CHAPTER -5

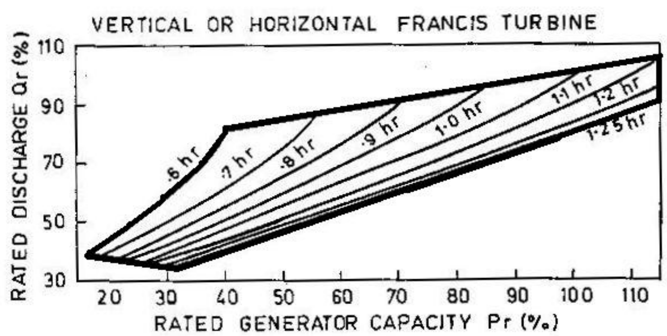
TURBINE PERFORMANCE CHARACTERISTICS
(Reviewed by Dr. R. P. Saini, AHEC)

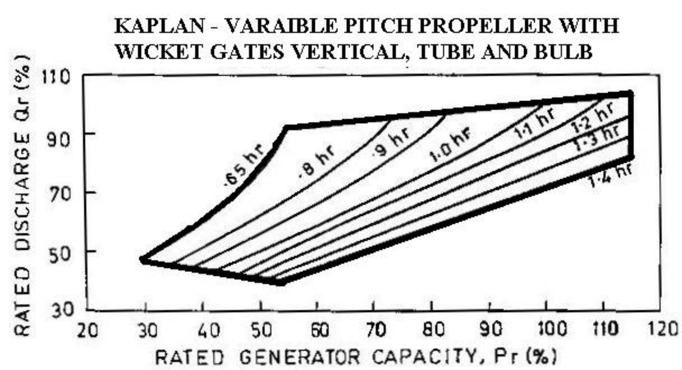
5.1 Turbine Performance Characteristics

Turbine Performance Characteristics of output and efficiency are important parameters. At project feasibility stage these parameters are required to fix number and size of units and determine economic feasibility. For this purpose output and efficiency at part load of the head range for the turbine is required.

In tender documents for procurement these characteristics of turbines are specified to be guaranteed under penalty. In evaluation of bids, equalization on accounts of differences in efficiencies of turbines of various bidders is made. Model tests are required to ensure that the guaranteed parameters offered will be met by the proto type.

Finally field tests for output and efficiency are conducted at different guide vane/needle openings to determine actual output and efficiency parameters. Penalty for shortfall in efficiency and output and rejection limits are specified.





Pr = 9.804, hr , Q r , η t. r η g (kW)

Where:
Pr = Rated capacity at hr (kW)
hr = Selected Design Head (meter)
Qr = Turbine Discharge at h r ε Pr (m^3/Second)
η t. r = Turbine efficiency at h r ε Pr (%)
η g = Generator efficiency , (%)

Figure 5.1 Francis and Kaplan performance curves (Typical)

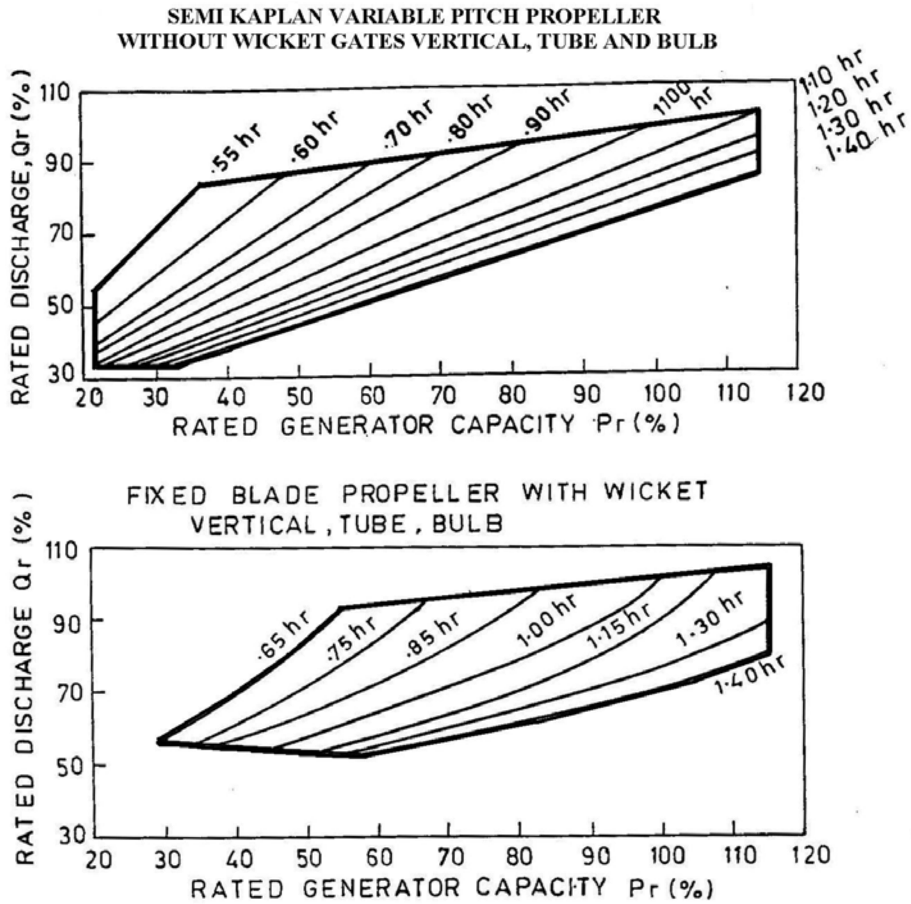


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Figure 5.2 Propeller turbine performance curves (Typical)

5.2 Turbine Performance Curves for Feasibility Studies

Figure 5.1 and figure 5.2 show typical performance characteristics for Francis, and Kaplan (variable pitch blade propeller with wicket gates).

Propeller (fixed blades with wicket gates) and semi Kaplan (variable pitch blades without wicket gates) type turbine. These curves are based on the Feasibility Studies for small scale hydro power Additions – Guide manual by US Army Corps of Engineers – 1979. These curves were developed from typical performance curves of the turbines of a special speed that was average for the head range considered in the guidelines. Comparisons of performance curves of various specific speed runners were made and the average performance values were used. The maximum error occurs at the lowest Pr and was approximately three percent. These curves may be used to determine the power output of the turbine and generator when the flow rates and heads are known. The curves show percent turbine discharge, percent Qr versus percent generator rating, percent Pr throughout the range of operating heads for the turbine.

Following determination of the selected turbine capacity the power output at heads and flows above and below rated head (hr) and flow (Qr) may be determined from the curves as follows:

Calculate the rated discharge Qr using the efficiency values-

$Qr = Pr / (9.804 \times hr \times \eta t.r \times \eta g)$, ($m^3/s$)

Where,
Pr, Dr = rated capacity and discharge
$\eta t.r$ = Turbine efficiency at rated load (%)
ηg = generator efficiency

Compute the % discharge, % Qr and find the % Pr on the approximate hr line. Calculate the power output.

P = % Pr x Pr (kW)

The thick lines at the boarder of the curves represent limits of satisfactory operation within normal industry guarantee standards. The top boundary line represents maximum recommended capacity at rated capacity.

The turbine can be operated beyond these gate openings; however, cavitation guarantee generally does not apply these points. The bottom boundary line represents the limit of stable operation. The bottom limits vary with manufacturer. Reaction turbines experience a rough operation somewhere between 20 to 40% of rated discharge with the vibration and/or power surge. It is difficult to predict the magnitude and range of the rough operation as the water passageway configuration of the powerhouse affects this condition. Where operation is required at lower output, strengthening vanes can be placed in the draft tube below the discharge of the runner to minimize the magnitude of the disturbance. These modifications reduce the efficiency at higher loads. The right hand boundary is established from generator guarantees of 115% of rated capacity. The head operation boundaries are typical; however, they do vary with manufacturer. It is seen that these typical performance curves are satisfactory for preliminary feasibility assessments.

When the % Q_r for a particular selection is beyond the curve boundaries, generation is limited to the maximum % pr for the hr. The excess water must be bypassed. When the % or is below the boundaries, no power can be generated. When the hr is above or below the boundaries, no power can be generated.

The optimum number of turbines may be determined by use of these curves for annual power generation. If power is being lost because the % or is consistently below the lower boundaries, the annual energy produced by lowering the kW rating of each unit and adding a unit should be computed. If the total construction cost of the powerhouse is assumed to roughly equal the cost of the turbine and generator, the cost per kWh derived above can be doubled and compared with the financial value of the energy. If the selection of more turbines seems favorable from this calculation, it should be pursued in further detail with more accurate studies. Conversely, the first selection of the number of turbines may be compared with a lesser number of units and compared on a cost per kWh basis as described above.

Following the establishment of the numbers of units, the rating point of the turbines can be optimized. This generally is done after an estimate of the total project cost has been made. Annual power production of turbines having a higher rating and a lower rating should be calculated and compared to the annual power production of the turbine selected. With the annual estimate, cost per kWh may be calculated for the selected. With the annual estimate, cost per kWh may be calculated for the selected turbine. Total project cost for the lower and higher capacity ratings may be estimated by adding the turbine/generator costs from the cost chart and correcting the remaining costs on a basis of constant cost per kW capacity. Rates of incremental cost divided by incremental energy generation indicate economic feasibility.

The rated head of the turbine can be further refined by optimization in a similar manner. The annual power production is computed for higher and lower heads with the same capacity rating. The rated head yielding the highest annual output should be used. The boundaries established on these curves are typical. Should energy output of a particular site curtailed, it is suggested that turbine manufacturers be consulted as these boundaries can be expanded under certain conditions.

5.3 Turbine Performance Characteristics – Model test

5.3.1 Model Testing

Model testing has evolved as an essential design element for hydro turbine manufacturers. Most hydro projects specification provide for proof – of – performance model tests as part of the specifications. Model cavitation testing to determine plant is also carried out.

Normally specifications require turbines with already tested model tests to meet the hydraulic design of the offered turbine as regard type, specific speed, rpm submergence and size of the unit. In most case the manufacturers have an existing design and accompanying model test that suits the requirement of a particular application. Existing model test data reduces the cost and lead time of the project.

Generally for small machines, it is not economical to conduct a comprehensive model test because model testing may cost as much as the equipment is being purchased. In this reliance on the experience of the manufacturer from tests on similar specific speed machines to verify operating characteristics of the machines with normal operating range.

5.3.2 Turbine Performance Hill Curves

Relevant model test report with operating points of the turbine offered on the hill chart of the model to substantiate output, efficiency and plant sigma figures offered and generated are normally obtained.

5.3.3 Index Testing

In case of constraints imposed by power house construction etc. index testing is done on an existing operating prototype to verify the performance characteristics.

5.3.4 Model Testing in India – BHEL

M/s (Bharat Heavy Eelctricals Limited) BHEL India has set up hydro machinery development station (HMD) for model testing and development of any type of hydro turbine model which is capable of delivering various turbine profile meeting international standard. Other equipment manufacturers have access to model tests carried out by calibrators table. M/s BHEL facility is described.

Scheme of tests loop is shown in figure 5.3 Lab layout and various parts of test stand is shown in fig. 5.3.2 Tests heads can accommodate following types of model runner.

Type of turbine	Max. Inlet Dia/Tip dia
Francs (high specific speed)	400 mm
Francis (low specific speed)	500 mm
Kaplan	500 mm
Pelton	500 mm

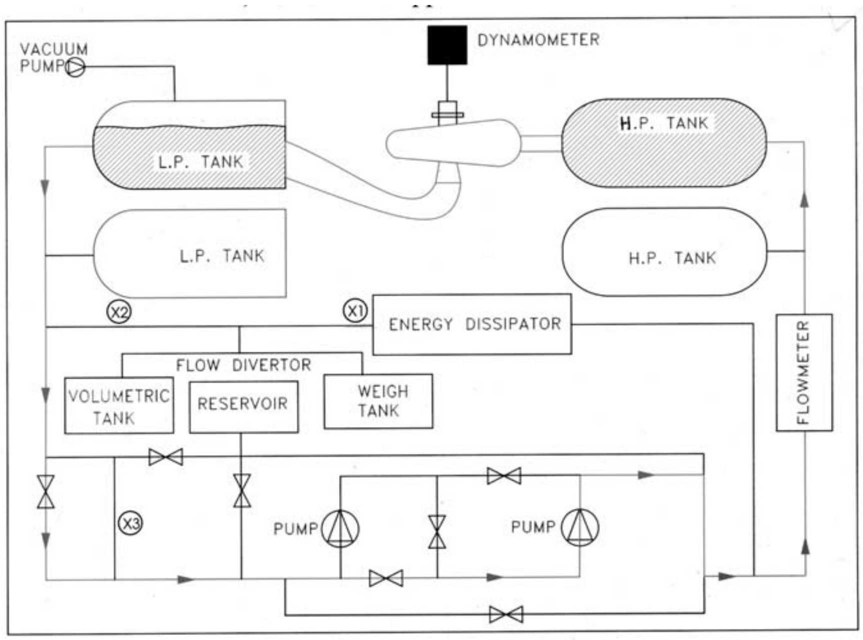
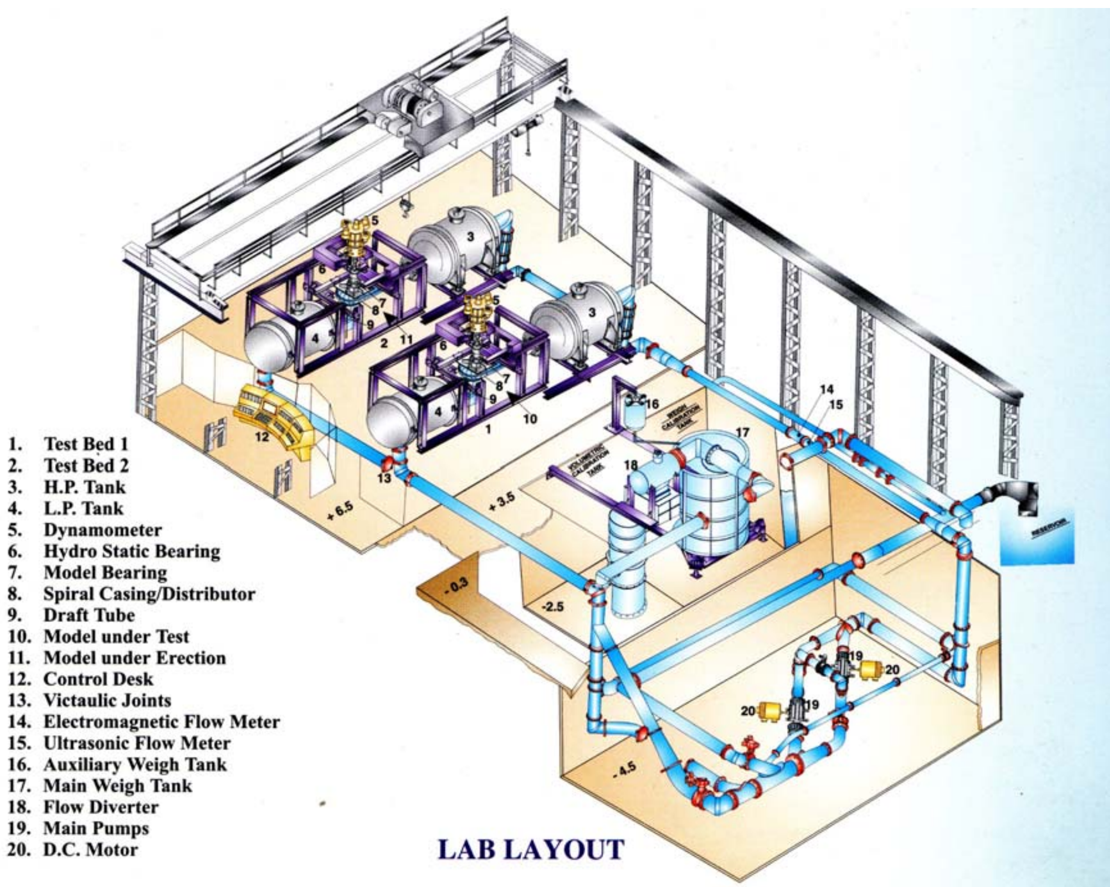


Fig. 5.3: Scheme of test Loop (BHEL Test Stand)
(Source: BHEL Brochure)



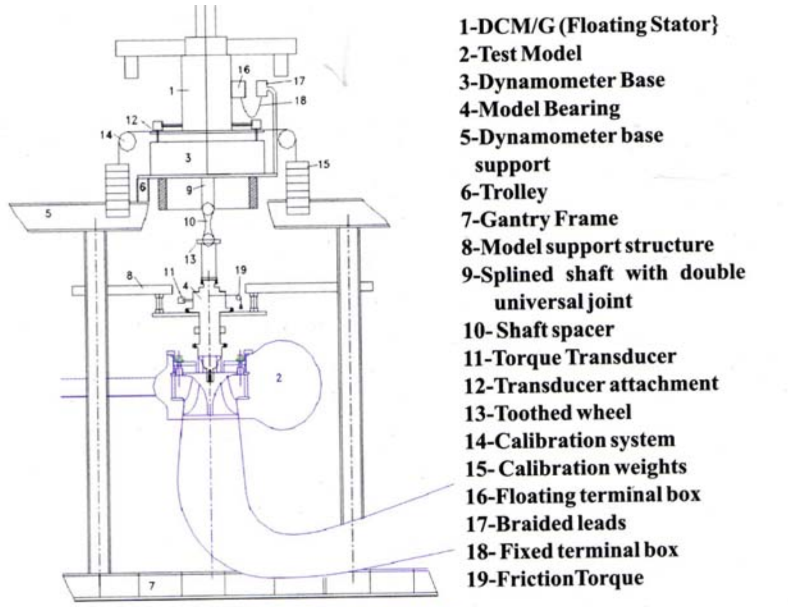


Fig. 5.4 : VARIOUS PARTS OF THE TEST STAND (BHEL)
(Source: BHEL Brochure)

A typical hill curve based on model test for a Francis Turbine is shown in figure 5.5

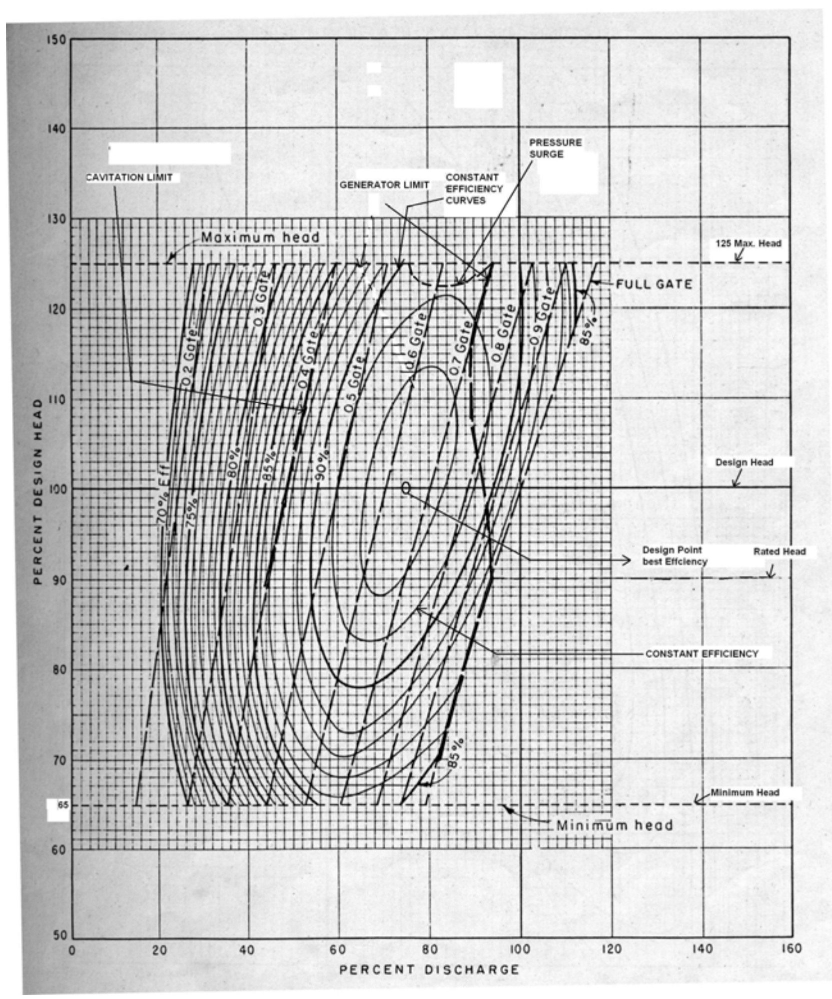


Fig. 5.5 hill curve based on model test for a Francis
(Source: Alternate Hydro Energy Centre)

The points marked are indicative only

Typical Turbine Hill Curve: Efficiency as a function of head and flow are summarized on a hill curve similar to the one shown above for Francis turbine operating limits are imposed by cavitation limits, maximum power and pressure surges.

Proto type tests or model tests to determine turbine performance characteristics are discussed with special reference to reaction turbine. Efficiency and flow as a function of head and operating speed are typically summarized on a turbine performance hill curve. Turbine speed is constant across head range. Limits of operation is the performance range of the turbine e.g. for Francis turbine it is 65% to 125% of design head. Low head operation is constraints by noise; vibration and cavitation. High head operation is limited by generator output, cavitation; or surging at high loads. Cavitation power limit depends upon turbine setting with respect to tailrace water and flow through turbine and determines cavitation based power limit. At part loads (low flow) cavitation damage is caused by vortices. Francis and fixed blade propeller turbines are susceptible to flow induced vibration and power swing. Surge induced vibration and power swings at part loads in Bhakra left bank runner were reduced by injecting compressed air below the runner. In Bhakra right bank, there were partly offset by increasing flows in turbine by avoiding part load operation (below 90%) and later on by increase capacity from 120 MW to 132 MW.

5.4 Model Test of Typical Francis Turbine

Model tests report of Bhakra Left Bank (5 x 90 MW) turbines were conducted in 1956. Main parameters of the turbine were as follows:

Type of turbine	: Vertical Francis
Net Heads (m)	
a. Rated	: 121.92
b. Design	: 121.92
c. Max.	: 156.06
d. Min.	: 87.79
Turbine Output (kW)	
a. At rated head	: 112000
b. At design head	: 112000
c. At max. head	: 112000
d. At min. head	: 53000
Rated Discharge (M^3/sec.)	: 10.2.3
Runner Nominal Dia. (mm)	: 4157
Rated Speed (rpm)	: 166.7
M/c Setting Hs (ft)	: - 1

For determining the up rating capacity of existing Bhakra Left Bank Runners, model test report of M/s Hitachi which gives efficiency and cavitation test results on a homologous model were made use of. The test result data given in the model test report was converted to obtain universal characteristics. Water path dimensions of the turbine are at figure 5.6. The hill curves are shown in figure 5.7. Field test and operation characteristics of a turbine are shown in figure 5.8.

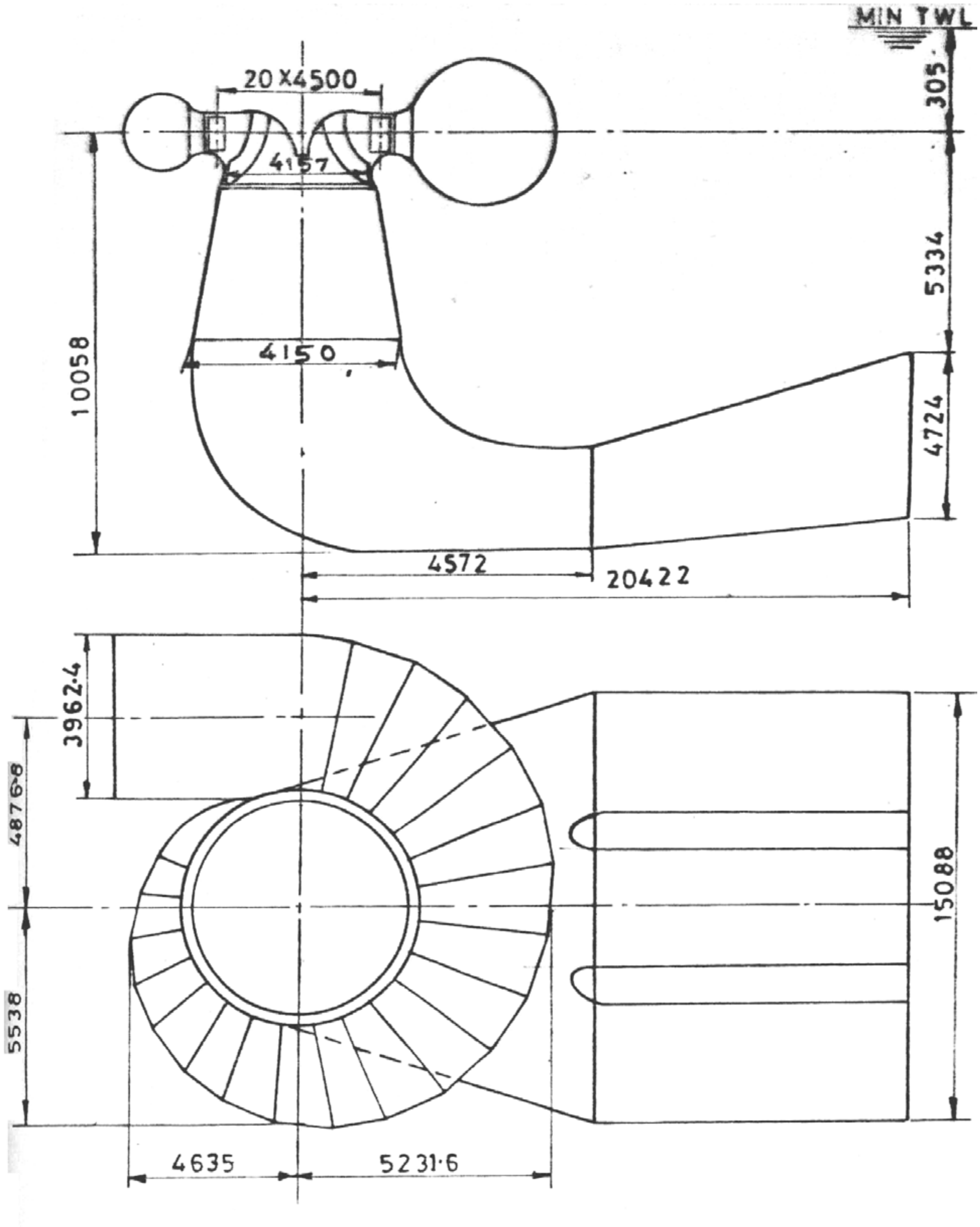


Fig. 5.6: Water Path Dimensions of Turbine
(Model Test Report Bhakra Left Bank Turbines)

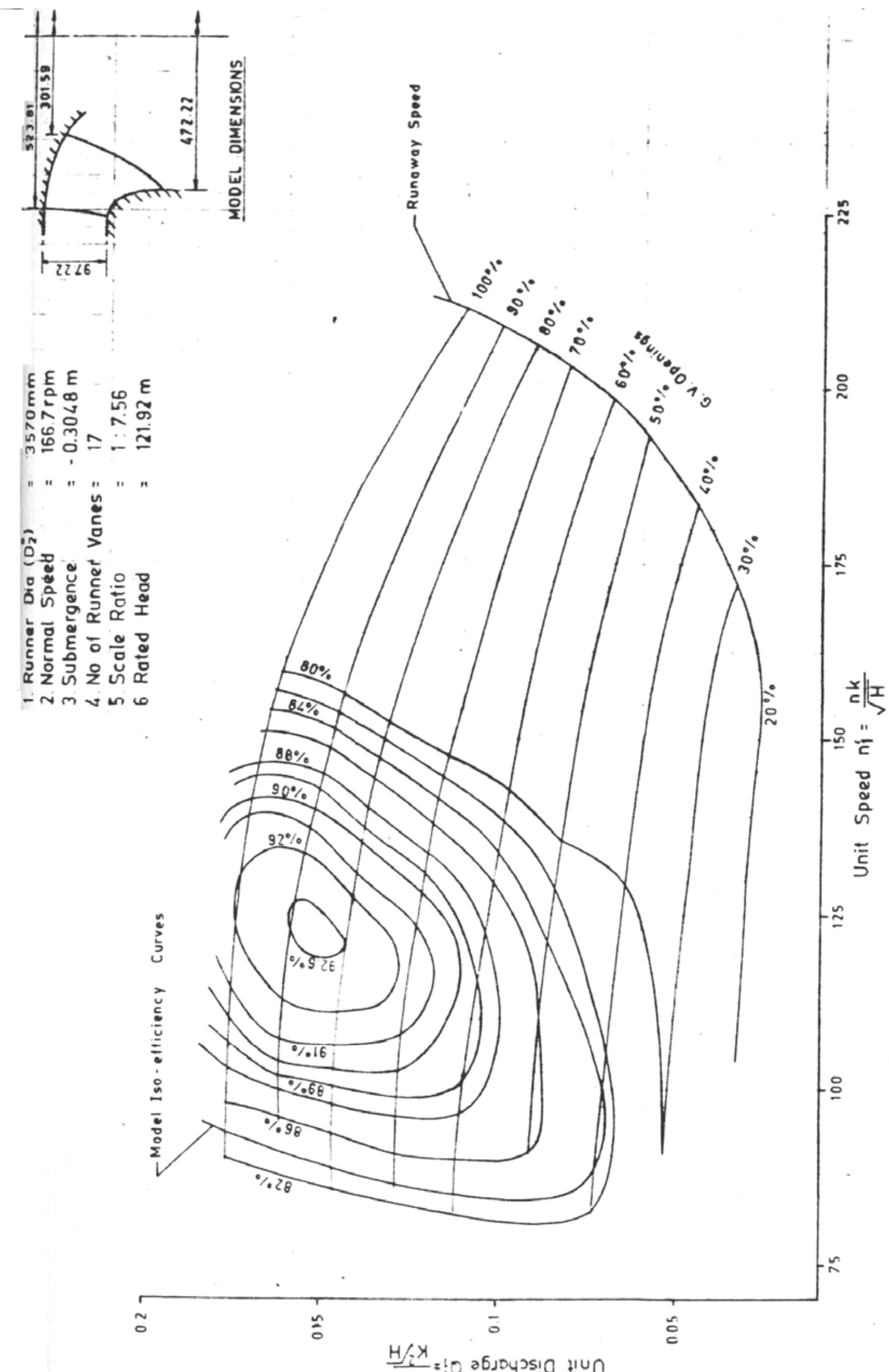


Fig. 5.7: Model Characteristics of Bhakra Left Bank Turbine
(Source: Model Test Report of Bhakra Left Bank Turbines)

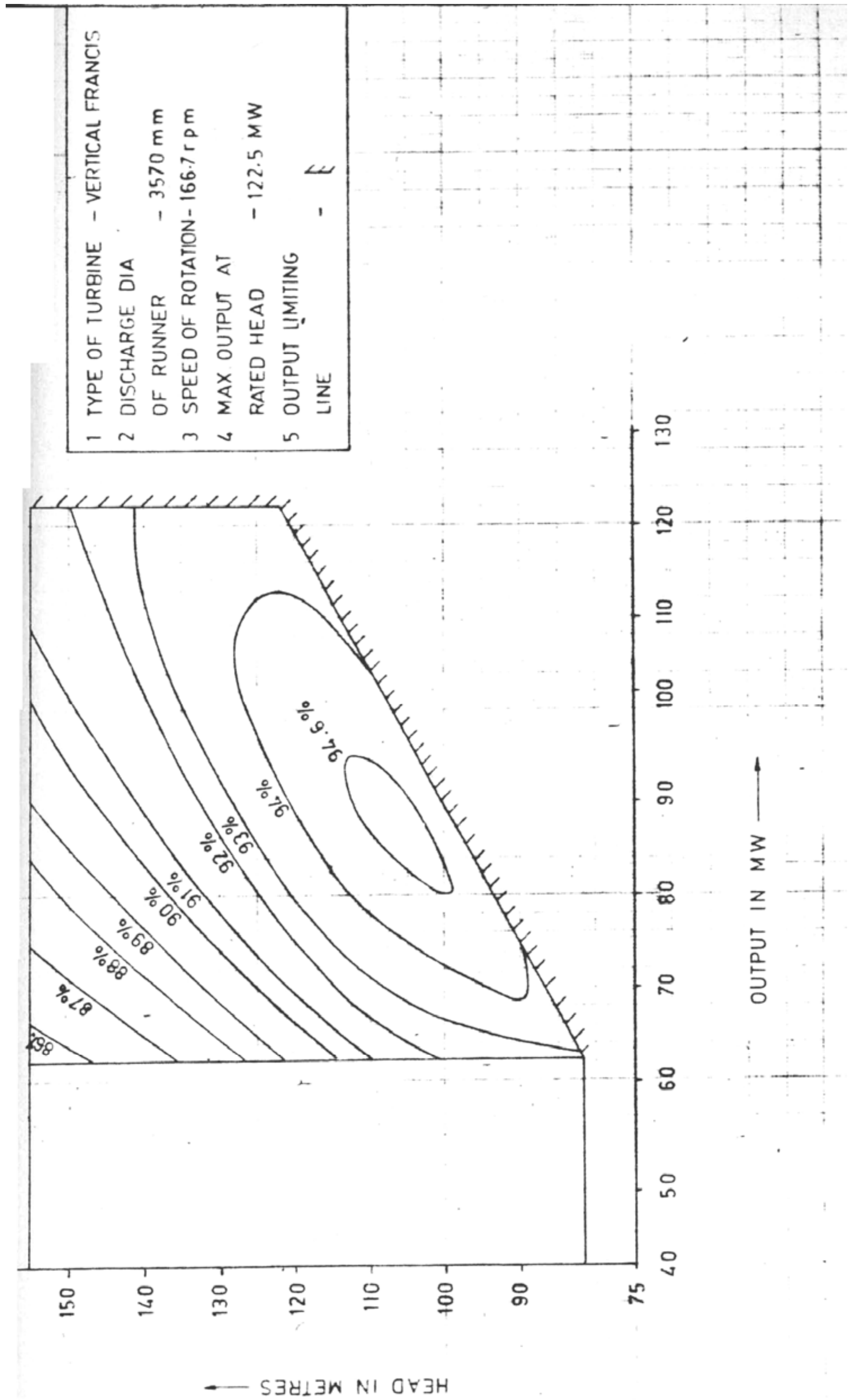


Fig. 5.8: Operational Characteristics of Turbines
(Source: Model Test Report of Bhakra Left Bank Turbines)

5.5 Hill Curves for a typical Small Hydro Turbine

Performance characteristics of a 1500 kW Francis turbine at rated head of 46.66m; maximum head 46.68m and minimum head 43.07m were obtained based on already tested model. Hill curves are at figure 5.9. Operating points of the turbine are marked on the hill chart of the model. It may be seen that test data shows on speed Vs power. Constant speed point for maximum (ratio) and minimum head were obtained by homologous model.

The hill curves are shown for speed Vs output. Constant speed lines at minimum head and maximum head for the turbines are marked and performance curves plotted on the figure 5.10. Based on theses chart turbine performance was guaranteed as follows:

Output (%)	Gate opening	Efficiency (%)
110	93.5	93.5
100	85.0	91.5
80	71.8	88
60	59.0	83

5.6 Hydraulic Vibration

Hydraulic vibrations are usually greater during part load operation and during overload. Natural frequencies due to resonance must be avoided. It is a practice to specify natural frequencies of the machine to be higher than the magnetic frequency i.e. above 100 Hz.

5.7 Small Hydro Turbine Research and Development Laboratory

Small hydro turbine Centre/Laboratory of International Standard is being set up at Alternate Hydro Energy Centre IIT Roorkee for testing (both Lab and Field), Design, Research and Development in the area of hydro turbines, including hydro mechanical equipment, control and instrumentation of small hydro electric plants. Hydraulic circuit of the proposed Lab is shown in figure 5.11. Objectives, Scope etc. as per project proposals are as under.

5.7.1 Objectives

a. Providing facilities for testing and certification of turbines.
b. Spearheading research and development activity in the country for hydro turbine;
c. Developing human resources for small hydropower in respect of entrepreneurs, engineers, plant operators and researchers
d. Generating data and building expertise for solving site specific problems;
e. Providing affordable facility to small hydro manufactures for design verification;
f. Validating designs of small hydro turbine and layouts using CFD technique,
g. Developing and validating flow-measuring techniques leading to optimum utilization and generation;
h. Providing calibration facility for measuring instruments used for, both, field-testing and power-plant operation.

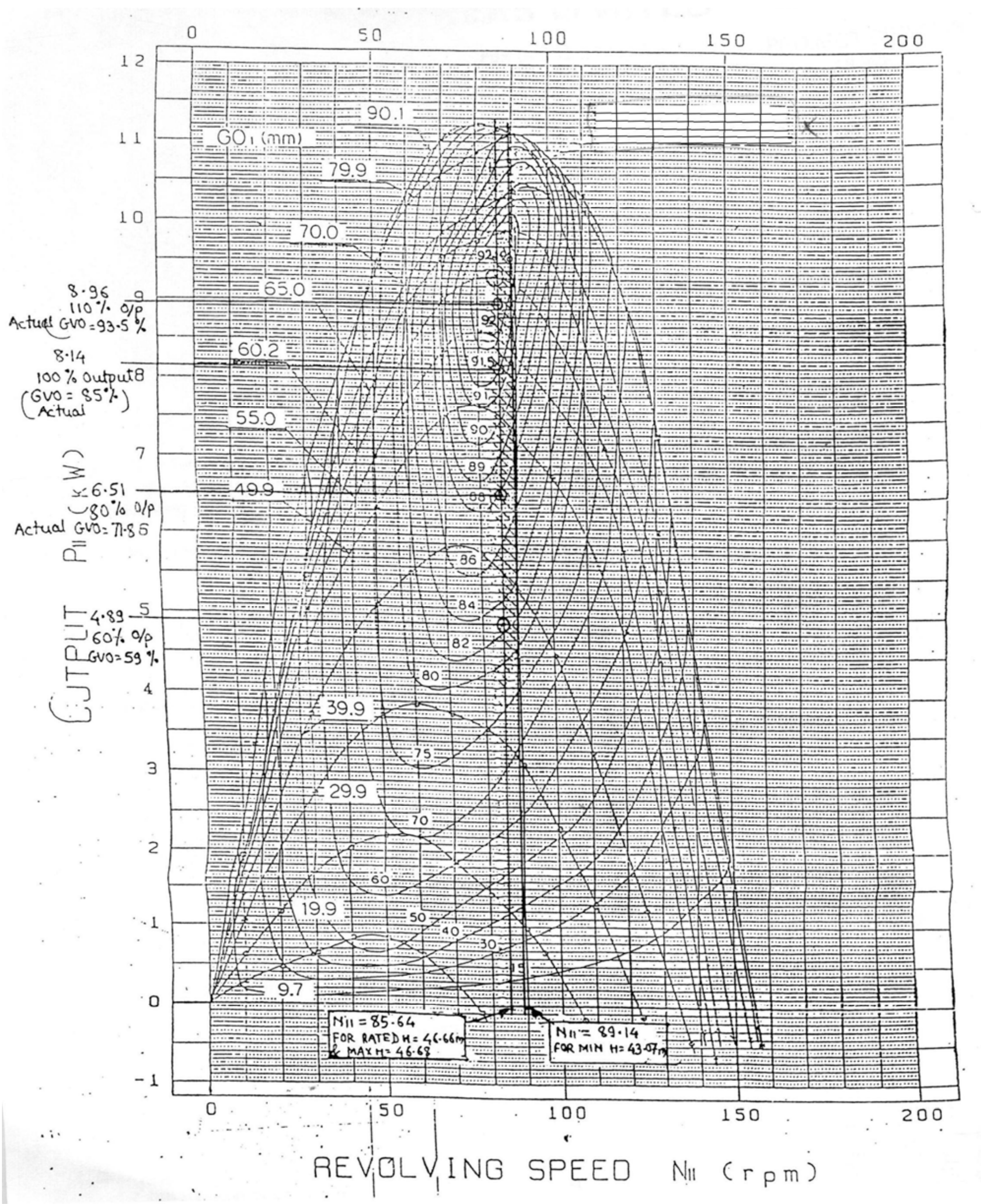


Fig. 5.9: Turbine Hill Curves for 1500 kW Francis Turbine Design and rated head – 46.66 m, minimum head – 43.07m
(Source: Alternate Hydro Energy Centre)

PERFORMANCE CURVES OF 1500 kW SHP

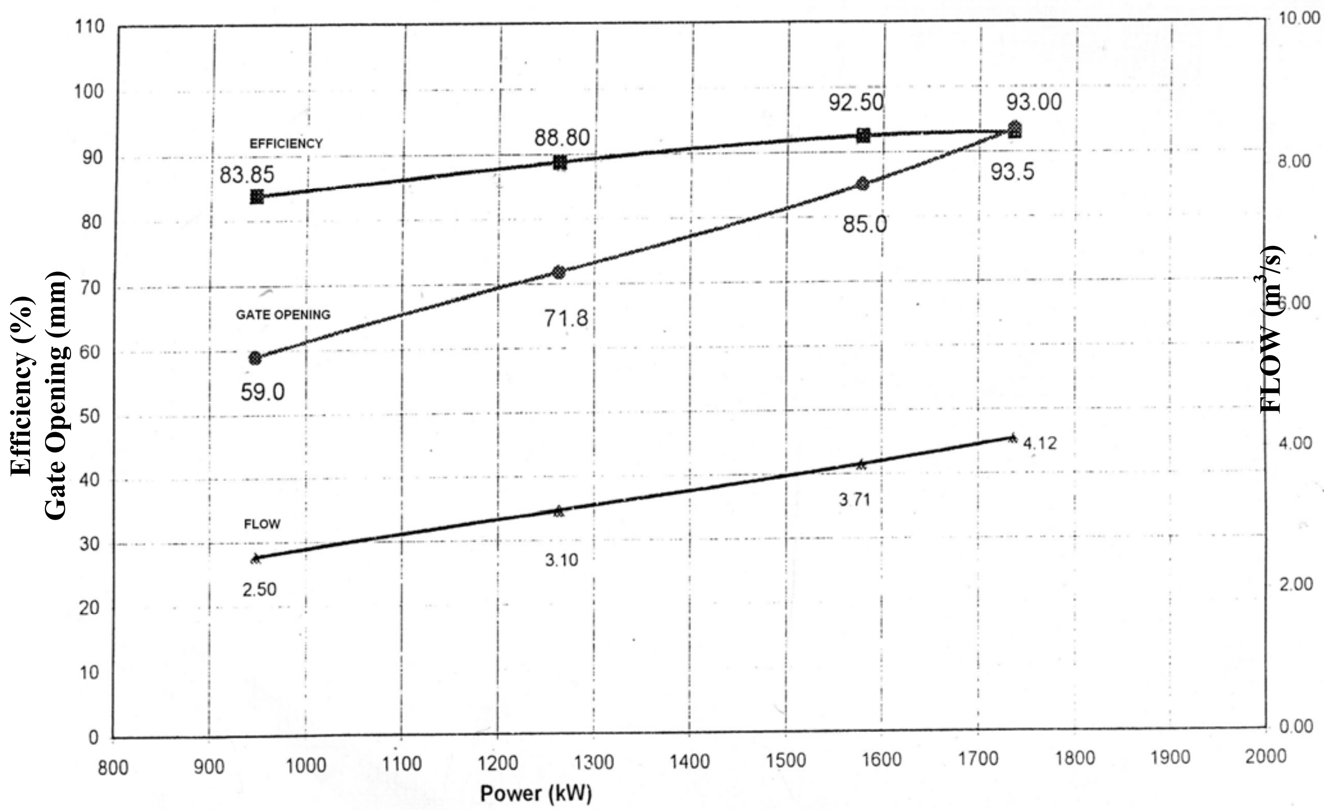


Fig. 5.10: performance Curves for 1500 kW Turbine
(Source: Alternate Hydro Energy Centre)

5.7.2 Facilities of the Lab

a. Testing of turbines,

b. Erection and commissioning checks

c. Operation and Maintenance of power plants

d. Functioning of various types of turbine components,

e. Transient study and analysis

f. Problem investigations and remedies

g. Hydraulic measurement methods and measuring instruments

h. Electrical measurements and measuring instruments

i. Calibration of instruments

j. Protection practices and equipment.

k. PLC and SCADA in power plants

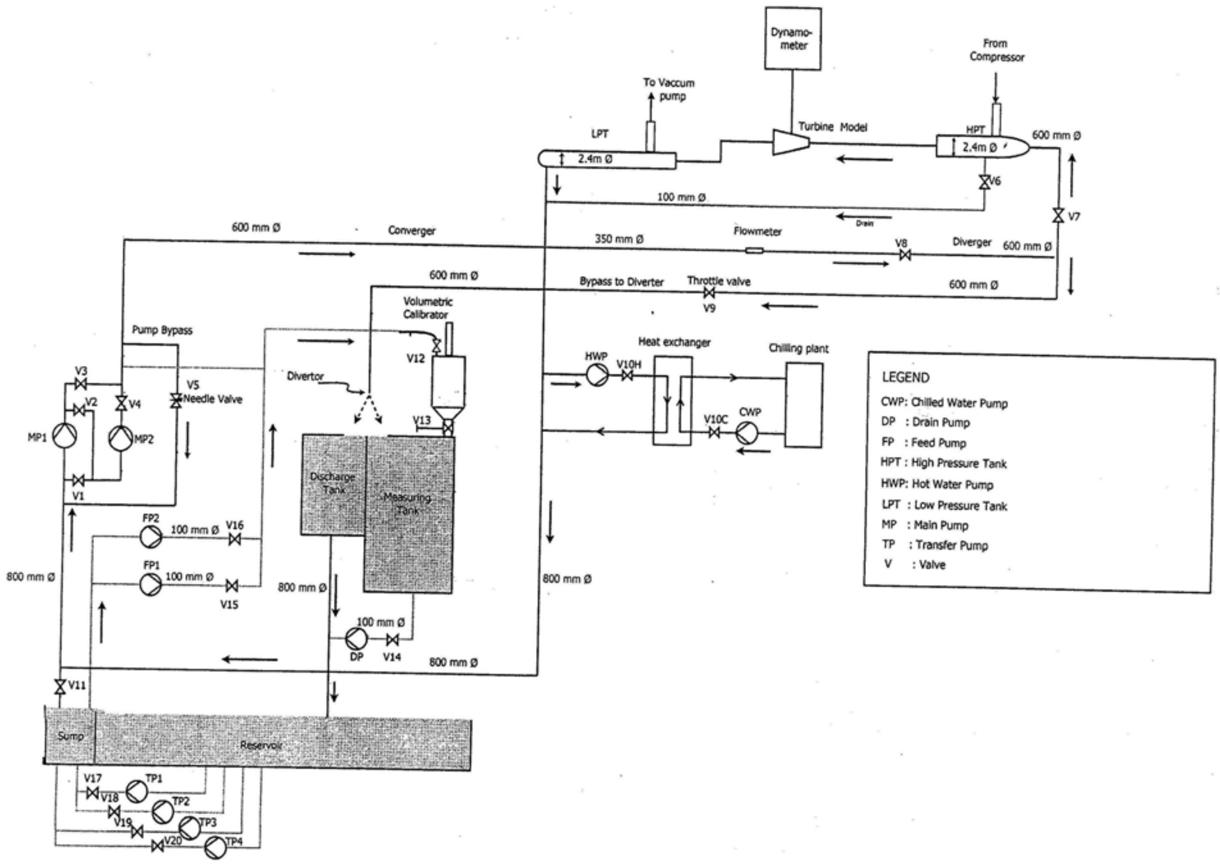


Fig. 5.11: Hydraulic Circuit with Valves (Turbine Testing Lab - IIT Roorkee)
(Source: Alternate Hydro Energy Centre)

5.7.3 Scope

A. Testing for research and site problem analysis and remedies:

Testing of all types of turbines will be done except.

1. *Vertical Pelton*

Vertical Peltons are normally of rating higher than 15MW unit size and are not very common in use in small hydro development. However if needed, in future; lab will be designed to accommodate an additional booster pump. Dynamometer capacity provided shall take such requirement and pipes and tank are designed for 10-bar pressure.

2. *Bulb Turbine*

Relatively very few projects are, as planned, using bulb turbine. These one though classified as small hydro are actually large machines manufactured by large manufacturers like BHEL, VA Tech, Alstom etc. All of them have their own test facilities. However for creating the capability, we need to have a special bulb dynamometer and can be added later.

3. *Pump turbines*

They are presently very rare in small hydro domain and not likely to be of relevance in next 10 to 15 years.

B. Training: Training will broadly cover**:**

- Functioning of various types of turbine components,

- Testing of turbines,

- Erection and commissioning checks

- Performance curve familiarization and interpretation,

- Measurement techniques.

- Transient study and analysis

- Problem oriented tests and remedies

- Profile measurement

- Calibration of instruments.

- Special instrumentation and tests.

C. Design Verification
Verification of manufactures designs and generation of design data (thrust, torque vibration etc).

D. Validation of designs
Validation of CFD technique by experimental measurement

E. Third party test
A neutral Laboratory is used for conducting the test.

F. Witness tests
Witness tests on turbines as a neutral agency.

5.7.4 Hydraulic Parameters

Minimum test parameters as per IEC 060191 are:
Pelton bucket width 80mm Test energy (gh) = 500
Francis 250 mm diameter gh = 100
300 mm mixed flow gh = 50
Kaplan 300 mm dia gh = 30
400 mm preferred gh = 20

Although min test head prescribed for Kaplan is 2m/3m. It is desirable that medium head Kaplan machine be tested at head not below 8m to avoid High Vacuum in the Test Turbine before the runner and the HP tank during cavitations test for clearer visualization of phenomena bellow the runner.

Min. Sigma value for Kaplan = say 0.25, therefore

$$0.25 = 9.7 - Hv/Htest$$

For Ht = 4m. Hv = 8.7

i.e. HP tank and test machine will be subjected to 8.7 - 4 = 4.7m of vacuum.

References

1. Feasibility Studies for small scale hydropower additions – A guide manual July 1979- US Army Corps of Engineers
2. Feasibility study report for up rating of Bhakra Left Bank hydro unit – 1982- Bharat Heavy Eelctricals India Ltd.
3. BHEL – Publication on Model Testing
4. AHEC 2009– Small Hydro Turbine Research & Development Laboratory Project Report