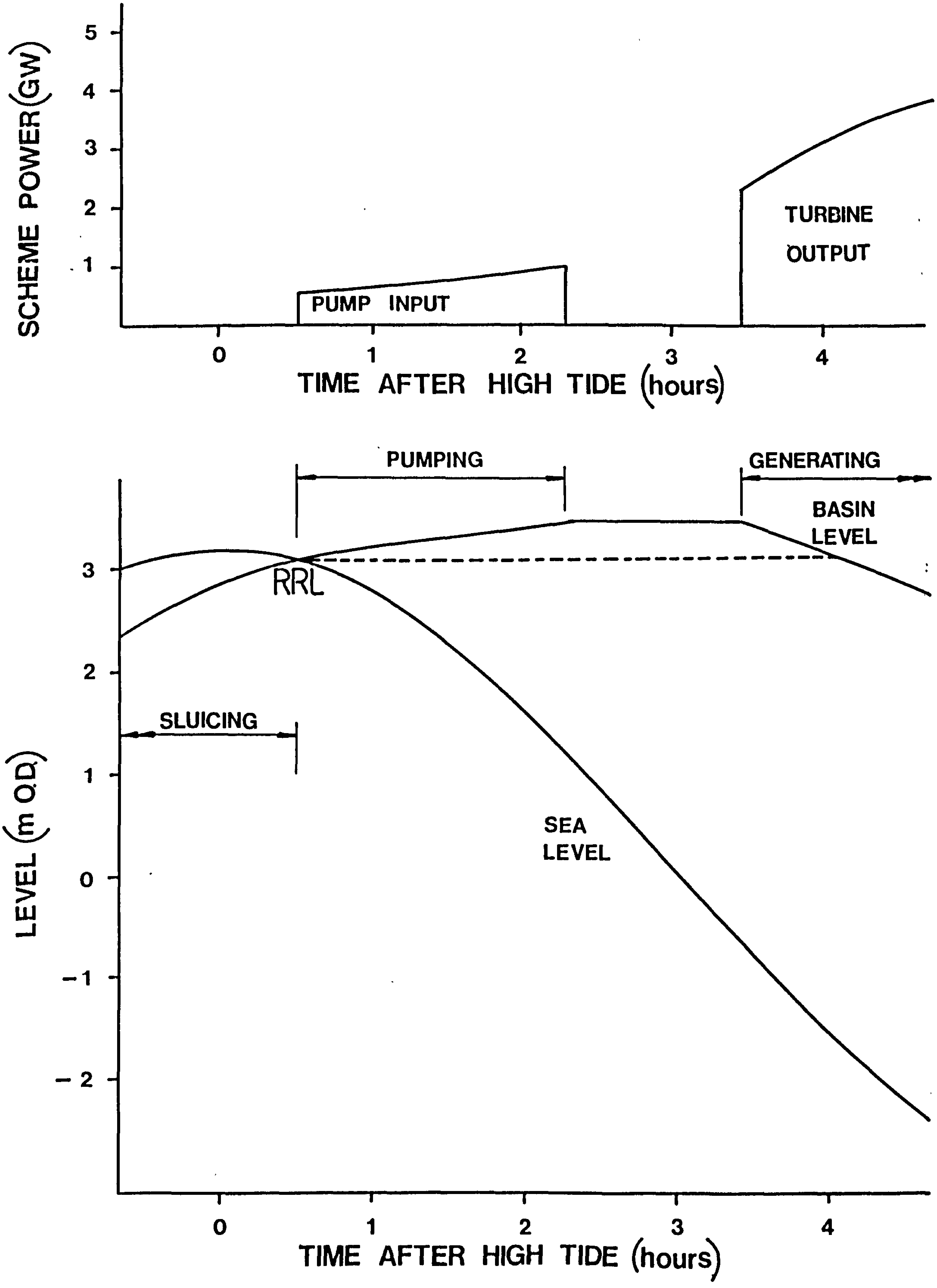
FIG. 4.3(b)





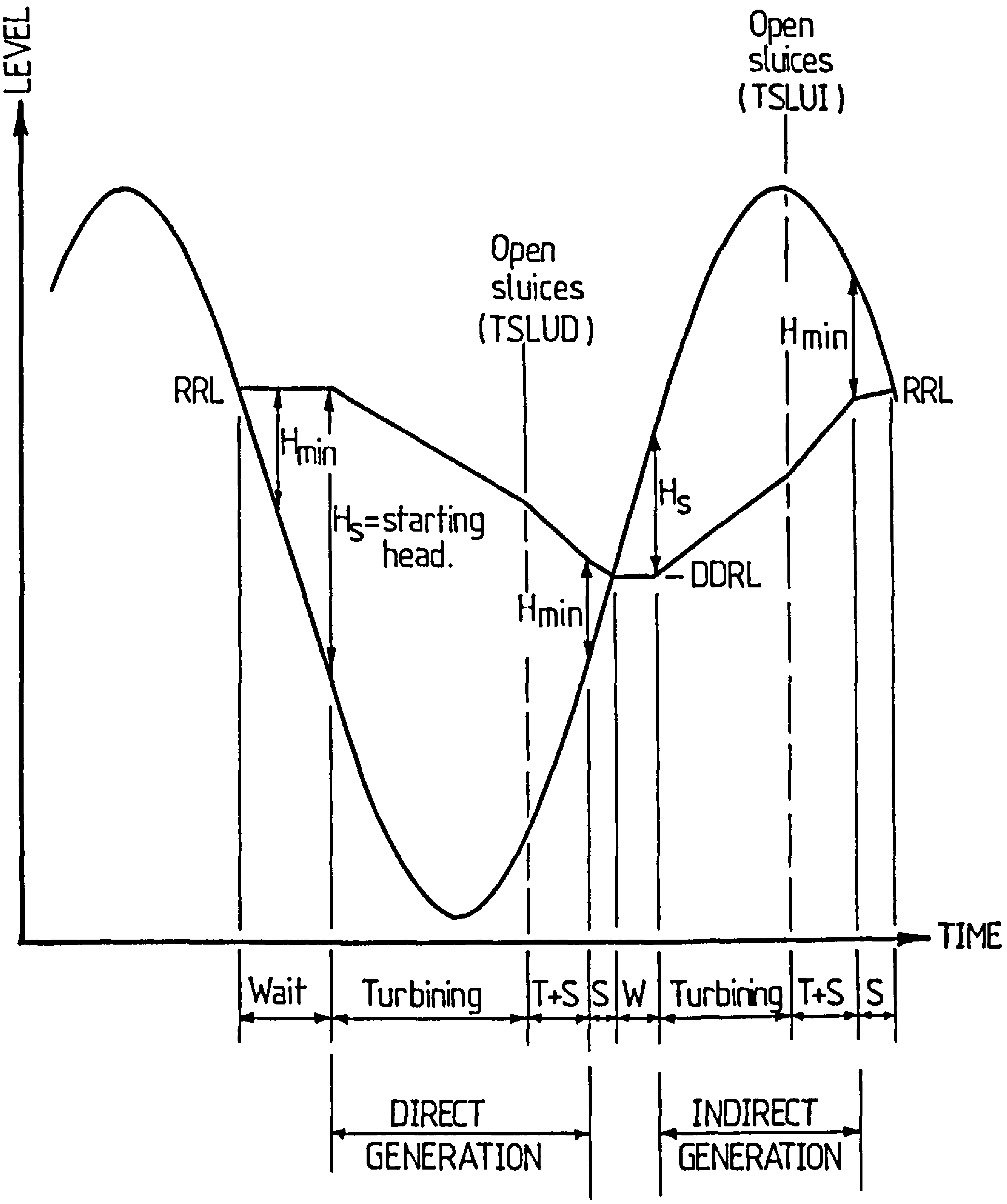
(a) ADJUSTMENTS TO OPERATING CONDITIONS BY ADDITION OF RIVER INFLOW TO THE RESERVOIR.

FIG. 4.3



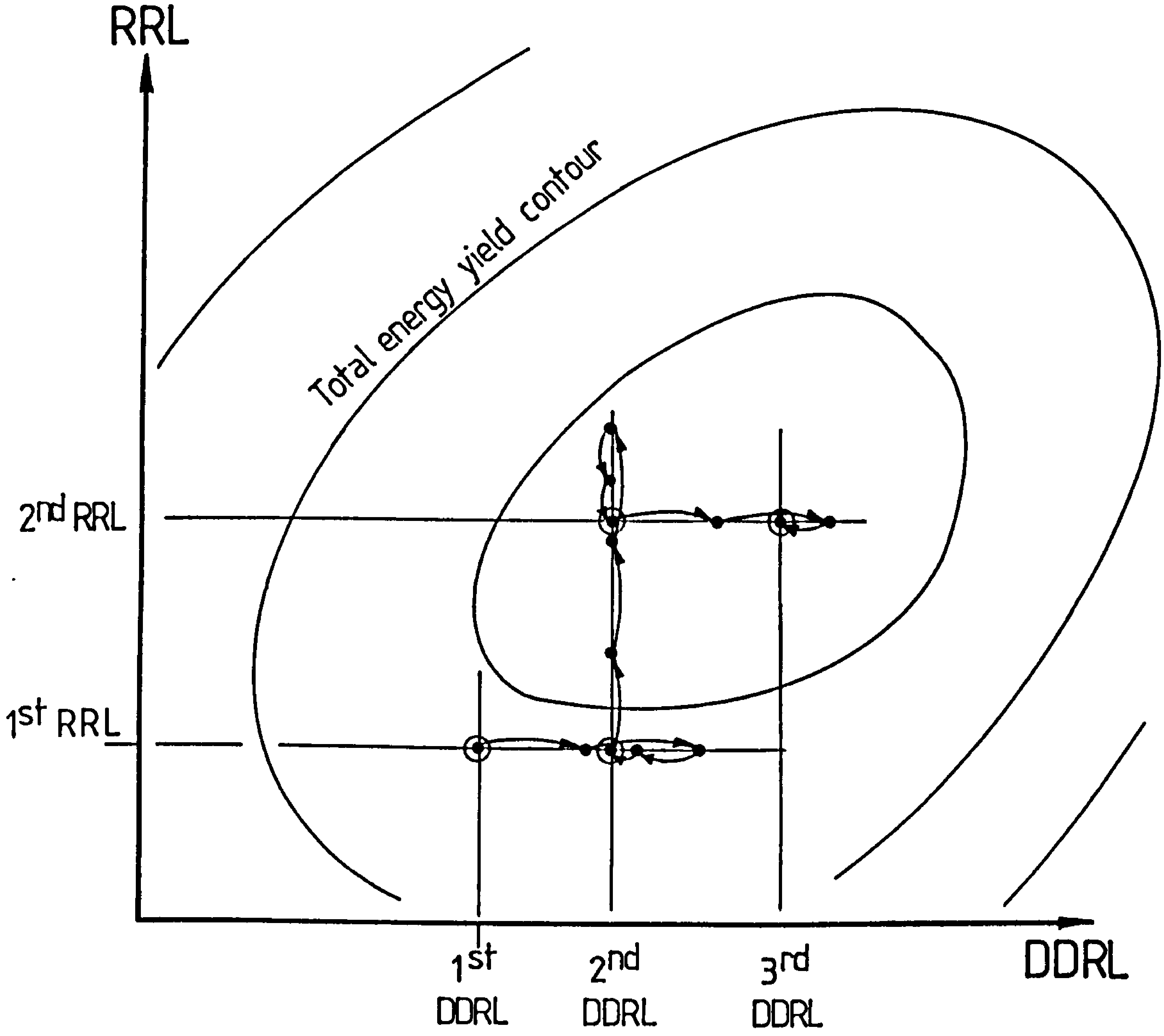
EBB-GENERATION + PUMPING
TYPICAL TIDE

FIG 4.4



DOUBLE-EFFECT OPERATION DURING ONE TIDAL CYCLE.

FIG. 4.5



OPTIMISATION PROCEDURE FOR DOUBLE-EFFECT OPERATION.

FIG. 4.6

5.0 APPLICATION OF THE PROGRAM(S)

5.1 Validating the Ebb-generation Program

Upon completion of the ebb-generation simulation model direct comparison of results with results from Gibson's CSOM program (Ref. 3) was possible for some simple cases. After some minor modifications and corrections these two programs were in very close agreement. For testing of the maximum energy routines and other features not incorporated in Gibson's model, check calculations were made by hand for each set of conditions, the computed results were presented graphically to identify any irregularities, and results were compared to the more simple cases to check that anticipated trends were reproduced. Checking by hand calculation was made less onerous because it was considered unnecessary to check further routines used in the simple cases which were validated by comparison with Gibson's model.

Checking that the maximum energy solution does indeed find the optimal route through the turbine hillchart was problematical. Although all results indicated more energy from this solution than by either maximum power output or maximum efficiency operation, was there another route which yields even more energy? In describing the maximum energy solution, Section 4.3.2, it is remarked that the Calculus of Variations indicates that turbine operation should begin with operation at maximum efficiency but that this condition is not utilised in the computer model. It is therefore reassuring that results of maximum energy operation indicate that the optimum computation ends at or near to the maximum efficiency line. For the sub-optimial DDRL's tried in the optimisation procedure the final computations can be substantially above or below maximum efficiency.

Further useful checks would have been to make comparative runs against recorded power and energy yields from specific tidal occurrences for La Rance and more recently for the Annapolis plant in Canada. Unfortunately in the case of La Rance comparison is made impossible because of the pre-occupation there with operation to maximise revenue and accordingly the plant operation is distorted to follow the cost of electricity functions derived by Electricite de France. In the case of Annapolis some data has become available however this was incomplete and any comparison would have been uncertain.

In addition to checks to establish the correct functioning of the optimisation program, it is also necessary to consider whether the method of energy analysis, the single-tide and histogram approach, is valid. By inspection it could be argued that this is a reasonable way to proceed since a large sample (one year's tides) is used and the variation of energy yield with tidal range is considered by the use of a number of sample tidal ranges. The counter argument is of course that this method implies that the tides occur as infinite series of constant amplitude, and since this is not the case the steady variation of tidal ranges influences in some way the energy yield.

Gibson in his thesis compared results from energy analyses using his single-tide model with a much more complex model developed by Tidal Power Consultants, of Montreal, Canada which could optimise energy yield over a spring-neap cycle. He reported a close agreement. This result is not surprising in view of the large sluice capacity required for ebb-generation barrages and the corresponding ability to almost completely refill the reservoir in preparation for the next generating period. Gibson compared the energy yield of individual tidal ranges which is not strictly appropriate. What is required is a comparison of annual energy yield firstly by the histogram method, described here, and secondly by use of a program which can optimise operation through a natural tidal series. The Tidal Power Consultants model was of the latter type however it was only operated through a natural spring-neap cycle from which the extrapolation of an annual energy yield may be inaccurate because of the monthly tidal variations.

At the conclusion of his period of study the writer has supervised the development of an optimisation program, like the TPC program, for the analysis of operation through a natural tidal series. Using the new program, 'the multi-tide optimisation model', annual energy yield has been computed through a complete years tides and the annual energy yield compared to the result from the same conditions using the single-tide model with a histogram derived from the years tides in question, Reference 24. The results differed by just 0.3% and would appear to completely validate the single-tide and histogram approach.

The multi-tide optimisation model was developed to examine specifically the changes in operating patterns and outputs brought about by operation to maximise revenue rather than energy yield and Reference 24 describes results of the models initial application, for the proposed Mersey Barrage scheme. This analysis also highlighted the difficulty in use of the model because of the variability of fortnightly neap-spring-neap tidal series. Because of which it becomes necessary to analyse a complete years tides to obtain a satisfactory result for annual energy yield and annual energy value.

5.2 Selection of appropriate time step for the numerical model

Having thoroughly checked the operation of the program using a time step of 10 minutes for the time increment of the numerical solution, as recommended by Gibson (Ref. 5), the writer considered independently an appropriate selection for this parameter. Figure 5.1 shows results of energy computations using the maximum energy routines with the finite difference method, and operation along the maximum power output curve using the Runge Kutta method. As anticipated using the VD FB type turbines the maximum energy solution gives only a slightly greater energy yield, about 0.26% more. Also shown is the variation in reported energy yield with respect to the time step used in the numerical solutions. For both methods of computation the variation of energy yield is found to be almost at a peak with a 1 minute step length and the reduction when using a 10 minute step length is less than 0.1%. Further extension of the step length to 15 minutes does not appear advisable in view of the shape of the curves.

Detailed consideration of the shape of the curves reveals that the energy yield variation stems from the method of energy evaluation from the instantaneous power outputs calculated at the ends of each time step. In the model the trapezium rule is used to calculate energy produced during a time step, which because of the shape of the power output curve, Figure 5.2 refers, underestimates the area under the curve and hence underestimates energy yield. Use of Simpson's rule for energy calculation improves accuracy of results for a time step of 20 minutes making it comparable with results using a 10 minute time step with the trapezium rule. Simpsons's rule was not used in the program because it is unsuitable when the time step has to be reduced to pinpoint the conditions at which an operating constraint is reached. In conclusion a 10 minute time step has been universally adopted in the knowledge that the computed energy yield will be very close to the maximum achievable.

5.3 Optimisation of generating equipment

Following the successful proving of the computer model in its basic form in 1979/80 it has been applied to many different and interesting proposals for tidal power development. References 25 to 41 inclusive contain details of energy production studies using the model. The computer model remains nevertheless a tool with which to investigate the options open to the designer of a tidal power scheme. Accordingly prior to discussing results of some of the studies it is worth considering some of the elementary considerations.

Optimization of tidal genenerating equipment for a specific barrage location is an iterative process requiring input from many engineering disciplines. Initially a number of assumptions must be made in order to select the optimum value of a particular parameter. Subsequently the initial assumptions should be progressively tested and where necessary revised.

The procedure is not as repetitive or time consuming as might be first thought, since tidal power studies, as with any other investigation, proceed by stages, each following by logical steps to the next. Typically these studies could be identified as follows:

i) Study of tidal energy potential.
ii) Preliminary optimization of plant and layout.
iii) Feasibility study.
iv) Project design.

It is anticipated that at each stage the findings of previous studies of the site can be utilized as a starting point; even though some of the results may have to be modified as the available data and knowledge of practical constraints develops. Initially of course in the study of tidal energy potential, with no previous site information to draw upon, assumptions must draw upon experience of analysis of previous schemes. The following paragraphs indicate a method of approach.

The physical parameters to be optimized are as follows:

1) Barrage location

2) Turbines - Diameter of runner
   - Number of machines
   - Turbine specification

3) Sluices - Type and discharge characteristics
   - Size of opening
   - Number of sluices

Now considering the case of an ebb-generation scheme where operation is to produce lowest cost energy, the parameters would be initially selected according to the following procedures.

5.3.1 Barrage Location

Selection of an optimum location depends upon several conflicting factors; such as: tidal regime, basin area, barrage length, and water depth along the barrage. The most important factor influencing output and economic viability is the tidal regime. Energy potential and the effectiveness with which it can be exploited, both increase with increasing tidal range. In conflict with location of the barrage for maximum tidal range is the requirement for a large basin area - the conflict arises because tidal range usually increases towards the landward end of an estuary. Barrage length has a direct relationship to construction cost and should be kept as short as possible but needs to be sufficienctly long to accommodate the number of turbines required. The depths of water along the barrage should be minimized from cost considerations but be deep enough over some distance to accommodate turbines (and sluices). Large scale dredging is particularly expensive unless bed material is soft, in which case foundations must be investigated carefully.

Other factors to consider when selecting a barrage location are for example:

- the avoidance of unfavourable foundation conditions.
- ease of access for construction.
- requirement for navigation lock(s).

5.3.2 Turbines

Axial-flow propeller turbines of one form of another are now universally adopted for tidal generation studies, refer to Section 3.1.

Diameter of Runner

The first turbine parameter to be selected is the runner diameter. Because of the large flows involved tidal power schemes usually require many turbines; the diameter of which should be as large as practicable within the constraints of manufacturing capability, transport and depth of water available. At present a manufacturing limit of about 9 metres runner diameter is indicated. Maximum diameter produced to date is 8.4m, and a 9m diameter machine is considered a reasonable extrapolation of present experience.

For the largest diameters a foundation level of 28m - 33m below mean sea level is generally required to provide adequate runner submergence to avoid cavitation. Where water depths are less than this runner diameter must be reduced. Approximate guides for selecting runner diameter are as follows:-

i) runner axis should be at least twice runner diameter below mean sea level

ii) foundation level should be approximately 1.5 times diameter below runner axis.

Number of turbines

Having selected turbine runner diameter it is then possible to make an estimate of the required number of these machines from the following empirical rule:

$$\text{No. of turbine} = 8.6 \times \frac{AH^{1/2}}{D^2}$$

where A = basin mid tide area (km^2)
H = mean tidal range (m)
D = runner diameter (m)

The number of machines indicated can only be a very approximate guide since economic and many other factors have not been considered. Where energy calculations are to be performed computations would normally be made for -50% to +50% of the number of turbines indicated. Subsequent costing and revenue exercises will indicate what is the true optimum number of machines.

Initial Turbine Specification

Since the case being considered is that for an ebb-generation scheme, turbine specification must initially identify what method of discharge regulation is to be adopted. Previous studies of ebb-generation schemes have determined that a double-regulated propeller turbine is not necessary, its small efficiency advantage being insufficient to compensate for the additional complexity and cost compared to either of the single-regulated derivatives, refer to Section 6.

Fixed distributor (FD), variable blade (VB), propeller turbines exhibit a wide range of efficient operation (although not as wide as the double-regulated machine), maintaining reasonable efficiency over a wide range of operating head. This type requires a downstream gate in the draft tube for operational and emergency purposes since closure of the runner blades does not stop the flow of water completely.

Variable distributor (VD), fixed blade (FB) propeller turbines have a narrow range of efficient operation and do not maintain efficiency well when operated away from the design head. Nevertheless because VD FB types can discharge larger volumes at low head conditions although at low efficiency, on balance there is little to choose between the generating potential of VD FB and FD VB types. The main reason behind this is that for tidal generation if volumes of water are not utilized they are effectively lost with the next incoming tide. Thus discharge capability is almost as important as the efficiency of operation.

In consequence, selection of the method of regulation can be deferred to a later date when the turbine/generator arrangement whether it be Bulb or Straflo is selected, since this has some bearing on matters also. Because of availability of data and ease of use, the VD FB type has been used almost universally for preliminary investigation. The remaining turbine specifications are as follows:

Rated Head

This is the operating head at which the unit reaches the generator limit capacity, thereafter as head increases turbine discharge is throttled by distributor or runner-blade adjustment to limit the power generated. A generator output limit is required because although higher outputs could be produced on a few extreme spring tides, it would not be economical to do so.

Experience indicates that for a preliminary appraisal, rated head should be choosen to be approximately the mean tidal range.

Rotational Speed

Ultimately this should be a convenient synchronous speed however, since speeds are inevitably low these are close together and only when speed is finally selected is it necessary to ensure that it is synchronous.

For the characteristics commonly used rotational speed is selected as follows:

$$n_{11} = 180 = \frac{nD}{\sqrt{h}}$$

where n_{11} = unitized turbine speed parameter (rpm)
n = rotational speed (rpm)
D = diameter (m)
h = rated head (m)

hence $$n = \frac{180\sqrt{h}}{D}$$

Generator Limit Capacity

This is evaluated directly from the turbine characteristics using the selected rated head.

Runner Submergence

At an early stage it is not convenient to specify a submergence but rather to consider the worst case (spring tide, sea level minimum and turbine head maximum) and establish the submergence required for this. Further refinement requires computer modelling to indicate energy loss if a reduced submergence is specified. The energy loss results from throttling of discharge for short periods of time when conditions indicate cavitation.

5.3.3 Sluices

Type and discharge characteristics

It has become established that where sufficient water depth is available the submerged Venturi-type sluice is adopted. The reasoning is because this type has good discharge characteristics and a low risk of storm damage. Alternative choices would be the flap gated type or radial gated sluice.

Venturi-type sluices incorporate a vertical lift gate located at the throat of a water passage which contracts sharply on the upstream side and expands more gradually on the downstream side acting as does a turbine draft-tube. Under operating conditions the water passage remains submerged at all times thereby maximising the available sluice discharge capacity and maintaining stable operating conditions. The coefficient of discharge has been established from model tests over the years, Refs 42 and 43, reported figures vary however; coefficients of 1.5 to 1.8 are widely accepted.

Size of Opening

As with turbine diameter, the larger the better to make best use of available barrage length - the width of gate is more restricted (to about 12m) and the height limited only by practicalities of construction and the depth of water to ensure submergence under all operating conditions. A size commonly considered has a throat area of 12m x 12m.

Number of Sluices

As for turbines an empirical rule is used to obtain a first estimate of the number of sluices which may be required for an optimum development. The rule is :

$$\text{No. of sluices} = \frac{15.3 \times AH^{\frac{1}{2}}}{\text{Throat area } (m^2)}$$

where A = basin mid tide area (km^2)
H = mean tidal range (m)

Again for economic optimization a range of sluice numbers should be considered which may extend to ±50% of the figure derived above.

5.4 Ebb-generation energy studies

Typical ebb-generation energy studies involve the initial selection of turbine generator parameters and sluice parameters as described in Section 5.3, followed by computation of annual energy yield for a range of turbine and sluice numbers so that the combination giving lowest cost energy can be identified. To indicate the type of data and the results of these studies details are given here of studies of the proposed tidal generating barrage across the Mersey estuary.

5.4.1 Mersey Barrage: Line 3 site data

Tidal data

The predictions of tidal ranges at Liverpool for 1974 made by the Admiralty Tide Tables Volume 1 form the basis for predictions of sea level outside the barrage. These predictions have been modified to allow for an anticipated reduction of tidal amplitude of 3.5% caused by the interference of the barrage upon the existing tidal regime. The magnitude of the tidal range reduction is at this stage tentative and is based upon figures provided by the Institute of Oceanographic Sciences (IOS) at Bidston. IOS have a 2-dimensional numerical model of the West coast of England and the Irish Sea areas. Their comparison of existing tidal amplitude at the barrage site using the model both with and without the Mersey estuary has indicated the overall reduction of tidal amplitude mentioned above. The situation modelled in this way, effectively an impermeable barrier at the barrage site, is not realistic but provides the best available estimate of this phenomenon.

Additionally the single-tide model requires a number of typical tides for evaluation; the data used derived from the Admiralty predictions is shown in Table 5.1.

Basin Data

Basin areas are obtained by linear interpolation between measured areas at a number of levels, refer to Figure 5.3 and 5.4 for Line 3.

Turbine Data

For these calculations, data for a variable distributor fixed blade (VD, FB, FS) turbine has been used. Turbine efficiencies are obtained from a bi-cubic spline fit to EWZ Drg. No. 1067309. The data is applicable to both bulb and Straflo turbines, the characteristic is shown in Figure 5.5:

Blade angle	14 degrees
Number of turbines	21 (20 operational)
Diameter	7.6m
Rotational speed	55.556 rpm
Installed capacity	23.0 MW
Rated head	6.0 m
Minimum net head	1.557m
Refilling capacity as sluice at 1m net head	260m^3/s
Centreline spacing	19.0m
Runner axis setting	-12.93m O.D.
Caisson bed depth	-22.33m O.D.
Caisson exit area	210.00m^2
Majoration at B.E.P (decreases linearly to 0 at 0% efficiency)	3.6%
Power system losses & Generator efficiency	Incorporated in electrical losses

Sluice Data

Number operational	15
Coefficient of discharge	1.8
Centreline spacing	19.0m
Caisson bed depth	-16.93m O.D.
Throat area	144.00m^2
Caisson exit area	270m^2

Electrical losses

The power system losses used are shown below and allow for all electrical losses including generator efficiency.

Power MW	Total Loss MW
0	0.586
1	0.586
2	0.590
4	0.601
8	0.647
12	0.724
16	0.831
20	0.969
23	1.093
24	1.093

5.4.2 Results of computations

Figure 5.6 provides the results of energy computations indicating the variation of energy output with tidal range. For each tide considered energy output per tide is multiplied by the appropriate number of annual occurrences and annual energy summated. Figure 5.7 indicates the variation of annual energy yield in response to changes in the number of turbines and sluices installed. This figure shows in particular the diminishing returns achieved by installing a large number of sluices. Also indicated are approximate contours of cost of energy production derived from a preliminary economic appraisal. The cost of energy contours indicate an optimal scheme to consist of approximately 21 Turbines and 15 Sluices.

Considering the indicated optimum scheme the predicted effect upon water levels inside the barrage is shown in Figure 5.8. It is typical for ebb-generation schemes that high water levels are only slightly reduced and that low water levels fall only to about the mean tide level.

For the same scheme, Figure 5.9 shows the variation of scheme power output with time and the tidal range. This shows that on extreme neap tides generation takes place over just 2 hours of the tidal cycle of 12 hours 20 minutes, whereas on extreme spring tides the generating period reaches almost 7 hours. On spring tides the generator capacity limit can be seen to limit power output at low tide. By combining Figure 5.9 with the histogram of tidal ranges it is possible to generate Figure 5.10 showing the hours per year when specific power output levels are exceeded. This is the annual power duration curve, which shows that the generator capacity limit only restricts power output for about 300 hours per year.

Many additional parameters can be considered, such as:

- turbine rotational speed, generator capacity and turbine type (as discussed in Section 6).
- turbine runner submergence and the cavitation limit.
- the turbine design point by considering the turbine head duration curve.

5.5 Ebb-generation plus sea-basin pumping studies

A cursory examination of the addition of sea-basin pumping operations to increase the volume and level of the retained water appears particularly attractive because the pumping would take place at low head and the pumped volume discharged at a greater head as the tide level outside the barrage falls; Figure 4.4 refers.

Unfortunately all the anticipated benefit cannot be realised because of a number of practical considerations. These are mostly concerned with the limitations of turbine-generator equipment, as follows:

- Turbines designed for ebb-generation operation are not capable of passing equivalent flows when pumping and turbining - hence large volumes cannot be pumped when the differential head is small.
- Pumping efficiency is considerably lower than turbine efficiency thereby increasing energy consumed.
- Motor efficiency reduces the amount of useful work done by a specific amount of input energy and the benefit of pumping is then further reduced by the subsequent generator efficiency loss.

Nevertheless ebb-generation plus pumping operation has been considered for the Severn Barrage, Refs. 32 and 45, using a modified version of the standard ebb-generation program. A FD VB turbine and pump characteristic provided by Neyrpic was used for the study because it has good ebb-generation performance and reasonable sea to basin pumping efficiencies. For this type there would be little additional capital expenditure required to facilitate pumping, over the cost of an ebb-generation only barrage. The additional equipment needed would be input power metering and additional switchgear and control equipment. The turbine characteristic proposed would be:

Turbine type	: FD VB Drg. HS9983
Runner diameter	: 8.2 m
Rotational speed	: 55.556 rpm
Generator capacity limit	: 30 MW
Rated head	: 6.07 m
Rated discharge	: 637 m^3/s
Minimum head	: 1.43 m

For this type the maximum efficiency pumping characteristic has been found most productive, pumping conditions are thus as follows:-

Pumping head (m)	0.80	1.21	1.71	2.20	4.08
Pump discharge (m^3/s)	189.00	178.00	170.00	167.00	167.00
Pump efficiency (%)	39.00	49.00	59.00	69.00	76.00
Electrical input power (MW)	4.07	4.66	5.22	5.63	9.49

When it is assumed that the input and output energy is of equal value, the annual energy yield is increased by 2.2% over ebb-generation only. Energy gain is variable according to the tidal range but the largest gain of 4% is found at near mean tidal range. The headpond level would be increased by up to 0.5 metres as a result.

It may be observed that:

i) pumping operations do not require the full motor capacity of 30MW, and

ii) pumping is beneficial at all tidal ranges.

The energy gain of 2.2% reported from this analysis contrasts sharply with the reported values for the La Rance tidal barrage. According to Electricite de France the energy gain by use of ebb-generation plus pumping compared to ebb-generation alone would be some 11%, reference 12.

In order to reconcile these two figures additional computer runs were made which progressively brought the conditions at Severn into close agreement with those at La Rance. These runs and the results obtained were as follows:

i) Using the same turbine and pump characteristic as before, the number of turbines and sluices was adjusted to give equivalent discharge capacity per square kilometre of basin area as at La Rance. This required an increase in the number of turbines from 182 to 300 machines but the number of sluices required remained at 150.

   Using the increased number of turbines annual energy yield was increased by 5.7% by the introduction of pumping.

ii) The turbine and pump characteristic was then changed to that of the VD VB machines installed at La Rance. These turbines, being capable of operation in both directions of flow, are not ideally suited to ebb-generation only but they do have good sea-basin pump efficiencies.

> Using the increased number of turbines <u>and</u> turbine and pump characteristics as installed at La Rance annual energy yield, compared to ebb-generation only, with the same machines, was increased by 10.2%.

The result is now in line with Electricite de France claims for the advangates of pumping at la Rance, where given the installed machinery, pumping is undoubtedly attractive. For the Severn, however, where the optimum number of turbines for ebb-generation operation is lower and the machinery different, the gains are likely to be much smaller ie. about 2.2%.

From the preceding comments the case for introducing pumping operations is not proven. Indeed there is considerably variability in the energy gain (and consequently value gain) attributable to pumping according to the relative performance of the turbine and pump. What is required for the detailed investigation of the Severn and Mersey Barrages is to determine the turbine characteristic(s) leading to greatest energy yield and to determine the energy gain based upon the corresponding pump performance characteristic. This is the approach which has been applied previously but information received from the manufacturers suggests that the turbine and pump performances may not be compatible since in general the turbine mode has been more thoroughly researched and tested. If pumping is seen to be advantageous further development could enhance the energy gain. Alternatively development of a specific tidal turbine with good efficiency over a wide range of head conditions could nullify the gains from pumping.

In conclusion it is considered that pumping operations could lead to a marginal improvement in the economic viability of the Severn and Mersey Barrage schemes but to quantify accurately the improvement requires a more consistent set of performance characteristics than is currently available.

5.6 Double-effect energy studies

Double-effect operation has been considered for the Severn Barrage project so that the two inherent advantages of this mode of operation could be evaluated, namely:

- generation takes place for a larger proportion of the tidal cycle and is therefore, more likely to correspond to the peaks of system demand,

- since generating head is generally reduced the maximum power output is correspondingly less which may alleviate some of the problems of integrating large power blocks, characteristic of single-effect operation, into the electricity system.

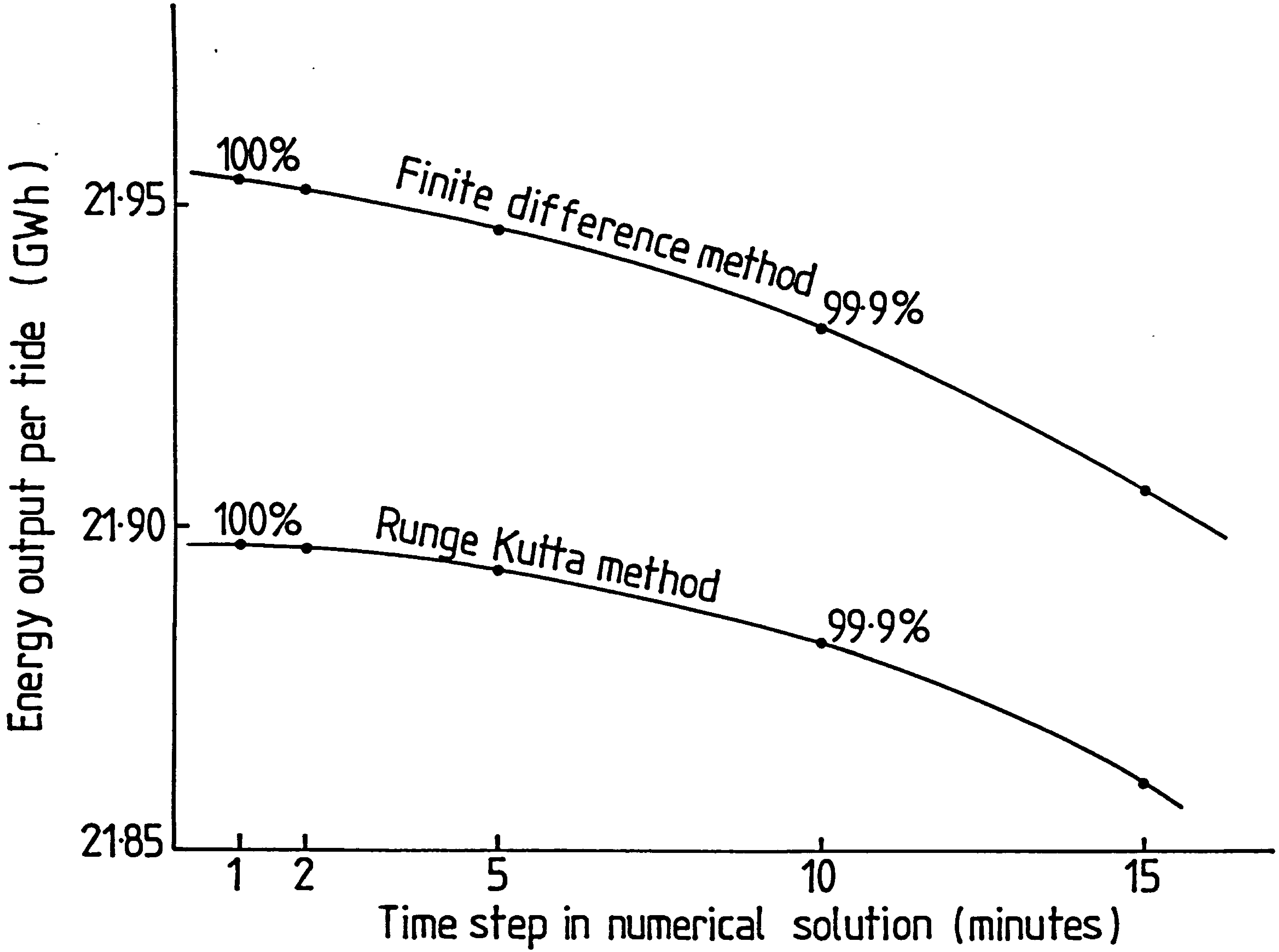
However, as a result of the compromises on runner blade design, water passage profile and distributor positioning which have to be made to allow the turbines to operate in both directions, turbine efficiency is less than for a specifically designed single-effect machine in ebb-mode and substantially less in the flood-mode. A reduced efficiency and reduced operating head combine to give substantially lower power outputs than for the ebb-generation operation. Analysis has shown that operation for maximum energy yield with generating equipment capable of double-effect operation gives a lower output than ebb-generation operation. The reduction reported was about 10%, reference 28, although it was anticipated that with more detailed investigation of this mode of operation and optimisation of the turbine-generator parameters that the reduction could be reduced.

Reference 31, details a study of the value of double-effect operation using a version of the energy optimisation program modified so that for a single tidal cycle the total value of generation, from two blocks of generation was optimised. The value of energy was determined according to time of day from the CEGB Bulk Supply Tariff. Results showed that ebb-generation operation was optimum for neap tide ranges when these coincided with a high tariff period. But for spring tides, and neap tides for which ebb-generation occurred during off-peak electricity supply periods, the double-effect mode of operation was more productive. Summated for a typical year the optimum value of double-effect operation was found to be within 7% of the corresponding ebb-generation scheme. Considering that the double-effect machine parameters were not optimised the difference could be narrowed to perhaps 1% or 2%.

In considering the economic case for double-effect machinery and operation the value of generation must be set against the increased scheme costs. For the Severn double-effect operation did not appear more economical than ebb-generation however, the principle reason for elimination of the mode from further study hinged upon the retained water levels in the reservoir. In this case the reduction in high water levels which would be experienced at the sea parts in the inner estuary would present serious restrictions upon their use by commercial shipping.

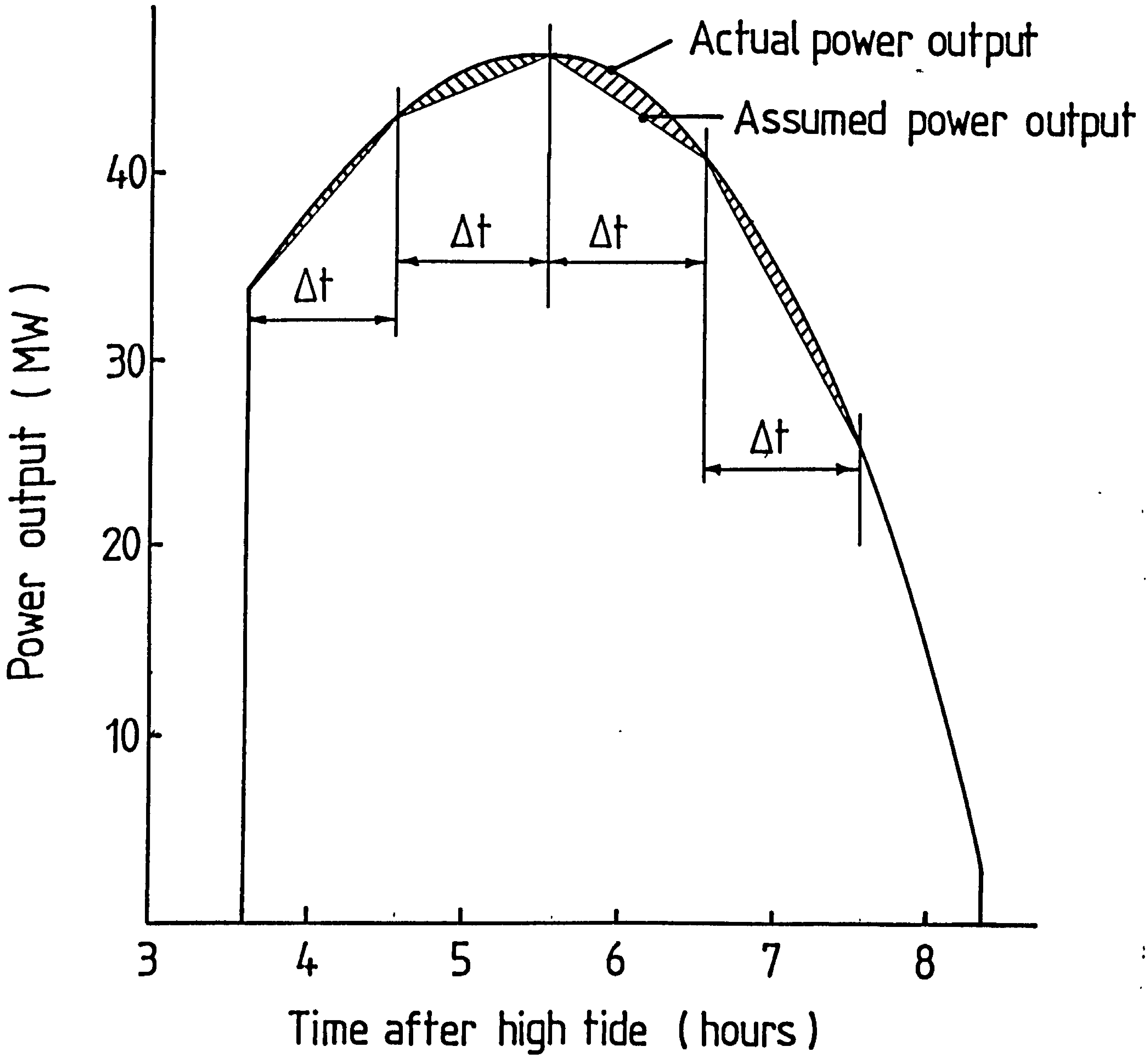
Tidal Range (m)	Levels (m A.O.D)		Rising time (mins)	Falling time (mins)	Number of annual occurences
	High	Low			
3.25	1.82	-1.43	320	420	22.5
4.25	2.32	-1.93	320	420	85.5
5.25	2.82	-2.43	320	420	135.5
6.25	3.32	-2.93	320	420	143.0
7.25	3.82	-3.43	320	420	167.0
8.25	4.32	-3.93	320	420	113.5
9.25	4.82	-4.43	320	420	35.5
10.25	5.32	-4.93	320	420	2.5

TABLE 5.1 TIDAL DATA FOR SINGLE-TIDE OPTIMISATION MODEL



TIME STEP ANALYSIS

FIG. 5.1



COMPUTATION OF ENERGY YIELD

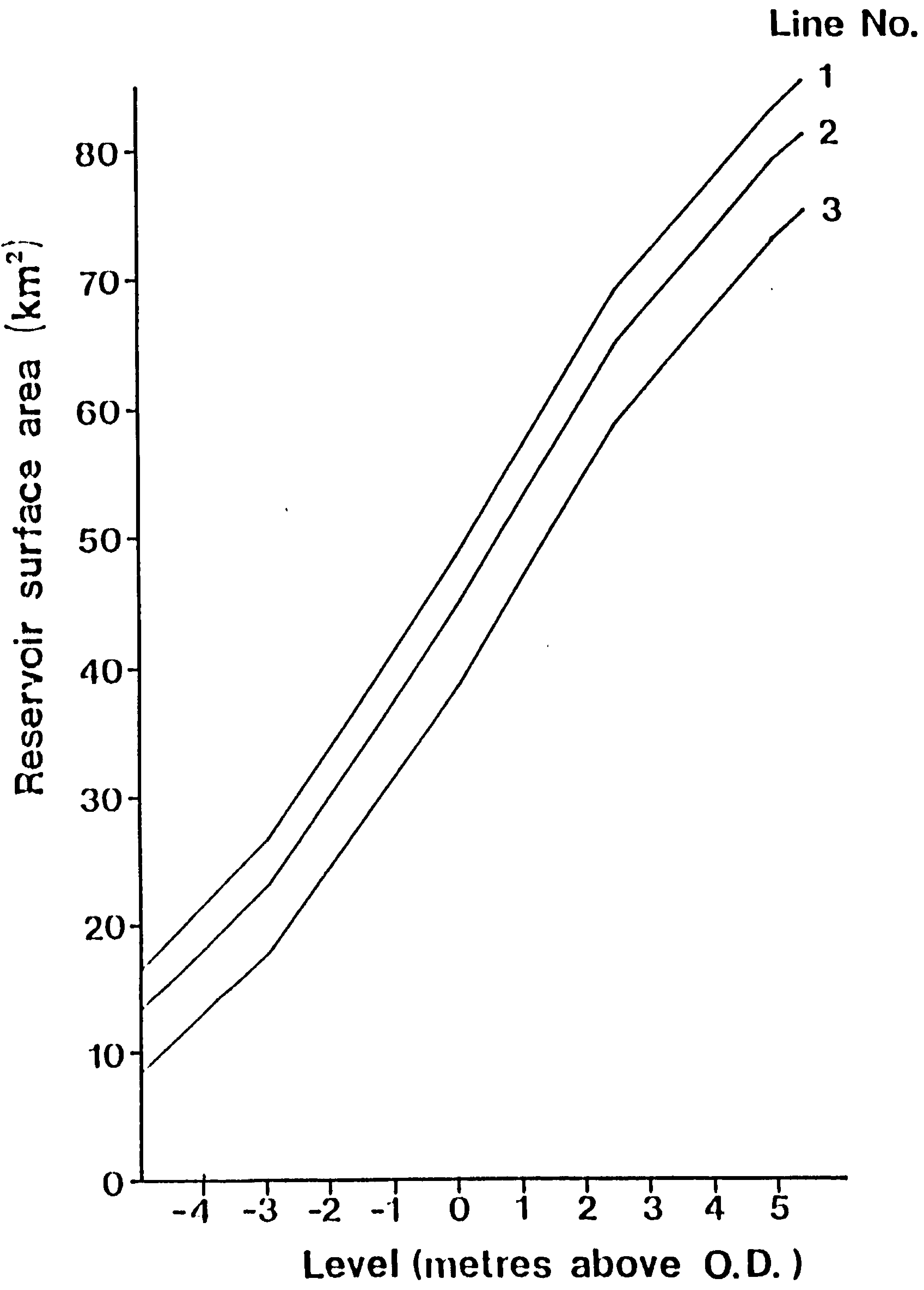
FIG. 5.2

MERSEY ESTUARY SHOWING PROPOSED BARRAGE POSITIONS

AREAS OF THE ESTUARY
(after Pugh Thomas, 1980)

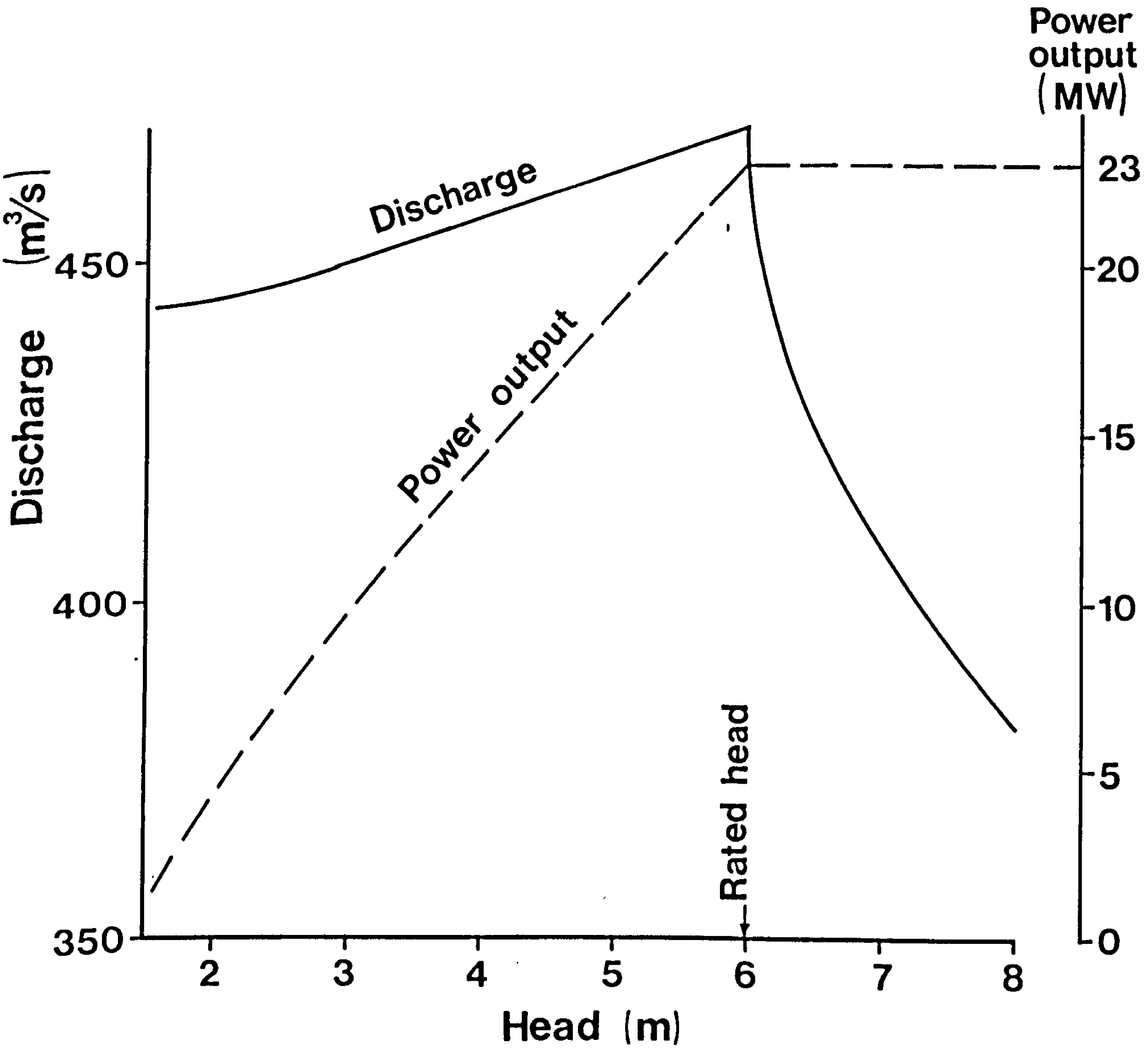
Area 1 - Outer estuary
Area 2 - Narrows
Area 3 - Inner estuary
Area 4 - Upper estuary

FIG 5.3



MERSEY BASIN AREAS

Fig 5.4



TURBINE CHARACTERISTICS

FIG 5.5

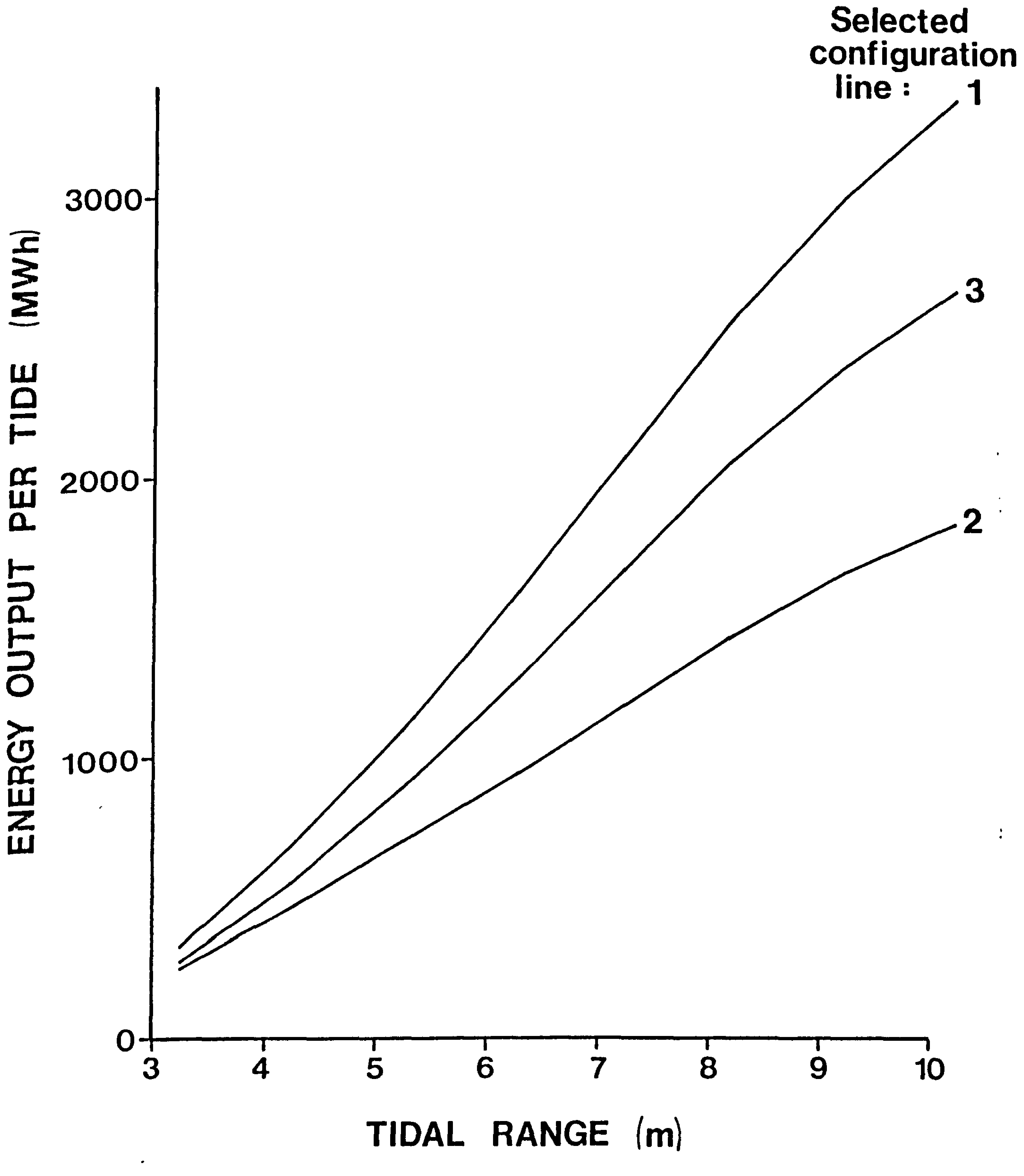
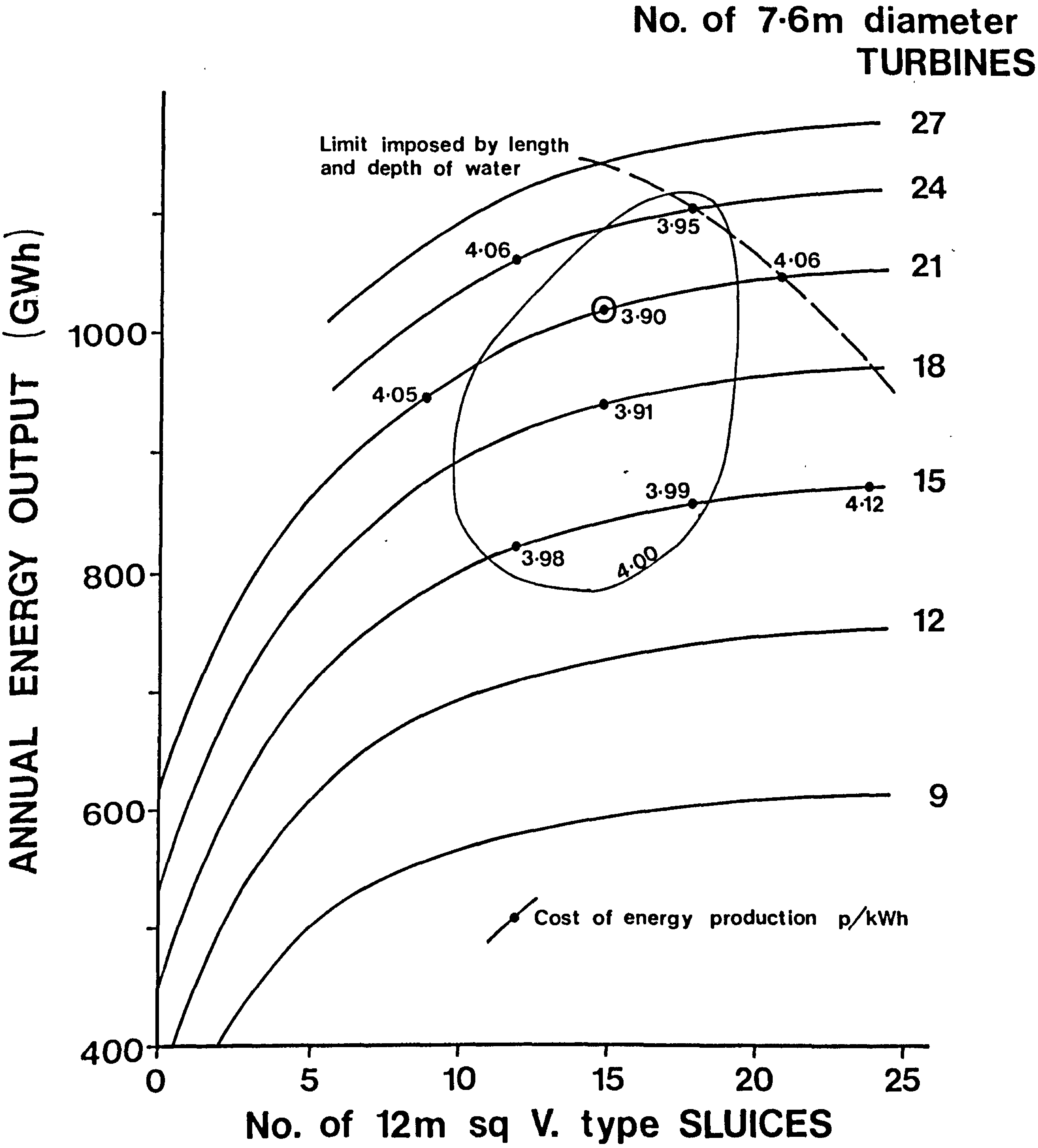
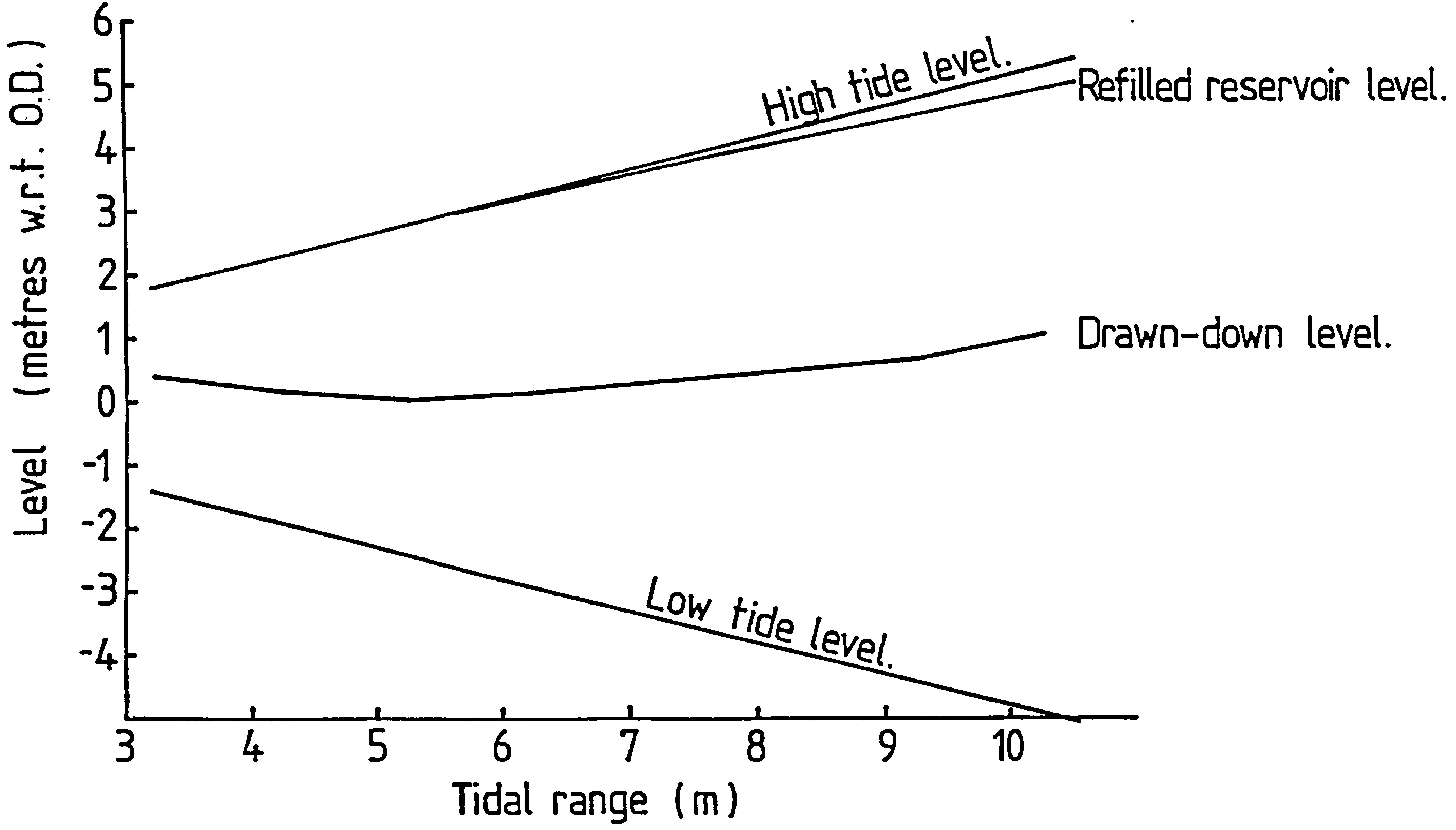

Selected configuration line :
1
3
2
3000
2000
1000
0
ENERGY OUTPUT PER TIDE (MWh)
3
4
5
6
7
8
9
10
TIDAL RANGE (m)

FIG 5.6



MERSEY BARRAGE LINE 3

FIG 5.7

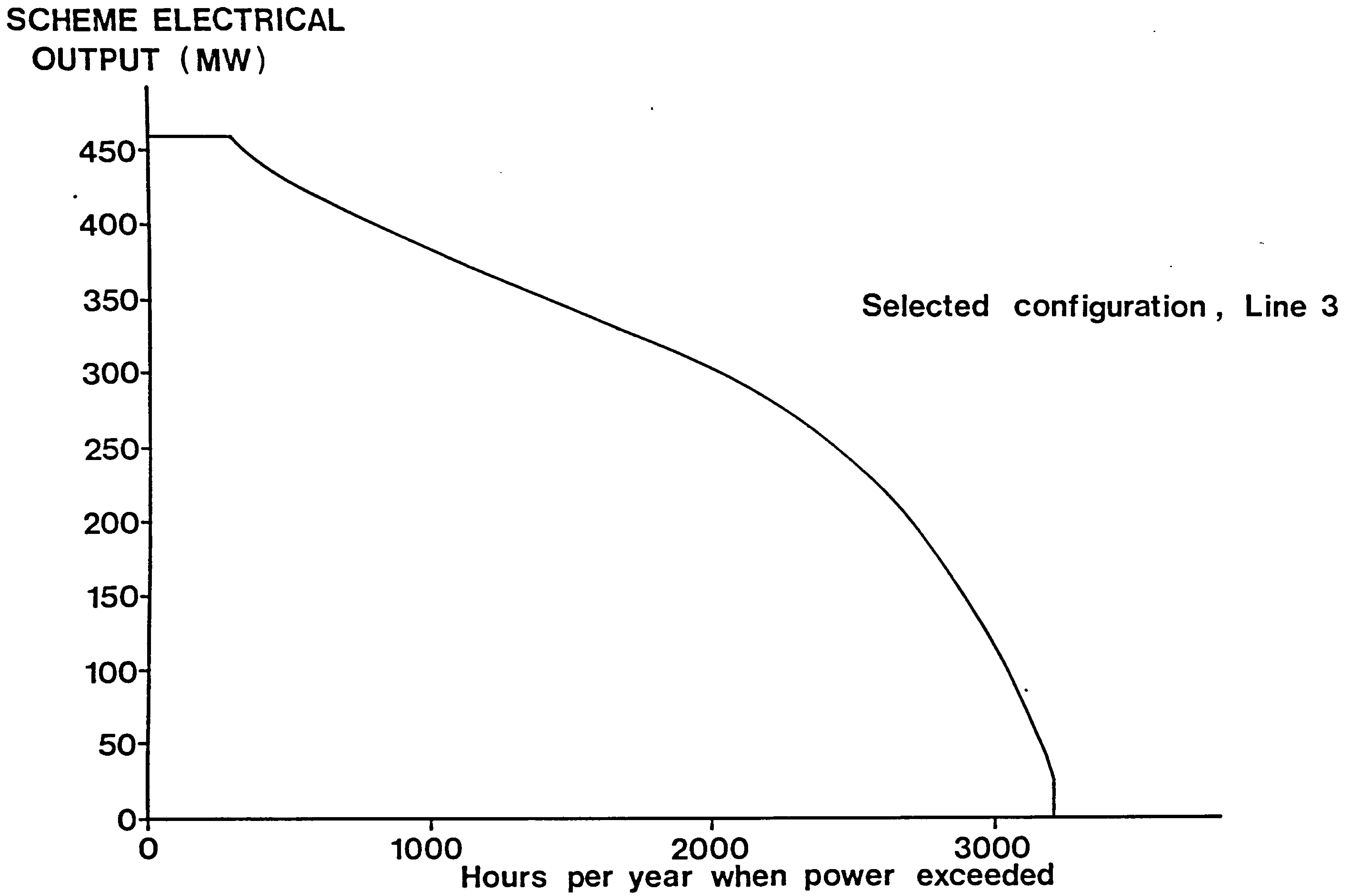


MERSEY BASIN LEVELS : LINE 3.

FIG. 5.8


SCHEME ELECTRICAL OUTPUT (MW)
450
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
11
12
High tide
Low tide
High tide
TIME (hours)
10·25
9·25
8·25
7·25
6·25
5·25
4·25
3·25
Tidal range (m)
Selected configuration, Line 3

Fig 5.9



ANNUAL POWER DURATION CURVE

Fig 5.10

6.0 COMPARISON OF TURBINE TYPES - FOR EBB-GENERATION

6.1 Introduction

Section 5 describes the common applications of the computer model in the early stages of a tidal power study when it is important to establish what are the major constraints and determine realistic values for the important parameters such as the number of turbines and sluices, and the outline specification of the turbines in terms of diameter, rotational speed and generator capacity. Having made the necessary energy yield calculations it will be possible to determine approximately the economic performance of the proposed scheme and thereby make recommendations about proceeding to refine the barrage design.

An initial assumption for ebb-generation schemes recommended in Section 5 was to adopt the VD FB turbine type on the basis of the availability and ease of use of the performance data. Clearly this is one assumption which should be investigated, particularly as the turbine manufacturers are not agreed upon which is the most appropriate solution. A comprehensive comparison of the turbine types was carried out by the writer for the Severn Barrage scheme for the UK Department of Energy and is reported in References 27, 28, 29 and 44.

The comparison was performed for Line 5, an alignment roughly between Lavernock Point on the Welsh shore and Sand Point on the English shore, one of six barrage locations considered when evaluating the tidal energy potential of the Severn Estuary. Line 5 was recognised early on to lead to lowest cost of energy produced and was considered in greatest detail in the Severn Barrage Committee report of 1981, Reference 1 and more recently by the Severn Tidal Power Group report of 1986, Reference 45. Following the initial turbine type comparisons the alignment of Line 5 has been modified to take advantage of improved water depths and foundation conditions, and the alignment now proposed is from Lavernock Point to Brean Down near Weston-Super-Mare.

The turbine type comparison for the Severn Barrage on Line 5 was completed in 1980, since that time there have been a number of changes to the site, the proposed installation and to the computer modelling methods. Accordingly the writer has recently made a new comparison using up to date data and methods and the results are presented for discussion in Section 6.5 following a description of the earlier work, Section 6.4.

In summary, the basis for the initial turbine type comparison was as follows:

Barrage location : Line 5 (reference 25)
Enclosed basin area at high water: 470km^2
Mean tidal range
(modified by barrage effect) : 7.9m

Turbine diameter : 9.0m
Number of operational turbines : 140
Submergence of the turbine axis : 10.5m below Chart Datum
Sluices, Venturi type (Cd = 1.5) : 12.2m x 12.2m throat
Number of sluices : 150

6.2 Comparison of fixed (synchronous speed options)

Section 3.4 indicates each of the seven practicable turbine options, of which there are 3 fixed speed variants and 4 variable speed types. Each of the fixed speed variants was considered in detail. Turbine performance hillcharts from Escher Wyss of Zurich were used to compare energy yield from the VD FB, FD VB and VD VB types.

Variable distributor, fixed blade turbines, VD FB

Performance characteristics were available for three fixed blade angles of 8.5°, 11.3° and 14° (referred to EWZ datum) for each of which a numerical model of the dimensionless efficiency characteristic (the 'hillchart') was provided. The objective of the turbine type comparison was to determine the sensitivity of the annual energy yield to the following parameters

- rotational speed
- installed generator capacity
- blade angle

Accordingly the energy optimisation computer program was run for each combination of the 3 blade angles, 3 installed capacities and usually 4 rotational speeds. For each combination a different head/discharge characteristic was evaluated by the program so that the turbine model efficiency was faithfully applied to the corresponding prototype conditions. For these VD FB turbines, discharge was regulated along the maximum power output curve unless the limits of generator capacity or restricted runner submergence leading to cavitation were encountered. Figure 6.1 shows the results obtained for the case of a 50MW generator capacity limit, results for the 60MW and 40MW limits indicated the same trends.

The results indicate that the 14° blade opening led to the greatest energy yield at just above 50rpm, however with this blade opening energy yield is particularly sensitive to the selected rotational speed. If it should be necessary to select a rotational speed above 50rpm a reduced blade opening would become optimum, as indicated by the significantly greater energy yield from the 11.3° blade angle when running at 60rpm. In this case the sensitivity to speed variation is enhanced by the limited runner submergence allowed, which limits the permitted discharge at low tide levels.

An envelope curve is shown on Figure 6.1 representing for the particular speed the optimum energy yield using the best blade angle. The curve shows the absolute peak energy yield has been reached and that increase of blade angle beyond 14° would not bring greater energy yield. This envelope curve is used in Section 6.4 for comparison of energy yields from the other machine types.

Fixed distributor, variable blade turbines, FD VB

Performance characteristics for three distributor settings were used, namely 73°, 77° and 80°. These characteristics each represent the results a series of model tests on a VD VB type machine with the distributor vanes held in a constant position. However, although the term 'fixed distributor' is used to describe non-moving guide vanes upstream of the runner, a prototype machine of this description would not have the number (approximately 16-18) of vanes, appropriate if they were to be moved, nor would they be the same shape. It is probable there would be between 6 and 8 fabricated guide vanes and that this fixed arrangement would be hydraulically more efficient than the variable distributor arrangement when held in a fixed position. The extent of the efficiency gain is however uncertain and in consequence the model test data has been applied without modification, but the potential gain, perhaps 1% to 2% has been noted.

The parameters have been varied in the same way as for the VD FB type and results for the 50MW case are shown in Figure 6.2(a). In the computer simulation the turbine discharge was regulated according to the Calculus of Variations solution to maximise energy yield. For this type - energy yield is less sensitive to variation of rotational speed than the VD FB case and there is no apparent requirement to adjust the fixed distributor angles in response to a change in the synchronous speed. The 73° distributor opening shows the highest energy yield over the range of speeds considered, this opening also shows that energy yield is approaching a maximum as speed is reduced below 50rpm. Considering vertical sections through Figure 6.2(a) as shown in Figure 6.2(b) it can be seen that the 73° distributor opening is optimum. This condition applies over the whole speed and capacity ranges and accordingly results for the 73° distributor opening are used in Section 6.4 for comparison with energy yield from the other machine types.

Variable distributor, variable blade turbines, VD VB

A single performance characteristic of this type was modelled using the bi-cubic spline modelling technique. In this case the dimensionless efficiency characteristic is presented for a variable blade machine up to a maximum blade opening of approximately 15° and this limit introduces a discontinuity on the diagram. Accordingly efficiencies were extrapolated for blade openings in excess of 15° to obtain a good fit to the model test data, and operation in the simulation model was restricted to a specific discharge below the 15° blade opening. Turbine discharge during each generating period of the simulation was regulated to maximise energy yield using the Calculus of Variations solution.

Generator capacity and rotational speed have been used as for the previous machine types to produce for each power capacity a curve of energy yield against rotational speed. The curves exhibit a maximum at about 50rpm, and are discussed in Section 6.4 in comparison with the other turbine types.

6.3 Analysis of variable speed turbine operation

The advantages of variable-speed turbine operation are described in Section 4.6, however until the writer had made energy production calculations the impact upon energy yield remained unknown. Only two of the four possible variable speed variants have been considered; the FD FB VS and VD FB VS types. The VD VB VS type was not considered because the energy gain over VD VB FS type was thought unlikely to offset the additional costs associated with VS operation, but future studies should consider the FD VB VS type.

When operating at variable speed the generator design parameter becomes the maximum required torque, although a maximum power output limit may also be necessary to reduce investment on increased transmission capacity. Generator torque is proportional to power output divided by rotational speed, accordingly the higher the power output for a given speed the higher the torque and the higher the generator cost. For comparison of the turbine types the variable speed options are compared with other types which require generators of equivalent torque so that the cost of generators is similar. With variable speed operation the number of poles can be selected and may be reduced below that required for synchronous operation, perhaps leading to a cost reduction.

Variable distributor, fixed blade, variable speed turbines VD, FB, VS

Considering the same dimensionless efficiency characteristics as for VD FB FS work it is noted that if speed is free to vary there is a range of Q_{11} and n_{11}

values for any particular operating head. The Calculus of Variations solution selects the appropriate discharge, hence Q_{11} , for each step in the computation and then an optimisation routine varies the value of n_{11} to maximise efficiency and power output.

In a prototype scheme the machines would be operated according to pre-programmed instructions dictating the distributor opening and rotational speed linked to the time-into-generation of a particular cycle. Speed control would be achieved by electrical loading of the turbines either singly or in groups. Figure 6.3 shows a typical prototype head/discharge characteristic for a VD FB VS turbine, indicating also the operating paths chosen by the maximum energy method for the selected tidal ranges. This diagram shows for each head and discharge the optimum efficiency, there is of course a range of efficiency for each point depending upon the selected rotational speed. Sub-optimal conditions are adopted when constraints such as the cavitation limits or generator torque are encountered. Figure 6.4 shows for a spring tidal range how the optimum operating paths are modified when these constraints are effected.

Operation of the turbines would begin at maximum efficiency at point A, and follow the optimum path until the cavitation limitation is reached as operating head increases and sea level falls, point B. From B, operation would be regulated to avoid cavitation conditions until at point C the generator torque limit is reached, whereupon speed is allowed to increase as head increases maintaining constant torque. As operating head falls the optimal solution departs from the limit torque at D and follows the cavitation limit until E and then follows optimal discharge regulation until F is reached where operation ceases at the minimum operating head on the maximum power output curve.

Inspection of Figure 6.3 shows high efficiency can be maintained even to very low operating head. Accordingly the VD FB VS type can produce significantly greater energy output on low tidal ranges than for example the corresponding VD FB FS machine. Table 6.1 shows how this energy gain deminishes as tidal range is increased, when the speed of operation of the VS machine approaches that of the FS option.

For the same site conditions as for the fixed speed machines, evaluation of annual energy yield, for the combination of fixed blade angle (8.5°, 11.3° and 14°) and maximum generator torque leads to the results shown in Figure 6.5. Again it is shown that optimum blade angle varies in this case according to the torque limit. As for synchronous operation the envelope curve is used in Section 6.4 for comparison of energy yield from the other machine types. It should be noted that no deduction has been made for the rectification and inversion losses which might be of the order 1-2% of annual energy yield.

Fixed distributor, fixed blade, variable speed turbines FD, FB, VS

With this option operational control is maintained solely by adjustments to the electrical load on the generator, to control rotational speed and hence discharge. For a particular Q_{11} there is only one value of n_{11} possible with this type of unregulated turbine. As with the VD FB VS type the generator design parameter is the maximum required torque, however in this case a power capacity limit is undesirable because as head increases a power output limit would force operation towards a lower discharge and hence lower speed which would increase torque. Consequently the maximum required torque is determined by the most severe operating conditions.

Figure 6.6 shows the maximum energy paths for operation through a neap tide, a mean tide and a spring tide cycle. The required generator torque rating being determined by the requirements of the spring tide. Figure 6.6 shows however the ideal situation where turbine operation is not influenced, for example, by cavitation limits. When the cavitation limit is enforced operation must deviate from the optimum path on large tides and an increased torque is required. Figure 6.7 shows the effect on the operating paths for three different tidal ranges, again indicating that the largest spring tide determines the torque requirement. Restriction of the level to which the basin refills was identified as one way of reducing the torque required on extreme spring tides, as indicated by Figure 6.8.

Alternatively, a different, reduced, blade opening was found to be advantageous, Figure 6.9, leading to a rather lower energy loss per annum than the restriction of refilling as shown by Figure 6.10. This figure indicates, as might be expected from the results obtained using the synchronous turbine types, that a distributor opening of 73° and a blade angle of 15° is optimum, but if a reduced generator torque is to be provided the blade angle and ultimately the distributor angle should be reduced.

6.4 Comparison of machine types

The turbine types are compared in Figure 6.11 on the basis of their annual energy yield for specific rotational speeds and generator capacity. For clarity only the envelope curves for optimum blade or distributor setting are shown for the VD FB FS, FD VB FS and FD FB VS types.

For the variable speed options the curves show torque plotted to correspond to the rotational speed axis at the particular generator capacity. The values of maximum torque are indicated at discrete points along the curves. Presentation of the variable speed results in this way is to demonstrate the energy producing potential of all the machine types in as comparable a fashion as possible. At each point with the variable speed machines there will be a speed variation from about 30-70 rpm and the maximum power production may exceed the capacity indicated for the three synchronous machines shown. However the object is to set the VS machines in a context where its generator size and cost is of the same order as for the synchronous types, though the turbine (and draft tube gate) cost will vary appreciably.

A specific comparison has been made assuming a 50MW generator capacity limit for the synchronous types since this is believed to be near optimum for the Severn Barrage (assuming 9m diameter turbines). The optimum rotational speed to consider appears to be 50 rpm and so assuming the energy yield of the VD VB FS type to be 100% the comparison is as follows:

Synchronous options:	VD VB FS	100.0%
	VD FB FS	97.1%
	FD VB FS	96.2%
Variable speed options:	VD FB VS	101.4%
	FD FB VS	97.2%

It can be seen that provision of single-regulated VD FB FS turbines leads to a reduction of almost 3% in energy yield when compared to the double-regulated VD VB FS type. It has been argued that the savings in first cost (perhaps 10%) and the reduced maintenance requirements of the single-regulated machine leads to a more economical scheme despite the reduction in energy yield, Reference 1 and 45.

Comparison of the two single-regulated, synchronous types shows a difference in favour of the VD FB type of about 1% of annual energy yield. This result is in apparent conflict with the belief of the French turbine manufacturers Neyrpic who rightly point to the wider range of good efficiency achieved by the FD VB type. In considering this dilemma the writer has made limited comparisons between the FD VB and VD FB types using Neyrpic performance data and the result confirms the manufacturers view. Because the Neyrpic FD VB performance data was for a purpose designed fixed distributor, which the Escher Wyss data was not, these results could indicate that the efficiency gain from redesign of the distributor is sufficient to swing the balance in favour of the FD VB type. Or, alternatively, through their greater experience with the VD FB type Escher Wyss could have developed a blade profile of superior overall performance. The former is thought more likely to be the case.

The variable-speed options show energy yields to be slightly above that of the VD VB FS machine for VD FB VS and about 3% below it for the FD FB VS machine. These results indicate that a significant energy gain is not obtained, particularly when it is recalled that rectification and inversion losses (approx 1-2%) have not been deducted. Consequently, following the publication of these results, in references 27 and 28 this option has not been considered in further detail for the Severn Barrage scheme. Conversely a study of tidal power generation in Cumberland Basin, in the Bay of Fundy, Canada reference 36, recommends variable speed operation on the grounds that because the output of the scheme was to be transmitted over 600km to New England a d.c. link would be required anyway and so the cost and energy losses associated with rectification and inversion of the output would be common to all generation options.

In comparison with VD FB FS, operation at variable speed would therefore allow either:

i) additional energy yield using VD FB VS machines or,
ii) reduced first cost and maintenance costs using FD FB VS machines.

It is fair to say however that unless special circumstances arise, such as for Cumberland Basin, that variable speed operation does not achieve substantial energy gains.

6.5 Update of the turbine type comparison

The turbine type comparisons made in Section 6.4 were made in 1980 when it was assumed in the energy computations that the difference in water levels across the barrage could be used directly as the turbine head to be applied when using the turbine performance characteristic. As stated in Section 3.6, to compensate for this over-estimation of head, model turbine efficiency was used without majoration. It was however appreciated that comparison of turbine types on this basis was not strictly appropriate because of variation of the downstream energy losses according to turbine discharge, which differs for a given head for the various turbine types. Consequently the writer has reworked the comparisons for the synchronous types using the net effective turbine head calculation described in Section 3.6 and applied majoration according to the Hutton scaling formula (with linear variation of efficiency step-up down to zero at zero model efficiency).

The results of the new turbine type comparison, using updated Severn Barrage data, are shown for VD FB FS machines on Figure 6.12, for FD VB FS machines on Figure

6.13 and for VD VB FS and the envelope curves for the other types on Figure 6.14. For each turbine type the trends shown are as before, although for the FD VB and VD VB types energy yield is shown to peak at about 50 rpm, the reduced energy yield at low rotational speed arising from introduction of a blade angle limit.

The turbine type comparison shown on Figure 6.14 indicates an optimum rotational speed of about 50 rpm with relative energy yields as follows:

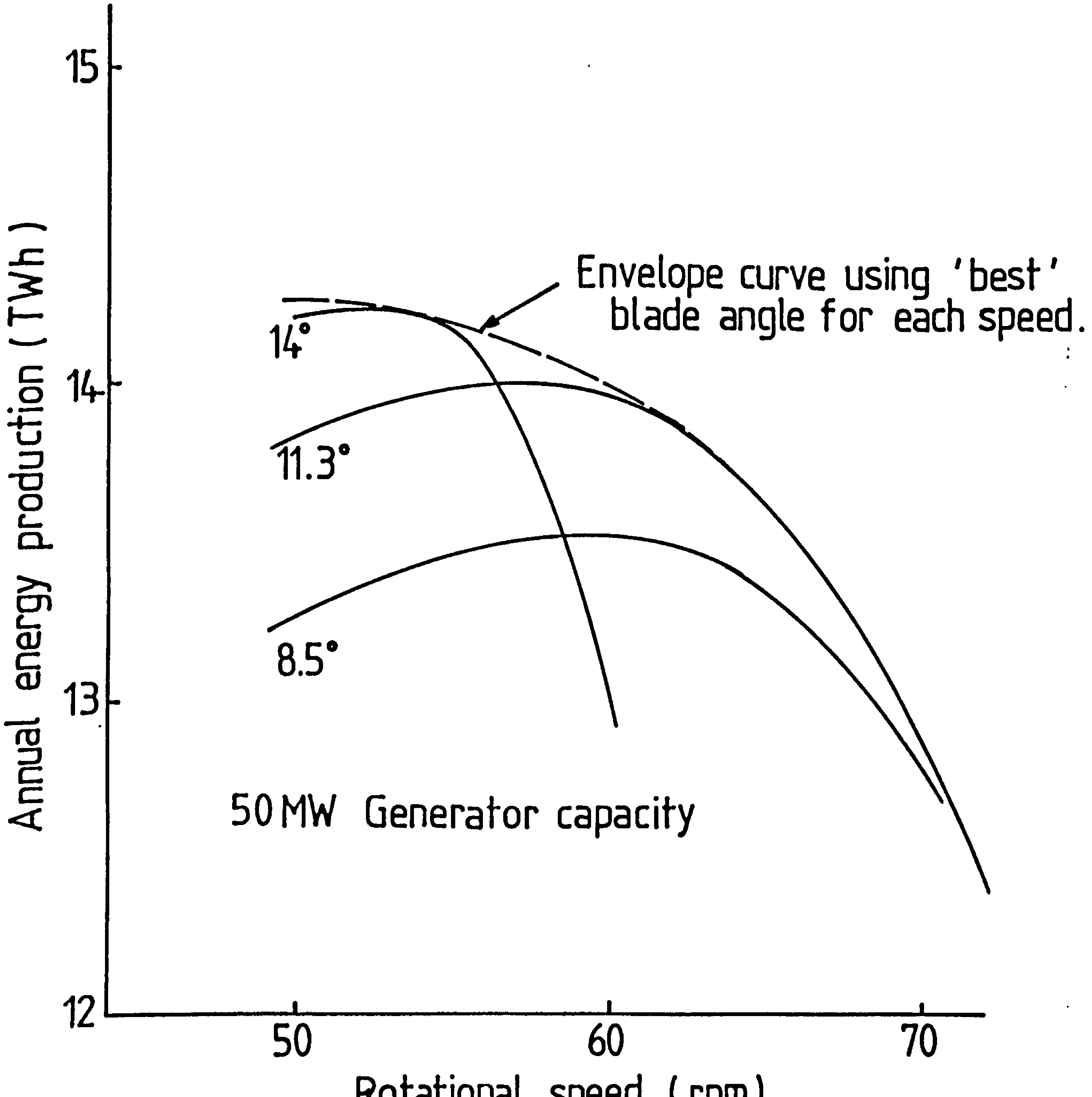
VD VB FS	100%
FD VB FS	97.2%
VD FB FS	96.3%

Interestingly the relative performance of the single-regulated types is interchanged which, when the anticipated efficiency gain of a truly fixed distributor is added to the FD VB FS type, begins to suggest a positive energy yield advantage for this type. Also with an improved distributor performance the FD VB FS type energy yield would further reduce the energy gain by selection of a double-regulated type.

Thus the latest comparison tends to confirm the view that a FD VB FS solution may be the preferred option for an ebb-generation scheme despite the requirements for provision and maintenance of a draft-tube gate. In addition this type has a reasonable performance characteristic for pumping at low head from the sea to the basin. The additional benefit, either energy yield or more importantly energy value, should be justified against the additional cost of equipment to allow motoring of the turbines to act as pumps. The justification for this is not presented here however the potential for further gains is emphasised because with the VD FB FS solution the pump characteristic is very poor making pumping unattractive, refer to Section 5.5.

Tidal Range (m)	Relative Energy Production Per Tidal Cycle	
	VD FB FS Synchronous generation	VD FB VS Variable-speed generation
4.5	100%	185%
6.5	100%	112%
8.5	100%	105%
9.5	100%	104%
11.5	100%	104%
13.5	100%	103%

TABLE 6.1 COMPARISON OF ENERGY OUTPUT PER TIDE FOR VD FB VS AND VD FB FS TYPES



VARIABLE DISTRIBUTOR, FIXED BLADE TURBINES

FIG. 6.1

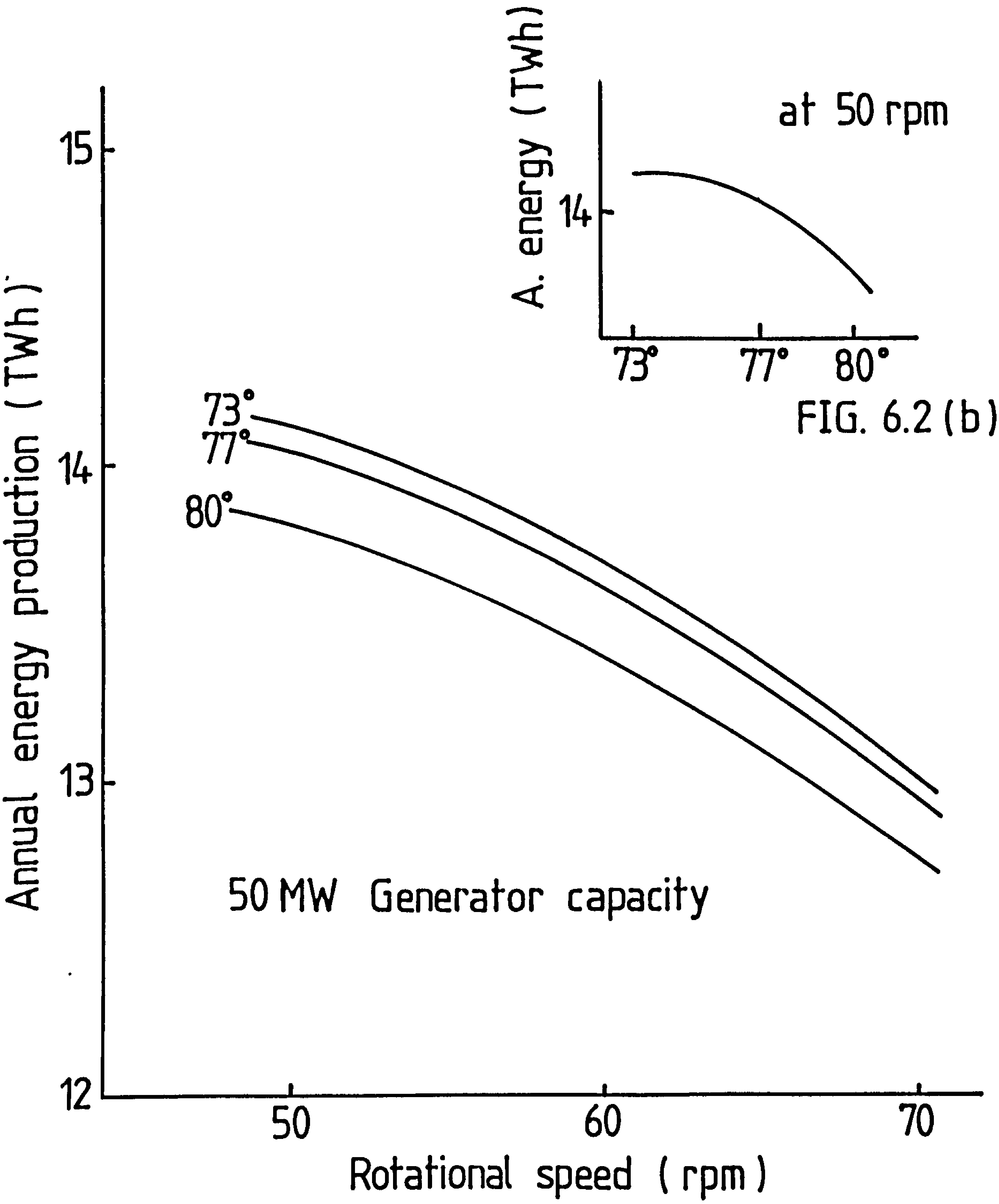
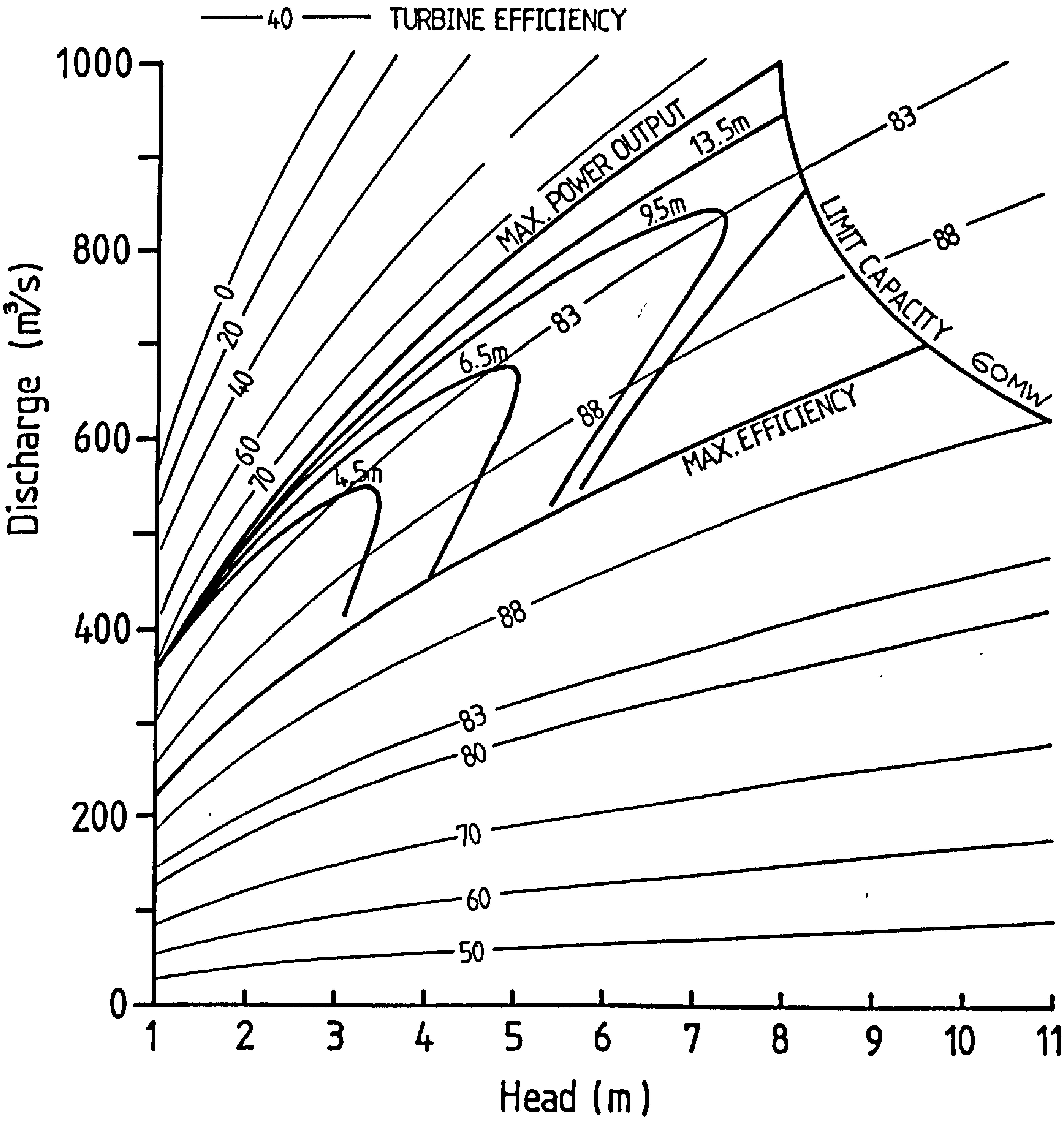


FIG. 6.2 (b)

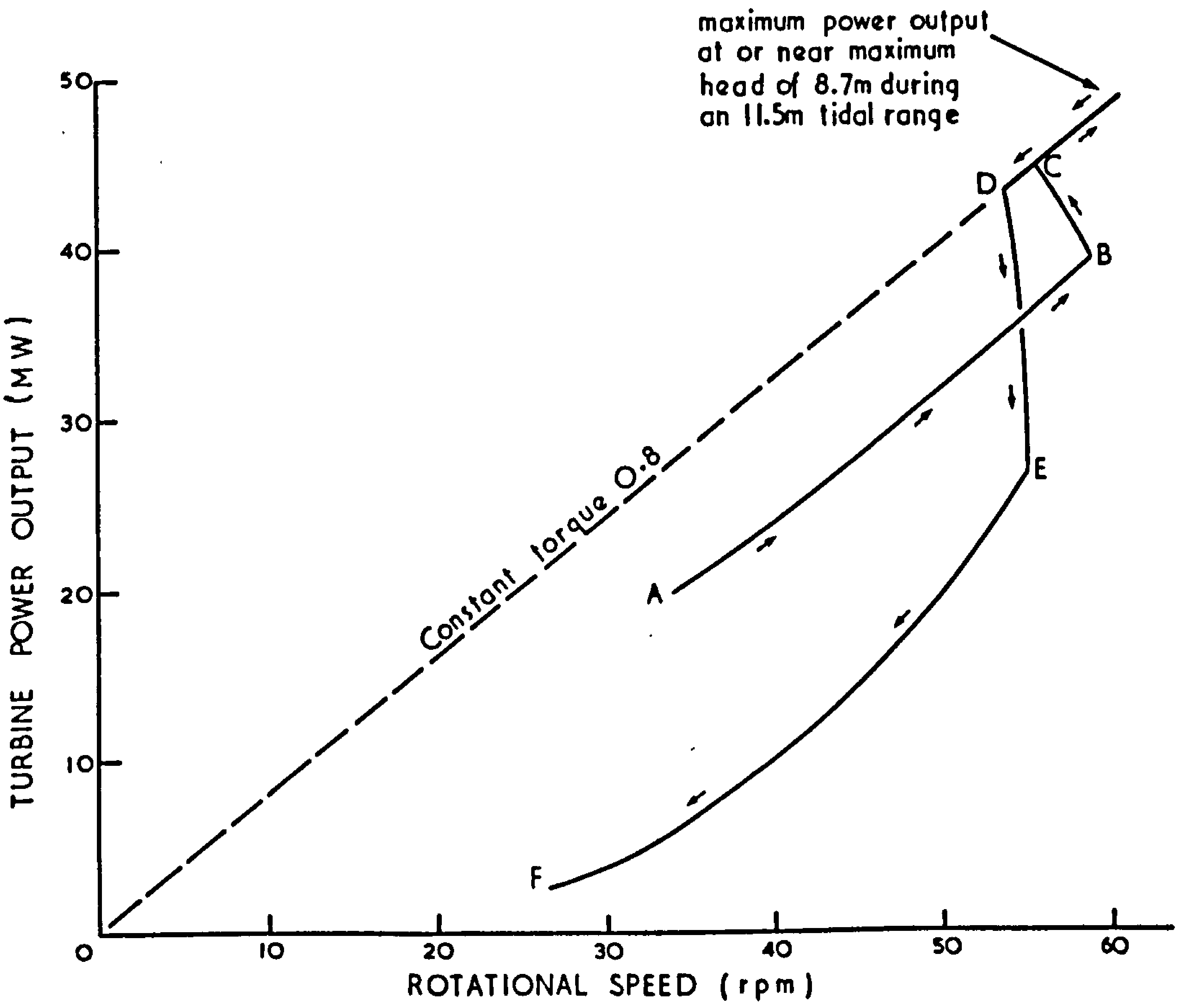
FIXED DISTRIBUTOR, VARIABLE BLADE TURBINES

FIG. 6.2 (a)



VARIABLE SPEED VD FB TURBINE OPERATION.

FIG. 6.3

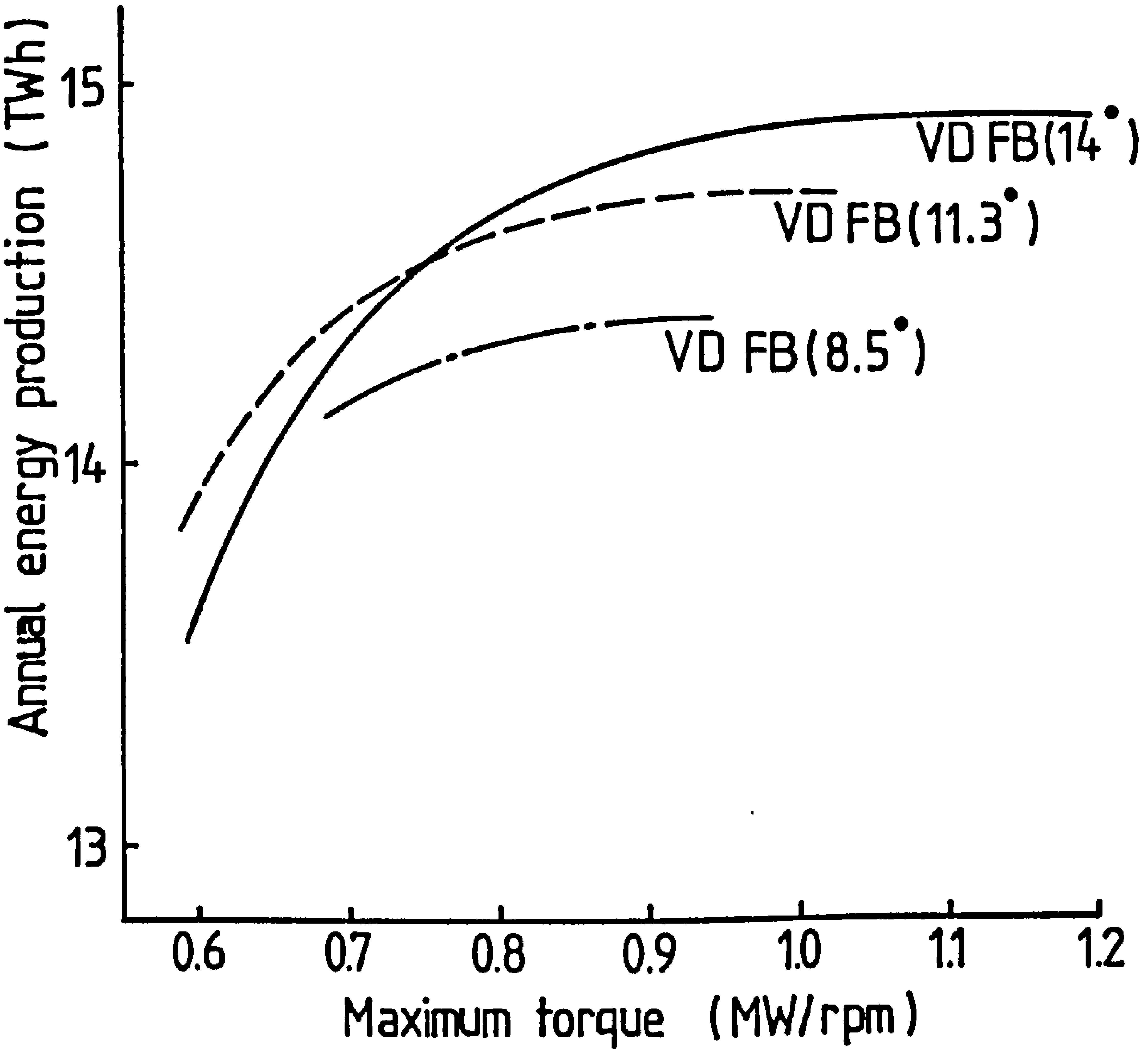


SITE 5 140 Turbo-generators (9m diameter) 150 Sluices (12.2m sq V type)
EWZ turbine characteristics. Turbine ℄ 10.5m below Chart Datum
Zero majoration.

VARIABLE SPEED OPERATION VD FB

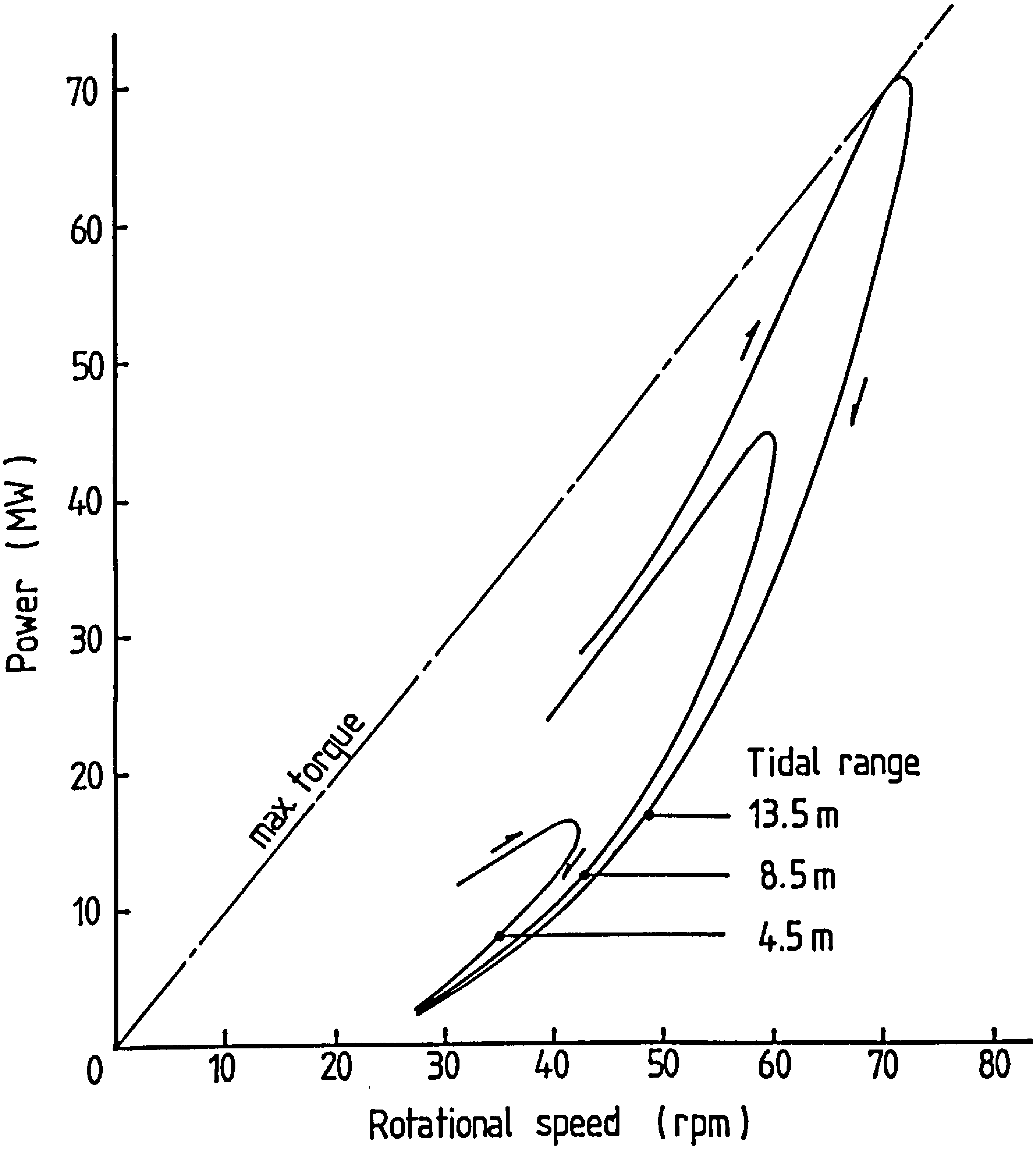
Severn Estuary Tidal Energy Survey
University of Salford: Dept of Civil Engineering
1980

Fig 6.4



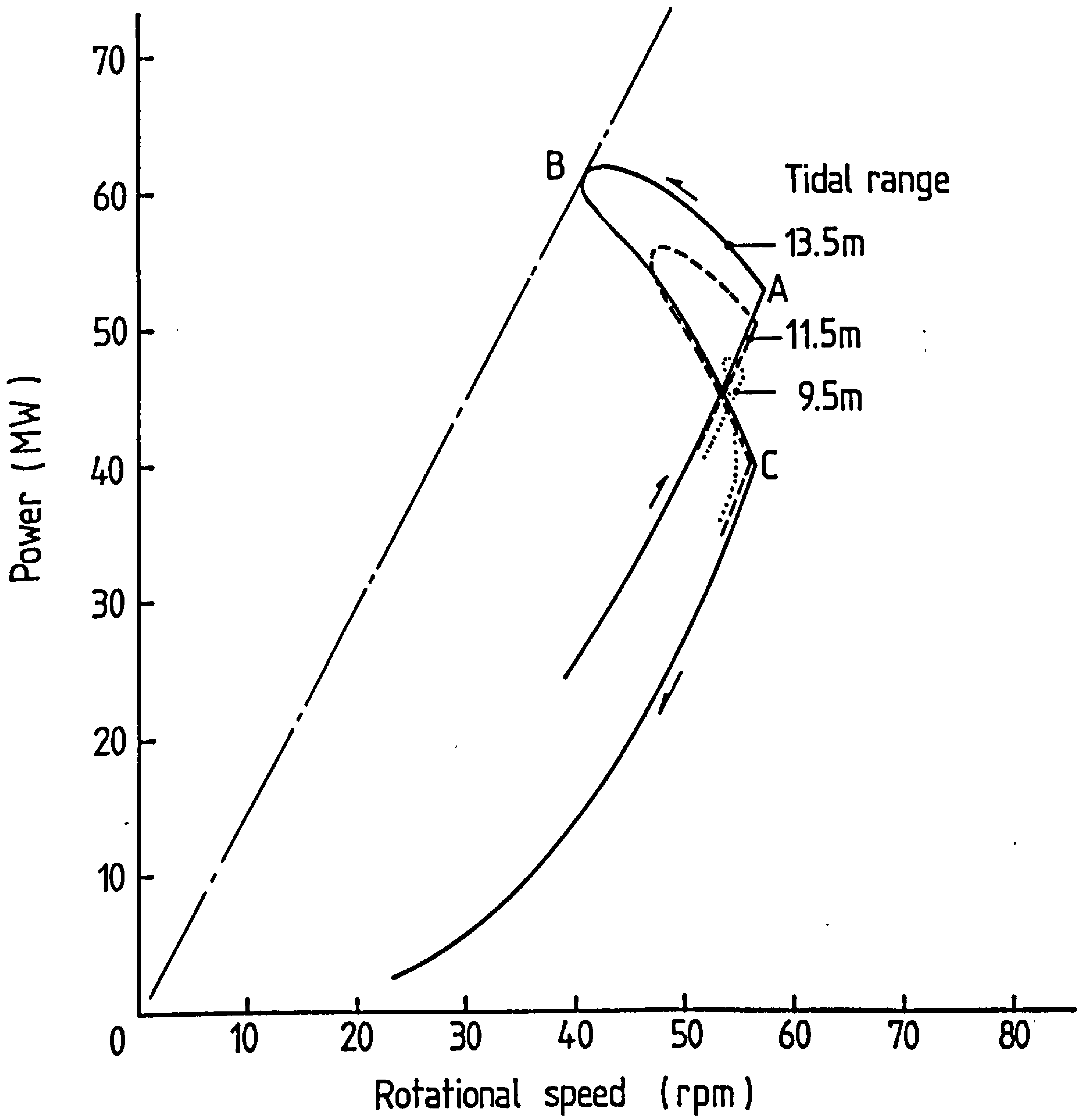
VARIABLE SPEED OPERATION VD FB

FIG. 6.5



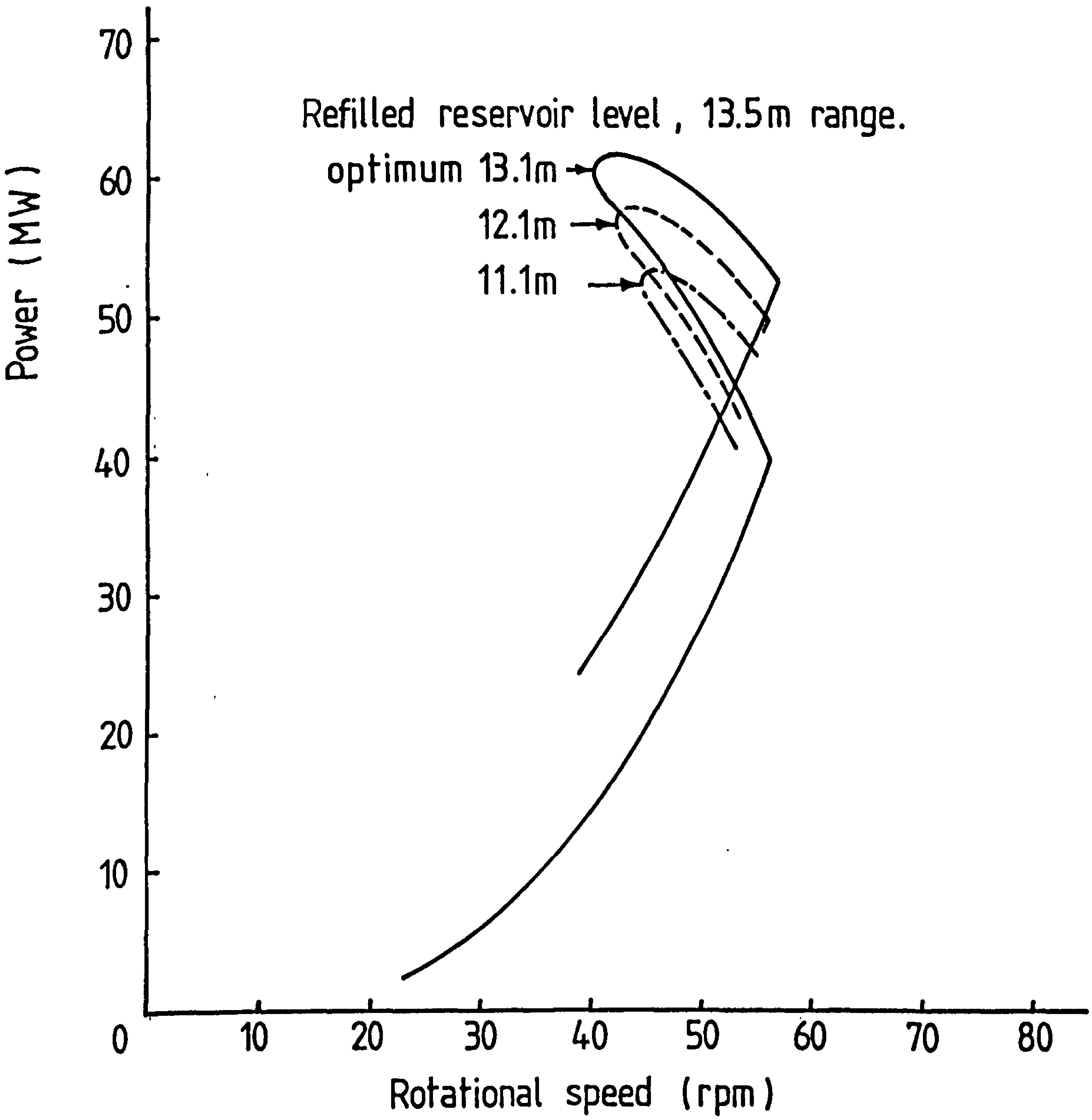
VARIABLE SPEED TURBINE OPERATION - FD FB

FIG. 6.6



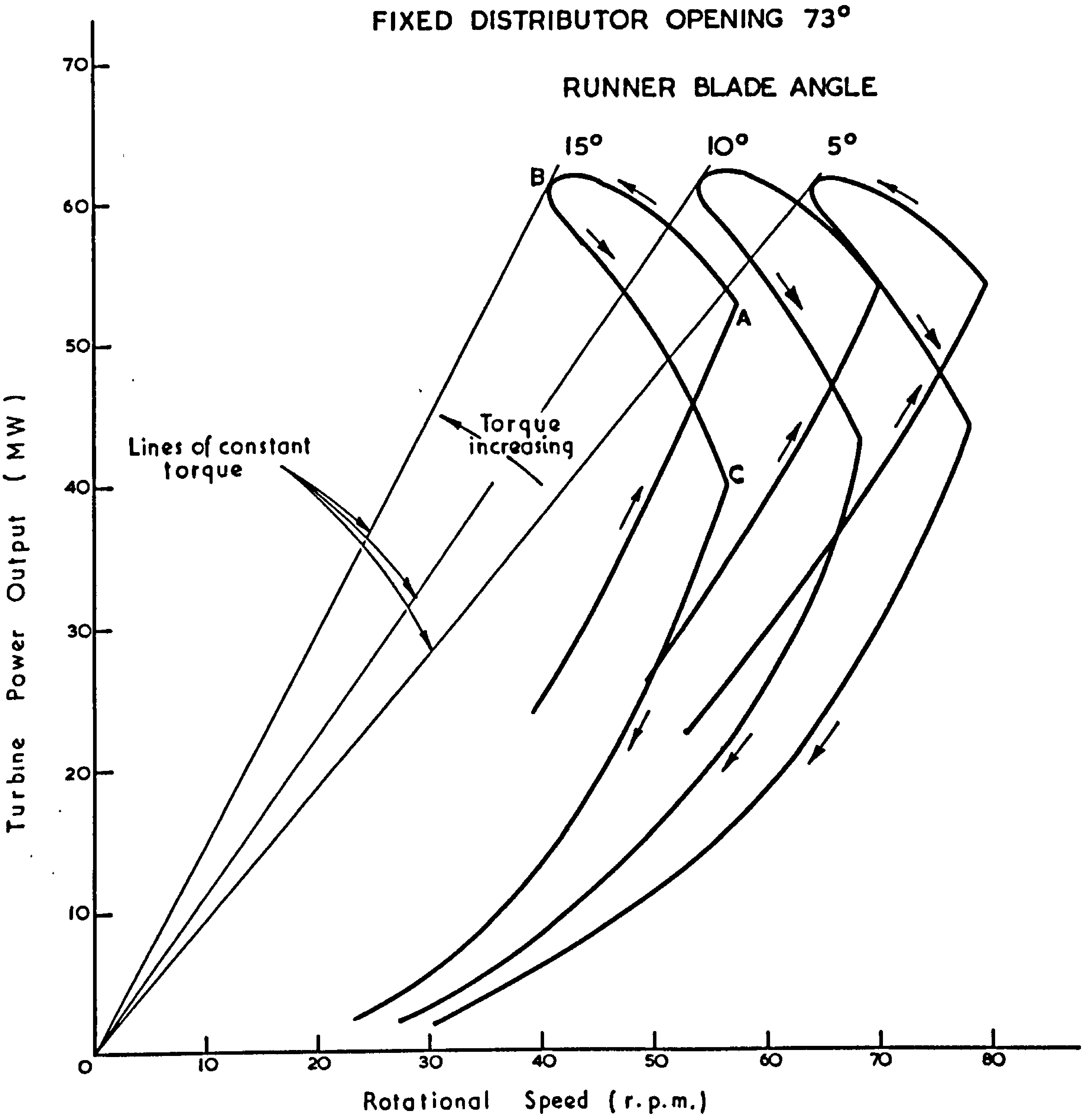
FD FB VS - EFFECT OF CAVITATION LIMIT

FIG. 6.7



FD FB VS - EFFECT OF RESTRICTING REFILLING.

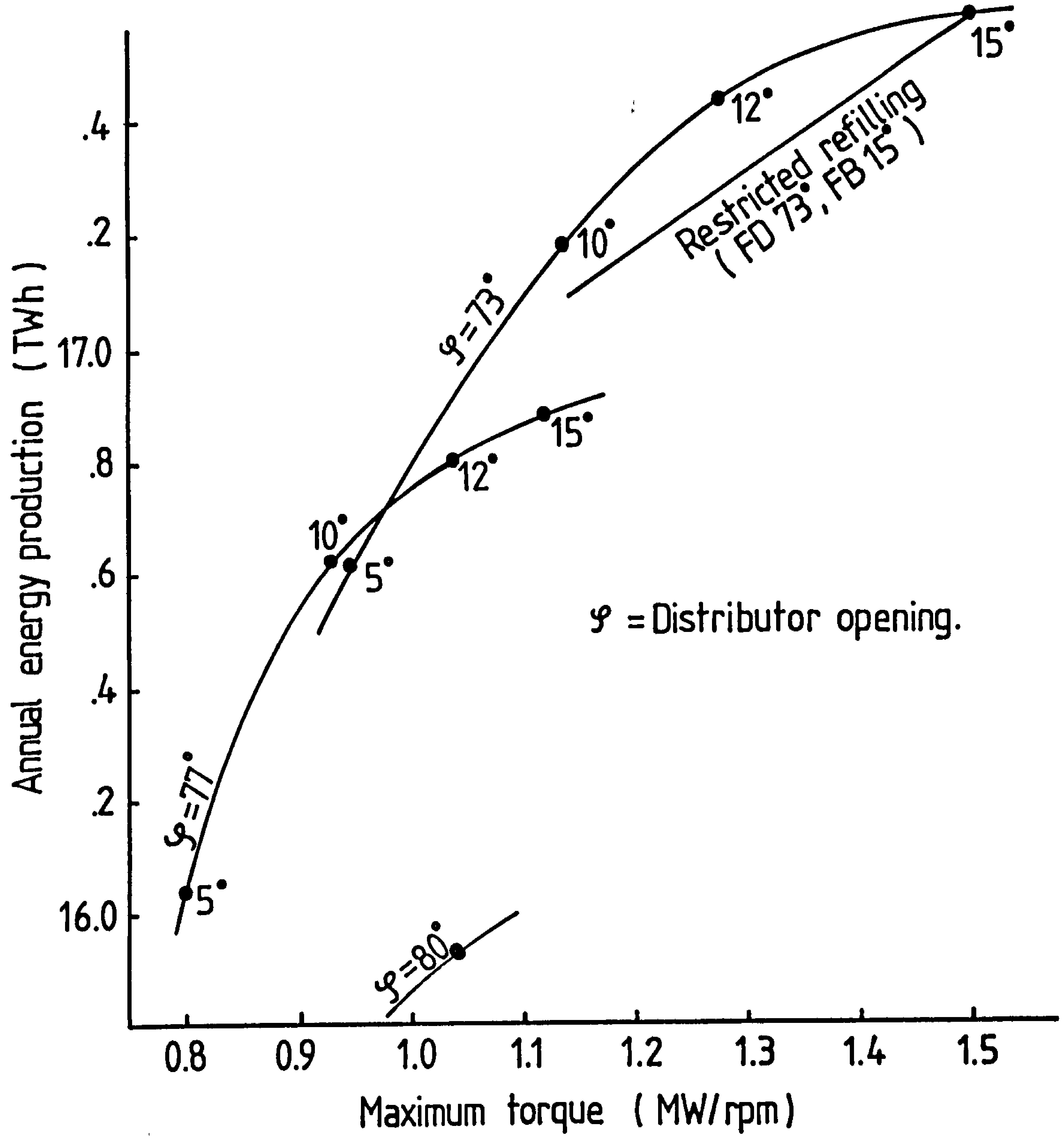
FIG. 6.8



VARIABLE SPEED OPERATION F D F B FOR HIGHEST TIDAL RANGE

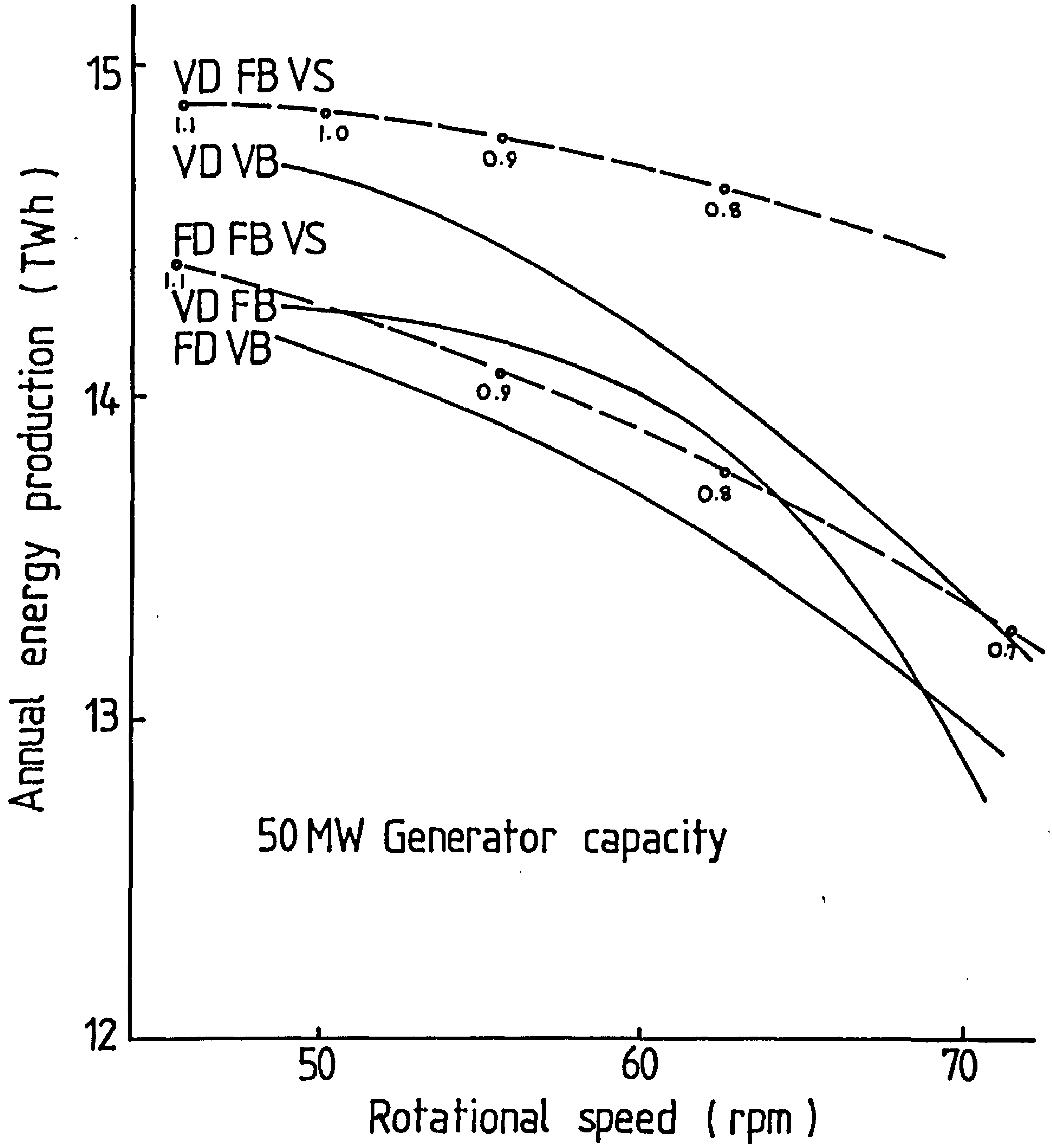
Fig 6.9

Note: This figure shows the results of annual energy computations using a histogram of tidal ranges unmodified by the operation of the tidal barrage. A similar variation of annual energy yield is achieved when the reduction in tidal range is considered.



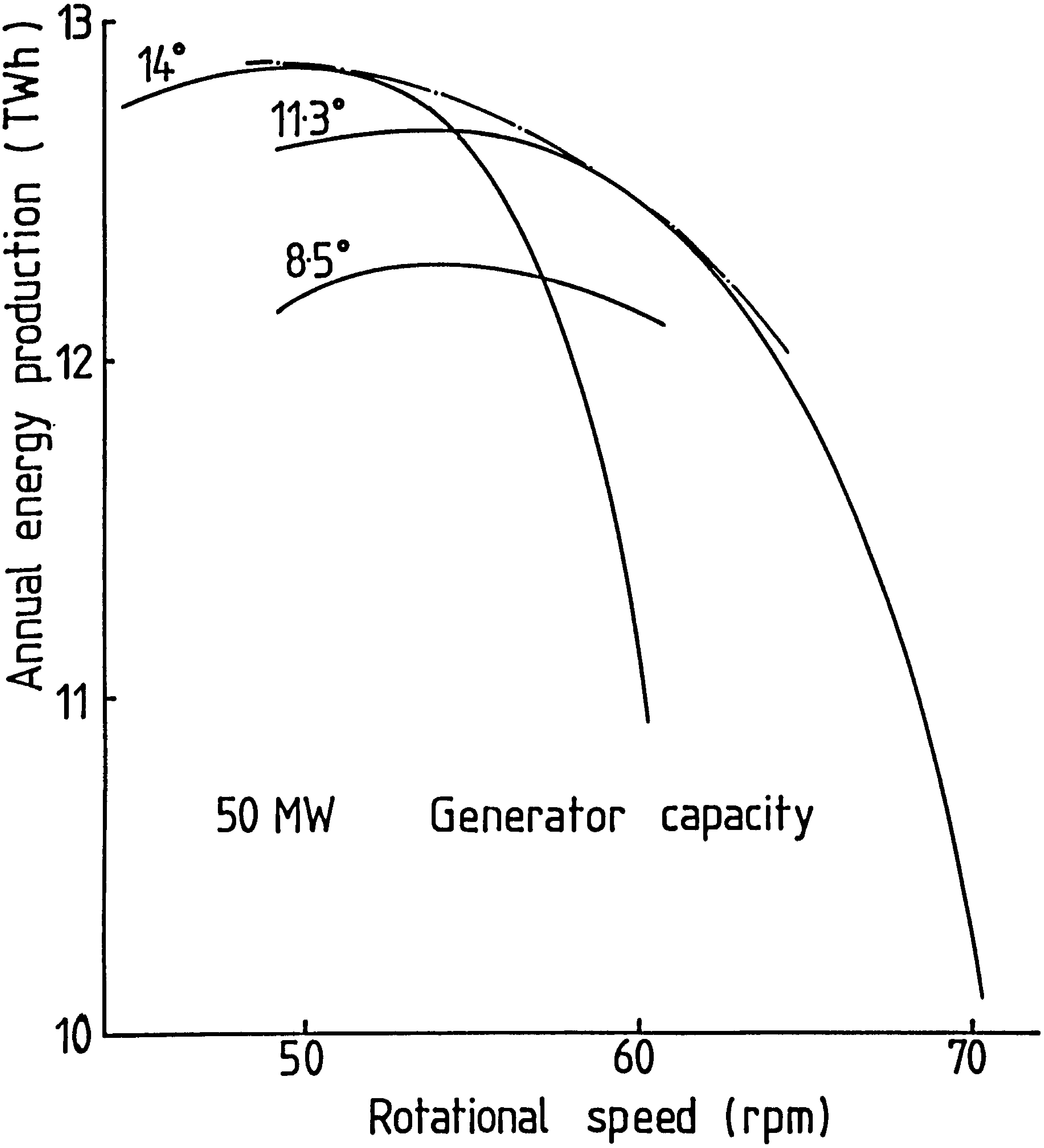
VARIABLE SPEED TURBINE OPERATION - FD FB VS

FIG. 6.10



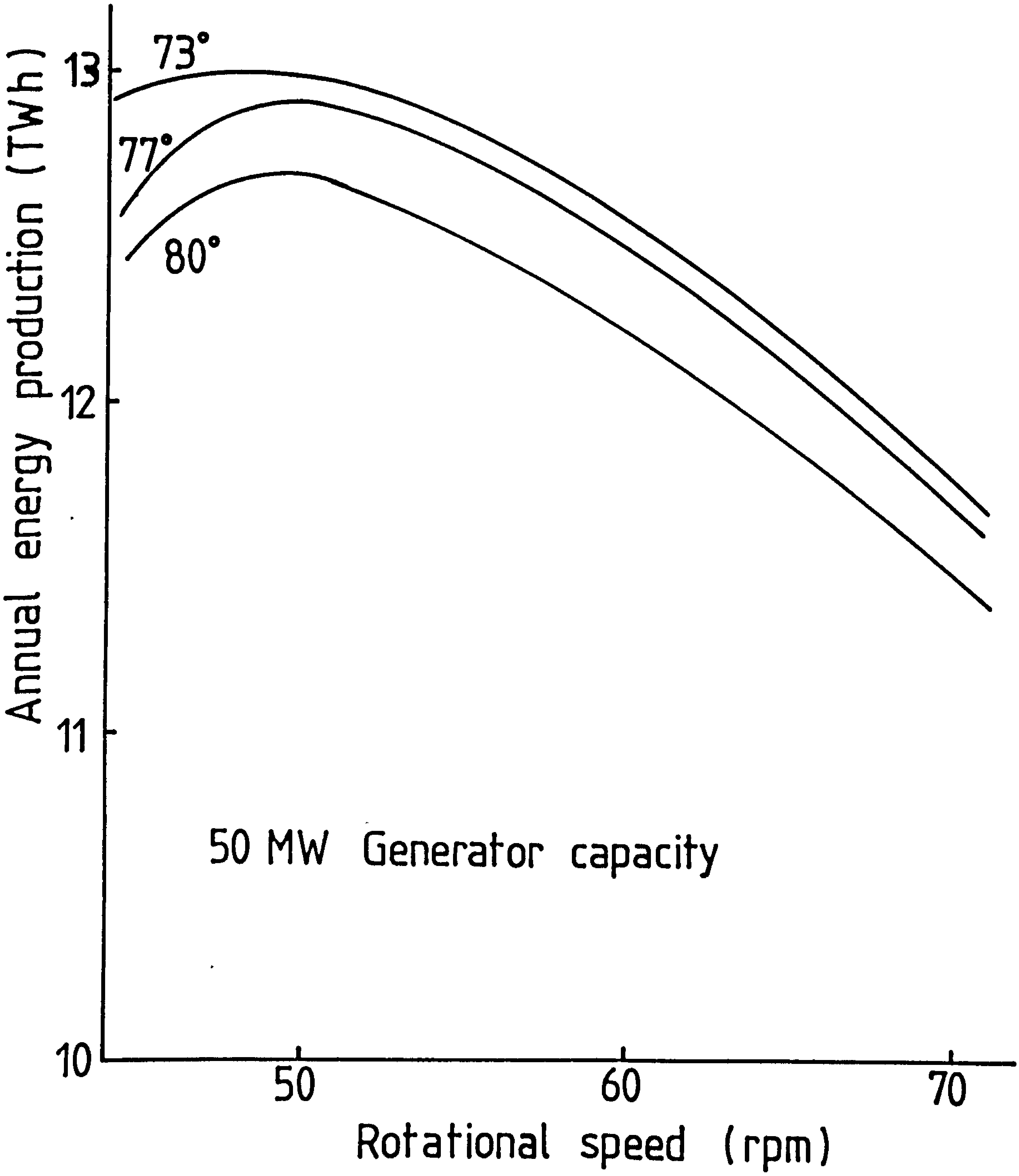
COMPARISON OF TURBINE TYPES - 1980

FIG. 6.11



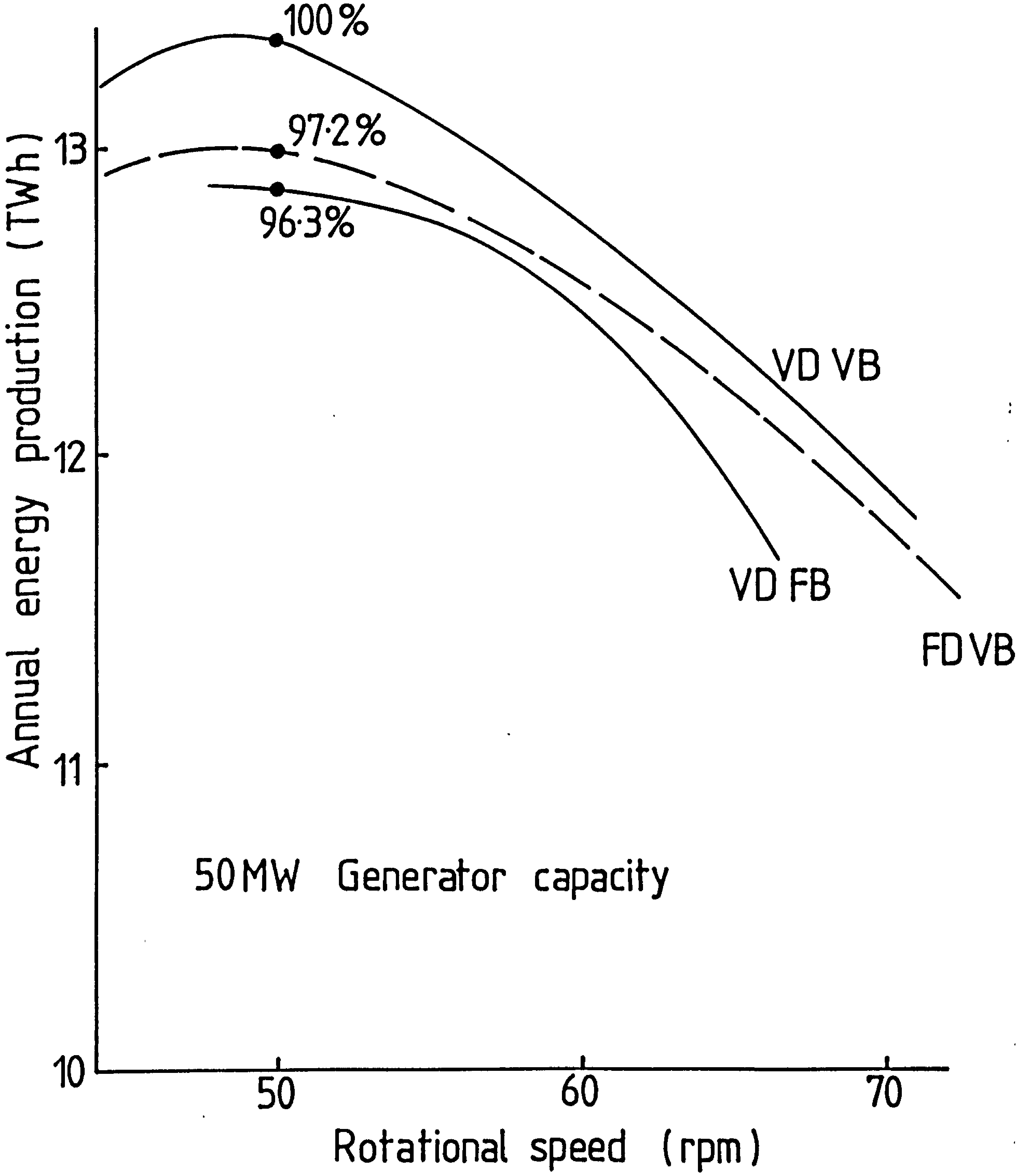
VARIABLE DISTRIBUTOR, FIXED BLADE TURBINES.

FIG. 6.12



FIXED DISTRBUTOR, VARIABLE BLADE TURBINES.

FIG. 6.13



COMPARISON OF TURBINE TYPES - 1988

FIG. 6.14

7.0 CONCLUSIONS

The single-tide ebb-generation energy optimisation models developed during the period of research have been found reliable and flexible in their application. A number of proposals for tidal power schemes have been assessed by considering the variation in energy yield according to varying turbine and sluice parameters. The computed annual energy yield has compared favourably with results from a more complicated and costly to operate model which allows real-time optimisation of the tidal plant.

Modified versions of the standard ebb-generation program have been developed to evaluate energy yield and assess turbine operating conditions for ebb-generation and pumping and double-effect operation.

For the Severn Barrage scheme with the numbers of turbines and sluices optimised for ebb-generation operation,annual energy yield is reduced when double-effect operation is considered. With the same conditions the energy gains reported by Electricité de France, the operators of La Rance, attributable to the addition of pumping to ebb-generation operation have not been reproduced by the computer model. If however the number of turbines (or more precisely the discharge capacity) is increased to the level at La Rance and comparable turbine and pump characteristics are used similar gains are shown. This helps confirm the model but emphasises the difference between conditions as constructed at La Rance and as proposed for the Severn.

The detailed comparison of turbine types for ebb-generation operation has not shown a clear advantage for any type based purely upon the energy yield obtained. The writer tends to favour the FD VB FS type despite the requirement for a draft-tube gate because of the slightly greater energy yield and the promise of an acceptable pump characteristic. The latter is considered important because with the exceptionally long operational life of a tidal scheme, other factors influencing machine type being equal, it would be prudent to select a machine type having the capability to pump, so that future changes in electricity supply conditions can be exploited.

Variable speed turbine operation, having the possibility of increased turbine efficiency at all operating conditions away from the design point of a synchronous machine, has not been found to give significantly increased energy yield. Its utilization is probably confined to tidal power schemes remote from the major load centres when a d.c. transmission link would prove most economical, such as for the Fundy schemes in Canada.

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APPENDIX A

SEGMENT INDEX OF PROGRAM MEMFP

Routine No.		Routine No.	
1.	Mainprog	31.	Qmaxef
2.	Genlim	32.	Qcav
3.	Maxout	33.	Pardvs
4.	Sluice	34.	Powvs
5.	Area	35.	Speed
6.	AreaI	36.	Qmefvs
7.	Acos	37.	Sealev
8.	Pread	38.	Rtide
9.	Pumpin	39.	Tdtime
10.	Qpump		
11.	Ppow		
12.	Pset		
13.	Endcon		
14.	Turbin		
15.	Bsread		
16.	ME01		
17.	Turbop		
18.	Tread		
19.	Sluing		
20.	Limcap		
21.	Maxpcu		
22.	Fintrp		
23.	ME02		
24.	Optim		
25.	Matrix		
26.	Hming		
27.	Hnet		
28.	Ploss		
29.	Pardif		
30.	Power		

Brief Description of Program Segments

1 Main program

- reads in basic data
- calls subroutines to read specific data
- makes calls to routines to establish turbine characteristics and make polynomial fits to the data ie.
  - . max power curve Q = f(h)
  - . max efficiency curve Q = f(h)
  - . limiting capacity curve Q = f(h)
- determines from data current no. of turbine and sluices
- sets up tide characteristic shape for tide range to be evaluated
- set maximum and minimum values for DDRL
- picks starting value for DDRL (1) - initially mid tide level unless otherwise constrained
- CALLS SLUING (Sluicing) to evaluate forwards in time from DDRL to RRL.
- sets up variables for turbining phase
- CALLS TURBIN to evaluate one time step of turbining backwards in time from DDRL
- CALLS PUMPIN to evaluate pumping forwards in time from RRL once turbining has reached RRL
- CALLS ENDCON which checks to see if an end condition has been reached ie. normally that reverse turbining has reached (and gone past) RRL in which case ENDCON shortens time step by a proportional amount and recalculates last step.
- CALLS PSET once turbining has reached RRL and continue to turbine, sets IP = 1
- evaluates basin level variation due to river inflow after RRL when turbines and sluices closed.

		- sums up benefits - usually energy but when pumping this is factored by "FINT". BENEFIT = TURB ENERGY - PUMP ENERGY*FINT. FINT is the ratio of input cost: output value - totals product of energy/tide multiplied by appropriate no. of annual occurences to obtain annual energy production (or benefit as appropriate).
2	GENLIM (F)	- Genlim is used in Runge Kutta method for calculation of Y1 given T0, Y0 and T1 - evaluates as appropriate either of i) max power output ii) max efficiency iii) limit capacity - evaluates discharge Q1 then GENLIM which is total of all discharge through barrage in time step divided by basin area at that level.
3	MAXOUT (S)	- takes in numerous variables through common blocks - this routine replaces the Runge Kutta method when operation is to be for maximum energy production. It follows the Calculus of Variations method to determine what Q1 should be.
4	SLUICE (F)	- takes values T and Y in same way as GENLIM, evaluates Q1 and calculates 'SLUICE' for Runge Kutta prediction of Y1 from T, Y and T1.
5	AREA (F)	- evaluates area of basin at level Y.

6 AREAI (F) - redundant

7 ACOS - redundant

8 PREAD (S) - reads in data concerning pumps

i) number of pumps
ii) Q = f(KU1)
iii) Power = f(head)
iv) min and max pump head
v) FINT as in main prog
vi) TMIN - minimum time between cease pumping and start generating
vii) PSTART & PFIN times when pumping power available

9 PUMPIN (S) - evaluates pumping for one level increment determined from turbine phase. Uses Runge Kutta method as Genlim. Uses QPUMP to evaluate pump discharge/area.

10 QPUMP (F) - takes T and Y and evaluates total pump discharge, +/- river flow, divided by area of basin.

11 PPOW (F) - evaluates for H and Q power input to ONE pump. Note: motor efficiency must be incorporated into the fit P = f(H) input to the program.

12 PSET (S) - this sets up variables in preparation for pumping.

13 ENDCON (S)

- this checks after each time step of generation whether or not an end condition has been reached ie. one of following:
  - i) Y1 (most recently computed basin level) > RRL
  - ii) Y2 > max permitted basin level YABS
  - iii) H1 (most recent head) < hmin turbines
- if end condition found last time step is shortened by proportioning
- this routine also copes with end conditions for double-effect work including control of operation of the sluices in the turbine phase.

14 TURBINE (S)

- called for one time step at a time
- determines what form of operation is to be used and makes appropriate calls to MAXOUT and/or GENLIM
- much is taken up with requirements of Calculus of Variations solution which requires totalling of some functions to determine at what point to leave limit capacity curve.

15 BSREAD (S)

- reads in data for bicubic spline model of turbine hillchart $\eta = f(Q_{11}, KU1)$ FROM CHANNEL 6

16 ME01 (S)

- this routine takes current Q_{11} & KU1 and evaluates effiency FF, adds efficiency majoration (S) and applies generator efficiency GEF.

17 TURBOP (S)

- this routine finds rated head of turbine by trial and error then proceeds to evaluate Q = f(h) characteristics with calls to MAXPCU and LIMCAP.

18 TREAD (S) - reads in turbine data FROM CHANNEL 4.

19 SLUING (S) - this routine takes DDRL and TDDRL (time at which DDRL occurs) and evaluates sluicing forwards in time to reach level equalization. It has in-built end conditions. Calls SLUICE for evaluation of Runge Kutta process. When end conditions reached time step is halved and recomputed - process repeated until time step <0.1min.

20 LIMCAP (S) - this routine finds by trial and error the discharge, for various heads, for producing the rated output of specified generator. Having evaluated a matrix of Q's for increments of Head a least squares fit is made to these points in the form

$$Q = f((h-hr),(h-hr)^2,(h-hr)^3,(h-hr)^{\frac{1}{2}}), \quad hr = \text{rated head}$$

- fit made using routine MATRIX to solve the simultaneous equations

21 MAXPCU (S) - similar to LIMCAP but for max power curve <u>and</u> max efficiency curve and fit to both in form

$$Q = f(h,\ h^2,\ h^3)$$

22 FINTRP (S)

23 ME02 (S) - this routine evaluates turbine efficiency by calling ME01 for bi-cubic spline hillchart model

24 OPTIM (S) - this routine used, predominantly for selection of new DDRL from results of previous trials. As DDRL is optimized increment is reduced as direction of search is changed. Final choice is when increment of DDRL is below a preset tolerance.

25 MATRIX (S) - solves simultaneous equations generated for curve fitting.

26 HMING (F) - this function evaluates minimum gross head given tailwater level. This is required because hmin is turbine head - for the turbine to 'see' this head the gross head as modelled by the programme must be evaluated by adding on the draft-tube exit losses.

27 HNET (F) - this evaluates net operating head given, sea level, basin level, and discharge.

28 PLOSS (F) - evaluates transmission line losses, linear interpolation between points input as data.

29 PARDIF (S) - calculates numerically $\frac{\partial N}{\partial H}$ and $\frac{\partial N}{\partial Q}$ using call to ME02. Effectively calculates power at small interval of H and Q and divides by the interval. Hence in call to ME02. 4 efficiencies are called for.

30 POWER (F) - calculates power from H(net) and Q; can also evaluate $\frac{\partial N}{\partial H}$ and $\frac{\partial N}{\partial Q}$.

31 QMAXEF (F) - This evaluates, for a given head, the discharge giving maximum efficiency. This makes use of routine OPTIM to optimise efficiency when a bicubic spline model is used.

32 QCAV (F) - This evaluates for given head(net) and time (and hence sea level) the maximum discharge permitted by the cavitation limitation. Also there is another constraint, a straight line Q11 = f(KU1) to limit the operation below this line on the turbine hillchart. Two models for cavitation limitation are possible EWZ or Neyrpic. EWZ version is much simpler.

33 PARDVS (S) - This routine equivalent to 29. Pardif but modified for variable speed operation.

34 POWVS (F) - This routine equivalent to 30. Power but modified for variable speed operation.

35 SPEED (S) - This routine used to optimise rotational speed when variable speed operation is used. OPTIM is used to find best speed by trial and error.

36 QMEFVS (F) - Equivalent to 31. QMAXEF but for variable speed operation.

37 SEALEV (F) - Evaluates sea level given T1. Tide model is in the form of a number of discrete points at 10 minute intervals. Intermediate levels are found by linear interpolation. Tide shape held in TIDELO.

Element 1 holds time = 0.0
2 holds time = 10.0
3 holds time = 20.0 etc. etc.

38	RTIDE (S)	- Reads in unitized tide shape used to generate TIDELO by multiplication by the required range. READS FROM CHANNEL 5.
39	TDTIME (F)	- Evaluates time given tide level and an approximate estimate of time (TEST).

APPENDIX B

PROGRAM MEMFP

```
C   TIDAL ENERGY PROGRAM  -  SINGLE-EFFECT
C   MOD 18:12:86  IN QMAXEF TO REDUCE QEST - PROBLEM USING B-SNPFDVB
C    MOD 23:2:87  MOD IN FUNCTION HNET TO ENSURE NET HEAD CALCULATED WHEN
C                 USING TURBINES IN REVERSE AS SLUICES.
C    MOD 23:2:87  EARLIER MOD MADE TO ALLOW FOR A PERIOD OF SLUICING
C                 IMMEDIATELY FOLLOWING TURBINING. FOR THIS A NUMBER OF ASSUM
C                 ARE MADE, AS FOLLOWS: EXIT AREAS FROM TURBS AND SLUICES ARE
C                                       AS FOR NORMAL DIRECTION OF FLOW
C                                       COEFF. OF DISCHARGES (T&S)ARE MODIFIED
C                                       INTERNAL TO PROG (SEE MAIN PROG.)
C   MOD 15:4:87  IN QMAXEF REVERSING CHANGE OF 18:12:86 TO ALLOW USE OF
C                B-SEW309 WHERE LOW ESTIMATE OF Q IS IN AREA OF NO DATA
C
C
C   MOD 20:5:87   ERROR MESSAGES INCORPORATED TO IDENTIFY POSITION OF ERROR
C
C   MOD 21:5:87   NEW FUNCTION HNET INCORPORATED TO REPLACE ORIGINAL,
C                 ADJUSTMENTS TO /BLKX/ & INPUT OF DATA RE BARRAGE GEOMETRY
C
C   MOD 22:5:87   NEW SLUICE ROUTING INCORPORATED WHICH CALCS NET HEAD DIRECT
C                 FROM GROSS HEAD WITHOUT ITERATION (WHICH DIDNT WORK WELL)
C
C   MOD 27:5:87   PROG WILL NOT WORK WITH PUMPING AND RIVER FLOW .
C
C   MOD 16:10:87   MAJORATION APPLIED IN ME01 ADJUSTED SO THAT COMPUTED
C                  EFF STEP UP MAX AT BEST EFFICIENCY POINT BUT REDUCES
C                  LINEARLY TO ZERO AT ZERO EFF. HENCE DATA INPUT MUST CHANGE
C                  ACCORDINGLY IE (STEP UP/BEST EFF).
C
C  MOD 23:10:87   FUNCTION HNET MODIFIED TO ENSURE WHEN PUMPING THAT
C                 HNET=HGROSS+HLOSSES
C
C
C     IMPLICIT REAL*8 (A-H),(O-Z)
      CHARACTER*10 SITEDT,RESFIL,TURBDT,RUBFIL,ANS,TDAT
      COMMON /TIDE/TSHAPE(120),TINC,HTL,TLTL,TIDELO(120),NINC
      COMMON /BLKP/NFUMPS,QA,QB,QCC,QD,ZA,ZB,ZC,ZD,PHMIN,PHMAX,FINT,
     1TMIN,PSTART,PFIN
      COMMON /BLKP1/PT0,PH0,PQ0,PP0,FP0,PT1,PH1,PQ1,PP1,FP1
      COMMON /BLK1/RTSPS(10),FTSPS(10),AD,WR,B,WF,K
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
     *CHSIG(2),FMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK6/ACMP(2),BCMP(2),CCMP(2),DCMP(2),
     *ACME(2),BCME(2),CCME(2),DCME(2),IMEF
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
      COMMON /BLK10/TORQUE,UK1MIN(2),UK1MAX(2),Q11MEF(2)
      COMMON /BLKX/EXITA(2,2),DS(2),SPACE(2),INET,
```

```
     *ISLOP,A0SLOP,A1SLOP,SNOS,TNOS
      COMMON /BLKTL/NTL,ITL,PO(15),PL(15),TLOSS
      DIMENSION NOT(10),AB(15),TRANGE(10),HTLEV(10),TLTLEV(10)
      DIMENSION FREQ(10),NSLU(25),NTURB(25)
      DIMENSION RX(3,2),OPTLIM(4),D2O(2),OPTTOL(2),TRX(3),
     *SLOTOP(4),ENOPT(2),CON(2)
C
C
C
C
C
      WRITE(*,'('' SITE DATA FILE =  '',$)')
      READ(*,'(A)')SITEDT
      OPEN (UNIT=4,FILE=SITEDT,STATUS='OLD')
      WRITE(*,'('' RESULTS FILE ='',$)')
      READ(*,'(A)') RESFIL
      OPEN (UNIT=5,FILE=RESFIL,STATUS='UNKNOWN')
      WRITE(*,'('' B-SPLINE DATA FILE =  '',$)')
      READ(*,'(A)')TURBDT
      OPEN (UNIT=6,FILE=TURBDT,STATUS='OLD')
C
C
C    TIDE SHAPE
C
      WRITE(*,'('' TIDE SHAPE DATA FILE = '',$)')
      READ(*,'(A)')TDAT
      OPEN(UNIT=3,FILE=TDAT,STATUS='OLD')
C
C
      WRITE(5,'(''1'')')
      WRITE(5,'('' SITE DATA FILE =  '',A10)')SITEDT
      WRITE(5,'('' RESULTS FILE   =  '',A10)')RESFIL
      WRITE(5,'('' B-SPLINE DATA  =  '',A10)')TURBDT
      WRITE(5,'('' TIDE SHAPE FILE=  '',A10)')TDAT
C
C
      CALL RTIDE
C
C
C
C
      WRITE(*,'(//'' ARE NET HEADS TO BE EVALUATED ? (Y/N) '',$)')
      READ(*,'(A)')ANS
      IF(ANS.EQ.'Y')WRITE(5,'(//'' NET HEADS ARE UTILISED''//)')
      IF(ANS.EQ.'N')WRITE(5,'(//'' GROSS HEADS USED''//)')
      IF(ANS.EQ.'Y')INET=1
      IF(ANS.EQ.'N')INET=0
C
C
C
C
      WRITE(*,'(//'' IS RESERVOIR SLOPE TO BE EVALUATED ? (Y/N) '',$)')
      READ(*,'(A)')ANS
      IF(ANS.EQ.'Y')WRITE(5,'(//'' RESERVOIR SLOPE EVALUATED''//)')
```

```
      IF(ANS.EQ.'N')WRITE(5,'(//'' FLAT RESERVOIR ASSUMED''//)')
      IF(ANS.EQ.'Y')ISLOP=1
      IF(ANS.EQ.'N')ISLOP=0
C
C
C
      WRITE(*,'(//'' IS REVERSE SLUICING TO BE EVALUATED ? (Y/N) '',$)')
      READ(*,'(A)')ANS
      IF(ANS.EQ.'Y')WRITE(5,'(//'' REVERSE SLUICING EVALUATED''//)')
      IF(ANS.EQ.'N')WRITE(5,'(//'' NO REVERSE SLUICING''//)')
      IF(ANS.EQ.'Y')IRSLU=1
      IF(ANS.EQ.'N')IRSLU=0
C
      WRITE(*,'(//'' IS START HEAD TO BE FIXED ON INPUT ? (Y/N) '',$)')
      READ(*,'(A)')ANS
      IF(ANS.EQ.'Y')WRITE(5,'(//'' START HEAD FIXED ON INPUT''//)')
      IF(ANS.EQ.'N')WRITE(5,'(//'' ENERGY YIELD OPTIMIZED''//)')
      IF(ANS.EQ.'Y')IOPTSH=1
      IF(ANS.EQ.'N')IOPTSH=0
C
      READ(4,100)IPUMP,(AB(I),I=1,15)
  100 FORMAT(I1,15A4)
C  READ IN MODE OF TURBINE OPERATION 1,2,3,AND NOPRT=0 IFLIMITED PRINT REQD
C   NOPRT=-1 IF BARE MINIMUM OUTPUT REQD
C
C
C   MODE 1,2,3  EBB-GENERATION
C   MODE 4,5,6  FLOOD-GENERATION
C   MODE 7,8,9  DOUBLE-EFFECT
C
C
C   ISE=1  SINGLE-EFFECT
C   ISE=2  DOUBLE-EFFECT
C
      READ(4,150)MODE,NOPRT
  150 FORMAT(I1,6X,I2,50X)
      ID=1
      ISLU=0
      ISE=1
      WRITE(5,9334)
      IF (MODE.LT.4) GO TO 14
      MODE=MODE-3
      ID=-1
      IF (MODE.LT.4) GO TO 321
C  DOUBLE-EFFECT GEN
      MODE=MODE-3
      ISE=2
      IF (IPUMP.EQ.0) WRITE(5,9440)
      IF (IPUMP.EQ.1) WRITE(5,9441)
      GO TO 9337
C  FLOOD GENERATION
  321 IF (IPUMP.EQ.0) WRITE(5,9335)
      IF (IPUMP.EQ.1) WRITE(5,9336)
      GO TO 9337
```

```
C   EBB GENERATION
   14 IF (IPUMP.EQ.0) WRITE(5,9338)
      IF (IPUMP.EQ.1) WRITE(5,9339)
C
C
 9334 FORMAT(//10X,42(1H*)/10X,1H*,40X,1H*)
 9333 FORMAT(10X,1H*,40X,1H*/10X,42(1H*))
 9335 FORMAT(10X,42H*  SINGLE BASIN,FLOOD-GENERATION          *)
 9336 FORMAT(10X,42H*  SINGLE BASIN,FLOOD-GENERATION+PUMPING *)
 9338 FORMAT(10X,42H*  SINGLE BASIN,EBB-GENERATION            *)
 9339 FORMAT(10X,42H*  SINGLE BASIN,EBB-GENERATION+PUMPING    *)
 9440 FORMAT(10X,42H*  SINGLE BASIN,DOUBLE-EFFECT GEN         *)
 9441 FORMAT(10X,42H*  SINGLE BASIN,DOUBLE-EFFECT+PUMPING     *,
     *25H  NOT TESTED CHECK DATA  )
C
C
 9337 CONTINUE
      WRITE(5,9333)
      WRITE(5,101)(AB(I),I=1,15)
  101 FORMAT(/////10X,15A4///)
      IF (MODE-2)300,301,302
  300 WRITE(5,310)
      GO TO 303
  301 WRITE(5,311)
      GO TO 303
  302 WRITE(5,312)
  310 FORMAT(1X,43HTURBINE OPERATION FOR MAXIMUM ENERGY OUTPUT//)
  311 FORMAT(1X,39HTURBINE OPERATION AT MAXIMUM EFFICIENCY//)
  312 FORMAT(1X,40HTURBINE OPERATION ON MAXIMUM POWER CURVE//)
C
C
C  READ IN POOL LEVEL RESTRICTION ,NO. OF TIDES RANGES,NO OF AREA/LEVELS
C
C
  303 READ (4,102)YABS,NTR,NAL,AABS
  102 FORMAT(F10.4,2I3,F10.4)
      WRITE(5,208)YABS,AABS
  208 FORMAT(/26H POOL LEVEL RESTRICTION    ,F5.2/
     C/34H UPPER LIMIT OF AREA/LEVEL CURVE   ,F5.2)
      J=NAL
      DO 1 I=1,NAL
    1 READ(4,103)AC(I),AX(I),AXX(I)
      WRITE(5,241)(AC(I),AX(I),AXX(I),I=1,NAL)
241   FORMAT(//,' RESERVOIR AREA MODELLED AS SERIES OF ST. LINES',/
     *10(' AREA(M*M)=',E12.5,'+Y*',E12.5,'  UP TO Y=',E12.5/)//)
      WRITE(5,205)
      WRITE(5,206)
      WRITE(5,207)
      DO 2 N=1,NTR
      READ(4,104)TRANGE(N),HTLEV(N),TLTLEV(N),RTSPS(N),FTSPS(N),FREQ(N)
    2 WRITE(5,209)TRANGE(N),HTLEV(N),TLTLEV(N),RTSPS(N),FTSPS(N),FREQ(N)
  103 FORMAT(3E15.5,I5)
  104 FORMAT(6F10.4)
C
```

```
C   READ IN GEOMETRY OF BARAGE LOCATION
C   IE  DEPTHS  INTO WHICH T & S DISCHARGE
C   & DIMENSIONS OF T & S  PASSAGES  FOR CALC OF H LOSSES
C
      READ (4,'(3F10.0)')(EXITA(I,1),SPACE(I),EXITA(I,2),I=1,2)
      READ (4,'(2F10.0)') DS(1),DS(2)
C
      WRITE (5,527)EXITA(1,1),EXITA(1,2),EXITA(2,1),EXITA(2,2),SPACE(1),
     *SPACE(2),DS(1),DS(2)
  527 FORMAT(1X,'TURBINE DRAFT TUBE EXIT AREA -  SEA   (M*M) ',F10.2,/
     *       1X,'                             - BASIN (M*M) ',F10.2,/
     *       1X,'SLUICE DRAFT TUBE EXIT AREA  -  SEA   (M*M) ',F10.2,/
     *       1X,'                             - BASIN (M*M) ',F10.2,/
     *       1X,'HORIZ. SPACING OF TURBINE CENTRES     (M)   ',F10.2,/
     *       1X,'                   SLUICE  CENTRES    (M)   ',F10.2,/
     *       1X,'BED DEPTHS (WRT DATUM OF TIDES) - TURBS     ',F10.2,/
     *       1X,'                                  SLUICES   ',F10.2)
C
      IF (EXITA(1,2).EQ.0.0.OR.EXITA(2,2).EQ.0.0) WRITE(*,
     *'(''DATA NOT SUPPLIED FOR INLET/EXIT AREAS TO TURBS/SLUICES'')')
      IF (EXITA(1,2).EQ.0.0.OR.EXITA(2,2).EQ.0.0) STOP
      READ(4,4733)A0SLOP,A1SLOP
      WRITE(5,4732)A0SLOP,A1SLOP
 4732 FORMAT(//1X,'RESERVOIR SLOPE'/
     *1X,'DH=',E10.4,'*Q**2*(',F10.4,'-ELEV)**2',/)
 4733 FORMAT(E10.4,F10.0)
C
      READ(4,105)NTS,TSTEP
  105 FORMAT(I2,F10.4)
      WRITE(5,225)TSTEP
  225 FORMAT(//37H TIME STEP USED IN NUMERICAL SOLUTION,F10.2,5H MINS)
      DO 9 N=1,NTS
    9 READ(4,106)NTURB(N),NSLU(N)
  106 FORMAT(2I5)
      READ(4,109)DAXIS,RIVQ,EFFAR1
      WRITE(5,223)DAXIS
      WRITE(5,299)RIVQ
      IF(IPUMP.EQ.1.AND.RIVQ.NE.0.0)WRITE(*,'(''PROGRAM NOT UP TO  '',
     *'' PUMPING WHEN RIVER FLOW NON ZERO'')')
      IF (IPUMP.EQ.1.AND.RIVQ.NE.0.0) STOP
  299 FORMAT(/1X,25HRIVER FLOW INTO RESERVOIR,F10.2,7H M**3/S)
      WRITE(5,224)EFFAR1
  223 FORMAT(/1X,22HWATER DEPTH RESRICTION,F10.2,26H M (DATUM TO TURBINE
     1 AXIS))
  224 FORMAT(/1X,32HEFFECTIVE SLUICE AREA PER SLUICE,F10.2,4H M*M)
C
C   READ TURBINE DATA
C
      DO 270 N=1,ISE
  270 CALL TREAD(N,RSLU(N))
C
C   READ PUMPING DATA
C
      IF (IPUMP.EQ.1) CALL PREAD
```

```
C
C
C   DOUBLE EFFECT + PUMPING NOT TESTED
C
C
C
  109 FORMAT(3F10.4)
C
C
C
  205 FORMAT(//6H TIDES,47X,8HADJUSTED)
  206 FORMAT(1X,8H--------,10X,9HLEVELS(M),9X,10HTIME(MINS),6X,9HNO,ANNU
     1AL)
  207 FORMAT(3X,60H   RANGE      HIGH       LOW     RISING   FALLING  OCC
     1URENCES)
  209 FORMAT(1X,6F10.2)





C   READ IN TRANSMISSION LOSSES - LOSS IN MW PER TURBINE
C
C   NTL = NO. OF DATA POINTS  , IF NTL=1 ONE SET OF POINTS READ
C                               AND CONSTANT POWER LOSS USED
C   FUNCTION PLOSS INTERPOLATES LINEARLY BETWEEN DATA POINTS
C
      READ(4,'(I2)')NTL
      READ(4,107)(PO(I),PL(I),I=1,NTL)
      WRITE(5,9163) (PO(I),PL(I),I=1,NTL)
 9163 FORMAT(//,' TRANSMISSION LOSSES - LOSS IN MW PER GENERATOR'/
     *' GENERATION OUTPUT    POWER LOSS (MW)',/
     *20(6X,F10.3,9X,F10.3,/),//)



C
C  ESTABLISH CURRENT TURBINE CHARACTERISTICS
C
  234 FORMAT(///1X,15HCURRENT TURBINE)
  235 FORMAT(1X,15H---------------)
      IVS=0
   10 READ(4,107)DIA,GEF
      ITL=0
      IF(DIA.LE.0.1) GO TO 11
      WRITE(5,234)
      WRITE(5,235)
      READ(4,107)RPM,HMINVS
      READ(4,107)PMAX,S
  107 FORMAT(2F10.0)
      PI=3.141593
      UK=DIA*RPM*PI/265.713
C
C   FOR VARIABLE SPEED OPERATION
```

```
C
      IF (HMINVS.EQ.0.0) GO TO 111
      IVS=1
C   HMIN CALCULATED IN TURBOP AS HMIN=(UK/UK1MAX)**2
      UK=SQRT(HMINVS)*UK1MAX(1)
      TORQUE=RPM
      WRITE(5,'(//'' VARIABLE SPEED OPERATION'',
     */'' ------------------------''/)')
  111 CONTINUE
C
C
      D2=DIA*DIA
      D4=D2*D2
      D6=D4*D2
      WRITE(5,236)DIA
      IF (IVS.EQ.0) WRITE(5,237)RPM
      IF (IVS.EQ.1) WRITE(5,3216)TORQUE
 3216 FORMAT(1X,19HMAXIMUM TORQUE     ,F10.3,12H (POWER/RPM))
      WRITE(5,238)PMAX
      WRITE(5,239)S,GEF
      GEF=GEF/100.0
  236 FORMAT(/1X,19HRUNNER DIAMETER    ,F10.3,2H M)
  237 FORMAT(1X,19HROTATIONAL SPEED   ,F10.3,4H RPM)
  238 FORMAT(1X,19HINSTALLED CAPACITY ,F10.3,3H MW,
     *21H MAX GEN ELECT OUTPUT)
  239 FORMAT(1X,'EFFICIENCY STEP UP   ',F10.3,'%'/
     *       1X,'GENERATOR EFFICIENCY ',F10.3,'%')
C
C   THIS FINDS MAX HEAD FOR EVALUATION IN TURBOP
C
      TIDMAX=0.0
      DO 400 IT=1,NTR
      IF (TRANGE(IT).GT.TIDMAX) TIDMAX=TRANGE(IT)
  400 CONTINUE
      HMAX=TIDMAX-0.5
      DO 261 MD=1,ISE
  261 CALL TURBOP(HMAX,UK1MAX(MD))
      ITL=1
      PMAX=PMAX-PLOSS(PMAX)
C
C   TURBINE CHARACTERISTICS EVALUATED ABOVE
C
C
C   ESTABLISH CURRENT NUMBER OF TURBINES AND SLUICES
C
      DO 12 I=1,NTS
      TURBN=NTURB(I)
      TNOS=TURBN
      SLUN=NSLU(I)
      SNOS=SLUN
      EFFAR=EFFAR1*NSLU(I)
   22 ANENG=0.0
      WRITE(5,244)
      WRITE(5,242)NTURB(I)
```

```
      WRITE(5,243)NSLU(I)
      WRITE(5,244)
  242 FORMAT(1X,2H* ,I4,12H TURBINES  *)
  243 FORMAT(1X,2H* ,I4,12H SLUICES   *)
  244 FORMAT(1X,18H******************)
C
C  ESTABLISH CURRENT TIDE RANGE
C
      DO 13 K=1,NTR
      NPRT=NOPRT
      B=(HTLEV(K)+TLTLEV(K))/2.0
      AD=(HTLEV(K)-TLTLEV(K))/2.0
C     WR=PI/(RTSPS(K))
C     WF=PI/(FTSPS(K))
      HTL=HTLEV(K)
      TLTL=TLTLEV(K)
      AMPL=AD*2.0
      FMSL=HTL-AMPL*TSHAPE(1)
      DO 245 NP=1,NINC
  245 TIDELO(NP)=TSHAPE(NP)*AMPL+FMSL
C
C   ABOVE COMPUTES ACTUAL TIDE SHAPE
C
      FLTT=TDTIME((TLTL+0.001),0.0)
      FHTT=TDTIME((HTL-0.001),FLTT)
      WRITE(5,246)TRANGE(K)
      WRITE(*,246)TRANGE(K)
  246 FORMAT(////1X,F5.2,9H M  RANGE)
      IF (IOPTSH.EQ.0) GO TO 784
      WRITE(*,'(//'' ENTER REQUIRED START HEAD '',$)')
      READ(*,'(F20.0)')HNOM
C
  784  CONTINUE
C
C
C
C
C
C
C
C
C
C
C
C
C
C
C   THIS SINGLE TIDE,SINGLE EFFECT PROGRAM
C   EVALUATES  FOR EBB-GEN  1 SLUICING FORWARDS FROM DDRL
C                             TO ESTABLISH RRL
C                   2 TURBINING BACKWARDS TO REACHRRL
C
C  ESTIMATE A VALUE FOR DDRL,LESS THAN POOL LEVEL RESTRICTION
C   AND GREATER THAN LOW TIDE+HMIN
```

```
C
C              FOR FLOOD-GEN 1 SLUICING FORWARD FROM RRL TO DDRL
C                            2 TURBINING BACKWARDS TO DDRL
C                            3 ESTIMATE NEW RRL , GO TO 1
C
C     DDRL AND RRL ARE INTERCHANGED FOR FLOOD-GEN
C
      MD=1
      DDRMAX=HTLEV(K)
      TWL=TLTLEV(K)
      DDRMIN=TLTLEV(K)+HMING(MD,TWL,ID)
      IF (ID.GT.0) GO TO 32
      TWL=HTLEV(K)-HMIN(MD)
      DDRMAX=HTLEV(K)-HMING(MD,TWL,ID)
      DDRMIN=TLTLEV(K)
   32 IF (DDRMAX.GT.YABS) DDRMAX=YABS
      DDRTOL=0.002*TRANGE(K)
      IF (IOPTSH.EQ.1) DDRTOL=DDRTOL/10.0
      E0=0.0
      DDRL0=0.0
      IF (ID.EQ.-1) DDRL0=HTLEV(K)
      D=0.05*TRANGE(K)
      DDRL=B
      IF (DDRL.GE.DDRMAX) DDRL=DDRMAX-0.1
      IF (DDRL.LE.DDRMIN) DDRL=DDRMIN+0.1
   15 IF (ID.EQ.-1) GO TO 228
      TWL=DDRL-HMIN(MD)
      YE=DDRL-HMING(MD,TWL,ID)
      TDDRL=TDTIME(YE,FLTT)
C     TDDRL=(ACOS((B-DDRL+HMING(MD,TWL,ID))/AD))/WR+FTSPS(K)
      IF(NPRT.GE.0) WRITE(5,204)DDRL
  204 FORMAT(//38H ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL,F10.4,2H M)
      GO TO 229
  228 TWL=DDRL
      YE=DDRL+HMING(MD,TWL,ID)
      TDDRL=TDTIME(YE,0.0)
C     TDDRL=(ACOS((DDRL+HMING(MD,TWL,ID)-B)/AD))/WF
      IF(NPRT.GE.0) WRITE(5,226)DDRL
  226 FORMAT(//38H ESTIMATE OF REFILLED  RESERVOIR LEVEL,F10.4,2H M)
  229 IF(NPRT.GT.0) WRITE(5,221)
      IF (RIVQ.LE.0.0001.AND.IRSLU.EQ.0) GO TO 620
C
C
C
C   THIS SECTION FOR SLUICING FOLLOWING TURBINE PHASE -
C   REQUESTED FOR MERSEY BARRAGE WORK TO ACHIEVE MORE
C   NATURAL BASIN LEVELS.
C
C
      T0=TDDRL
      Y0=DDRL
      IF (IRSLU.NE.1) GO TO 789
      FACT1 = 0.65
      FACT2 = 0.85
```

```
C
C    THIS IS AN ESTIMATE BASED UPON RESULTS OF MODEL TESTS
C    AT BRISTOL UNIV. FACTOR REDUCES COEFFICIENT OF DISCHARGE
C    FOR SLUICES, AND INCREASES REVERSE SLUICE CAPACITY OF TURBINES.
C
C
      EFFAR=EFFAR*FACT1
      RSLU(MD)=RSLU(MD)/FACT2
      ID= -1*ID
      C=TSTEP
      CALL SLUING(NPRT,Y0,T0,10.0,YABS)
      ID=-1*ID
      EFFAR=EFFAR/FACT1
      RSLU(MD)=RSLU(MD)*FACT2
      GO TO 618
789   CONTINUE
C   THIS SECTION FOR RIVER FLOW WHEN TURBS & SLUS CLOSED
C
C   STEP IS DELTA LEVEL
C
      C=RIVQ*600.0/AREA(Y0)
      DC=C/500.0
      SL=SEALEV(T0)
      H0=(SL-Y0)*ID
  619 IF (NPRT.GT.0) WRITE(5,203)T0,SL,Y0,H0
  203 FORMAT(1X,4F10.4)
  617 Y1=Y0+C
      IF (Y1.GT.YABS) GO TO 406
      T1=T0+(AREAI(Y1)-AREAI(Y0))/(RIVQ*60.0)
      SL=SEALEV(T1)
      H1=(SL-Y1)*ID
      IF (H1.LT.0.0) GO TO 688
  406 C=C/2.0
      IF (C.LT.DC) GO TO 618
      GO TO 617
  688 Y0=Y1
      T0=T1
      H0=H1
      GO TO 619
C 620 IF(ID.EQ.1) T0=(ACOS((B-DDRL)/AD))/WR+FTSPS(K)
C     IF(ID.EQ.-1) T0=(ACOS((DDRL-B)/AD))/WF
  620 IF(ID.EQ.1) T0=TDTIME(DDRL,FLTT)
      IF(ID.EQ.-1)T0=TDTIME(DDRL,0.0)
      SL=SEALEV(T0)
      H0=0.0
      Y0=DDRL
  618 CONTINUE
C   RUNGE KUTTA SOLUTION TO FIND REFILLED LEVEL
      C=TSTEP
      CALL SLUING(NPRT,Y0,T0,10.0,YABS)
      RRL=Y0
      TRRL=T0
      IF (ID.EQ.1)TRRL=TDTIME(RRL,0.0)
      IF (NPRT.LE.0) GO TO 240
```

```
      WRITE(5,201)
      IF(ID.EQ.1)WRITE(5,202)RRL,TO,DDRL,TDDRL
      IF(ID.EQ.-1)WRITE(5,202)DDRL,TDDRL,RRL,TO
201   FORMAT(///6X,'MAX.POOL LEVEL   TIME MAX.P.L   MIN ',
     *'POOL LEV   T MIN PL')
202   FORMAT(6X,F10.4,8X,F10.4,5X,F10.4,3X,F10.4)
240   CONTINUE
C
C
C
C
C   NOW TURBINING WITH NEGATIVE TIME STEP FROM
C   DDRL UP TO RRL
C
      IF (IVS.EQ.1) UK=30.0
      ENERGY=0.0
      PENGY=0.0
      IP=0
      IC=0
      IMEF=0
      ICTEMP=0
      SUMO=0.00001
      INTERP=0
      C=TSTEP*(-1.0)
C  SOLVING FINITE DIFFERENCE EQUATION FOR MAX ENERGY
C  NEGATIVE TIME STEP,WORKING FROM DDRL,WHERE HEAD=HMIN,START GENERATION
C  AT MAX POWER OUTPUT
      IF (NPRT.LE.0) GO TO 222
      IF (IVS.NE.1) WRITE(5,221)
      IF (IVS.EQ.1) WRITE(5,1937)
1937  FORMAT(///3X,'   TIME    SEA LEVEL POOL LEVEL    HEAD     ',
     *'DISCHARGE    POWER  CAVITATION',',    TRANS LOSS',2X,
     *'TORQUE  ROT.SPEED',/3X,'  (MINS)       (M)         (M)',
     *'       (M)      M**3/SEC      (MW)    DISCHARGE',6X,'  (MW)',
     *4X,'POWER/RPM    RPM'/)
222   YO=DDRL
      TO=TDDRL
      YE=DDRL+HMING(MD,DDRL,ID)
      IF (ID.EQ.-1) TO=TDTIME(YE,FHTT)
      T1=TO+C
      SL=SEALEV(TO)
      HO=HMIN(MD)
      JO=0
      QO=ACMP(MD)+HO*(BCMP(MD)+HO*(CCMP(MD)+HO*DCMP(MD)))
      IF (MODE-2)53,52,53
   52 QO=ACME(MD)+HO*(BCME(MD)+HO*(CCME(MD)+HO*DCME(MD)))
   53 PO=POWER(HO,QO,1)
      QC=QCAV(HO,TO)
      IFLAG=2
      IF (QO.LT.QC) GO TO 501
      QO=QC
      IF (MODE.EQ.1) IFLAG=1
  501 PO=POWER(HO,QO,1)
      IF (PO.GE.0.0) GO TO 30
```

```
      P0=0.0
      Q0=0.0
   30 TQ=P0/UK
      IF (NPRT.LE.0) GO TO 927
      IF (IP.NE.1.AND.IVS.NE.1) GO TO 999
      IF (IP.EQ.1) WRITE(5,210)T0,SL,Y0,H0,Q0,P0,QC,J0,TLOSS,
     *PT0,PH0,PQ0,PP0,FP0
      IF (IVS.EQ.1) WRITE(5,210)T0,SL,Y0,H0,Q0,P0,QC,J0,TLOSS,
     *TQ,UK,SUM0
      GO TO 927
  999 WRITE(5,210)T0,SL,Y0,H0,Q0,P0,QC,J0,TLOSS
  927 INTERP=0
      C=TSTEP*(-1.0)
      IF(IP.EQ.1) C=C/5.0
      Q1=Q0
      J0=0
      IF (IC.GT.0) GO TO 27
C
      IF (MODE.EQ.1) DNDQ0=POWER(H0,Q0,3)
  502 CALL TURBIN(P0,P1,SL,QC,IC,ICTEMP,SUM0,INTERP,DNDQ0)
C
C
      IF (IP.EQ.1) CALL PUMPIN(P0,RRL)
C
C
C   CHECKING END CONDITIONS NOT VIOLATED
C
      CALL ENDCON(SL,QC,TRRL,0.0,YABS,HMIN(MD),RRL,TSTEP,
     *IC,MODE,MODE,P0,P1,ENERGY,PENGY,IP,INTERP)
C
C  IC=-1 LAST SHORTENED TSTEP BEFORE CLOSE SLUICES
C  IC=0  NO VIOLATION
C  IC=1  RECALCULATION A SHORT END STEP
C  IC=2  ONLY TO PRINT RESULT FROM IC=1
C
      IF (IC)30,30,25
   25 IF (IC-2)502,30,27
C
C   THE ABOVE RESETS LEVELS ETC. AND
C   RETURNS TO COMPUTE NEXT TIME STEP
C
   27 IF ((Y0-(RRL-ID*0.01))*ID.GT.0.0) GO TO 33
      IF (NPRT.GE.0) WRITE(5,220)
      IF (NPRT.GE.0) WRITE(5,260)ENERGY
      IF (H0.LT.(HMIN(MD)+0.5)) IRRL=ID
      BEN=ENERGY
      GO TO 70
C
C   SET UP VALUES IF PUMPING
C
   33 IF (IPUMP.EQ.1) CALL PSET(RRL,TRRL,YABS,IP,IC,NPRT)
      IF (IP.EQ.1) GO TO 30
      IF (NPRT.LT.1) GO TO 23
      IF (RIVQ.LT.0.0001) GO TO 23
```

```
C
C   THE FOLLOWING PLOTS RESERVOIR LEVEL FOLLOWING EQUALISATION
C   WHEN RIVQ INCREASES RRL
C
C   STEP IS NOW DELTA LEVEL
      WRITE(5,203)
      C=RIVQ*600.0/AREA(Y0)
  621 Y1=Y0-C
      IF (Y1.LT.RRL) GO TO 23
      T1=T0+(AREAI(Y1)-AREAI(Y0))/(RIVQ*60.0)
      IF (T1.LT.TRRL) GO TO 23
      SL=SEALEV(T1)
      H1=(Y1-SL)*ID
      WRITE(5,203)T1,SL,Y1,H1
      T0=T1
      Y0=Y1
      GO TO 621
   23 IF(NPRT.GE.0) WRITE(5,260)ENERGY
      BEN=ENERGY
      IF (IP.EQ.0) GO TO 998
      FPENGY=PENGY*FINT
      BEN=ENERGY-FPENGY
      IF (NPRT.GE.0) WRITE(5,995) PENGY,FPENGY,BEN
  995 FORMAT(5X,13HENERGY INPUT ,F15.5,7H(MWHRS),5X,
     *10HINPUT COST,F15.5,31H(MWHRS)*INPUT/OUTPUT COST RATIO/
     *5X,13HBENEFIT      ,F15.5,21H  (OUTPUT-INPUT COST))
C
C
  220 FORMAT(//5X,54HREVERSE TURBINE SOLUTION DOES NOT REACH REQUIRED LE
     1VEL)
  260 FORMAT(/5X,13HENERGY OUTPUT,F15.5,7H(MWHRS))
  221 FORMAT(///3X,70H   TIME    SEA LEVEL POOL LEVEL   HEAD     DISCHARGE
     1   POWER  CAVITATION,'    TRANS LOSS',/
     *3X,'  (MINS)      (M)        (M)          (M)    M**3/SEC    ',
     1' (MW)   DISCHARGE','          (MW)',/)
  210 FORMAT(1X,6F10.4,1X,F10.4,I4,3F10.5,F10.0,2F10.5)
C
C  ESTABLISH NEW DDRL AND RETURN TO 15, SEE FLOW CHART
C
  998 IRRL=0
   70 CONTINUE
      IF (IOPTSH.EQ.1) BEN=1000.0-(HNOM-H0)**2
      CALL OPTIM(DDRL,DDRL0,BEN,E0,DDRMAX,DDRMIN,DDRMAX,IRRL,
     *D,NPRT,N0,DDRTOL)
      IF (NPRT.NE.20) GO TO 15
      IF (ID.EQ.1) WRITE(5,250)DDRL0
      IF (ID.EQ.-1) WRITE(5,233)DDRL0
      IF (IP.EQ.0) WRITE(5,251)E0
      IF (IP.NE.0) WRITE(5,997)E0
   13 ANENG=E0*FREQ(K)+ANENG
      ANENG=ANENG/1000.0
      IF (IP.EQ.0) WRITE(5,252)ANENG
   12 IF (IP.NE.0) WRITE(5,996)ANENG
      WRITE(*,252)ANENG
```

```
      GO TO 10
   11 CONTINUE
      Q=0.0
      H=0.0
      WRITE(*,'(''STOP - END OF MAIN PROGRAM'')')
      STOP
  250 FORMAT(//1X,35HOPTIMUM DRAWNDOWN RESERVOIR LEVEL =,F10.4,2H M)
  233 FORMAT(//1X,35HOPTIMUM REFILLED  RESERVOIR LEVEL =,F10.4,2H M)
  251 FORMAT(/1X,23HOPTIMUM ENERGY OUTPUT =,F15.5,8H (MWHRS))
  252 FORMAT(///1X,25HANNUAL ENERGY PRODUCTION ,F15.5,8H (GWHRS)///)
  997 FORMAT(/1X,17HOPTIMUM BENEFIT =,F15.5,8H (MWHRS),
     *38H INCORPORATING INPUT/OUTPUT COST RATIO)
  996 FORMAT(///1X,15HANNUAL BENEFIT ,F15.5,8H (GWHRS),
     *38H INCORPORATING INPUT/OUTPUT COST RATIO///)
      END
      FUNCTION GENLIM(T,Y)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK1/RTSPS(10),FTSPS(10),AD,WR,B,WF,K
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
     *CHSIG(2),PMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK6/ACMP(2),BCMP(2),CCMP(2),DCMP(2),
     *ACME(2),BCME(2),CCME(2),DCME(2),IMEF
      SL=SEALEV(T)
      H=HNET(Y,SL,Q1,ID,1)
      IF (ISLU.EQ.1) WRITE(5,100)
      IF (ISLU.EQ.1) HS=SQRT(-1.0)
  100 FORMAT(51HTURBINE+SLUICING - MUST INCORPORATE NET SLUICE HEAD)
      IF (IFLAG-1)11,3,9
   11 IF (H.LT.HR(MD)) GO TO 10
   13 HD=H-HR(MD)
      Q1=PM(1,MD)+HD*(PM(2,MD)+HD*(PM(3,MD)+HD*PM(4,MD)))+
     * PM(5,MD)*SQRT(HD)
   12 GENLIM=-60.0*ID*(TURBN*Q1+ISLU*EFFAR*4.4285*SQRT(H)-RIVQ*ID)/
     *AREA(Y)
      RETURN
    3 Q1=QCAV(H,T)
      GO TO 12
    9 IF (MODE.EQ.3)GO TO 10
      Q1=ACME(MD)+H*(BCME(MD)+H*(CCME(MD)+H*DCME(MD)))
      IF (H.GT.HR(MD)) Q1=QMAXEF(H)
      IF (POWER(H,Q1,1).GT.PMAX) GO TO 11
      GO TO 12
   10 IF (H.GT.HR(MD)) GO TO 13
      Q1=ACMP(MD)+H*(BCMP(MD)+H*(CCMP(MD)+H*DCMP(MD)))
      GO TO 12
      END
      SUBROUTINE MAXOUT(QHR,DNDQ0)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK1/RTSPS(10),FTSPS(10),AD,WR,B,WF,K
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
```

```
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK6/ACMP(2),BCMP(2),CCMP(2),DCMP(2),
     *ACME(2),BCME(2),CCME(2),DCME(2),IMEF
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
      QME(H)=ACME(MD)+H*(BCME(MD)+H*(CCME(MD)+H*DCME(MD)))
      T1=T0+C
      SL=SEALEV(T1)
      IF (IMEF.EQ.1) GO TO 8
      VALUE=0.0
      Q1=Q0
      Q=Q0
C ITERATE,TO LABEL 6,TO FIND CORRESPONDING Y1 AND Q1
    5 QA=(Q0+Q1)/2.0
      Y1=Y0-(C*60.0*(TURBN*QA*ID-RIVQ))/AREA(Y0)
      H1=HNET(Y1,SL,Q1,ID,1)
      IF (MT.EQ.1)GO TO 20
      RH=SQRT(H1)
      IF (MD.EQ.2) GO TO 50
      QMAX=RMU(IPY-3)*D2*RH
      QMIN=RMU(4)*D2*RH
      GO TO 20
   50 QMAX=RM2(IPY2-3)*D2*RH
      QMIN=RM2(4)*D2*RH
   20 CONTINUE
      HA=(H0+H1)/2.0
      YA=(Y0+Y1)/2.0
      DQ=Q0/300.0
      NFLAG=0
      JJ=0
C   JJ IS USED TO COUNT FIRST 2 Q1 ESTIMATES AND USE AST. LINE
C   TO FIND A MORE ACCURATE Q1EST
C   IF SOLUTION NOT FOUND IN 20 ST. LINE ITERATIONS
C   Q1=Q0 IS RETURNED
C   IF OPERATION BELOW MAX EFF CURVE NO SOLUTION CAN BE
C   FOUND BY ST. LINE OR ITERATION METHOD
C   IF ITERATION IS REQUIRED CAN START THIS BY GOING TO LABEL 9
C ITERATE,TO LABEL 4,TO FIND Q1 WHICH GIVES VALUE=0.0
    3 VA=VALUE
      QA=(Q0+Q1)/2.0
      J0=J0+1
      CALL PARDIF(HA,QA,H1,Q1,DNDH,DNDQ1)
      VALUE=TURBN*DNDH+(AREA(YA)/(C*60.0))*(DNDQ1-DNDQ0)
      JJ=JJ+1
      IF (JJ.LT.2) GO TO 7
      IF(JJ.GT.20) GO TO 8
      Q2=Q1+(Q1-QV)*VALUE/(VA-VALUE)
      IF (MT.EQ.1) GO TO 30
      IF (Q2.GT.QMAX) Q2=QMAX
      IF (Q2.LT.QMIN) Q2=QMIN
```

```
   30 CONTINUE
      QV=Q1
      IF (ABS(Q1-Q2).LE.(Q1*0.0005)) GO TO 4
      Q1=Q2
      GO TO 3
    9 Q1=Q0
    7 QV=Q1
      IF (VALUE.GT.0.0) GO TO 1
      IF (NFLAG.EQ.1) GO TO 2
      Q1=Q1+DQ
      GO TO 3
    2 DQ=DQ/5.0
      IF (DQ.LE.(Q1*0.0005)) GO TO 4
      Q1=Q1+4.0*DQ
      GO TO 3
    1 Q1=Q1-DQ
      NFLAG=1
      GO TO 3
    4 CONTINUE
      DQ=SQRT((Q-Q1)**2)
      IF (DQ.LE.(Q1*0.0005)) GO TO 6
      Q=Q1
      GO TO 5
    6 CONTINUE
      IF (QME(H1).LT.Q1) GO TO 10
    8 C2=C/2.0
      RK1=GENLIM(T0,Y0)
      TE=T0+C2
      YE=Y0+C2*RK1
      RK2=GENLIM(TE,YE)
      YE=Y0+C2*RK2
      RK3=GENLIM(TE,YE)
      YE=Y0+C*RK3
      RK4=GENLIM(T1,YE)
      Y1=Y0+C/6.0*(RK1+RK4+2.0*(RK2+RK3))
      H1=HNET(Y1,SL,Q1,ID,1)
      Q1=QME(H1)
C   IMEF IS A FLAG SET TO 1 WHEN MAX ENERGY SOLUTION REACHES
C   MAX.EFF. CURVE.REMAINDER OF GENERATION IS ON MAX.EFF CURVE
C   IMEF IS RESET IN FORTPROG FOR EACH DDRL
      IMEF=1
   10 CONTINUE
      RETURN
      END
      FUNCTION SLUICE(T,Y)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHIT
      COMMON /BLKX/EXITA(2,2),DS(2),SPACE(2),INET,ISLOP,A0SLOP,A1SLOP,
     *XXX,XXXX
      TWL=Y
      SL=SEALEV(T)
      HG=(SL-Y)*ID
```

```
      H1=HG
      HT=HG
      IF (H1.LE.0.0) GO TO 30
      IFLAG=0
      IF (INET.NE.1) GO TO 10
      IF (TWL.GT.SL) TWL=SL
C    FOR SLUICES
      IQ=2
      IF (ID.EQ.-1) IQ=1
      CONST2=(EFFAR*4.42854/SLUN)**2
      AE=EXITA(2,IQ)
      A2=(TWL+DS(2))*SPACE(2)
      XX=((A2/AE)**2-2.0*A2/AE+2.0)/(19.62*A2*A2)
      Q1=SQRT(CONST2*HG/(1.0+CONST2*XX))
C    FOR TURBINES AS SLUICES
      IQ=2
      IF (ID.EQ.-1) IQ=1
      CONST2=RSLU(MD)**2
      AE=EXITA(1,IQ)
      A2=(TWL+DS(1))*SPACE(1)
      XX=((A2/AE)**2-2.0*A2/AE+2.0)/(19.62*A2*A2)
      Q0=SQRT(CONST2*HG/(1.0+CONST2*XX))
C
C
      H1=HNET(SL,Y,Q1,ID,2)
      HT=HNET(SL,Y,Q0,ID,4)
   10 CONTINUE
      Q1=EFFAR*4.42854*SQRT(H1)/SLUN
      Q0=RSLU(MD)*SQRT(HT)
C     WRITE(*,'(5F6.3,2F6.1)')SL,Y,HG,H1,HT,Q1,Q0
      SLUICE=(Q1*SLUN+Q0*TURBN+RIVQ*ID)*60.0*ID/AREA(Y)
      RETURN
   30 IFLAG=1
      SLUICE=0.0
      RETURN
      END








      FUNCTION AREA(Y)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      YL=Y
      IF (YL.GT.AABS) YL=AABS
      DO 10 I=1,J
      IF (YL.LT.AXX(I)) GO TO 20
   10 CONTINUE
      WRITE(5,'(''STOP - ERROR IN FUNCTION AREA'')')
      STOP
```

```
   20 AREA=AC(I)+YL*AX(I)
      RETURN
C
      END






      FUNCTION AREAI(Y)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      YL=Y
      ADD=0.0
      IF (Y.LE.AABS) GO TO 10
      ADD=AREA(AABS)*(Y-AABS)
      YL=AABS
   10 CONTINUE
      DO 20 I=1,J
      IF (YL.LE.AXX(I)) GO TO 30
   20 CONTINUE
      WRITE (5,'(''STOP - ERROR IN FUNCTION AREAI'')')
      STOP
   30 CONTINUE
      YLL=-10.0
      DO 40 K=1,I
      YH=AXX(K)
      IF (K.EQ.I) YH=YL
      ADD=YH*(AC(K)+YH*AX(K)/2.0)-YLL*(AC(K)+YLL*AX(K)/2.0)+ADD
      YLL=AXX(K)
   40 CONTINUE
      AREAI=ADD
      RETURN
      END





      FUNCTION ACOS(Y)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      ACOS=ATAN(SQRT(1.0/(Y*Y)-1))
      RETURN
      END





      SUBROUTINE PREAD
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLKP/NPUMPS,QA,QB,QCC,QD,ZA,ZB,ZC,ZD,PHMIN,PHMAX,FINT,
     1TMIN,PSTART,PFIN
```

```
      WRITE(5,200)
      READ(4,100)NPUMPS
      READ(4,101)QA,QB,QCC,QD,ZA,ZB,ZC,ZD
      READ(4,102)PHMIN,PHMAX,FINT,TMIN,PSTART,PFIN,FMGEN,PMAJ
      WRITE(5,201)NPUMPS
      WRITE(5,202)QA,QB,QCC,QD
      WRITE(5,203)ZA,ZB,ZC,ZD
      WRITE(5,204)PHMIN,PHMAX
      WRITE(5,205)FINT
      WRITE(5,206)TMIN
      WRITE(5,207)PSTART,PFIN
  200 FORMAT(1X,5HPUMPS/1X,5H-----//)
  100 FORMAT(I5)
  101 FORMAT(4F10.4)
  102 FORMAT(2F10.4)
  201 FORMAT(1X,19HNUMBER OF PUMPS    ,I5/)
  202 FORMAT(1X,10HQ11      = ,F10.4,3H + ,F10.4,7H*KU1 + ,F10.4,
     111H*KU1*KU1 + ,F10.4,12H*KU1*KU1*KU1/)
  203 FORMAT(1X,10HPOWER   = ,F10.4,3H + ,F10.4,7H* H  + ,F10.4,
     111H* H * H  + ,F10.3,12H* H * H * H /)
  204 FORMAT(1X,23HMINIMUM PUMPING HEAD = ,F10.4,2H M/
     11X,23HMAXIMUM PUMPING HEAD = ,F10.4,2H M/)
  205 FORMAT(1X,52HRATIO OF INPUT ENERGY COST TO OUTPUT ENERGY VALUE = ,
     1F10.4/)
  206 FORMAT(1X,41HMINIMUM TIME BETWEEN PUMP AND GENERATE = ,F10.4,
     15H MINS/)
  207 FORMAT(1X,51HTIMES AFTER HW WHEN INPUT POWER AVALIABLE.    START,
     1F10.4,10H   FINISH ,F10.4,8H  (MINS)/)
C
C
      WRITE(5,208) FMGEN,PMAJ
  208 FORMAT(1X,'EFFICIENCY OF MOTOR WHEN MOTORING',F10.2,'%',
     1/,1X,'MAJORATION APPLIED TO PUMP EFFICIENCIES',F10.2,'%',
     1/,1X,'FMGEN & PMAJ APPLIED OUTSIDE PROG. WHEN FITTING ',
     1'P=F(HEAD)'//)
C
C
      RETURN
      END






      SUBROUTINE PUMPIN(PO,RRL)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLKP/NPUMPS,QA,QB,QCC,QD,ZA,ZB,ZC,ZD,PHMIN,PHMAX,FINT,
     1TMIN,PSTART,PFIN
      COMMON /BLKP1/PT0,PH0,PQ0,PP0,FP0,PT1,PH1,PQ1,PP1,FP1
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      DIMENSION F(5)
C RUNGE KUTTA SOLUTION FOR PUMPING IN INCREMENTS
```

```
C OF LEVEL , STEP IS VARIABLE-DEPENDENT UPON TURBINING PHASE
      RK1=QPUMP(Y0,PT0)
      C2=(Y1-Y0)/2.0
      TE=PT0+C2*RK1
      YE=Y0+C2
      RK2=QPUMP(YE,TE)
      TE=PT0+C2*RK2
      RK3=QPUMP(YE,TE)
      TE=PT0+C2*RK3*2.0
      RK4=QPUMP(Y1,TE)
      PT1=PT0+(Y1-Y0)/6.0*(RK1+RK4+2.0*(RK2+RK3))
      X=QPUMP(Y1,PT1)
      PQ1=PQ1
      SL=SEALEV(PT1)
      PH1=HNET(Y1,SL,PQ1,ID,3)
      PP1=PPOW(PH1,PQ1)
      PENINC=((PP0+PP1)/2.0)*(PT1-PT0)*NPUMPS/60.0
      P1=POWER(H1,Q1,1)
      TENINC=((P0+P1)/2.0)*(T0-T1)*TURBN/60.0
C FP1 IS FACTORED BENEFIT
      FP1=TENINC-PENINC*FINT
      DO 20 KK=1,4
   20 F(KK)=1.0
      IF(FP1.LT.0.0)F(1)=FP0/(FP0-FP1)
      IF((T1-PT1).LT.TMIN)F(2)=(TMIN-(T0-PT0))/((T1-PT1)-(T0-PT0))
      IF(PT1.GT.PFIN)F(3)=(PFIN-PT0)/(PT1-PT0)
      IF(PH1.GT.PHMAX)F(4)=(PHMAX-PH0)/(PH1-PH0)
      DO 10 KK=2,4
   10 IF(F(KK).LT.F(1))F(1)=F(KK)
      RRL=Y0+F(1)*(Y1-Y0)
      RETURN
      END






      FUNCTION QPUMP(Y,T)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLKP/NPUMPS,QA,QB,QCC,QD,ZA,ZB,ZC,ZD,PHMIN,PHMAX,FINT,
     1TMIN,PSTART,PFIN
      COMMON /BLKP1/PT0,PH0,PQ0,PP0,FP0,PT1,PH1,PQ1,PP1,FP1
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      SL=SEALEV(T)
      H=HNET(Y,SL,PQ1,ID,3)
      IF (H.EQ.0.0) H=0.0001
      X=UK/SQRT(H)
      PQ1=(QA+X*(QB+X*(QCC+X*QD)))*D2*SQRT(H)
      QPUMP=ID*AREA(Y)/((NPUMPS*PQ1+RIVQ*ID)*60.0)
      RETURN
```

```
      END






      FUNCTION PPOW(H,Q)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLKP/NPUMPS,QA,QB,QCC,QD,ZA,ZB,ZC,ZD,PHMIN,PHMAX,FINT,
     1TMIN,PSTART,PFIN
      PPOW=ZA+H*(ZB+H*(ZC+H*ZD))
      RETURN
      END






      SUBROUTINE PSET(RRL,TRRL,YABS,IP,IC,NPRT)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLKP/NPUMPS,QA,QB,QCC,QD,ZA,ZB,ZC,ZD,PHMIN,PHMAX,FINT,
     1TMIN,PSTART,PFIN
      COMMON /BLKP1/PT0,PH0,PQ0,PP0,FP0,PT1,PH1,PQ1,PP1,FP1
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK1/RTSPS(10),FTSPS(10),AD,WR,B,WF,K
      IF (IP.EQ.0) GO TO 10
      IP=2
      RETURN
   10 IF(ABS(Y0-YABS).LT.0.01)RETURN
      PT0=TRRL
      IF(PT0.LT.PSTART)PT0=PSTART
      TEMP=RRL-ID*PHMIN
      PTHMIN=TDTIME(TEMP,0.0)
      IF(ID.EQ.-1) PTHMIN=TDTIME(TEMP,FLTT)
      IF(PT0.LT.PTHMIN)PT0=PTHMIN
      IF(T0-PT0.LT.TMIN)RETURN
C O.K. TO PUMP
      IP=1
      IC=0
      SL=SEALEV(PT0)
      PQ1=0.0
      PH0=HNET(RRL,SL,PQ1,ID,3)
      X=QPUMP(RRL,PT0)
      PQ0=PQ1
      PP0=PPOW(PH0,PQ0)
      FP0=0.0
      IF (NPRT.LE.0) RETURN
      WRITE(5,100)
  100 FORMAT(1H+,87X,40HPUMP TIME PUMP HEAD    Q PUMP    POWER IN ,
     *8H BENEFIT/
     *1X,86X,49H  (MINS)       (M)     (M**3/S)     (MW)     (ET-FEP))
```

```
      RETURN
      END





      SUBROUTINE ENDCON(SL,QC,TSTOP,SLOT,YABS,HMIN,STOPL,TSTEP,
     *IC,MODE,MODET,P0,P1,ENERGY,PENGY,IP,INTERP)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLKP/NPUMPS,QA,QB,QCC,QD,ZA,ZB,ZC,ZD,PHMIN,PHMAX,FINT,
     1TMIN,PSTART,PFIN
      COMMON /BLKP1/PT0,PH0,PQ0,PP0,FP0,PT1,PH1,PQ1,PP1,FP1
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
C
C  CHECKING END CONDITIONS NOT VIOLATED
C  AND IF NOT RESETS LEVELS ETC FOR NEXT STEP
C
      CONST=AREAI(STOPL)
      F=1.0
      FH=1.0
      FABS=1.0
      IF (H1.LT.HMIN-0.01) FH=(H0-HMIN)/(H0-H1)
      IF (RIVQ.LE.0.0001) GO TO 26
      IF (Y1.GT.YABS) FABS=(YABS-Y0)/(Y1-Y0)
C
C   RIVER FLOW END CONDITIONS
C
      TRIV=TSTOP+(AREAI(Y1)-CONST)/(RIVQ*60.0)
      IF ((ID*(TRIV-T1)).LT.0.0) GO TO 29
      TRIV0=TSTOP+(AREAI(Y0)-CONST)/(RIVQ*60.0)
      GRIV=(Y1-Y0)/(TRIV-TRIV0)
      GRT=(Y1-Y0)/(T1-T0)
      T=(GRIV*TRIV0-GRT*T0)/(GRIV-GRT)
      F=(T0-T)/(T0-T1)
      GO TO 29
C  ONLY USE NEXT LINE WHEN ZERO RIVER FLOW
   26 IF (((STOPL-Y1)*ID).LT.0.0) F=(Y0-STOPL)/(Y0-Y1)
   29 IF (FABS.LT.F) F=FABS
      IF (FH.LT.F) F=FH
      IF (IC.EQ.1) GO TO 20
      IF (ABS(F-1.0).LT.0.0001) GO TO 25
      C=C*F
      IF (C.EQ.0.0) C=0.00001
      IF (IC.EQ.-1) IC=0
   20 IC=IC+1
      IF (IC.NE.2) GO TO 11
      GO TO 35
   25 IF (ISLU.EQ.0) GO TO 35
C
C  IF DURING NEXT TIME STEP SLUICES SHOULD BE CLOSED,SHORTEN
C  TIME STEP PUT IC=-1
```

```
C
      IF (IC.EQ.1) GO TO 35
      TEMP=T1-SLOT
      IF (ABS(TEMP).LE.0.001) GO TO 10
      IF (TEMP.GT.(-1.0*C)) GO TO 35
      C=TEMP*(-1.0)
      IC=-1
      GO TO 35
   10 IC=0
      ISLU=0
      MODE=MODET
   35 P1=POWER(H1,Q1,1)
      IF (INTERP.EQ.1) IFLAG=0
      SL=SEALEV(T1)
      IF (P1.GT.0.0) GO TO 500
      P1=0.0
      Q1=0.0
      Y1=Y0
      H1=(Y1-SL)*ID
  500 ENERGY=((P0+P1)/2.0)*(T0-T1)*TURBN/60.0+ENERGY
      IF (IFLAG.EQ.1) QC=0.0
      Q0=Q1
      T0=T1
      H0=H1
      Y0=Y1
      P0=P1
      IF (IP.NE.1) GO TO 11
      PENGY=((PP0+PP1)/2.0)*(PT1-PT0)*NPUMPS/60.0+PENGY
      PT0=PT1
      PH0=PH1
      PQ0=PQ1
      PP0=PP1
      FP0=FP1
   11 RETURN
      END
      SUBROUTINE TURBIN(P0,P1,SL,QC,IC,ICTEMP,SUM0,INTERP,DNDQ0)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK1/RTSPS(10),FTSPS(10),AD,WR,B,WF,K
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
     *CHSIG(2),PMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK6/ACMP(2),BCMP(2),CCMP(2),DCMP(2),
     *ACME(2),BCME(2),CCME(2),DCME(2),IMEF
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
      IF (MODE-2)50,24,24
   50 IF (IFLAG-1)24,24,28
   28 CALL MAXOUT(QHR(MD),DNDQ0)
      P1=POWER(H1,Q1,1)
```

```
      IF (P1.LE.PMAX) GO TO 21
C    LINEAR INTERPOLATION TO FIND Q,T,H AT INTERSECTION
C    WITH LIMITING CAPACITY CURVE
      F=(PMAX-P0)/(P1-P0)
      CALL FINTRP(F,H1,H0,Q1,Q0,C,T1,T0,Y1,Y0)
      INTERP=1
      GO TO 21
C  NOW RUNGE KUTTA SOLUTION ALONG LIMITING CAPACITY CURVE OR MAXEFF OR MAXPOWER
   24 C2=C/2.0
      RK1=GENLIM(T0,Y0)
      TE=T0+C2
      YE=Y0+C2*RK1
      RK2=GENLIM(TE,YE)
      YE=Y0+C2*RK2
      RK3=GENLIM(TE,YE)
      TE=T0+C
      YE=Y0+C*RK3
      RK4=GENLIM(TE,YE)
      Y1=Y0+C/6.0*(RK1+2.0*RK2+2.0*RK3+RK4)
      T1=T0+C
      X=GENLIM(T1,Y1)
      Q1=Q1
      SL=SEALEV(T1)
      H1=HNET(Y1,SL,Q1,ID,1)
      IF (IFLAG.NE.1) GO TO 21
      IF (MODE.NE.1) GO TO 60
      P1=POWER(H1,Q1,1)
      IF (P1.LE.PMAX) GO TO 95
      F=(PMAX-P0)/(P1-P0)
      CALL FINTRP(F,H1,H0,Q1,Q0,C,T1,T0,Y1,Y0)
      IFLAG=0
      GO TO 95
   21 QC=QCAV(H1,T1)
      IF (QC.GT.Q1) GO TO 94
C    NOW RUNGE KUTTA SOLUTION ALONG LIM.WATER DEPTH CURVE
      IFLAG=1
      GO TO 24
   94 IF (MODE.NE.1) GO TO 60
      IF (IFLAG.EQ.2) GO TO 25
C CALCULATING THE VALUE OF FINITE DIFF. INTEGRAL WHICH GIVES CONDION
C  WHEN OPERATION RETURNS TO THAT FOR MAX ENERGY
   95 YA=(Y0+Y1)/2.0
      QA=(Q0+Q1)/2.0
      HA=(H0+H1)/2.0
      CALL PARDIF(HA,QA,H1,Q1,DNDH,DNDQ1)
      FINDIF=C*60.0*(TURBN*DNDH+AREA(YA)*(DNDQ1-DNDQ0)/(C*60.0))*
     *(Y1-Y0)
      SUM1=SUM0+FINDIF
      IF (SUM0.LT.0.0) GO TO 91
      IF (SUM1.LT.0.0) GO TO 92
      GO TO 93
   91 IF (SUM1.GT.0.0) GO TO 92
   93 SUM0=SUM1
      GO TO 25
```

```
   92 F=(0.0-SUM0)/(SUM1-SUM0)
      SUM0=0.00001
      CALL FINTRP(F,H1,H0,Q1,Q0,C,T1,T0,Y1,Y0)
      IF (IFLAG.EQ.1) GO TO 60
      Q1=QHR(MD)
      IF (H1.LE.HR(MD)) GO TO 60
      H=H1-HR(MD)
      Q1=PM(1,MD)+H*(PM(2,MD)+H*(PM(3,MD)+H*PM(4,MD)))+PM(5,MD)*SQRT(H)
   60 IFLAG=2
   25 RETURN
      END
      SUBROUTINE BSREAD(IPX,IPY,RLAMDA,RMU,NC,COEFFS,NADRES)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      DIMENSION RLAMDA(20),RMU(20),COEFFS(256),AB(15)
C
C    READ IN DATA FOR BICUBIC SPLINE FIT TO
C    TURBINE HILL CHART
C
      READ(6,9300)(AB(I),I=1,15)
      READ(6,9301)IPX,IPY
      READ(6,9302)(RLAMDA(I),I=1,IPX)
      READ(6,9302)(RMU(I),I=1,IPY)
      READ(6,9303)NC
      READ(6,9302)(COEFFS(I),I=1,NC)
      NADRES=(IPX-7)*(IPY-7)
 9300 FORMAT(15A4)
 9301 FORMAT(2I4)
 9302 FORMAT(F15.5)
 9303 FORMAT(I4)
      WRITE(5,9998)(AB(I),I=1,15)
 9998 FORMAT(//53H TURBINE HILLCHART FROM BICUBIC SPLINE REPRESENTATION/
     *10X,15A4)
      RETURN
      END
      SUBROUTINE ME01(M,IPX,IPY,UK1,Q11,FF,RLAMDA,RMU,
     *COEFFS,NC,NADRES)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      DIMENSION UK1(6),Q11(6),FF(6),RLAMDA(20),RMU(20),
     *IPOINT(180),COEFFS(256),IADRES(180)
      DO 50 I=1,M
      IF (UK1(I).GT.RLAMDA(IPX)) UK1(I)=RLAMDA(IPX)
      IF (UK1(I).LT.RLAMDA(1)) UK1(I)=RLAMDA(1)
      IF (Q11(I).GT.RMU(IPY)) Q11(I)=RMU(IPY)
   50 IF (Q11(I).LT.RMU(1)) Q11(I)=RMU(1)
      IFAIL=0
      NPOINT=M+NADRES
      CALL E02ZAF(IPX,IPY,RLAMDA,RMU,M,UK1,Q11,
     *IPOINT,NPOINT,IADRES,NADRES,IFAIL)
      IF(IFAIL.EQ.0) GO TO 40
      WRITE(5,99993)IFAIL
99993 FORMAT(23H E02ZAF FAILURE NUMBER ,I4)
      RH=SQRT(-1.0)
   40 CONTINUE
```

```
      IFAIL=0
      CALL E02DBF(M,IPX,IPY,UK1,Q11,FF,RLAMDA,RMU,IPOINT,NPOINT,
     *COEFFS,NC,IFAIL)
      IF (IFAIL.EQ.0) GO TO 240
      WRITE(5,99994)IFAIL
99994 FORMAT(23H E02DBF FAILURE NUMBER ,I4)
      RH=SQRT(-1.0)
  240 DO 30 I=1,M
   30 FF(I)=FF(I)*GEF*(1.0+S)
      RETURN
      END
      SUBROUTINE TURBOP(HMAX,UK1MAX)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
     *CHSIG(2),PMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK6/ACMP(2),BCMP(2),CCMP(2),DCMP(2),
     *ACME(2),BCME(2),CCME(2),DCME(2),IMEF
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
      DIMENSION PMT(5)
      IF (MT.EQ.1) GO TO 10
      RL=RLAMDA(1)
      IF (MD.EQ.2) RL=RLAMD2(1)
      HMAX1=(UK/RL)**2
      IF (HMAX.GT.HMAX1) HMAX=HMAX1
   10 HMIN(MD)=(UK/UK1MAX)**2
C
C    FIND RATED HEAD - WHERE PMAX REACHED ON MAX POWER CURVE
C
      IHALT=1
      DH=1.0
      H=(HMIN(MD)+HMAX)/2.0
   20 CALL QMAXP(H,Q,QME,P)
      P=POWER(H,Q,1)
      DP=ABS(PMAX-P)
      IF (DP.LE.0.001) GO TO 40
      IF (P.GT.PMAX) GO TO 50
      H=H+DH
      IHALT=0
      GO TO 20
   50 IF (IHALT.EQ.0) GO TO 70
      H=H-DH
   80 IHALT=1
      GO TO 20
   70 DH=DH/5.0
      H=H-4.0*DH
      GO TO 80
   40 HR(MD)=H
      QHR(MD)=Q
```

```
      IF(MD.EQ.1)WRITE(5,100)
      IF(MD.EQ.2)WRITE(5,101)
      WRITE(5,102)
  101 FORMAT(//1X,18HINDIRECT OPERATION)
  100 FORMAT(//1X,16HDIRECT OPERATION)
      WRITE(5,103)HMIN(MD)
      WRITE(5,104)HR(MD)
      WRITE(5,105)RSLU(MD)
  102 FORMAT(1X,18H------------------)
  103 FORMAT(/1X,19HMIN GENERATION HEAD,F10.3,2H M)
  104 FORMAT(1X,10HRATED HEAD,9X,F10.3,2H M)
  105 FORMAT(1X,23HREVERSE SLUICE CAPACITY,F10.2,
     *21HM**3/SEC AT 1.0M HEAD///)
C
C   COMPUTE CUBIC EQUATIONS TO FIT MAX POWER AND
C   MAX EFFICIENCY CURVES
C
      CALL MAXPCU(PMAX,HR(MD),HMIN(MD),ACMP(MD),BCMP(MD),
     *CCMP(MD),DCMP(MD),ACME(MD),BCME(MD),CCME(MD),DCME(MD))
C
C   COMPUTE AND FIT POLYNOMIAL TO LIMITING CAPACITY CURVE
C
      CALL LIMCAP(HMAX,PMAX,HR(MD),QHR(MD),PMT)
      DO 30 IT=1,5
   30 PM(IT,MD)=PMT(IT)
      RETURN
      END
      SUBROUTINE TREAD(MD,RSLU)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),JO,MT,GEF,IVS
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
     *CHSIG(2),PMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
      COMMON /BLK10/TORQUE,UK1MIN(2),UK1MAX(2),Q11MEF(2)
      COMMON /BLKC/CAVR(10,2),ICAV
      IF (MD.EQ.1) WRITE(5,100)
      IF (MD.EQ.2) WRITE(5,101)
  100 FORMAT(////1X,14HDIRECT TURBINE)
  101 FORMAT(////1X,16HINDIRECT TURBINE)
      WRITE(5,102)
  102 FORMAT(1X,16H----------------)
      READ(4,103)MT,ICAV,BANGLE,QHILL(MD),CHILL(MD),RSLU,
     *UK1MIN(MD),UK1MAX(MD),Q11MIN,Q11MEF(MD),Q11MAX
  103 FORMAT(I1,I1,4F10.0/5F10.0)
      WRITE(5,104)BANGLE,UK1MAX(MD),UK1MIN(MD),Q11MIN,
     *Q11MEF(MD),Q11MAX
      WRITE(5,105)QHILL(MD),CHILL(MD)
  104 FORMAT(/1X,18HRUNNER BLADE ANGLE,F10.2,8H DEGREES,
     *8H, KU1MAX,F9.4,' , KU1MIN',F9.4/
     *'RESPECTIVELY Q11MIN,Q11MAXEFF,Q11MAX  ',3F10.2)
  105 FORMAT(/1X,30H HILLCHART RESTRICTION Q11.LE.,F10.4,
```

```
     *5H*KU1+,F10.4)
      IF (MT.EQ.1) GO TO 10
      IF (MD.EQ.1) CALL BSREAD(IPX,IPY,RLAMDA,RMU,NC,
     *COEFFS,NADRES)
      IF (MD.EQ.2) CALL BSREAD(IPX2,IPY2,RLAMD2,RM2,NC2,
     *COEFF2,NADRE2)
      GO TO 20
C
C   READ IN A1-A10 FOR TEN CONSTANTS HILLCHART MODEL
C
   10 WRITE(5,106)
      RMU(4)=Q11MIN
      IF (MD.EQ.2) RM2(4)=Q11MIN
      IPY=10
      IPY2=10
      RMU(IPY-3)=Q11MAX
      IF (MD.EQ.2) RM2(IPY-3)=Q11MAX
  106 FORMAT(//1X,16HCONSTANTS A1-A10)
      READ(4,107)(A(I,MD),I=1,10)
      WRITE(5,108)(A(I,MD),I=1,10)
  107 FORMAT(5F10.0)
  108 FORMAT(1X,5E15.5)
   20 CONTINUE
      IF (ICAV.EQ.2) GO TO 40
C
C   READ EWZ  CAVITATION EQS.
C
      READ(4,109)A1(MD),B1(MD),C1(MD),A2(MD),B2(MD),
     *CC2(MD),HUB,CHSIG(MD)
  109 FORMAT(8F10.0)
      WRITE(5,110)
  110 FORMAT(/1X,26HCAVITATION CONSTANTS A,B,C)
      WRITE(5,111)A1(MD),B1(MD),C1(MD),CHSIG(MD)
      WRITE(5,112)A2(MD),B2(MD),CC2(MD),HUB
  111 FORMAT(/1X,3F15.5,22H    FOR SIGMA LESS THAN,F10.4)
  112 FORMAT(1X,3F15.5,11H    HUB DIA=,F7.3,12H *RUNNER DIA)
      RETURN
C
C   READ NEYRPIC  CAVITATION EQS
C
   40 READ(4,120)(CAVR(I,MD),I=1,10)
      WRITE(5,231)(CAVR(I,MD),I=1,10)
      HUB=1.0
  120 FORMAT(6F10.0)
  231 FORMAT(1X,29H CAVITATION RESTRICTION MODEL/
     *6F10.5/36H VALID AREA DEFINED WITHIN FOLLOWING/
     *1X,F10.5,9H < N11 < ,F10.5/
     *1X,F10.5,11H < SIGMA < ,F10.5/
     *1X,46H DATUM FOR CALCULATION OF SIGMA IS RUNNER TIPS)
      RETURN
      END
      SUBROUTINE SLUING(NPRT,DDRL,TDDRL,HMAXS,YABS)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK1/RTSPS(10),FTSPS(10),AD,WR,B,WF,K
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      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
     *CHSIG(2),PMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK4/AC(10),AX(10),AXX(10),J,RIVQ,AABS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
C   RUNGE KUTTA SOLUTION FOR SLUICING ONLY
C   FORWARDS OR BACKWARDS IN TIME
C
C   DDRL   START LEVEL
C   TDDRL  START TIME
C   HMAXS  MAX HEAD FOR SLUICING - AN END CONDITION
C   YABS   MAX BASIN LEVEL - AN END CONDITION
C
C   OTHER END CONDITION - NEGATIVE HEAD
C
C   RETURNS FINISH VALUES Y0 &T0
C
      T0=TDDRL
      Y0=DDRL
      SL=SEALEV(T0)
      Q1=0.0
      Q0=0.0
      X=SLUICE(T0,Y0)
      IF(IFLAG.EQ.1) H1=0.0
      H0=H1
   19 IF(NPRT.GT.0) WRITE(5,203)T0,SL,Y0,H0
   17 C2=C/2.0
      RK1=SLUICE(T0,Y0)
      TE=T0+C2
      YE=Y0+C2*RK1
      RK2=SLUICE(TE,YE)
      IF(IFLAG.EQ.1) GO TO 20
      YE=Y0+C2*RK2
      RK3=SLUICE(TE,YE)
      IF(IFLAG.EQ.1) GO TO 20
      TE=T0+C
      YE=Y0+C*RK3
      RK4=SLUICE(TE,YE)
      IF(IFLAG.EQ.1) GO TO 20
      Y1=Y0+C/6.0*(RK1+2.0*RK2+2.0*RK3+RK4)
      IF (Y1.GT.YABS) GO TO 20
      T1=T0+C
      SL=SEALEV(T1)
      X=SLUICE(T1,Y1)
      IF (H1.LE.0.0) GO TO 20
      IF (H1.LT.HMAXS) GO TO 88
   20 C=C/2.0
      IF (ABS(C).LT.0.1) GO TO 18
      GO TO 17
   88 Y0=Y1
      T0=T1
      H0=H1
      GO TO 19
```

```
   18 CONTINUE
  203 FORMAT(1X,4F10.4)
      RETURN
      END
      SUBROUTINE LIMCAP(HMAX,PMAX,HR,QHR,PM)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      DIMENSION R(5,5),PM(5)
C   THIS SECTION SELECTS RANGE OF HEADS TO BE CONSIDERED ON LIM CAP
C  CURVE,LEAST SQUARES CURVE FIT OF FORM
C   QLC=PM(1)+PM(2)*HD+PM(3)*HD**2+PM(4)*HD**3+PM(5)*SQRT(HD)
C   WHERE HD=H-HR
      DO 498 ITT=1,5
      PM(ITT)=0.0
      DO 499 IT=1,5
  499 R(IT,ITT)=0.0
  498 CONTINUE
      DH=0.1
      H=HR+0.00001
      WRITE(5,313)
  313 FORMAT(1X,34HLIMITING CAPACITY CURVE  H        Q)
      QEST=QHR
      GO TO 402
  405 DQ=QEST/20.0
      NFLAG=1
  401 P=POWER(H,QEST,1)
      DP=SQRT((P-PMAX)**2)
      IF (DP.LE.0.001) GO TO 402
      IF (P.GT.PMAX) GO TO 404
      QEST=QEST+DQ
C  THIS NOT NEEDED      IF (POWER(H,QEST,3).LT.0.0) GO TO 407
      NFLAG=0
      GO TO 401
  404 IF (NFLAG.EQ.0) GO TO 407
      QEST=QEST-DQ
  408 NFLAG=1
      GO TO 401
  407 DQ=DQ/5.0
      QEST=QEST-4.0*DQ
      GO TO 408
  402 Q=QEST
      WRITE(5,314)H,Q
C     WRITE(*,314)H,Q
  314 FORMAT(24X,F5.2,F9.3)
      HD=H-HR
      H2=HD*HD
      H3=HD*H2
      RH=SQRT(HD)
      R(1,1)=R(1,1)+HD
      R(1,2)=R(1,2)+H2
      R(1,3)=R(1,3)+H3
      R(1,4)=R(1,4)+H2*H2
      R(1,5)=R(1,5)+RH*HD
      R(2,4)=R(2,4)+H3*H2
      R(2,5)=R(2,5)+RH*H2
```

```
      R(3,4)=R(3,4)+H3*H3
      R(3,5)=R(3,5)+H3*RH
       R(4,1)=R(4,1)+1.0
      R(4,5)=R(4,5)+RH
      PM(1)=PM(1)+HD*Q
      PM(2)=PM(2)+H2*Q
      PM(3)=PM(3)+H3*Q
      PM(4)=PM(4)+Q
      PM(5)=PM(5)+RH*Q
      H=H+DH
      IF(H.GT.(HR+0.5)) GO TO 497
      GO TO 405
  497 DH=0.5
      IF(H.GT.HMAX) GO TO 403
      GO TO 405
  403 CALL MATRIX(5,PM,R)
      WRITE(5,315)PM(1),PM(2),PM(3),PM(4),PM(5)
  315 FORMAT(//1X,4HQLC=,F10.3,1H+,F10.5,7H(H-HR)+,F10.5,10H(H-HR)**2+,F
     110.5,10H(H-HR)**3+,F10.5,10HSQRT(H-HR)//)
      RETURN
      END
      SUBROUTINE MAXPCU(PMAX,HR,HMIN,ACMP,BCMP,CCMP,DCMP,
     *ACME,BCME,CCME,DCME)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      DIMENSION R(5,5),PME(5),R1(5,5),PM(5)
  314 FORMAT(24X,F5.2,3F9.3)
C
C   COMPUTE A CUBIC EQUATION TO FIT MAX POWER CURVE
C
  316 FORMAT(1X,34HMAXIMUM POWER CURVE      H       Q,5X,6HQMAXEF)
      WRITE(5,316)
      DO 450 ITT=1,5
      PM(ITT)=0.0
      PME(ITT)=0.0
      DO 410 IT=1,5
      R1(IT,ITT)=0.0
  410 R(IT,ITT)=0.0
  450 CONTINUE
      DH=(HR-HMIN)/10.0
      H=HMIN
      POW=0.0
      DO 411 IT=1,11
      H2=H*H
      CALL QMAXP(H,Q0,QME,POW)
      H3=H2*H
      R(1,1)=R(1,1)+H
      R(1,2)=R(1,2)+H2
      R(1,3)=R(1,3)+H3
      R(1,4)=R(1,4)+H2*H2
      R(2,4)=R(2,4)+H2*H3
      R(3,4)=R(3,4)+H3*H3
      R(4,1)=R(4,1)+1.0
      PM(1)=PM(1)+H*Q0
      PM(2)=PM(2)+H2*Q0
```

```
      PM(3)=PM(3)+H3*Q0
      PM(4)=PM(4)+Q0
      PME(1)=PME(1)+H*QME
      PME(2)=PME(2)+H2*QME
      PME(3)=PME(3)+H3*QME
      PME(4)=PME(4)+QME
      WRITE(5,314)H,Q0,QME,POW
  411 H=H+DH
C   NEED TO SAVE R FOR FIT TO QMAXEF
      DO 20 ITT=1,4
   20 R1(1,ITT)=R(1,ITT)
      R1(2,4)=R(2,4)
      R1(3,4)=R(3,4)
      R1(4,1)=R(4,1)
      CALL MATRIX(4,PM,R1)
      ACMP=PM(1)
      BCMP=PM(2)
      CCMP=PM(3)
      DCMP=PM(4)
      WRITE(5,317)ACMP,BCMP,CCMP,DCMP
  317 FORMAT(/7H QMAXP= ,F10.4,3H + ,F10.4,3HH+ ,F10.4,4HH*H+,F10.5,5HH*
     1H*H/)
      CALL MATRIX(4,PME,R)
      ACME=PME(1)
      BCME=PME(2)
      CCME=PME(3)
      DCME=PME(4)
      WRITE(5,318)ACME,BCME,CCME,DCME
  318 FORMAT(/9H QMAXEF= ,F10.4,3H + ,F10.4,3HH+ ,F10.4,4HH*H+,F10.5,
     *5HH*H*H/)
      RETURN
      END
      SUBROUTINE FINTRP(F,H1,H0,Q1,Q0,C,T1,T0,Y1,Y0)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      H1=H0+F*(H1-H0)
      Q1=Q0+F*(Q1-Q0)
      T1=T0+F*C
      C=C*F
      Y1=Y0+F*(Y1-Y0)
      RETURN
      END
      SUBROUTINE ME02(M)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
C
C   GENERATOR EFFICIENCY APPLIED IN ME01 WHEN USING BSPLINE FIT
C
      IF (MT.EQ.1) GO TO 10
```

```
      IF (MD.EQ.1) CALL ME01(M,IPX,IPY,UK1,Q11,FF,RLAMDA,
     *RMU,COEFFS,NC,NADRES)
      IF (MD.EQ.2) CALL ME01(M,IPX2,IPY2,UK1,Q11,FF,RLAMD2,
     *RM2,COEFF2,NC2,NADRE2)
      RETURN
   10 DO 20 I=1,M
      X=UK1(I)
      Y=Q11(I)
      FF(I)=A(1,MD)+X*(A(2,MD)+A(5,MD)*Y+A(9,MD)*Y*Y+X*(A(4,MD)+A(8,MD
     * )*Y+X*A(7,MD)))+Y*(A(3,MD)+Y*(A(6,MD)+Y*A(10,MD)))
   20 FF(I)=FF(I)*GEF*(1.0+S)
      RETURN
      END
      SUBROUTINE OPTIM(DDRL,DDRLO,ENERGY,EO,YABS,DDRMIN,DDRMAX,IRRL,D,NP
     1RT,NO,DDRTOL)
C     IMPLICIT REAL*8 (A-H),(O-Z)
C ESTABLISH NEW DDRL AND RETURN
      IF (IRRL.EQ.0) GO TO 31
      IF (EO.LT.1.0) GO TO 36
      DDRL=(DDRL+DDRLO)/2.0
C       D=(ABS(DDRL-DDRLO))/2.0
      RETURN
   36 DDRLO=DDRL
      DDRL=DDRL+D*IRRL
      RETURN
   31 DE=SQRT((ENERGY-EO)**2)
      IF (DE.LE.(0.0005*EO)) GO TO 32
   38 IF (ENERGY.GT.EO) GO TO 33
      IF (DDRL.GT.DDRLO) GO TO 41
      IF (NO.EQ.3) D=D/2.0
      NO=2
      DDRL=DDRL+D
   37 IF (ABS(DDRL-DDRLO).LE.0.0001) DDRL=DDRL+D
   35 IF (DDRL.GT.DDRMAX) IRRL=1
      IF (DDRL.LT.DDRMIN) IRRL=1
      IF (IRRL.EQ.0) GO TO 412
      DDRL=(DDRL+DDRLO)/2.0
      D=(ABS(DDRL-DDRLO))/2.0
      IRRL=0
      GO TO 35
  412 CONTINUE
      RETURN
   32 IF (D.GT.DDRTOL) GO TO 38
      IF (SQRT((DDRL-DDRLO)**2).LT.DDRTOL) GO TO 34
      DDRL=(DDRL+DDRLO)/2.0
      D=D/5.0
      RETURN
   33 IF (DDRL.GT.DDRLO) GO TO 39
      DDRLO=DDRL
      IF (NO.EQ.2) D=D/2.0
      NO=3
      DDRL=DDRL-D
   40 EO=ENERGY
      GO TO 37
```

```
   39 DDRLO=DDRL
      DDRL=DDRL+D
      NO=0
      GO TO 40
   41 IF (NO.NE.1) D=D/5.0
      DDRL=DDRL-4.0*D
      IF (DDRLO.GE.DDRL) DDRL=DDRL+D
      NO=1
      GO TO 37
   34 IF (ENERGY.LT.E0) GO TO 71
      E0=ENERGY
      DDRLO=DDRL
   71 IF (NPRT.GT.0) GO TO 72
      DDRL=DDRLO
      NPRT=1
      RETURN
   72 NPRT=20
      RETURN
      END
      SUBROUTINE QMAXP(H,QEST,QME,P0)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      QEST=QMAXEF(H)
      QME=QEST
      D=QEST/10.0
      P0=POWER(H,QEST,1)
      P1=0.0
    1 QEST=QEST+D
      P=POWER(H,QEST,1)
C     WRITE(*,'(3F10.3)')H,QEST,P
      IF(P.LE.P0) GO TO 2
      P1=P0
      P0=P
      GO TO 1
    2 QEST=QEST-(2.0*D)
      D=D/10.0
      IF (D.LE.0.001) GO TO 3
      P0=P1
      GO TO 1
    3 QEST=QEST+D*10.0
      RETURN
      END
      SUBROUTINE MATRIX(N,B,R)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      DIMENSION R(5,5),B(5)
      R(2,1)=R(1,2)
      R(2,2)=R(1,3)
      R(2,3)=R(1,4)
      R(3,1)=R(1,3)
      R(3,2)=R(1,4)
      R(3,3)=R(2,4)
      R(4,2)=R(1,1)
      R(4,3)=R(1,2)
      R(4,4)=R(1,3)
      R(5,1)=R(4,5)
```

```
      R(5,2)=R(1,5)
      R(5,3)=R(2,5)
      R(5,4)=R(3,5)
      R(5,5)=R(1,1)
      NZ=N-1
      DO 5 K=1,NZ
      KK=K+1
      DO 10 I=KK,N
      X=R(I,K)
      X=X/R(K,K)
      DO 2 J=KK,N
    2 R(I,J)=R(I,J)-R(K,J)*X
      B(I)=B(I)-B(K)*X
   10 CONTINUE
    5 CONTINUE
      I=N
    9 II=I+1
      X=B(I)
      IF (I.EQ.N) GO TO 6
      DO 7 K=II,N
    7 X=X-R(I,K)*B(K)
    6 B(I)=X/R(I,I)
      I=I-1
      IF (I.NE.0) GO TO 9
      RETURN
      END




      FUNCTION HMING(MD,TWL,ID)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),JO,MT,GEF,IVS
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
     *CHSIG(2),PMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK6/ACMP(2),BCMP(2),CCMP(2),DCMP(2),
     *ACME(2),BCME(2),CCME(2),DCME(2),IMEF
      COMMON /BLKX/EXITA(2,2),DS(2),SPACE(2),INET,
     *ISLOP,A0SLOP,A1SLOP,SLUN,TURBN
C
C
C   EVALUATES MIN GROSS HEAD
C   TWL = TAILWATER LEVEL
C
      H=HMIN(MD)
      QMINH=ACMP(MD)+H*(BCMP(MD)+H*(CCMP(MD)+H*DCMP(MD)))
      IF(MODE.EQ.2)QMINH=ACME(MD)+H*(BCME(MD)+H*(CCME(MD)+
     *H*DCME(MD)))
      UWL=TWL+H*ID
      HT=HNET(UWL,TWL,QMINH,ID,1)
      HMING=H+(H-HT)
      RETURN
      END

```

```
      FUNCTION PLOSS(AP)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLKTL/NTL,ITL,PO(15),PL(15),T
      IF (AP.LT.0.0) GO TO 30
      IF (NTL.LT.1) GO TO 40
      IF (NTL.EQ.1) GO TO 30
      IF (ITL.EQ.0) GO TO 30
      DO 10 I=1,NTL
      IF (AP.LT.PO(I)) GO TO 20
   10 CONTINUE
   40 CONTINUE
      WRITE(5,100)
  100 FORMAT(1X,'ERROR : MORE TRANSMISSION LOSS DATA EXPECTED',/)
      AP=SQRT(-1.0)
   20 T=PL(I-1)+(PL(I)-PL(I-1))*(AP-PO(I-1))/(PO(I)-PO(I-1))
      T=ITL*T
      PLOSS=T
      RETURN
   30 T=PL(1)*ITL
      PLOSS=T
      RETURN
      END




      SUBROUTINE PARDIF(HA,QA,H1,Q1,DNDH,DNDQ1)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),JO,MT,GEF,IVS
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      DIMENSION H(6),Q(6)
      IF (IVS.EQ.0) GO TO 1
      CALL PARDVS(HA,QA,H1,Q1,DNDH,DNDQ1)
      RETURN
    1 H(1)=HA
      Q(1)=QA
      H(2)=1.00001*H(1)
      Q(2)=Q(1)
      H(3)=H1
      Q(3)=Q1
      H(4)=H(3)
      Q(4)=1.00001*Q(3)
      DO 10 I=1,4
      RH=SQRT(H(I))
```

```
      Q11(I)=Q(I)/(D2*RH)
   10 UK1(I)=UK/RH
      CALL ME02(4)
      DNDH=1.00522E-4*Q(1)*(FF(1)*H(1)-FF(2)*H(2))/(H(1)-H(2))
      DNDQ1=1.00522E-4*H(3)*(FF(3)*Q(3)-FF(4)*Q(4))/(Q(3)-Q(4))
      RETURN
      END




      FUNCTION POWER(H,Q,ND)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),JO,MT,GEF,IVS
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      IF (IVS.EQ.0) GO TO 10
      POWER=POWVS(H,Q,ND)
      RETURN
   10 RH=SQRT(H)
      UK1(1)=UK/RH
      Q11(1)=Q/(D2*RH)
C   ND=1 POWER,ND=2 DNDH,ND=3 DNDQ
      IF (ND-2)1,2,3
    1 CALL ME02(1)
      AP=1.00522E-4*FF(1)*Q*H
      POWER=AP-PLOSS(AP)
      RETURN
    2 H1=1.00001*H
      RH=SQRT(H1)
      Q11(2)=Q/(D2*RH)
      UK1(2)=UK/RH
      CALL ME02(2)
      POWER=1.00522E-4*Q*(FF(1)*H-FF(2)*H1)/(H-H1)
      RETURN
    3 Q1=1.00001*Q
      Q11(2)=Q1/(D2*RH)
      UK1(2)=UK1(1)
      CALL ME02(2)
      POWER=1.00522E-4*H*(FF(1)*Q-FF(2)*Q1)/(Q-Q1)
      RETURN
      END





      FUNCTION QMAXEF(H)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),JO,MT,GEF,IVS
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
```

```
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      IF (IVS.EQ.0) GO TO 1
      QMAXEF=QMEFVS(H)
      RETURN
    1 IF(MT.EQ.1) GO TO 20
      NSTOP=1
      RH=SQRT(H)
      IF (MD.EQ.2) GO TO 30
      QMIN=RMU(4)*D2*RH
      QMAX=RMU(IPY-3)*D2*RH
      GO TO 50
   30 QMIN=RM2(4)*D2*RH
      QMAX=RM2(IPY2-3)*D2*RH
   50 QEST=QMIN+(QMAX-QMIN)/2.0
      UK1(1)=UK/RH
      Z0=-1000.0
      Q00=0.0
      DQ=QEST/10.0
   10 Q11(1)=QEST/(D2*RH)
      CALL ME02(1)
      Z=FF(1)
C     WRITE(5,100)H,QEST,Z
  100 FORMAT(3F10.3)
      CALL OPTIM(QEST,Q00,Z,Z0,QMAX,QMIN,QMAX,0,DQ,NSTOP,NO,0.001)
      IF (NSTOP.NE.20) GO TO 10
      QMAXEF=QEST
      RETURN
   20 CONTINUE
      RH=SQRT(H)
      AA=3.0*A(10,MD)/(D6*H*RH)
      B=(A(6,MD)+A(9,MD)*UK/RH)*2.0/(D4*H)
      CD=(A(3,MD)+A(5,MD)*UK/RH+A(8,MD)*UK*UK/H)*1.0/(D2*RH)
      QMAXEF=(-B-SQRT(B*B-4.0*AA*CD))/(2.0*AA)
      D2Z=B+2.0*AA*QMAXEF
      IF (D2Z.GT.0.0) GO TO 40
      RETURN
   40 QMAXEF=(-B+SQRT(B*B-4.0*AA*CD))/(2.0*AA)
      RETURN
      END
      FUNCTION QCAV(H,T)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK1/RTSPS(10),FTSPS(10),AD,WR,B,WF,K
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
     *CHSIG(2),PMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLKC/CAVR(10,2),ICAV
      RH=SQRT(H)
      TWL=SEALEV(T)
      IF (ID.EQ.-1) TWL=TWL-H
      UKT=UK
      IF (IVS.EQ.1) UKT=UK*DIA/84.579
```

```
      QLIM=(QHILL(MD)*UKT/RH+CHILL(MD))*D2*RH
C
C
C SELECT RELEVANT CAVITATION MODEL
C
C  ICAV=1    EWZ   ,  ICAV=2    NEYRPIC
C
      IF (ICAV.EQ.1) GO TO 10
C
C   NEYRPIC CAVITATION MODEL
C
      SIGM=((10.0+DAXIS+TWL-(DIA*HUB)/2.0)/H)-0.2
      FN11=UKT*84.579/RH
      IF (FN11.LT.CAVR(7,MD)) FN11=CAVR(7,MD)
      IF (FN11.GT.CAVR(8,MD)) GO TO 1
      IF (SIGM.LT.CAVR(9,MD).OR.SIGM.GT.CAVR(10,MD)) GO TO 1
      FN11=FN11/100.0
      S2=SIGM*SIGM
      FN2=FN11*FN11
      QCAV=CAVR(1,MD)*SIGM+CAVR(2,MD)*FN2*SIGM+CAVR(3,MD)*FN2+
     *CAVR(4,MD)*S2+CAVR(5,MD)*FN11+CAVR(6,MD)
      QCAV=QCAV*D2*RH
      GO TO 2
    1 QCAV=2000.0
      GO TO 2
C
C  EWZ CAVITATION MODEL
C
   10 CONTINUE
      SIGM=(10.0+DAXIS+TWL-(DIA*HUB)/2.0)/H
      IF (SIGM.GT.CHSIG(MD)) GO TO 3
      QCAV=((LOG(SIGM-C1(MD))-LOG(A1(MD)))/B1(MD))*D2*RH
      GO TO 2
    3 QCAV=((LOG(SIGM-CC2(MD))-LOG(A2(MD)))/B2(MD))*D2*RH
    2 IF (QLIM.LT.QCAV) QCAV=QLIM
      RETURN
      END
C
C
C
C
      SUBROUTINE PARDVS(HA,QA,H1,Q1,DNDH,DNDQ1)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),JO,MT,GEF,IVS
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
      DIMENSION H(6),Q(6)
      H(1)=HA
      Q(1)=QA
      H(2)=1.00001*H(1)
      Q(2)=Q(1)
      H(3)=H1
```

```
      Q(3)=Q1
      H(4)=H(3)
      Q(4)=1.00001*Q(3)
      DO 10 I=1,4
      RH=SQRT(H(I))
      Q11(1)=Q(I)/(D2*RH)
      CALL SPEED(H(I),Q(I),RH)
      IF (I.EQ.1) F=FF(1)
   10 FF(I)=FF(1)
      DNDH=1.00522E-4*Q(1)*(F*H(1)-FF(2)*H(2))/(H(1)-H(2))
      DNDQ1=1.00522E-4*H(3)*(FF(3)*Q(3)-FF(4)*Q(4))/(Q(3)-Q(4))
      RETURN
      END





      FUNCTION POWVS(H,Q,ND)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),JO,MT,GEF,IVS
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
      RH=SQRT(H)
      Q11(1)=Q/(D2*RH)
      CALL SPEED(H,Q,RH)
      F=FF(1)
C    ND=1 POWER,ND=2 DNDH,ND=3 DNDQ
      IF (ND-2)1,2,3
    1 AP=1.00522E-4*FF(1)*Q*H
      POWVS=AP-PLOSS(AP)
      RETURN
    2 H1=1.00001*H
      RH=SQRT(H1)
      CALL SPEED(H1,Q,RH)
      POWVS=1.00522E-4*Q*(F*H-FF(1)*H1)/(H-H1)
      RETURN
    3 Q1=1.00001*Q
      Q11(1)=Q1/(D2*RH)
      CALL SPEED(H,Q1,RH)
      POWVS=1.00522E-4*H*(F*Q-FF(1)*Q1)/(Q-Q1)
      RETURN
      END






      SUBROUTINE SPEED(H,Q,RH)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK3/A1(2),B1(2),C1(2),A2(2),B2(2),CC2(2),HUB,
```

```
     *CHSIG(2),PMAX,MODE,HR(2),QHR(2),PM(5,2),QHILL(2),CHILL(2)
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK7/IPX,IPY,UK1(6),Q11(6),FF(6),RLAMDA(20),
     *RMU(20),COEFFS(256),NC,NADRES
      COMMON /BLK8/IPX2,IPY2,RLAMD2(20),RM2(20),NC2,COEFF2(256),
     *NADRE2
      COMMON /BLK10/TORQUE,UK1MIN(2),UK1MAX(2),Q11MEF(2)
      CONST=1.00522E-4*Q*H
      CON2=84.6*RH/DIA
      UKLIM=UK1MAX(MD)
      IF (MT.NE.1) GO TO 30
C   WHEN 10 CONSTANTS MODEL OPT SPEED FOUND BELOW
      AA=3.0*A(7,MD)
      B=2.0*(A(4,MD)+A(8,MD)*Q11(1))
      CD=A(2,MD)+Q11(1)*(A(5,MD)+Q11(1)*A(9,MD))
      UK1(1)=(-B-SQRT(B*B-4.0*AA*CD))/(2.0*AA)
      D2Z=B+2.0*AA*UK1(1)
      TEMP=(-B+SQRT(B*B-4.0*AA*CD))/(2.0*AA)
      IF (D2Z.LE.0.0) GO TO 50
      UK1(1)=TEMP
      GO TO 40
   50 IF (TEMP.LT.UK1MAX(MD)) UKLIM=TEMP
   40 IF (UK1(1).GT.UK1MAX(MD)) UK1(1)=UK1MAX(MD)
      IF (UK1(1).LT.UK1MIN(MD)) UK1(1)=UK1MIN(MD)
      CALL ME02(1)
      QLIM=(QHILL(MD)*UK1(1)+CHILL(MD))*D2*RH-1.0
      IF (Q.GT.QLIM) GO TO 30
      UK0=CON2*UK1(1)
      T=FF(1)*CONST/UK0
      IF (T.GT.TORQUE) GO TO 30
      UK=UK0
      RETURN
   30 UTOL=0.01
      IRRL=0
      UKMIN=UK1MIN(MD)
      NPRT=1
      NO=0
      D=0.5
      Z0=0.0
      UK0=0.0
      UK1(1)=UK/CON2
      IF (UK1(1).GT.UKLIM) UK1(1)=UKLIM-0.11
      IF (UK1(1).LT.UK1MIN(MD)) UK1(1)=UK1MIN(MD)+0.11
   20 CALL ME02(1)
      QLIM=(QHILL(MD)*UK1(1)+CHILL(MD))*D2*RH-1.0
      UK=CON2*UK1(1)
      T=FF(1)*CONST/UK
C     WRITE(*,100)Q,H,UK1(1),FF(1),Z0,UK0,UK,T,QLIM
  100 FORMAT(1X,9F8.4)
      IF (T.LE.TORQUE.AND.Q.LE.QLIM) GO TO 33
      UKMIN=UK1(1)
      IRRL=1
```

```
   33 CALL OPTIM(UK1(1),UK0,FF(1),Z0,UKLIM,UKMIN,UKLIM,
     *IRRL,D,NPRT,N0,UTOL)
      IF (NPRT.EQ.20) GO TO 10
      IRRL=0
      GO TO 20
C   RETURNING OPTIMISED VALUES OF RPM AND EFF
   10 UK=CON2*UK0
      FF(1)=Z0
      RETURN
      END




      FUNCTION QMEFVS(H)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLK10/TORQUE,UK1MIN(2),UK1MAX(2),Q11MEF(2)
      COMMON /BLK2/A(10,2),S,DIA,UK,D2,D4,D6,DAXIS,HMIN(2),J0,MT,GEF,IVS
      COMMON /BLK5/H0,Q0,T0,Y0,C,TURBN,EFFAR,RSLU(2),IFLAG,H1,Q1,Y1,T1,
     *ID,MD,ISLU,SLUN,FLTT,FHTT
      QMEFVS=Q11MEF(MD)*D2*SQRT(H)
      RETURN
      END





C
C
C
C
      FUNCTION SEALEV(T1)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /TIDE/TSHAPE(120),TINC,HTL,TLTL,TIDELO(120),NINC
      I=(T1/TINC)+1
      IF(I.GT.0.AND.I.LE.NINC) GO TO 10
C
      WRITE (*,'(''ERROR IN SEALEV, TIME OUTSIDE RANGE'')')
      WRITE(*,'(F10.4)')T1
      AXAX=SQRT(-1.0)
      STOP
C
   10 CONTINUE
      EL1=TIDELO(I)
      EL2=TIDELO(I+1)
      SEALEV=EL1+(T1/TINC-(I-1))*(EL2-EL1)
      RETURN
      END
C
C
C
      SUBROUTINE RTIDE
C     IMPLICIT REAL*8 (A-H),(O-Z)
```

```
      COMMON /TIDE/TSHAPE(120),TINC,HTL,TLTL,TIDELO(120),NINC
      READ(3,'(F5.0,I3)')TINC,NINC
      READ(3,'(6F10.0)')(TSHAPE(I),I=1,NINC)
C
C     READ(3,*) TINC ,NINC
C     DO 55 I=1,NINC
C      READ(3,57)TSHAPE(I)
C  55 CONTINUE
C  57 FORMAT(8X,F10.0)

      WRITE(5,100)TINC,(TSHAPE(I),I=1,NINC)

  100 FORMAT(///1X,'TIDE SHAPE AT ',F10.2,'MIN INTERVALS',//
     *1X,'TIME-MIN    0',8X,'10',8X,'20',8X,'30',8X,'40',8X,'50',/
     *1X,'HOUR',/
     *1X,' 0        ',24(6F10.4,/,1X,2X,6X))
C
      RETURN
      END
C
C
C
C
      FUNCTION TDTIME(Y,TEST)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /TIDE/TSHAPE(120),TINC,HTL,TLTL,TIDELO(120),NINC
      IF (Y.LE.HTL.AND.Y.GE.TLTL) GO TO 1
C   LEVEL OUTSIDE RANGE
      WRITE(*,'(''ERROR IN FUNCTION TDTIME LEVEL OUT OF RANGE'')')
      WRITE(*,'(2F10.4)')Y,TEST
      STOP
C
    1 I1=(TEST/TINC)+1
      DO 10 JJ=I1,NINC
      IF (Y-TIDELO(JJ))2,7,3
    2 IF (Y-TIDELO(JJ+1))10,8,16
    3 IF (Y-TIDELO(JJ+1))16,8,10
   10 CONTINUE
      WRITE(*,'(''ERROR IN FUNCTION TDTIME TEST INCORRECTLY SET'')')
      STOP
    7 TDTIME=(JJ-1)*TINC
      RETURN
    8 TDTIME=JJ*TINC
      RETURN
   16 TDTIME=TINC*(JJ-1)+TINC*(Y-TIDELO(JJ))/(TIDELO(JJ+1)
     *-TIDELO(JJ))
      RETURN
      END
```

```
C
C
C
      FUNCTION HNET (UWL,TWL,Q,ID,ITZ)
C     IMPLICIT REAL*8 (A-H),(O-Z)
      COMMON /BLKX/EXITA(2,2),DS(2),SPACE(2),INET,ISLOP,A0SLOP,A1SLOP,
     *SLUN,TURBN
C
C
C   HNET = UPSTREAM LEVEL - DOWNSTREAM LEV - (HLOSS + EXPANSION LOSS)
C
C
C
C   EQUIPMENT                                  POOL LEV
C
C   TURBINING   ID= 1    BASIN>SEA    **    Y(1)     IE=1     IQ=1
C    ITZ=1      ID=-1    SEA  >BASIN  **    Y(1)     IE=1     IQ=2
C
C   SLUICING    ID= 1    SEA  >BASIN  **    Y(2)     IE=2     IQ=2
C    ITZ=2      ID=-1    BASIN>SEA    **    Y(2)     IE=2     IQ=1
C
C   PUMPING     ID= 1    SEA  >BASIN  **    Y(1)     IE=1     IQ=2
C   ITZ=3       ID=-1    BASIN>SEA    **    Y(1)     IE=1     IQ=1
C
C   TURBS/SLUICING ID=1  SEA  >BASIN  **    Y(2)     IE=1     IQ=2
C   ITZ=4          ID=-1 BASIN>SEA    **    Y(2)     IE=1     IQ=1
C
C
      DIMENSION Y(3)
      IP=1
      Y(1)=UWL
      Y(2)=TWL
      Y(3)=UWL
      MACNO=TURBN
      T2=0.0
      IF (ITZ.NE.1) GO TO 10
C    TURBINING ITZ=1
      IE=1
      PL=Y(1)
      DL=Y(2)
      IF (ID.EQ.-1) DL=Y(1)
      IQ=1
      IF (ID.EQ.-1) IQ=2
      GO TO 20
   10 IF (ITZ.NE.2) GO TO 30
C    SLUICING ITZ=2
      MACNO=SLUN
      IE=2
      PL=Y(2)
      DL=Y(2)
      IF (ID.EQ.-1) DL=Y(1)
      IQ=2
      IF (ID.EQ.-1) IQ=1
      GO TO 20
```

```
   30 IF (ITZ.NE.3) GO TO 40
C   PUMPING ITZ=3
      IE=1
      IP=-1
      PL=Y(1)
      DL=Y(1)
      IF (ID.EQ.-1) DL=Y(2)
      IQ=2
      IF (ID.EQ.-1) IQ=1
      GO TO 20
   40 IF (ITZ.NE.4) GO TO 50
C   TURBINES SLUICING ITZ=4
      IE=1
      PL=Y(2)
      DL=Y(2)
      IF (ID.EQ.-1) DL=Y(1)
      IQ=2
      IF (ID.EQ.-1) IQ=1
      GO TO 20
   50 CONTINUE
      WRITE(*,'(''STOP - ERROR IN ITZ IN F(HNET)'')')
      STOP
   20 CONTINUE
      HEADG=(UWL-TWL)*ID
C
C   RESERVOIR SLOPE CORRECTION NOT MODELLED NOW SEE FUNDY WORK
C
      IF (ISLOP.EQ.1) WRITE(*,'(''STOP - RESERVOIR SLOPE IN F(HNET)'')')
      AE=EXITA(IE,IQ)
      A2=(DL+DS(IE))*SPACE(IE)
      T=IP*INET*Q*Q/(19.62*A2*A2)
      HN=HEADG-T2-T*((A2/AE)**2-2.0*A2/AE+2.0)
C     WRITE(*,'(6F6.3,3F6.1,2I2)')UWL,TWL,Y(1),Y(2),HEADG,HN,Q,AE,A2,
C    *IE,IQ
      IF (HN.LT.0.0) HN = 0.0
      HNET=HN
      RETURN
C
C
C
      END
```

APPENDIX C

DATA REQUIREMENTS AND SAMPLE DATA

SITE DATA FILE

Line 1 format (I1,15A4)

I1 is IPump 0 = No pumping
1 = Pumping

15A4 is title up to 60 characters (ie. Site 5, Neyrpic FD VB Direct Turbine Only).

Line 2 format (I1, 6X, I2, 50X)

variables MODE, NOPRT

MODE - mode of turbine operation

Ebb-generation		Flood generation
1 = maximum energy	=	6
2 = maximum efficiency	=	7
3 = max power output	=	8

NOPRT - control of output quantity

-1 only optimum DDRL in detail
0 energy & DDRL's + optimum DDRL in detail
>1 all DDRL's in detail

Line 3 format (F10.4, 2I3)

variables YABS, NTR, NAL

YABS - pool level restriction

NTR - No of tide ranges to be considered

NAL - No of area/level curves given as data.

Line 4 format (3E15.5, I5)

variables AC(I), AX(I), AXX(I), NOT(I)

AC(I) - AXX(I) are basin area/level coeffs

Area = AC + AX x level + AXX x level^2

NOT(I) is no. of turbines to which equation corresponds

REPEAT NAL times

NB: Of NOT(I) equal 0 then last area/level equation used throughout.

Line 5 format (6F10.4)

variable TRANGE, HTLEV, TLTLEV, RTSPS, FTSPS, FREQ

TRANGE = Tidal Range

HTLEV = High tide level

TLTLEV = Low tide level

RTSPS = time (mins) for rising tide

FTSPS = time (mins) for falling tide

FREQ = adjusted no of annual occurences of tidal range

REPEAT NTR times

Line 6 format (I2, F10.4)

variables NTS, TSTEP

NTS = No. of turbine/sluice combinations

TSTEP = time-step used in numerical solution (mins)

Line 7 format (2I5)

variables NTURB(N), NSLU(N)

No. of turbines, no. of sluices

REPEAT NTS times.

Line 8 format (3F10.4)

variables DAXIS, RIVQ, EFFAR1

DAXIS - depth in metres from datum to turbine centreline

RIVQ - discharge (m^3/s) from rivers flowing into reservoir

EFFAR1 - effective area of one sluice

$Q = EFFAR1 \times (2gH)^{\frac{1}{2}}$

Line 9 format (I1, 4F10.0)
variables MT, BANGLE, UK1MAX, QHILL, CHILL
MT = hillchart model type, if MT = 1 a 10 constants model expected
BANGLE = blade angle of turbine (zero for variable b.a. machines)
UK1MAX = KU1 at minimum head, a property of the hillchart
QHILL) Restrictions on operation within hill chart,
CHILL) operates below Q11 = QHILL x KU1 + CHILL

Line 10) format (510.0)
) variables A(1) - A(5) first five constants
) in hill chart model
) $= A(1) + A(2)x + A(3)y + A(4)x^2 + A(5)xy + A(6)y^2 +$
) $A(7)x^3 + A(8)x^2y + A(9)xy^2 + A(10)y^3$
) $x = KU1,\ y = Q11$
Line 11) A(6) - A(10) as above

NB: OMIT Lines 10 and 11 if MT = 0, a bi-cubic spline model is read from data file 2.

Line 12 format (8FI0.0)
variables A1, B1, C1, A2, B2, CC2, HUB, CHSIG
Cavitation constants $\sigma = A1.e^{(B1.Q11)} + C1$
If $\sigma >$ CHSIG use A2, B2, CC2.
HUB is ratio HUB dia/runner dia.
This parameter HUB enables the datum of the cavitation equations to be varied (ie. if equations based upon runner tip then HUB input is 1.0)
(EWZ Hub diameter = 0.44)

If IPUMP = 0 Lines 13 - 19 inclusive omitted.

Line 13 format (I5)
variable NPUMPS - number of pumps

Line 14) format (4F10.0)
) variables QA, QB, QCC, QD, ZA, ZB, ZC, ZD
) $Q11 = f(KU1) \quad Q11 = QA + QBKU1 + QCCKU1^2 + QDKU1^3$
Line 15) $P = f(H) \quad P = ZA + ZBH + ZCH^2 + ZDH^3$

Line 16 format (2F10.0)
variables PHMIN, PHMAX
PHMIN - minimum pumping head
PHMAX - maximum pumping head

Line 17 format (2F10.0)
variables FINT, TMIN
FINT - Ratio of input energy cost/output energy value
TMIN - Minimum time between start and finish of pumping

Line 18 format (2F10.0)
variables PSTART, PFIN
PSTART - permissible time of start of pumping
PFIN - permissible time of finish of pumping

Line 19 format (2F10.0)
variables FMGEN, PMAJ

Line 20 format (2F10.0)
variables DIA, RSLU
DIA - runner diameter
RSLU - coefficient of discharge of turbine when used as orifice during sluicing Q = RSLU x h for one turbine.

Line 21 format (1F10.0)
variable RPM
RPM = rotational speed of turbine (revs/min)

Line 22 format (2F10.0)

variables HR, S

HR - rated head of machine: defined at the point where maximum power output and limiting capacity curves intersect

S - efficiency step-up, model to prototype

REPEAT LINES 20, 21, 22 if require runs or more than one turbine specification

Line 23 Terminator is DIA = 0.0 RSLU = 0.0

SAMPLE DATA

```
 STPG 5S,FIXED BLADES(14DEG),VARIABLE DISTRIBUTOR
3,MODE,-1,PRINT FLAG,1-9 IF DETAIL OF EVERY DDRL REQD
  99.9      9  3   11.6
 321.083E06      25.4825E06      3.6E00
 315.467E06      27.0425E06      7.6E00
 437.7415E06     10.95375E06     11.7E00
3.50        7.50        4.00        370.0       370.0       28.0
4.50        8.10        3.60        370.0       370.0       58.0
5.50        8.70        3.20        370.0       370.0       97.0
6.50        9.30        2.80        370.0       370.0       87.0
7.50        9.90        2.40        370.0       370.0       106.0
8.50        10.50       2.00        370.0       370.0       129.0
9.50        11.15       1.65        370.0       370.0       125.0
10.50       11.75       1.25        370.0       370.0       64.0
11.50       12.35       0.85        370.0       370.0       12.0
262.2      20.0        262.2
243.9      20.0        243.9
25.0       13.0
0.0E00      0.0
 1  10.0
  140  150
   10.5     0.0         222.967
11   14.0   1.385       0.6610     364.6
1.6         4.0         2.0         2.55        6.4
97.8151     -109.1821 57.3439     -49.1197    125.1541
-54.0008    47.4394     -119.472    86.1447     -19.593
 0.13733    0.87699     0.47122     1.23551     0.37889     -1.5000     0.44        1.60
 1       THIS NO. (I2) INDICATES NO. OF TRANS LOSS DATA POINTS TO FOLLOW(F10.)
 0.0       0.0
7.6        95.0
55.556     0.0
23.0       0.0420
9.0        95.0
50.000     0.0
50.0       0.0420
9.0        95.0
55.000     0.0
50.0       0.0420
9.0        95.0
60.000     0.0
50.0       0.0420
0.0         0.0
```

TURBINE PERFORMANCE CHARACTERISTIC DATA FILE

(Bi-cubic spline fit in terms of KU1 and Q11)

Line 1 format (15A4)
variables AB(I) - title of hill chart ie. Neyrpic FD VB turbine

Line 2 format (2I4)
variables IPX, IPY
IPX - number of X knots (X = KU1)
IPY - number of Y knots (Y = Q11)

Line 3 format (F15.5)
variables RLAMDA(I)
RLAMDA(I) - position of X knots
REPEAT IPX times

Line 4 format (F15.5)
variables RMU(I)
RMU(I) - position of Y knots
REPEAT IPY times

Line 5 format (I4)
variables NC
NC - number of coefficients

Line 6 format (F15.5)
variables COEFFS(I)
COEFFS(I) - coefficients required in the fit
REPEAT NC times

APPENDIX D

SAMPLE RESULTS FILE

```
SITE DATA FILE =  D_VDFB14
RESULTS FILE   =  R_VDFB14
B-SPLINE DATA  =  DUMMY
TIDE SHAPE FILE=  TIDE_SYM



TIDE SHAPE AT       10.00MIN INTERVALS

TIME-MIN  0         10          20          30          40          50
HOUR
 0          0.5000      0.4982      0.4928      0.4839      0.4714      0.4556
            0.4365      0.4143      0.3890      0.3610      0.3303      0.2973
            0.2622      0.2251      0.1864      0.1464      0.1053      0.0635
            0.0212     -0.0212     -0.0635     -0.1053     -0.1464     -0.1864
           -0.2251     -0.2621     -0.2973     -0.3303     -0.3610     -0.3890
           -0.4142     -0.4365     -0.4556     -0.4714     -0.4839     -0.4928
           -0.4982     -0.5000     -0.4982     -0.4928     -0.4839     -0.4714
           -0.4556     -0.4365     -0.4143     -0.3890     -0.3610     -0.3304
           -0.2973     -0.2622     -0.2251     -0.1865     -0.1464     -0.1054
           -0.0635     -0.0212      0.0212      0.0635      0.1053      0.1464
            0.1864      0.2251      0.2621      0.2973      0.3303      0.3610
            0.3890      0.4142      0.4365      0.4556      0.4714      0.4839
            0.4928      0.4982      0.5000      0.4982      0.4928      0.4839
            0.4715      0.4556      0.4365      0.4143      0.3890      0.3610
            0.3304      0.2973      0.2622      0.2251      0.1865      0.1465
            0.1054      0.0636      0.0213     -0.0212     -0.0635     -0.1053
           -0.1464     -0.1864     -0.2251     -0.2621

NET HEADS ARE UTILISED



FLAT RESERVOIR ASSUMED



NO REVERSE SLUICING
```

```
ENERGY YIELD OPTIMIZED



          ******************************************
          *                                        *
          *  SINGLE BASIN,EBB-GENERATION           *
          *                                        *
          ******************************************



          STPG 5S,FIXED BLADES(14DEG),VARIABLE DISTRIBUTOR


TURBINE OPERATION ON MAXIMUM POWER CURVE


POOL LEVEL RESTRICTION   99.90

UPPER LIMIT OF AREA/LEVEL CURVE  11.60


RESERVOIR AREA MODELLED AS SERIES OF ST. LINES
AREA(M*M)= 0.32108E+09+Y* 0.25482E+08  UP TO Y= 0.36000E+01
AREA(M*M)= 0.31547E+09+Y* 0.27042E+08  UP TO Y= 0.76000E+01
AREA(M*M)= 0.43774E+09+Y* 0.10954E+08  UP TO Y= 0.11700E+02
AREA(M*M)=


TIDES                                                   ADJUSTED
-----            LEVELS(M)          TIME(MINS)          NO,ANNUAL
     RANGE       HIGH        LOW    RISING   FALLING    OCCURENCES
      3.50       7.50       4.00    370.00    370.00      28.00
      4.50       8.10       3.60    370.00    370.00      58.00
      5.50       8.70       3.20    370.00    370.00      97.00
      6.50       9.30       2.80    370.00    370.00      87.00
      7.50       9.90       2.40    370.00    370.00     106.00
      8.50      10.50       2.00    370.00    370.00     129.00
      9.50      11.15       1.65    370.00    370.00     125.00
     10.50      11.75       1.25    370.00    370.00      64.00
     11.50      12.35       0.85    370.00    370.00      12.00
```

```
TURBINE DRAFT TUBE EXIT AREA -  SEA   (M*M)      262.20
                              - BASIN (M*M)      262.20
SLUICE DRAFT TUBE EXIT AREA  -  SEA   (M*M)      243.90
                              - BASIN (M*M)      243.90
HORIZ. SPACING OF TURBINE CENTRES      (M)        20.00
                  SLUICE  CENTRES      (M)        20.00
BED DEPTHS (WRT DATUM OF TIDES) - TURBS           25.00
                                  SLUICES         13.00


RESERVOIR SLOPE
DH=0.0000E+00*Q**2*(    0.0000-ELEV)**2


TIME STEP USED IN NUMERICAL SOLUTION     10.00 MINS

WATER DEPTH RESRICTION     10.50 M (DATUM TO TURBINE AXIS)

RIVER FLOW INTO RESERVOIR      0.00 M**3/S

EFFECTIVE SLUICE AREA PER SLUICE    222.97 M*M



DIRECT TURBINE
--------------

RUNNER BLADE ANGLE     14.00 DEGREES, KU1MAX   4.0000 , KU1MIN   1.6000
RESPECTIVELY Q11MIN,Q11MAXEFF,Q11MAX         2.00       2.55       6.40

 HILLCHART RESTRICTION Q11.LE.    1.3850*KU1+    0.6610


CONSTANTS A1-A10
   0.97815E+02  -0.10918E+03   0.57344E+02  -0.49120E+02   0.12515E+03
  -0.54001E+02   0.47439E+02  -0.11947E+03   0.86145E+02  -0.19593E+02

CAVITATION CONSTANTS A,B,C

       0.13733        0.87699        0.47122   FOR SIGMA LESS THAN    1.6000
       1.23551        0.37889       -1.50000   HUB DIA=  0.440 *RUNNER DIA


TRANSMISSION LOSSES - LOSS IN MW PER GENERATOR
GENERATION OUTPUT      POWER LOSS (MW)
          0.000              0.000
```

Note: Constants A1-A10 are polynomial coefficients used in modelling of the turbine efficiency hillchart. This method, using coefficients provided by the turbine manufacturer, is used as an alternative to the bi-cubic spline modelling described in Section 3.6. The form of the polynomial fit is indicated on page C3.

```
CURRENT TURBINE
_______________

RUNNER DIAMETER         9.000 M
ROTATIONAL SPEED       45.000 RPM
INSTALLED CAPACITY     50.000 MW MAX GEN ELECT OUTPUT
EFFICIENCY STEP UP       0.042%
GENERATOR EFFICIENCY    95.000%


DIRECT OPERATION
________________

MIN GENERATION HEAD     1.433 M
RATED HEAD              8.832 M
REVERSE SLUICE CAPACITY    364.60M**3/SEC AT 1.0M HEAD



MAXIMUM POWER CURVE      H       Q      QMAXEF
                       1.43  596.699  594.511    1.666
                       2.17  601.011  589.851    8.229
                       2.91  607.497  589.431   13.505
                       3.65  614.677  590.882   18.284
                       4.39  622.055  593.247   22.852
                       5.13  629.441  596.084   27.337
                       5.87  636.742  599.168   31.803
                       6.61  643.922  602.376   36.286
                       7.35  650.977  605.639   40.806
                       8.09  657.888  608.913   45.375
                       8.83  664.662  612.174   50.000

QMAXP=  588.3687 +     4.0366H+     1.0986H*H+  -0.06579H*H*H


QMAXEF=    605.8156 +   -11.9743H+     2.6521H*H+  -0.13828H*H*H

LIMITING CAPACITY CURVE  H       Q
                       8.83  664.662
                       8.93  638.235
                       9.03  627.359
                       9.13  619.038
                       9.23  612.026
                       9.33  605.866
                       9.83  581.777
                      10.33  563.411
                      10.83  548.015


QLC=   664.926+   2.67622(H-HR)+  -0.86074(H-HR)**2+   0.19932(H-HR)**3+ -85.14401SQRT(H-HR)
```

```
******************
*  140 TURBINES  *
*  150 SLUICES   *
******************



 3.50 M  RANGE


ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL    5.8725 M


     TIME    SEA LEVEL POOL LEVEL   HEAD    DISCHARGE   POWER  CAVITATION     TRANS LOSS
    (MINS)     (M)       (M)         (M)    M**3/SEC    (MW)   DISCHARGE         (MW)

  563.2624   5.8725    5.8725     0.0000
  573.2624   6.0200    5.9192     0.0694
  583.2624   6.1655    5.9990     0.1147
  593.2624   6.3081    6.0937     0.1478
  603.2624   6.4466    6.1976     0.1719
  613.2624   6.5801    6.3072     0.1887
  623.2624   6.7075    6.4200     0.1990
  633.2624   6.8282    6.5343     0.2036
  643.2624   6.9411    6.6484     0.2030
  653.2624   7.0455    6.7609     0.1975
  663.2624   7.1403    6.8705     0.1874
  673.2624   7.2252    6.9760     0.1732
  683.2624   7.2996    7.0762     0.1555
  693.2624   7.3626    7.1697     0.1344
  703.2624   7.4142    7.2553     0.1107
  713.2624   7.4538    7.3315     0.0853
  723.2624   7.4810    7.3965     0.0589
  733.2624   7.4958    7.4482     0.0332
  743.2624   7.4979    7.4830     0.0104
  748.2624   7.4948    7.4919     0.0020
  749.5124   7.4940    7.4930     0.0007
  750.1374   7.4934    7.4933     0.0001


    MAX.POOL LEVEL   TIME MAX.P.L   MIN POOL LEV   T MIN PL
        7.4933          750.1374        5.8725     440.6940
```

```
   TIME    SEA LEVEL POOL LEVEL   HEAD    DISCHARGE    POWER  CAVITATION      TRANS LOSS
  (MINS)      (M)       (M)        (M)    M**3/SEC     (MW)   DISCHARGE          (MW)

 440.6940   4.3061    5.8725    1.4331  596.2158    1.6662   601.2830   0   0.00000
 430.6940   4.2276    5.9779    1.6165  597.4867    3.5038   605.2621   0   0.00000
 420.6940   4.1600    6.0829    1.7886  598.7265    5.0764   608.7939   0   0.00000
 410.6940   4.1039    6.1875    1.9488  599.9204    6.4411   611.9318   0   0.00000
 400.6940   4.0594    6.2916    2.0971  601.0579    7.6372   614.7226   0   0.00000
 390.6940   4.0274    6.3954    2.2324  602.1227    8.6838   617.1853   0   0.00000
 380.6940   4.0076    6.4987    2.3551  603.1086    9.6012   619.3538   0   0.00000
 370.6940   4.0004    6.6017    2.4648  604.0064   10.4003   621.2456   0   0.00000
 360.6940   4.0059    6.7042    2.5614  604.8101   11.0901   622.8786   0   0.00000
 350.6940   4.0239    6.8062    2.6451  605.5146   11.6773   624.2671   0   0.00000
 340.6940   4.0542    6.9078    2.7161  606.1186   12.1691   625.4280   0   0.00000
 330.6940   4.0971    7.0089    2.7741  606.6163   12.5668   626.3651   0   0.00000
 320.6940   4.1516    7.1096    2.8201  607.0131   12.8795   627.1005   0   0.00000
 310.6940   4.2176    7.2098    2.8540  607.3078   13.1092   627.6400   0   0.00000
 300.6940   4.2949    7.3095    2.8763  607.5017   13.2593   627.9921   0   0.00000
 290.6940   4.3824    7.4087    2.8879  607.6028   13.3372   628.1747   0   0.00000
 282.1219   4.4657    7.4933    2.8891  607.6135   13.3455   628.1940   0   0.00000

  ENERGY OUTPUT      3664.11025(MWHRS)


OPTIMUM DRAWNDOWN RESERVOIR LEVEL =      5.8725 M

OPTIMUM ENERGY OUTPUT =       3664.11025  (MWHRS)
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```
4.50 M  RANGE


ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL     5.8950 M


    TIME    SEA LEVEL POOL LEVEL   HEAD    DISCHARGE   POWER  CAVITATION    TRANS LOSS
   (MINS)     (M)       (M)        (M)     M**3/SEC    (MW)   DISCHARGE        (MW)

  557.3585   5.8950    5.8950    0.0000
  567.3585   6.0855    5.9489    0.0941
  577.3585   6.2742    6.0423    0.1598
  587.3585   6.4599    6.1544    0.2109
  597.3585   6.6413    6.2786    0.2506
  607.3585   6.8169    6.4109    0.2810
  617.3585   6.9855    6.5484    0.3028
  627.3585   7.1460    6.6890    0.3170
  637.3585   7.2971    6.8308    0.3239
  647.3585   7.4380    6.9723    0.3238
  657.3585   7.5672    7.1119    0.3169
  667.3585   7.6839    7.2483    0.3036
  677.3585   7.7877    7.3801    0.2843
  687.3585   7.8775    7.5059    0.2594
  697.3585   7.9525    7.6245    0.2292
  707.3585   8.0127    7.7344    0.1945
  717.3585   8.0570    7.8342    0.1559
  727.3585   8.0855    7.9216    0.1147
  737.3585   8.0979    7.9941    0.0727
  747.3585   8.0940    8.0478    0.0323
  752.3585   8.0862    8.0659    0.0142
  754.8585   8.0801    8.0718    0.0058
  756.1085   8.0771    8.0736    0.0024
  756.7335   8.0755    8.0742    0.0009
  757.0460   8.0748    8.0744    0.0003


   MAX.POOL LEVEL   TIME MAX.P.L   MIN POOL LEV   T MIN PL
      8.0744          757.0460        5.8950      467.4855
```

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     TIME     SEA LEVEL POOL LEVEL    HEAD    DISCHARGE    POWER  CAVITATION      TRANS LOSS
    (MINS)       (M)       (M)         (M)    M**3/SEC     (MW)   DISCHARGE          (MW)

   467.4855    4.3286    5.8950    1.4331   596.2158     1.6662   601.2830   0   0.00000
   457.4855    4.1938    6.0003    1.6726   597.8857     4.0302   606.4327   0   0.00000
   447.4855    4.0709    6.1053    1.8999   599.5516     6.0328   610.9871   0   0.00000
   437.4855    3.9605    6.2099    2.1142   601.1913     7.7719   615.0386   0   0.00000
   427.4855    3.8641    6.3142    2.3142   602.7784     9.2989   618.6387   0   0.00000
   417.4855    3.7819    6.4182    2.4998   604.2965    10.6518   621.8412   0   0.0000
   407.4855    3.7146    6.5218    2.6702   605.7272    11.8516   624.6788   0   0.00000
   397.4855    3.6624    6.6251    2.8251   607.0566    12.9135   627.1805   0   0.00000
  ·387.4855    3.6263    6.7280    2.9636   608.2672    13.8437   629.3596   0   0.00000
   377.4855    3.6061    6.8305    3.0858   609.3525    14.6522   631.2419   0   0.00000
   367.4855    3.6020    6.9326    3.1916   610.3028    15.3428   632.8396   0   0.00000
   357.4855    3.6142    7.0344    3.2807   611.1124    15.9199   634.1666   0   0.00000
   347.4855    3.6425    7.1357    3.3535   611.7779    16.3871   635.2354   0   0.00000
   337.4855    3.6866    7.2365    3.4099   612.2978    16.7480   636.0572   0   0.00000
   327.4855    3.7466    7.3369    3.4501   612.6696    17.0039   636.6381   0   0.00000
   317.4855    3.8214    7.4368    3.4750   612.9007    17.1622   636.9965   0   0.00000
   307.4855    3.9110    7.5362    3.4847   612.9911    17.2240   637.1361   0   0.00000
   297.4855    4.0146    7.6351    3.4800   612.9467    17.1937   637.0676   0   0.00000
   287.4855    4.1312    7.7338    3.4620   612.7800    17.0797   636.8097   0   0.00000
   277.4855    4.2602    7.8322    3.4314   612.4962    16.8848   636.3679   0   0.00000
   267.4855    4.4010    7.9303    3.3888   612.1033    16.6133   635.7510   0   0.00000
   257.4855    4.5520    8.0282    3.3358   611.6157    16.2738   634.9767   0   0.00000
   252.7488    4.6270    8.0744    3.3071   611.3528    16.0893   634.5548   0   0.00000

     ENERGY OUTPUT      6795.62183(MWHRS)


 OPTIMUM DRAWNDOWN RESERVOIR LEVEL =     5.8950 M

 OPTIMUM ENERGY OUTPUT =      6795.62183 (MWHRS)
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```
 5.50 M  RANGE


ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL    6.0600 M


     TIME    SEA LEVEL POOL LEVEL    HEAD     DISCHARGE    POWER  CAVITATION     TRANS LOSS
    (MINS)      (M)       (M)         (M)     M**3/SEC     (MW)   DISCHARGE         (MW)

  559.7170   6.0600    6.0600    0.0000
  569.7170   6.2927    6.1198    0.1193
  579.7170   6.5226    6.2243    0.2060
  589.7170   6.7488    6.3506    0.2754
  599.7170   6.9690    6.4912    0.3309
  609.7170   7.1820    6.6416    0.3748
  619.7170   7.3858    6.7986    0.4078
  629.7170   7.5797    6.9596    0.4311
  639.7170   7.7615    7.1228    0.4447
  649.7170   7.9307    7.2861    0.4493
  659.7170   8.0851    7.4480    0.4446
  669.7170   8.2242    7.6069    0.4312
  679.7170   8.3473    7.7616    0.4094
  689.7170   8.4528    7.9110    0.3791
  699.7170   8.5402    8.0532    0.3410
  709.7170   8.6095    8.1866    0.2963
  719.7170   8.6590    8.3091    0.2453
  729.7170   8.6893    8.4186    0.1898
  739.7170   8.6997    8.5123    0.1315
  749.7170   8.6904    8.5865    0.0729
  759.7170   8.6612    8.6347    0.0186
  762.2170   8.6495    8.6411    0.0060
  763.4670   8.6434    8.6426    0.0006


      MAX.POOL LEVEL   TIME MAX.P.L   MIN POOL LEV   T MIN PL
         8.6426          763.4670        6.0600      489.2504
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```
   TIME   SEA LEVEL POOL LEVEL  HEAD    DISCHARGE   POWER  CAVITATION    TRANS LOSS
  (MINS)     (M)       (M)       (M)    M**3/SEC     (MW)   DISCHARGE       (MW)

 489.2504   4.4934    6.0600   1.4331  596.2158    1.6662   601.2830   0   0.00000
 479.2504   4.3012    6.1644   1.7290  598.2919    4.5456   607.5905   0   0.00000
 469.2504   4.1202    6.2685   2.0133  600.4117    6.9687   613.1590   0   0.00000
 459.2504   3.9530    6.3723   2.2836  602.5320    9.0702   618.0979   0   0.00000
 449.2504   3.8001    6.4760   2.5393  604.6251   10.9333   622.5075   0   0.00000
 439.2504   3.6622    6.5794   2.7798  606.6649   12.6054   626.4558   0   0.00000
 429.2504   3.5414    6.6825   3.0030  608.6151   14.1054   629.9702   0   0.00000
 419.2504   3.4377    6.7854   3.2088  610.4585   15.4545   633.0972   0   0.00000
 409.2504   3.3521    6.8881   3.3962  612.1716   16.6607   635.8587   0   0.00000
 399.2504   3.2849    6.9904   3.5652  613.7414   17.7328   638.2829   0   0.00000
 389.2504   3.2374    7.0924   3.7141  615.1439   18.6684   640.3728   0   0.00000
 379.2504   3.2092    7.1941   3.8434  616.3755   19.4748   642.1543   0   0.00000
 369.2504   3.2007    7.2955   3.9527  617.4247   20.1522   643.6360   0   0.00000
 359.2504   3.2121    7.3964   4.0419  618.2864   20.7026   644.8299   0   0.00000
 349.2504   3.2433    7.4970   4.1109  618.9573   21.1278   645.7457   0   0.00000
 339.2504   3.2937    7.5971   4.1604  619.4390   21.4313   646.3962   0   0.00000
 329.2504   3.3638    7.6969   4.1899  619.7272   21.6124   646.7828   0   0.00000
 319.2504   3.4521    7.7965   4.2011  619.8372   21.6813   646.9298   0   0.00000
 309.2504   3.5584    7.8959   4.1941  619.7688   21.6384   646.8384   0   0.00000
 299.2504   3.6823    7.9951   4.1695  619.5280   21.4873   646.5158   0   0.00000
 289.2504   3.8220    8.0940   4.1287  619.1305   21.2371   645.9803   0   0.00000
 279.2504   3.9772    8.1927   4.0724  618.5825   20.8906   645.2355   0   0.00000
 269.2504   4.1470    8.2910   4.0011  617.8919   20.4513   644.2858   0   0.00000
 259.2504   4.3294    8.3891   3.9170  617.0805   19.9309   643.1535   0   0.00000
 249.2504   4.5237    8.4868   3.8206  616.1568   19.3326   641.8414   0   0.00000
 239.2504   4.7279    8.5841   3.7140  615.1430   18.6677   640.3714   0   0.00000
 233.2159   4.8563    8.6427   3.6443  614.4845   18.2309   639.3986   0   0.00000

   ENERGY OUTPUT     10247.90090(MWHRS)

OPTIMUM DRAWNDOWN RESERVOIR LEVEL =     6.0600 M

OPTIMUM ENERGY OUTPUT =     10247.90090 (MWHRS)
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```
6.50 M  RANGE


ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL     6.2775 M



   TIME     SEA LEVEL  POOL LEVEL    HEAD    DISCHARGE   POWER  CAVITATION     TRANS LOSS
  (MINS)       (M)        (M)         (M)    M**3/SEC    (MW)   DISCHARGE         (MW)

 563.2624    6.2775     6.2775     0.0000
 573.2624    6.5514     6.3423     0.1446
 583.2624    6.8216     6.4564     0.2528
 593.2624    7.0864     6.5948     0.3407
 603.2624    7.3437     6.7494     0.4124
 613.2624    7.5916     6.9153     0.4701
 623.2624    7.8283     7.0888     0.5147
 633.2624    8.0524     7.2673     0.5472
 643.2624    8.2621     7.4484     0.5677
 653.2624    8.4559     7.6301     0.5768
 663.2624    8.6319     7.8113     0.5739
 673.2624    8.7896     7.9903     0.5594
 683.2624    8.9278     8.1656     0.5340
 693.2624    9.0449     8.3351     0.4976
 703.2624    9.1406     8.4972     0.4514
 713.2624    9.2142     8.6499     0.3962
 723.2624    9.2647     8.7910     0.3327
 733.2624    9.2921     8.9181     0.2628
 743.2624    9.2962     9.0284     0.1882
 753.2624    9.2768     9.1181     0.1117
 763.2624    9.2343     9.1805     0.0379
 768.2624    9.2054     9.1968     0.0061
 768.8874    9.2018     9.1978     0.0028
 769.1999    9.2000     9.1981     0.0013
 769.3562    9.1991     9.1982     0.0006



   MAX.POOL LEVEL    TIME MAX.P.L    MIN POOL LEV    T MIN PL
       9.1982          769.3562         6.2775       504.9373
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    TIME    SEA LEVEL POOL LEVEL   HEAD    DISCHARGE   POWER  CAVITATION      TRANS LOSS
   (MINS)     (M)        (M)       (M)     M**3/SEC    (MW)   DISCHARGE          (MW)

  504.9373   4.7107    6.2775    1.4331   596.2158    1.6662   601.2830   0   0.00000
  494.9373   4.4648    6.3806    1.7814   598.6737    5.0129   608.6494   0   0.00000
  484.9373   4.2302    6.4836    2.1180   601.2211    7.8018   615.1088   0   0.00000
  474.9373   4.0086    6.5864    2.4414   603.8141   10.2318   620.8466   0   0.00000
  464.9373   3.8017    6.6891    2.7500   606.4089   12.4019   625.9768   0   0.00000
  454.9373   3.6114    6.7917    3.0419   608.9608   14.3629   630.5699   0   0.00000
  444.9373   3.4382    6.8941    3.3164   611.4384   16.1495   634.6926   0   0.00000
  434.9373   3.2840    6.9964    3.5720   613.8049   17.7757   638.3792   0   0.00000
  424.9373   3.1499    7.0984    3.8072   616.0292   19.2494   641.6582   0   0.00000
  414.9373   3.0366    7.2003    4.0215   618.0889   20.5769   644.5580   0   0.00000
  404.9373   2.9448    7.3020    4.2142   619.9650   21.7613   647.1002   0   0.00000
  394.9373   2.8754    7.4034    4.3842   621.6374   22.8010   649.2961   0   0.00000
  384.9373   2.8290    7.5045    4.5310   623.0919   23.6950   651.1576   0   0.00000
  374.9373   2.8058    7.6053    4.6546   624.3224   24.4451   652.7003   0   0.00000
  364.9373   2.8059    7.7059    4.7546   625.3230   25.0515   653.9348   0   0.00000
  354.9373   2.8295    7.8065    4.8312   626.0920   25.5157   654.8720   0   0.00000
  344.9373   2.8761    7.9069    4.8848   626.6303   25.8398   655.5225   0   0.00000
  334.9373   2.9458    8.0072    4.9152   626.9366   26.0239   655.8905   0   0.00000
  324.9373   3.0379    8.1074    4.9231   627.0164   26.0718   655.9862   0   0.00000
  314.9373   3.1515    8.2073    4.9095   626.8790   25.9893   655.8214   0   0.00000
  304.9373   3.2861    8.3070    4.8745   626.5275   25.7779   655.3986   0   0.00000
  294.9373   3.4406    8.4064    4.8196   625.9753   25.4453   654.7304   0   0.00000
  284.9373   3.6136    8.5054    4.7459   625.2360   24.9989   653.8281   0   0.00000
  274.9373   3.8045    8.6042    4.6540   624.3172   24.4419   652.6938   0   0.00000
  264.9373   4.0116    8.7026    4.5456   623.2370   23.7837   651.3409   0   0.00000
  254.9373   4.2334    8.8006    4.4223   622.0134   23.0329   649.7814   0   0.00000
  244.9373   4.4681    8.8982    4.2856   620.6655   22.1985   648.0276   0   0.00000
  234.9373   4.7142    8.9954    4.1371   619.2124   21.2887   646.0909   0   0.00000
  224.9373   4.9700    9.0922    3.9785   617.6738   20.3118   643.9832   0   0.00000
  214.9373   5.2336    9.1886    3.8117   616.0725   19.2776   641.7204   0   0.00000
  213.9322   5.2605    9.1982    3.7946   615.9089   19.1708   641.4850   0   0.00000

     ENERGY OUTPUT     13870.29505(MWHRS)


OPTIMUM DRAWNDOWN RESERVOIR LEVEL =     6.2775 M

OPTIMUM ENERGY OUTPUT =     13870.29505 (MWHRS)
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 7.50 M  RANGE


ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL    6.6000 M



    TIME    SEA LEVEL POOL LEVEL    HEAD     DISCHARGE    POWER  CAVITATION      TRANS LOSS
   (MINS)     (M)        (M)         (M)     M**3/SEC     (MW)    DISCHARGE         (MW)

  569.1726   6.6000     6.6000     0.0000
  579.1726   6.9138     6.6687     0.1700
  589.1726   7.2225     6.7904     0.3000
  599.1726   7.5232     6.9385     0.4065
  609.1726   7.8142     7.1042     0.4942
  619.1726   8.0928     7.2822     0.5650
  629.1726   8.3579     7.4686     0.6206
  639.1726   8.6068     7.6606     0.6611
  649.1726   8.8384     7.8563     0.6869
  659.1726   9.0501     8.0539     0.6976
  669.1726   9.2409     8.2510     0.6937
  679.1726   9.4099     8.4458     0.6763
  689.1726   9.5551     8.6363     0.6450
  699.1726   9.6757     8.8206     0.6007
  709.1726   9.7715     8.9965     0.5447
  719.1726   9.8405     9.1621     0.4771
  729.1726   9.8831     9.3149     0.3998
  739.1726   9.8989     9.4524     0.3143
  749.1726   9.8876     9.5711     0.2229
  759.1726   9.8494     9.6666     0.1287
  769.1726   9.7848     9.7309     0.0379
  771.6726   9.7637     9.7403     0.0164
  772.9226   9.7521     9.7433     0.0061
  773.5476   9.7463     9.7442     0.0014
  773.7038   9.7448     9.7443     0.0004


      MAX.POOL LEVEL   TIME MAX.P.L   MIN POOL LEV   T MIN PL
          9.7443         773.7038        6.6000      519.3654
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   TIME    SEA LEVEL POOL LEVEL   HEAD    DISCHARGE    POWER   CAVITATION      TRANS LOSS
  (MINS)      (M)       (M)        (M)     M**3/SEC     (MW)   DISCHARGE          (MW)

 519.3654   5.0329    6.6000    1.4331   596.2158    1.6662   601.2830   0   0.00000
 509.3654   4.7329    6.7013    1.8336   599.0579    5.4681   609.6886   0   0.00000
 499.3654   4.4441    6.8026    2.2226   602.0446    8.6091   617.0093   0   0.00000
 489.3654   4.1668    6.9039    2.6000   605.1332   11.3614   623.5203   0   0.00000
 479.3654   3.9045    7.0051    2.9623   608.2556   13.8350   629.3393   0   0.00000
 469.3654   3.6574    7.1063    3.3093   611.3729   16.1035   634.5873   0   0.00000
 459.3654   3.4292    7.2074    3.6374   614.4200   18.1880   639.3027   0   0.00000
 449.3654   3.2205    7.3085    3.9461   617.3604   20.1110   643.5462   0   0.00000
 439.3654   3.0322    7.4095    4.2342   620.1610   21.8839   647.3608   0   0.00000
 429.3654   2.8672    7.5105    4.4990   622.7739   23.5002   650.7542   0   0.00000
 419.3654   2.7255    7.6113    4.7405   625.1820   24.9662   653.7618   0   0.00000
 409.3654   2.6086    7.7121    4.9573   627.3607   26.2785   656.3979   0   0.00000
 399.3654   2.5165    7.8131    5.1494   629.3010   27.4394   658.6862   0   0.00000
 389.3654   2.4514    7.9141    5.3148   630.9759   28.4376   660.6216   0   0.00000
 379.3654   2.4126    8.0152    5.4540   632.3881   29.2777   662.2278   0   0.00000
 369.3654   2.4009    8.1163    5.5664   633.5281   29.9556   663.5087   0   0.00000
 359.3654   2.4161    8.2173    5.6517   634.3948   30.4709   664.4739   0   0.00000
 349.3654   2.4582    8.3182    5.7102   634.9879   30.8238   665.1304   0   0.00000
 339.3654   2.5267    8.4190    5.7423   635.3139   31.0178   665.4898   0   0.00000
 329.3654   2.6220    8.5196    5.7475   635.3667   31.0492   665.5480   0   0.00000
 319.3654   2.7421    8.6200    5.7279   635.1672   30.9305   665.3282   0   0.00000
 309.3654   2.8869    8.7201    5.6833   634.7155   30.6617   664.8292   0   0.00000
 299.3654   3.0555    8.8199    5.6148   634.0194   30.2477   664.0568   0   0.00000
 289.3654   3.2458    8.9194    5.5242   633.1005   29.7013   663.0298   0   0.00000
 279.3654   3.4571    9.0185    5.4125   631.9662   29.0268   661.7502   0   0.00000
 269.3654   3.6885    9.1173    5.2803   630.6260   28.2293   660.2201   0   0.00000
 259.3654   3.9370    9.2156    5.1306   629.1101   27.3254   658.4633   0   0.00000
 249.3654   4.2019    9.3135    4.9641   627.4296   26.3198   656.4800   0   0.00000
 239.3654   4.4802    9.4109    4.7838   625.6164   25.2288   654.2935   0   0.00000
 229.3654   4.7710    9.5078    4.5905   623.6836   24.0563   651.9028   0   0.00000
 219.3654   5.0716    9.6042    4.3870   621.6650   22.8180   649.3318   0   0.00000
 209.3654   5.3801    9.7001    4.1750   619.5821   21.5213   646.5884   0   0.00000
 204.7361   5.5253    9.7444    4.0744   618.6022   20.9031   645.2624   0   0.00000

   ENERGY OUTPUT     17610.50397(MWHRS)


OPTIMUM DRAWNDOWN RESERVOIR LEVEL =     6.6000 M

OPTIMUM ENERGY OUTPUT =     17610.50397 (MWHRS)
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8.50 M  RANGE


ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL    6.9300 M


    TIME     SEA LEVEL POOL LEVEL    HEAD     DISCHARGE    POWER  CAVITATION     TRANS LOSS
   (MINS)      (M)        (M)         (M)     M**3/SEC     (MW)   DISCHARGE         (MW)

  573.9474    6.9300     6.9300     0.0000
  583.9474    7.2830     7.0023     0.1952
  593.9474    7.6286     7.1307     0.3467
  603.9474    7.9642     7.2872     0.4719
  613.9474    8.2875     7.4627     0.5756
  623.9474    8.5960     7.6514     0.6599
  633.9474    8.8878     7.8501     0.7258
  643.9474    9.1606     8.0559     0.7735
  653.9474    9.4124     8.2660     0.8035
  663.9474    9.6411     8.4780     0.8160
  673.9474    9.8455     8.6895     0.8117
  683.9474   10.0243     8.8985     0.7911
  693.9474   10.1756     9.1028     0.7543
  703.9474   10.2988     9.3004     0.7025
  713.9474   10.3930     9.4890     0.6363
  723.9474   10.4569     9.6664     0.5567
  733.9474   10.4907     9.8300     0.4654
  743.9474   10.4940     9.9770     0.3643
  753.9474   10.4666    10.1036     0.2558
  763.9474   10.4089    10.2049     0.1438
  773.9474   10.3215    10.2714     0.0354
  776.4474   10.2952    10.2798     0.0108
  777.6974   10.2820    10.2817     0.0002


     MAX.POOL LEVEL     TIME MAX.P.L    MIN POOL LEV    T MIN PL
        10.2817           777.6974          6.9300     530.2381
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   TIME     SEA LEVEL POOL LEVEL   HEAD    DISCHARGE   POWER  CAVITATION    TRANS LOSS
  (MINS)      (M)        (M)        (M)    M**3/SEC     (MW)   DISCHARGE        (MW)

 530.2381   5.3626    6.9300    1.4331  596.2158   1.6662   601.2830  0   0.00000
 520.2381   5.0139    7.0296    1.8804  599.4059   5.8684   610.6079  0   0.00000
 510.2381   4.6729    7.1292    2.3198  602.8232   9.3403   618.7365  0   0.00000
 500.2381   4.3445    7.2289    2.7465  606.3791  12.3781   625.9207  0   0.00000
 490.2381   4.0288    7.3286    3.1605  610.0227  15.1408   632.3734  0   0.00000
 480.2381   3.7301    7.4284    3.5577  613.6711  17.6855   638.1764  0   0.00000
 470.2381   3.4483    7.5282    3.9378  617.2812  20.0601   643.4353  0   0.00000
 460.2381   3.1877    7.6282    4.2969  620.7769  22.2678   648.1741  0   0.00000
 450.2381   2.9492    7.7284    4.6343  624.1198  24.3219   652.4482  0   0.00000
 440.2381   2.7336    7.8289    4.9490  627.2770  26.2283   656.2980  0   0.00000
 430.2381   2.5442    7.9296    5.2378  630.1958  27.9731   659.7246  0   0.00000
 420.2381   2.3813    8.0307    5.5007  632.8613  29.5591   662.7612  0   0.00000
 410.2381   2.2463    8.1319    5.7358  635.2475  30.9782   665.4167  0   0.00000
 400.2381   2.1394    8.2332    5.9431  637.3487  32.2306   667.7135  0   0.00000
 390.2381   2.0630    8.3347    6.1201  639.1377  33.3011   669.6429  0   0.00000
 380.2381   2.0164    8.4362    6.2675  640.6225  34.1937   671.2286  0   0.00000
 370.2381   2.0004    8.5377    6.3845  641.7964  34.9028   672.4736  0   0.00000
 360.2381   2.0149    8.6391    6.4709  642.6613  35.4274   673.3865  0   0.00000
 350.2381   2.0601    8.7404    6.5268  643.2190  35.7668   673.9734  0   0.00000
 340.2381   2.1350    8.8416    6.5529  643.4790  35.9254   674.2466  0   0.00000
 330.2381   2.2406    8.9426    6.5484  643.4338  35.8978   674.1991  0   0.00000
 320.2381   2.3742    9.0434    6.5156  643.1072  35.6988   673.8559  0   0.00000
 310.2381   2.5359    9.1439    6.4546  642.4984  35.3285   673.2148  0   0.00000
 300.2381   2.7248    9.2440    6.3662  641.6134  34.7920   672.2799  0   0.00000
 290.2381   2.9384    9.3438    6.2528  640.4748  34.1047   671.0714  0   0.00000
 280.2381   3.1758    9.4433    6.1153  639.0892  33.2720   669.5909  0   0.00000
 270.2381   3.4362    9.5422    5.9544  637.4636  32.2992   667.8380  0   0.00000
 260.2381   3.7163    9.6407    5.7736  635.6308  31.2064   665.8383  0   0.00000
 250.2381   4.0150    9.7387    5.5735  633.6009  29.9988   663.5900  0   0.00000
 240.2381   4.3292    9.8362    5.3576  631.4100  28.6960   661.1178  0   0.00000
 230.2381   4.6578    9.9332    5.1268  629.0716  27.3024   658.4182  0   0.00000
 220.2381   4.9975   10.0296    4.8842  626.6249  25.8365   655.5160  0   0.00000
 210.2381   5.3466   10.1254    4.6318  624.0949  24.3067   652.4171  0   0.00000
 200.2381   5.7018   10.2207    4.3727  621.5230  22.7303   649.1479  0   0.00000
 193.7937   5.9334   10.2818    4.2027  619.8522  21.6907   646.9498  0   0.00000

   ENERGY OUTPUT     21438.69343(MWHRS)


OPTIMUM DRAWNDOWN RESERVOIR LEVEL =     6.9300 M

OPTIMUM ENERGY OUTPUT =     21438.69343 (MWHRS)
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9.50 M  RANGE


ESTIMATE OF DRAWDOWN RESERVOIR LEVEL    7.3500 M



   TIME    SEA LEVEL  POOL LEVEL   HEAD    DISCHARGE   POWER  CAVITATION     TRANS LOSS
  (MINS)     (M)        (M)        (M)     M**3/SEC    (MW)   DISCHARGE        (MW)

 578.7321   7.3500     7.3500    0.0000
 588.7321   7.7413     7.4248    0.2208
 598.7321   8.1226     7.5583    0.3940
 608.7321   8.4918     7.7216    0.5383
 618.7321   8.8454     7.9059    0.6573
 628.7321   9.1819     8.1052    0.7542
 638.7321   9.4981     8.3153    0.8292
 648.7321   9.7925     8.5329    0.8839
 658.7321  10.0618     8.7549    0.9178
 668.7321  10.3045     8.9789    0.9318
 678.7321  10.5199     9.2023    0.9267
 688.7321  10.7052     9.4229    0.9024
 698.7321  10.8593     9.6384    0.8596
 708.7321  10.9820     9.8467    0.7997
 718.7321  11.0709    10.0453    0.7227
 728.7321  11.1264    10.2318    0.6306
 738.7321  11.1478    10.4035    0.5248
 748.7321  11.1351    10.5571    0.4076
 758.7321  11.0881    10.6886    0.2817
 768.7321  11.0078    10.7923    0.1520
 778.7321  10.8942    10.8565    0.0266
 779.9821  10.8795    10.8605    0.0134
 780.6071  10.8701    10.8618    0.0058
 780.9196  10.8654    10.8623    0.0022
 781.0758  10.8630    10.8624    0.0004



    MAX.POOL LEVEL   TIME MAX.P.L   MIN POOL LEV   T MIN PL
       10.8624         781.0758        7.3500      539.6327
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     TIME     SEA LEVEL POOL LEVEL   HEAD    DISCHARGE   POWER  CAVITATION    TRANS LOSS
    (MINS)      (M)        (M)       (M)     M**3/SEC    (MW)   DISCHARGE        (MW)

 539.6327     5.7821     7.3500    1.4331   596.2158    1.6662   601.2830   0   0.00000
 529.6327     5.3844     7.4474    1.9272   599.7571    6.2617   611.5161   0   0.00000
 519.6327     4.9952     7.5450    2.4126   603.5774   10.0225   620.3510   0   0.00000
 509.6327     4.6148     7.6426    2.8892   607.6147   13.3463   628.1961   0   0.00000
 499.6327     4.2486     7.7408    3.3519   611.7640   16.3774   635.2132   0   0.00000
 489.6327     3.8969     7.8393    3.8006   615.9666   19.2085   641.5681   0   0.00000
 479.6327     3.5641     7.9384    4.2308   620.1275   21.8630   647.3164   0   0.00000
 469.6327     3.2505     8.0379    4.6422   624.1990   24.3701   652.5468   0   0.00000
 459.6327     2.9607     8.1378    5.0303   628.0967   26.7196   657.2721   0   0.00000
 449.6327     2.6957     8.2381    5.3941   631.7798   28.9160   661.5387   0   0.00000
 439.6327     2.4564     8.3388    5.7325   635.2147   30.9588   665.3806   0   0.00000
 429.6327     2.2466     8.4398    6.0420   638.3488   32.8285   668.7948   0   0.00000
 419.6327     2.0663     8.5411    6.3223   641.1724   34.5255   671.8127   0   0.00000
 409.6327     1.9173     8.6425    6.5715   643.6642   36.0385   674.4410   0   0.00000
 399.6327     1.7998     8.7442    6.7896   645.8245   37.3657   676.7001   0   0.00000
 389.6327     1.7165     8.8459    6.9738   647.6311   38.4893   678.5799   0   0.00000
 379.6327     1.6665     8.9476    7.1249   649.0993   39.4132   680.1036   0   0.00000
 369.6327     1.6506     9.0494    7.2420   650.2270   40.1301   681.2728   0   0.00000
 359.6327     1.6690     9.1511    7.3250   651.0207   40.6389   682.0956   0   0.00000
 349.6327     1.7215     9.2527    7.3738   651.4856   40.9387   682.5778   0   0.00000
 339.6327     1.8073     9.3541    7.3893   651.6331   41.0340   682.7307   0   0.00000
 329.6327     1.9272     9.4553    7.3707   651.4560   40.9196   682.5471   0   0.00000
 319.6327     2.0785     9.5563    7.3205   650.9786   40.6119   682.0520   0   0.00000
 309.6327     2.2610     9.6569    7.2389   650.1976   40.1113   681.2423   0   0.00000
 299.6327     2.4739     9.7572    7.1268   649.1173   39.4245   680.1222   0   0.00000
 289.6327     2.7143     9.8571    6.9869   647.7583   38.5689   678.7119   0   0.00000
 279.6327     2.9812     9.9566    6.8200   646.1238   37.5509   677.0120   0   0.00000
 269.6327     3.2737    10.0556    6.6273   644.2186   36.3776   675.0223   0   0.00000
 259.6327     3.5879    10.1541    6.4123   642.0753   35.0718   672.7683   0   0.00000
 249.6327     3.9230    10.2521    6.1761   639.7026   33.6402   670.2478   0   0.00000
 239.6327     4.2751    10.3495    5.9223   637.1385   32.1051   667.4852   0   0.00000
 229.6327     4.6432    10.4463    5.6520   634.3972   30.4723   664.4765   0   0.00000
 219.6327     5.0235    10.5425    5.3688   631.5229   28.7631   661.2463   0   0.00000
 209.6327     5.4142    10.6381    5.0746   628.5444   26.9874   657.8000   0   0.00000
 199.6327     5.8115    10.7330    4.7732   625.5103   25.1647   654.1639   0   0.00000
 189.6327     6.2134    10.8273    4.4666   622.4525   23.3030   650.3444   0   0.00000
 185.8893     6.3642    10.8624    4.3513   621.3126   22.6001   648.8744   0   0.00000

     ENERGY OUTPUT     25346.81013(MWHRS)


 OPTIMUM DRAWNDOWN RESERVOIR LEVEL =     7.3500 M

 OPTIMUM ENERGY OUTPUT =     25346.81013 (MWHRS)
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10.50 M  RANGE


ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL     7.7600 M



   TIME    SEA LEVEL POOL LEVEL   HEAD    DISCHARGE   POWER  CAVITATION     TRANS LOSS
  (MINS)     (M)       (M)        (M)     M**3/SEC    (MW)   DISCHARGE        (MW)

 583.5766    7.7600    7.7600    0.0000
 593.5766    8.1874    7.8377    0.2446
 603.5766    8.6025    7.9767    0.4380
 613.5766    9.0025    8.1475    0.5989
 623.5766    9.3842    8.3402    0.7320
 633.5766    9.7456    8.5487    0.8399
 643.5766   10.0834    8.7686    0.9235
 653.5766   10.3957    8.9961    0.9838
 663.5766   10.6791    9.2282    1.0206
 673.5766   10.9328    9.4621    1.0352
 683.5766   11.1550    9.6954    1.0279
 693.5766   11.3431    9.9254    0.9988
 703.5766   11.4966   10.1499    0.9491
 713.5766   11.6144   10.3665    0.8797
 723.5766   11.6947   10.5727    0.7912
 733.5766   11.7379   10.7657    0.6856
 743.5766   11.7432   10.9426    0.5647
 753.5766   11.7108   11.1000    0.4309
 763.5766   11.6410   11.2332    0.2877
 773.5766   11.5344   11.3354    0.1404
 778.5766   11.4693   11.3709    0.0694
 781.0766   11.4328   11.3835    0.0347
 783.5766   11.3910   11.3902    0.0006


    MAX.POOL LEVEL   TIME MAX.P.L   MIN POOL LEV   T MIN PL
       11.3902         783.5766        7.7600      548.0698
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   TIME    SEA LEVEL POOL LEVEL   HEAD    DISCHARGE    POWER  CAVITATION    TRANS LOSS
  (MINS)      (M)       (M)        (M)    M**3/SEC     (MW)   DISCHARGE        (MW)

548.0698    6.1917    7.7600    1.4331  596.2158    1.6662   601.2830   0   0.00000
538.0698    5.7483    7.8560    1.9713  600.0910    6.6264   612.3620   0   0.00000
528.0698    5.3102    7.9525    2.5044  604.3349   10.6850   621.9197   0   0.00000
518.0698    4.8815    8.0495    3.0285  608.8414   14.2742   630.3635   0   0.00000
508.0698    4.4635    8.1470    3.5423  613.5271   17.5882   637.9576   0   0.00000
498.0698    4.0613    8.2451    4.0408  618.2755   20.6957   644.8149   0   0.00000
488.0698    3.6758    8.3437    4.5230  623.0119   23.6460   651.0562   0   0.00000
478.0698    3.3113    8.4429    4.9848  627.6376   26.4446   656.7277   0   0.00000
468.0698    2.9688    8.5426    5.4251  632.0943   29.1030   661.8955   0   0.00000
458.0698    2.6528    8.6427    5.8395  636.2991   31.6046   666.5707   0   0.00000
448.0698    2.3642    8.7433    6.2269  640.2139   33.9477   670.7936   0   0.00000
438.0698    2.1049    8.8443    6.5856  643.8046   36.1243   674.5883   0   0.00000
428.0698    1.8780    8.9456    6.9123  647.0295   38.1136   677.9546   0   0.00000
418.0698    1.6842    9.0472    7.2064  649.8849   39.9119   680.9182   0   0.00000
408.0698    1.5250    9.1490    7.4662  652.3612   41.5068   683.4863   0   0.00000
398.0698    1.4010    9.2509    7.6911  654.4638   42.8923   685.6731   0   0.00000
388.0698    1.3147    9.3529    7.8786  656.1850   44.0514   687.4725   0   0.00000
378.0698    1.2653    9.4549    8.0294  657.5457   44.9860   688.9038   0   0.00000
368.0698    1.2536    9.5570    8.1425  658.5521   45.6886   689.9688   0   0.00000
358.0698    1.2798    9.6589    8.2180  659.2159   46.1578   690.6746   0   0.00000
348.0698    1.3436    9.7607    8.2558  659.5467   46.3935   691.0276   0   0.00000
338.0698    1.4444    9.8623    8.2567  659.5542   46.3988   691.0357   0   0.00000
328.0698    1.5823    9.9637    8.2202  659.2359   46.1721   690.6960   0   0.00000
318.0698    1.7549   10.0648    8.1490  658.6096   45.7290   690.0297   0   0.00000
308.0698    1.9619   10.1656    8.0432  657.6689   45.0715   689.0339   0   0.00000
298.0698    2.2020   10.2660    7.9041  656.4164   44.2091   687.7152   0   0.00000
288.0698    2.4722   10.3660    7.7345  654.8646   43.1600   686.0911   0   0.00000
278.0698    2.7717   10.4656    7.5353  653.0111   41.9317   684.1612   0   0.00000
268.0698    3.0987   10.5646    7.3081  650.8602   40.5357   681.9292   0   0.00000
258.0698    3.4497   10.6631    7.0566  648.4369   38.9951   679.4164   0   0.00000
248.0698    3.8229   10.7610    6.7823  645.7518   37.3208   676.6244   0   0.00000
238.0698    4.2149   10.8583    6.4887  642.8385   35.5352   673.5731   0   0.00000
228.0698    4.6239   10.9550    6.1775  639.7161   33.6483   670.2621   0   0.00000
218.0698    5.0461   11.0510    5.8524  636.4297   31.6823   666.7132   0   0.00000
208.0698    5.4791   11.1464    5.5159  633.0155   29.6508   662.9344   0   0.00000
198.0698    5.9190   11.2410    5.1717  629.5263   27.5738   658.9485   0   0.00000
188.0698    6.3633   11.3349    4.8224  626.0037   25.4624   654.7648   0   0.00000
182.1442    6.6271   11.3902    4.6146  623.9237   24.2026   652.2034   0   0.00000

    ENERGY OUTPUT     29314.47808(MWHRS)


OPTIMUM DRAWNDOWN RESERVOIR LEVEL =     7.7600 M

OPTIMUM ENERGY OUTPUT =      29314.47808 (MWHRS)
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11.50 M  RANGE

ESTIMATE OF DRAWNDOWN RESERVOIR LEVEL     8.1065 M


   TIME    SEA LEVEL POOL LEVEL   HEAD    DISCHARGE    POWER  CAVITATION    TRANS LOSS
  (MINS)      (M)       (M)        (M)    M**3/SEC     (MW)   DISCHARGE        (MW)

 586.2530    8.1065    8.1065    0.0000
 596.2530    8.5712    8.1873    0.2690
 606.2530    9.0219    8.3321    0.4836
 616.2530    9.4547    8.5103    0.6627
 626.2530    9.8673    8.7115    0.8116
 636.2530   10.2563    8.9294    0.9324
 646.2530   10.6192    9.1593    1.0267
 656.2530   10.9528    9.3973    1.0947
 666.2530   11.2547    9.6401    1.1369
 676.2530   11.5237    9.8850    1.1544
 686.2530   11.7571   10.1292    1.1473
 696.2530   11.9530   10.3702    1.1159
 706.2530   12.1110   10.6054    1.0616
 716.2530   12.2288   10.8324    0.9848
 726.2530   12.3060   11.0486    0.8869
 736.2530   12.3422   11.2511    0.7697
 746.2530   12.3371   11.4369    0.6350
 756.2530   12.2905   11.6022    0.4855
 766.2530   12.2032   11.7425    0.3249
 776.2530   12.0757   11.8506    0.1588
 781.2530   11.9993   11.8883    0.0783
 783.7530   11.9536   11.9014    0.0368
 785.0030   11.9308   11.9059    0.0175
 785.6280   11.9193   11.9075    0.0084
 785.9405   11.9136   11.9080    0.0039
 786.0968   11.9108   11.9082    0.0018


    MAX.POOL LEVEL   TIME MAX.P.L   MIN POOL LEV   T MIN PL
       11.9082         786.0968        8.1065      553.7236
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   TIME    SEA LEVEL POOL LEVEL   HEAD   DISCHARGE   POWER  CAVITATION     TRANS LOSS
  (MINS)      (M)       (M)        (M)   M**3/SEC    (MW)   DISCHARGE         (MW)

 553.7236   6.5378    8.1065    1.4331  596.2158    1.6662  601.2830  0   0.00000
 543.7236   6.0509    8.2019    2.0141  600.4176    6.9750  613.1736  0   0.00000
 533.7236   5.5673    8.2977    2.5919  605.0658   11.3051  623.3871  0   0.00000
 523.7236   5.0920    8.3942    3.1620  610.0355   15.1501  632.3948  0   0.00000
 513.7236   4.6270    8.4912    3.7221  615.2198   18.7184  640.4839  0   0.00000
 503.7236   4.1766    8.5889    4.2681  620.4934   22.0913  647.8009  0   0.00000
 493.7236   3.7436    8.6872    4.7974  625.7524   25.3109  654.4593  0   0.00000
 483.7236   3.3314    8.7862    5.3065  630.8911   28.3871  660.5245  0   0.00000
 473.7236   2.9421    8.8857    5.7931  635.8293   31.3246  666.0563  0   0.00000
 463.7236   2.5795    8.9858    6.2538  640.4849   34.1109  671.0823  0   0.00000
 453.7236   2.2464    9.0864    6.6856  644.7971   36.7325  675.6277  0   0.00000
 443.7236   1.9439    9.1874    7.0874  648.7357   39.1834  679.7265  0   0.00000
 433.7236   1.6753    9.2888    7.4557  652.2622   41.4423  683.3835  0   0.00000
 423.7236   1.4424    9.3905    7.7889  655.3652   43.4963  686.6141  0   0.00000
 413.7236   1.2466    9.4924    8.0854  658.0451   45.3334  689.4315  0   0.00000
 403.7236   1.0887    9.5946    8.3443  660.3140   46.9449  691.8496  0   0.00000
 393.7236   0.9709    9.6968    8.5633  662.1768   48.3141  693.8667  0   0.00000
 383.7236   0.8938    9.7991    8.7419  663.6538   49.4344  695.4923  0   0.00000
 373.7236   0.8577    9.9008    8.8890  644.8633   50.0058  695.6488  0   0.00000
 363.7236   0.8630    9.9987    8.9878  631.7162   49.9999  695.4199  0   0.00000
 353.7236   0.9097   10.0951    9.0399  626.6190   49.9989  696.1543  0   0.00000
 343.7236   0.9970   10.1909    9.0487  625.8242   49.9986  697.8247  0   0.00000
 333.7236   1.1254   10.2867    9.0146  628.9849   49.9986  697.9424  0   0.00000
 323.7236   1.2929   10.3831    8.9396  637.2440   49.9993  697.2719  0   0.00000
 313.7236   1.4985   10.4815    8.8194  664.2817   49.9212  696.1920  0   0.00000
 303.7236   1.7412   10.5823    8.6780  663.1294   49.0328  694.9121  0   0.00000
 293.7236   2.0186   10.6827    8.5016  661.6579   47.9281  693.3014  0   0.00000
 283.7236   2.3286   10.7826    8.2923  659.8648   46.6212  691.3678  0   0.00000
 273.7236   2.6701   10.8821    8.0512  657.7404   45.1211  689.1093  0   0.00000
 263.7236   3.0397   10.9810    7.7814  655.2967   43.4501  686.5425  0   0.00000
 253.7236   3.4351   11.0794    7.4854  652.5425   41.6250  683.6744  0   0.00000
 243.7236   3.8529   11.1771    7.1665  649.5006   39.6675  680.5197  0   0.00000
 233.7236   4.2907   11.2741    6.8270  646.1921   37.5933  677.0832  0   0.00000
 223.7236   4.7451   11.3705    6.4701  642.6535   35.4227  673.3782  0   0.00000
 213.7236   5.2131   11.4661    6.0991  638.9261   33.1742  669.4157  0   0.00000
 203.7236   5.6908   11.5610    5.7176  635.0632   30.8685  665.2134  0   0.00000
 193.7236   6.1751   11.6552    5.3288  631.1173   28.5218  660.7834  0   0.00000
 183.7236   6.6622   11.7488    4.9364  627.1504   26.1522  656.1466  0   0.00000
 173.7236   7.1491   11.8417    4.5438  623.2184   23.7723  651.3173  0   0.00000
 166.5294   7.4971   11.9083    4.2632  620.4454   22.0614  647.7373  0   0.00000

    ENERGY OUTPUT     33333.10733(MWHRS)


OPTIMUM DRAWDOWN RESERVOIR LEVEL =     8.1065 M

OPTIMUM ENERGY OUTPUT =      33333.10733  (MWHRS)


ANNUAL ENERGY PRODUCTION       12774.28323  (GWHRS)
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