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09140

Distr.
LIMITED

ID/WG.305/7
8 August 1979

ENGLISH
Original: Spanish

United Nations Industrial Development Organization

Seminar-Workshop on the Exchange of
Experiences and Technology Transfer on
Mini-Hydro Electric Generation Units

Kathmandu, Nepal, 10-14 September 1979

IN PERU*

by

E. M. Indacochea**

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id.79-6291

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ANNEX

## 1. INTRODUCTION

It is well known that the principal source of energy in Peru consists of its water resources; the country's large hydroelectric projects undoubtedly constitute one of the pillars of the future development of Peru.

However, it can also be said that smaller-scale hydroelectric projects constitute the principal base for the development of rural energy.

The object of this study is to present the most important aspects of the process of design and construction of a pilot hydroelectric micro-power-station in a small rural locality, as part of the experimental implementation of a research project aimed at developing national technologies that will enable the initial investment required for the installation of small hydroelectric power-stations to be reduced, and at the same time permit the development of equipment design and manufacturing capacity in Peru.

## 2. SUMMARY

This is a report on the technological research project being conducted by ITINTEC (Institute of Industrial Technological Research and Technical Standards), the main purpose of which is the development of the technology for equipping small hydroelectric power-stations of limited capacity (initially within the range of 5-50 kW) and low specific speeds.

It likewise contains a description of the project for the installation and functioning of the pilot hydroelectric micro-plant at Obrajillo (Peru) as an experimental unit for the application of technologies developed and adapted through the research project, mainly covering:

- Adaptation of existing irrigation canals;
- Use of non-metallic pressure tubing (PVC and polyethylene);
- Development of standardized series of turbines (Michell-Banki and Pelton), to be manufactured in Peru;
- Development of speed regulators;
- Turbine/generator transmission by V-belts;
- Asynchronous alternators and generators;
- Various aspects (instrument panels, lightning conductors, etc.).

The following conclusions have been drawn from the experience gained at the pilot plant with respect to the technology developed:

- It is possible substantially to reduce investment in equipment and civil engineering.
- The entire equipment (except for the instrumentation) can be manufactured in Peru under satisfactory conditions as regards cost, quality and efficiency.

Another conclusion is that, although small hydroelectric power-stations are one of the best energy solutions in a country with water resources such as Peru possesses, rural electrification will have to be subsidized in its initial development stages if the aim is to pursue an aggressive policy of transforming productive structures in rural areas.

## 3. BACKGROUND

### 3.1. The technological research project on hydroelectric micro-power-stations

In October 1977 the Institute of Industrial Technological Research and Technical Standards (ITINTEC) initiated the applied technology research project on hydroelectric micro-power-stations with the object of studying, in the first instance, the problems of micro-plants within the 5 to 50 kW range under conditions characteristic of their potential use in the Andean region, i.e. with low specific speeds, resulting from high heads (drops) in relation to small flows, using water from irrigation canals.

The project is aimed at the development and adaptation of technologies which will make it possible to overcome the factors limiting the installation of hydroelectric micro-plants, principally with regard to reducing initial investment to permit economic feasibility, with a view to installing the plants in isolated rural localities in the Andean region with less than 2,000 or so inhabitants.

Investment budgeted for the research project:

S/. 14,226,000.00 (approx. $US 61,000)

Duration: 30 months starting October 1977.

The following are the objectives of the project:

(a) Development of the technology for designing and constructing equipment, installations and materials for hydroelectric micro-plants

This mainly concerns:

Development of technologies for designing and manufacturing Pelton and Michell-Banki turbines, with an eye to standardization of sizes and interchangeability of components, as well as the use of materials available on the market and superficial treatments.

Development of technologies for the design and manufacture of speed regulators for turbines, both oil-mechanical and electro-electronic regulators.

Development of mechanical V-belt transmission systems between the turbine and the alternator, permitting standardization of wheel diameters and speeds of the alternator, and at the same time allowing the use of a wide range of heads.

Adaptation of the design of alternators for thermal units for use in hydroelectric power-stations (complementary management project being carried out by the firm ALGESA).

Adaptation of the use of asynchronous electric motors as generators for hydroelectric micro-plants (complementary management project being carried out by the firm DELCROSA).

Use of non-metallic PVC and polyethylene tubing as pressure tubes for power-stations with heads of under 100 m.

Perfecting the designs of basins and sand-removers to make them easy to adapt to irrigation canals, at low cost and with no loss of excess water.

Perfecting designs of water conduits from the main channel in order to lower initial investment, retaining acceptable levels of catchment and reliability.

Other complementary aspects such as modular electric instrument boards, plant disposition, transmission lines, etc.

(b) Development of instruction manuals for users and planners, as guidance for carrying out studies

Manual for the approximate evaluation of hydroelectric resources, for use by persons with secondary-school education, to provide a better technical basis for preliminary evaluations, principally as regards estimating demand, available flow, available head and the order of magnitude of utilizable power, and investment required.

Project and design manual for hydroelectric micro-plants, for use by non-specialized and/or recently graduated engineers, to aid in the preparation of projects for hydroelectric micro-plants, in order to reduce consultant costs which become very burdensome in the case of low-capacity plants.

3.2. The need for a pilot hydroelectric micro-plant

The purposes of the building of a pilot plant as part of the technological research project were the following:

(a) To have an experimental unit for making thorough tests of all the technologies developed.

(b) To experiment in the assembly, installation and start-up of equipments whose technology had been developed.

(c) To obtain comparative costs for evaluating the economic parameters of the technology developed as compared with conventional technologies.

(d) To orient the design and construction of prototypes towards practical application.

(e) To evaluate the socio-economic aspects of the installation of a hydro-electric micro-plant in co-operation with a rural community.

(f) To make immediate practical use of the experimental work involved in the technological research project.

Bearing in mind that the project was not specifically an investment project but concerned the installation of a pilot plant as part of a research project, Obrajillo was selected for the following reasons:

(a) The demand for electric power and the water resources available were typical cases within the ranges of application of the research project, with regard to power and head, other advantages being the existence of an irrigation canal and an apparent site for the power-station.

(b) The Obrajillo Rural Community[1/] was organized and was interested in the pilot plant being built there, for which purpose it was prepared to contribute the necessary unskilled labour and the aggregates for the concrete.

In November 1977 ITINTEC and the Obrajillo Rural Community signed an agreement to co-operate in installing a pilot hydroelectric micro-plant, whereby ITINTEC undertook to provide the designs, the main materials and equipment and the technical staff required for carrying out the project and, when the trials had been completed, to hand the plant over to the Community to operate it after an operator had been trained.

The Rural Community will make available to ITINTEC an old mill to be converted into a power-station, authorizes ITINTEC to use the water from the irrigation canal for the experimental operation of the plant, allows ITINTEC the use of the necessary lands for installing the tubing and undertakes to provide the unskilled labour and the concrete aggregates necessary to carry out the project.

## 4. CHARACTERISTICS AND SPECIFICATIONS OF THE PILOT PLANT

### 4.1. General description

The village of Obrajillo is situated near the town of Canta and 105 km north-east of Lima; it is on the left bank of the Chillón river at an altitude of approximately 2,700 m above sea-level (see fig. 1).

Its climate is particularly pleasant, the soil fertile, water fairly plentiful and the landscape rural and attractive.

The main economic activity is crop-farming (potatoes and maize) followed by the rearing of livestock (cattle and sheep). The low-lying land in the valley is split into small individual holdings, the higher lands are communally owned.

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1/ Rural Communities are rural organizations dating from pre-Spanish days. Originally they were based on collective land tenure, but today they comprise various forms of social organization and property patterns.

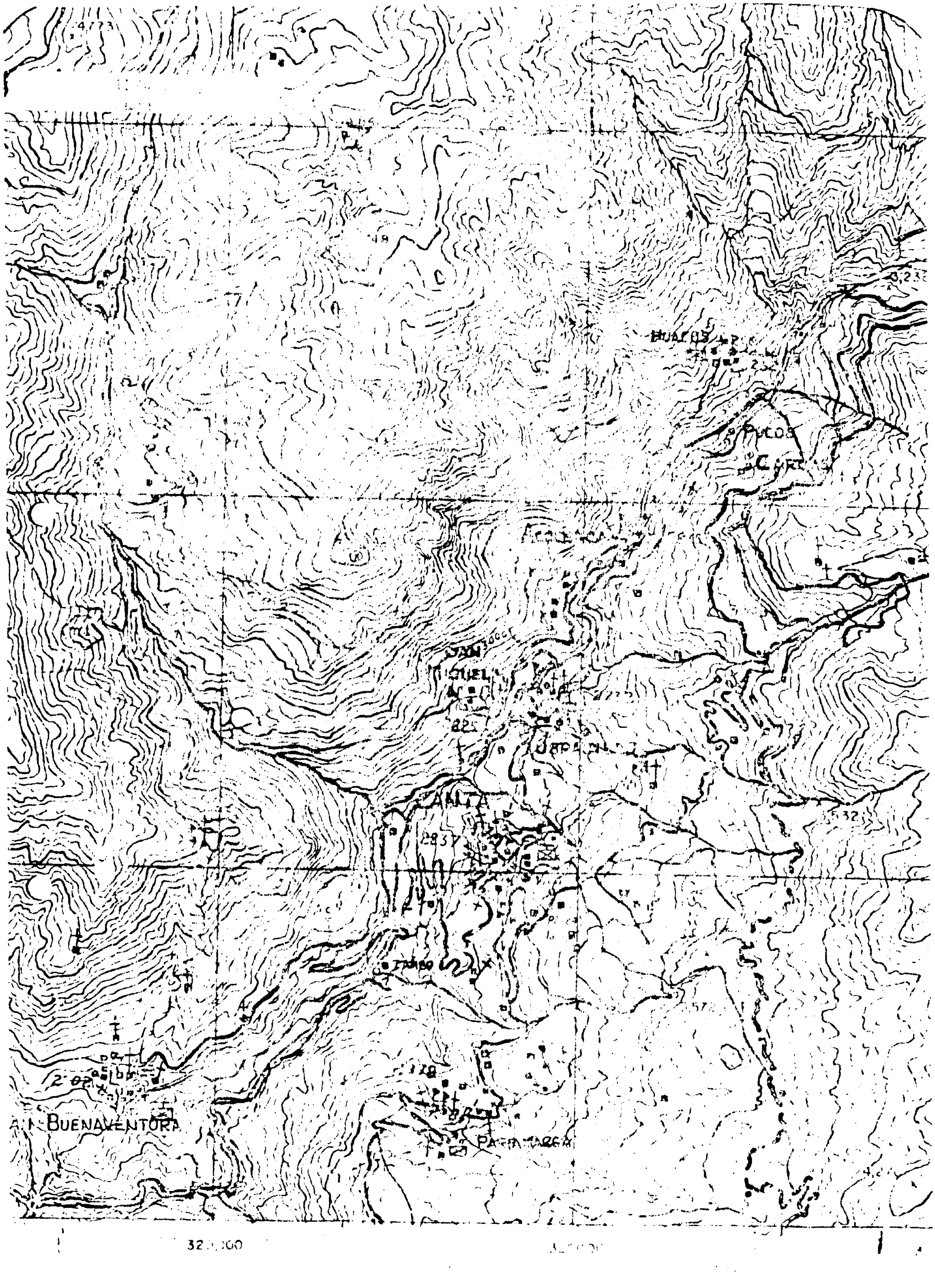


Figure 1. Map of the Obrajillo and Canta area. 1:50,000

Obrajillo has a drinking water service (not piped to the houses) but does not possess any drainage or electric power. Some 30 years ago it received electric current from a hydroelectric power-station which supplied Canta and the surrounding villages, but this was dismantled and later replaced by a thermal power-station which did not have sufficient capacity to meet the needs of the villages around Canta, so Obrajillo's supply was discontinued.

Canto is connected to Lima by a paved road which is normally open all year round, except for brief periods due to landslides during the rainy season.

It has a permanent population of 595 which has remained static for the past 20 years due to migrations to Lima.

## 4.2. Energy demand and potential

### 4.2.1. Demand

In isolated rural areas in Peru peak demand per head is reckoned at 20-30 watts, only minimal requirements for public lighting and domestic consumption being taken into consideration.

Consequently, it is reckoned that for the first year of operation peak demand will be of the order of 11 kW, rising to 18 kW from the second year.

Requirements for any eventual agro-industrial development will have a margin of demand-growth equivalent to evening consumption since the productive activities are carried out in the daytime; nevertheless, the installed capacity available will also be limited by the starting torque requirements of the electric motors used.

### 4.2.2. Resources available

It is planned to use an existing irrigation canal which takes its water from the Chillón river near the village of Acochaca. The existing intake installation is of artisan construction with no real civil engineering.

The canal extends some 3 km and has some 50 outlets for irrigation.

At its original intake point it can receive up to 80 litres/second, but under existing conditions it could not reach the site of the drop selected with a flow of more than 20 litres/second, without overflowing at certain points or leaking at others. The topographical survey made (1:1,000, plan No. 3215-T-00) showed that the channel could be improved to bring it up to a capacity of 80 litres/second.

According to the survey the gross usable drop is 56.5 m (plan No. 3215-C-07).

The compatibility of the irrigation with the generation of electric energy will be ensured by the Community itself, since both the quantities of water used for agriculture and the periods of irrigation vary throughout the year.

4.3. Specifications of the project

According to estimates for the demand at the end of the first year of operation, an installed capacity of approximately 18 kW will be required.

Research requirements called for the project to be implemented in two stages:

(a) First stage

Use of polyethylene tubing combined with a Michell-Banki turbine designed for experimental purposes, to operate with a 4 kVA (3.2 kW) alternator or alternatively with an equivalent asynchronous generator.

(b) Second stage

Use of polyvinyl chloride (PVC) tubing to feed either a Michell-Banki turbine or a Pelton turbine (both prototypes of an industrial series), with either of them driving a 20 kVA (16 kW) alternator or an equivalent asynchronous generator.

It should be pointed out that the civil engineering work required for the water intake and improvements to the channel, basin and sand-remover are common to both stages.

The principal specifications for the design of the pilot plant are summarized below. The annex shows some of the calculations considered for the second stage of the project.

| PARAMETER | SYMBOL | UNITS | 1st STAGE | 2nd STAGE | TOTAL |
|---|---|---|---|---|---|
| Frequency | f | $H_Z$ | 60 | 60 | |
| KVA, alternator | $kVA_A$ | kVA | 4 | 20 | 24 |
| RPM, alternator | $N_A$ | r.p.m. | 3 600 | 1 800 | |
| Power factor | Cos Ø | - | 0.8 | 0.8 | |
| Alternator efficiency | $\eta_A$ | - | 0.70 | 0.85 | |
| Maximum power generated | $P_A$ | kW | 3.20 | 16.00 | 19.2 |
| Power transmitted to the generator | $P_F$ | kW | 4.57 | 18.82 | |
| Transmission efficiency | $\eta_F$ | - | 0.95 | 0.95 | |
| Power at the turbine brake | $P_T$ | kW | 4.81 | 19.81 | |
| Mechanical efficiency of the turbine | $\eta_m$ | - | 0.95 | 0.95 | |
| Hydraulic power of the turbine | $P_H$ | kW | 5.065 | 20.86 | |
| Hydraulic power of the turbine | $P_H$ | hp | 6.887 | 28.36 | |
| Hydraulic efficiency of the turbine | $\eta_H$ | - | 0.75 | 0.8 | |
| Power absorbed by the power-station | $P_{ABS}$ | kW | 6.75 | 26.07 | |
| GROSS DROP | $H_B$ | m | 56.5 | 56.5 | |
| Material/nominal dia./type (tubing) | | | Polyethylene/4"/ class 10 | PVC/8"/ class 10 | |
| Internal diameter x wall thickness (tubing) | Di x e | mm x mm | 90.8 x 11.6 | 195.8 x 11.6 | |
| Minimum acceptable thickness | $e_{min}$ | mm | 8.67 | 9.35 | |
| Length of tubing | L | m | 115 | 115 | |
| Equivalent length | $L_e$ | m | 150 | 125 | |
| Loss of head in tubing | hw | m | 5 57 | 1.14 | |
| Net drop | $H_N$ | m | 50.93 | 55.36 | |

(continued)

| PARAMETER | SYMBOL | UNITS | 1st STAGE | 2nd STAGE | TOTAL |
|---|---|---|---|---|---|
| Flow required | Q | $m^3$/second | 0.01352 | 0.04802 | 0.06154 |
| Runner diameter (Michell-Banki turbine) | $D_E$ | m | 0.20 | 0.20 | |
| Runner diameter (Pelton turbine) | $D_p$ | m | - | 0.60 | |
| RPM, Michell-Banki turbine | N | r.p.m. | 1 420 | 1 480 | |
| RPM, Pelton turbine | N | r.p.m. | - | 514 | |
| Transmission ratio (Michell-Banki turbine) | | - | 2.54:1 | 1.22:1 | |
| Transmission ratio (Pelton turbine) | | - | | 3.50:1 | |
| Specific speed $n_s$ (Michell-Banki turbine) | $n_s$ | r.p.m. x (hp) 1/2 (m)-5/4 | 27.39 | 52.20 | |
| Specific speed $n_q$ (Michell-Banki turbine) | $n_q$ | r.p.m. x (m3/s) 1/2 (m)-3/4 | 8.66 | 15.98 | |
| Specific speed $n_s$ (Pelton turbine) | $n_s$ | r.p.m. x (hp) 1/2 (m) 5/4 | - | 18.13 | |
| Specific speed $n_q$ (Pelton turbine) | $n_q$ | r.p.m. x (m3/s) 1/2 (m) 3/[illegible] | - | 5.55 | |

## 5. OBJECTIVES ACHIEVED AND PROBLEMS OF TECHNOLOGICAL DEVELOPMENT

Below we review the objectives achieved during the execution of the project and some of the problems encountered, together with the solutions adopted, which we do not in any way claim to be unique or definitive. Rather do they illustrate the multiple options which may arise in the process of applied technological research.

This review also aims to make it clear that the development of the technology of hydroelectric micro-plants must be of an integrated nature, geared towards studying all the elements which go to make up a hydroelectric power-station. Any one-sided emphasis on the development of a particular component of the power-station, such as the turbine, or some methodological aspect, must be avoided.

### 5.1. Intake

The project is aimed primarily at studying the use of existing irrigation canals, where intake installations are frequently of artisan construction. Some criteria for improving and adapting existing intake installations have been developed but in the pilot plant only canal and flow control work has been done (see plan No. 3215-C-06).

### 5.2. Canal

In the context of the foregoing considerations, criteria have been developed for the evaluation of irrigation channels for use in combination with hydroelectric power generation. A methodology has been adopted for the study of particular improvements designed to increase the carrying capacity of an irrigation canal; this provides for a form of section grading and dimension tabulation which is easy for the contractor in charge of the extension work to understand. Some types of improved intake installations have also been developed which avoid loss of water (see plan No. 3215-T-00).

### 5.3. Basin or fore-bay

As the basin was built on an existing irrigation canal the following points had to be taken into consideration with regard to its design and construction:

- It was necessary to ensure that the water not used for power generation returned to the canal to be used downstream for irrigation.
- As the canal bed is of earth it was necessary to ensure that the sand removal was carried out within the basin.
- It was necessary to combine minimum technical requirements with economy of materials (principally cement and steel).

- In selecting the site for the basin, in addition to satisfactory utilization of the drop, economy in tubing and loss of head, one had to consider the degree of risk presented by alluvium, on the basis only of a geomorphological appraisal and historical information provided by the local inhabitants, as well as appraisals on the stability and behaviour of the soil obtained by visual observation and diggings: geological and mechanical studies of the soils were not conducted in view of the high cost in relation to the size of the project.
- The difficulties and costs of transporting the materials, mainly the concrete aggregates, and the limited space available for preparing the mixture by non-mechanical means. Planning this transport by animal-power called for a careful engineering study as regards conditioning of paths to ensure easy and rapid movement with minimum fatigue, loading and unloading systems, rotation of animals, regulation of weight, etc.
- It is worth drawing attention to the frequent mistake of ignoring these costs where they relate to the work contribution from rural communities in the carrying out of electrification projects, since such factors often have a decisive influence on their willingness and capacity to co-operate.
- The method and degree of mechanization in the construction has to be considered from the designing stage, mainly bearing in mind the production rate of mix and its transport.

### 5.4. Pressure tubing

Steel tubes with seams constitute the usual classical solution but their use is not always suitable for mini-power-stations in Peru for the following reasons:

- The high price of steel and of steel tubes in particular.
- In Peru standard cold-shaped seam tubes are only made up to 4" (schedule 40); larger-sized tubes are made from rolled and welded steel sheet.
- Imported standard tubes with diameter exceeding 4" are excessively expensive, constituting in some cases the most costly element of a power-station.
- In most cases the rolling of tubes is technically possible for diameters exceeding 10", but they must be rolled in short lengths which call for a great deal of welding and checking.
- The final joining of the steel tubes requires either installing clamps or welding on the spot, which presents difficulties, is costly and problematic as regards quality.
- Although the steel tubes are in short lengths and of small diameter, they are heavy and difficult to carry to their final site without the help of mechanical means of transport.
- A very careful topographical survey of the slope is needed as well as exact positioning of the supports, because a mistake here would make it necessary to excavate, reconstruct supports and/or recondition the tube using hot-processing.

- Long delivery periods.
- Expansion joints are necessary as well as careful calculation of anchorages and supports, which are fairly massive.
- Relatively high losses of head because of surface roughness.
- Sensitivity of long tubes to water impact because of their high modulus of elasticity.

The great advantage of steel tubes lies in their adaptability, as they are suitable for a very wide range of applications, ranging from high heads to conditions of large flow which call for large diameters. in many cases steel tubes are irreplaceable.

In the range of applications under consideration for the present project (5-50 kW for conditions in the Sierra), the heads usually vary between 20 m and 150 m; for the capacities indicated the diameter of the tubing generally varies between 4" and 15". Under these conditions consideration was first given to the possibility of using fibreglass, asbestos-cement, PVC and polyethylene.

Fibreglass was eliminated owing to its high price; asbestos-cement is a promising alternative for large flows: wood cannot be considered in the Andean area but its use could be studied for forest conditions, where falls are very low, and in heavily wooded areas.

PVC and polyethylene were short-listed and it was decided to investigate their possible use.

Research and experiments carried out during the implementation of the project and the utilization of PVC and polyethylene tubes in the pilot hydroelectric micro-plant showed the following characteristics for their use:

(a) PVC

- Peru makes PVC tubes in diameters up to 12" (305 mm) and adequate for manometric pressures of the order of 10 kg/cm$^2$ (class 10), which provides a coverage adequate to the project range of conditions (5-50 kW), for maximum gross drops of between 75 and 80 m, the margins being considered sufficient for water impact.

  It would be possible to produce class 15 tubes and larger diameters if the market were sufficient.
- The tubes are purchased in sections 5 m long, which can easily be transported. As an illustration, an 8" tube section, class 10, weighs 55 kg and can be carried by three people, even in hilly terrain.

- The tubes are joined by a system of socket and pin, using an appropriate adhesive.
- The purchase price of the PVC tubes is about 1/3 that of imported steel tubes. Taking an 8" tube, the cost of insulation is equivalent to that of assembling a steel tube whose sections are joined by means of clamps.
- Although a PVC tube is rigid, its elastic deformation properties make it possible to bend it up to 3° in a length of 5 m, which permits great adaptability to ground conformation without the need for accessories to change direction except in the case of very pronounced irregularities of terrain.
- Its thermal expansion properties are moderate and its elastic properties provide ample deformation margins, so that in most cases it does not require expansion joints.
- The anchorages and supports must be spaced fairly close, because the ratio of the weight of the tube when full of water to its maximum working force may be a critical factor.

  PVC does not integrate structurally with concrete, so the anchoring must be mechanical.
- PVC tubing has the disadvantage that it is fragile and its mechanical resistance is less than 1/10 that of ordinary steel, which makes it very liable to accidental breakage (stones), or to deliberate damage.

  It also ages rapidly in sunlight (mainly through the action of the ultra-violet band), as a result of which its fragility increases.

  To overcome this two alternatives were considered: to bury the tube underground or to put a protective covering over it. The first alternative is obvious and resorting to it depends on the costs of excavating and re-filling. At the pilot plant the tube was experimentally covered with jute stuck on with dextrine; this form of protection is relatively satisfactory except for the solubility of dextrine in water and its sweet taste which attracts goats.

  In our opinion, various low-cost alternatives still have to be tried out. In the near future, the tube installed at the pilot plant will be covered with a layer of pitch dissolved in kerosene.

  Sample experimentation with some alternatives is also being considered, e.g. the use of putty, direct application of pitch, forest planting, etc.
- Losses of head are considerably less than in the case of equivalent steel tube, as there is less surface roughness. Owing to the lower elasticity modulus, lower tolerances are required for water impact super-pressure.

(b) Polyethylene

- Peru produces polyethylene tubes of up to 8" nominal diameter with a resistance to working pressures of up to 10 kg/cm$^2$ (class 10): they are very flexible and possess substantial deformation capacity.
- Polyethylene tubes can be made of any length which facilitates handling them in the plant, and loading and transporting them to their final site.

They are delivered in rolls whose diameter is proportionate to the outside diameter of the tube.

- The lengths of tubing are joined on the spot by means of mechanical couplings inserted under pressure and heat into the ends of the tubes. The adjustment of interference between the coupling and the tube needs to be studied carefully in view of the frequent irregularities in the internal dimensions of the tube (calibre and shape). The dimensions and surface of the coupling must be carefully designed to avoid tearing or, conversely, loss of grip. Braces are used to strengthen the coupling. The couplings themselves are connected by means of universal joints or clamps.

  The pilot plant has experimented with steel cog couplings of various lengths and degrees of adjustment, and has succeeded in defining empirical design criteria which give perfectly satisfactory results.

  Welding the ends of the tube can also be considered as an alternative, but this has been abandoned as not being sufficiently reliable at pressures over 2 $kg/cm^2$. Commercial adhesives capable of joining polyethylene tubes do not exist.

- In view of their cost and of the care required to install them, it is desirable to reduce the number of joints to a minimum compatible with a section length allowing the section to be hoisted, moved and transported.

  For the pilot plant, 4" class 10 tubes were transported in 25 m sections from Lima to Obrajillo (105 km) and were then moved on community haycarts to the site (head 56.5 m and length of tubing 115 m).

- From the viewpoint of deformation or maintenance in place, no supports are necessary because of the ability of the tubing to adapt to any ground formation; it is recommended that the minimum design criteria of one anchorage at the foot of each joint be adopted, thereby avoiding traction on the couplings caused by the weight of the tube with its water content.

  The anchorages must be installed level with the ground and must hold the tube by means of braces since, like PVC, polyethylene does not integrate structurally with concrete.

- The purchase price of polyethylene tubing in Peru is higher than that of PVC but is in any case lower than that of equivalent steel tubing.

  The couplings with their universal joints are very costly items.

- Transport, haulage and installation costs are considerably lower than for PVC; polyethylene tubes are well suited to communal installation, skilled personnel only being required for putting in the couplings. The installation of a 4" class 10 tube 115 m long with a head of 56 m can be done in one day.

  Costs for anchorages are considerably lower than for PVC as the numbers and the sizes required are lower.

- The loss of head in polyethylene tubes is comparable to that of PVC tubes, if we do not consider the couplings. However, the introduction of these reduction elements markedly increases losses of head.

- Their behaviour vis-à-vis the water stroke phenomenon is even better than in the case of PVC tubes.
- Polyethylene tubes do not need outside protection and are impervious to solar radiation.
- Their resistance to impact is good and they are less fragile than PVC.

It may be stated that both PVC and polyethylene tubes are technically and economically viable alternatives for hydroelectric micro-plants. Nevertheless, practical and laboratory testing must be continued with a view to perfecting design criteria, and especially to establishing projections for useful life expectancy under various conditions of work and better defining the scope for economic use of such tubes.

## 5.5. Michell-Banki and Pelton turbines

Definition of the types of turbines to be used in the project was conditioned by the projected use (5-50 kW for conditions in the Sierra), with an approximate range of specific speeds ($n_s$) between 10 and 200, and by the development of technology enabling hydraulic machines to be constructed at low cost.

For the lower level of specific speeds ($n_s < 29$), the single-nozzle Pelton is an ideal option. For higher specific speeds it is traditionally considered better to use multiple-nozzle Pelton turbines ($n_s < 59$), and Francis turbines for still higher values; these two options imply constructing relatively costly machinery which can be satisfactorily substituted by Michell-Banki type turbines, whose design can be easily adapted to specific speeds of between 25 and 200.

Here consideration was given to developing and adapting the technology of the Pelton single-nozzle turbine and the Michell-Banki turbine, mainly for conditions of low specific speeds.

To sum up, the development of the technology of the above-mentioned turbines has the following objectives:

- Total manufacture within the country: technology at the level of the current stage of development of the engineering industry in Peru.
- To make maximum use of national materials and, in cases of imported materials, give preference to those which can be commercially obtained, in a manner compatible with the minimum requirements of resistance to erosion of essential parts and the service life required; to consider the low-cost renewal of parts most subject to wear and tear.

- To minimize the total cost of the turbines, making sure that the cost of national turbines will be lower than their imported equivalents.
- To ensure maximum interchangeability of components by means of standardization of the turbines (it is not advisable to consider "standardization" of hydroelectric power-stations, because that would lead to inadequate economic utilization of resources), and to benefit from the flexibility given to the rotation speed of the turbine by the use of a transmission system between the turbine and the generator.
- To have turbines which operate steadily and reliably, even bearing in mind a relatively short service life, limited to that of the parts most subject to wear.
- To develop modular units which are easy to install, operate and maintain.

In the context of the objectives listed, the research programme on hydraulic turbines has been pursued as follows:

(a) Michell-Banki turbines

- Emphasis has been given to turbines of low specific speed, concerning which little information is available at the international level.
- From the experience gained in the construction of the first experimental prototype, it has been found that it is possible to produce Michell-Banki turbines at highly competitive prices, equivalent to one fifth of the price of an imported machine suitable to similar conditions of use.
- Additional knowledge has been acquired for the theoretical/practical analysis, principally with regard to the profile of injector and blade, the dimensions of the runner, a theoretical analysis using the general equation of the turbine and the adimensional analysis, and the processing of design data by means of a minicomputer.
- An integrated methodology has been devised for the mechanical design, permitting certain optimizations such as analysis of the position of the bearings. To simplify construction for lower capacities the design of projecting runners has been given preference.

  A major conclusion has been the conformation of the importance of the mechanical design of the axle in consideration of its critical speed, because this is nearly always the decisive factor in determining the size of the axle, more than the bending and torsion loads in themselves.

  A suitable method has been devised permitting the injector to be positioned in exact relationship to the runner, with minimum gap.
- Mechanical design criteria have been perfected for simplifying the support structure of the turbine, combining it with its concrete base, for establishing adequate dimensional proportions for the framework in relation to the runner, defining limits for over-designing the width of the runner in relation to the width of the injector, optimizing the position of the injector in relation to the runner and perfecting criteria for dimensioning the turbine outlet.

- A hydraulic efficiency of 76 per cent was achieved in the experimental turbine installed at the pilot plant. Here it is worth mentioning for purposes of reference that in research carried out at the University of Oregon in the United States[2] a maximum hydraulic efficiency of 80 per cent was attained, while in experiments carried out at the University of the Andes[3] a maximum hydraulic efficiency of 61 per cent was achieved. The firm of Ossberger indicates that the maximum hydraulic efficiency reached by its Michell-Banki turbines is something over 80 per cent. We consider that with the second prototype to be installed at the pilot plant hydraulic efficiencies of the order of 80 per cent will be achieved.

  The literature on micro-power-stations often affirms that efficiency is not very important, on the basis of the supposed opposition between costs of equipment and efficiency achieved. But in our opinion this argument is not very realistic because a low rate of efficiency involves the use of larger-sized (and therefore more expensive) machinery, and unnecessary reduction of the water flow which might be used for irrigation at a higher level; moreover, the lost energy must be dissipated, and it frequently occurs that intensive wear and vibrations are associated with inefficiency.

- In the prototypes, welded steel-sheet construction is considered. For the runner and injector, experiments have been made with various types of stainless steel and surface hardening treatments.

(b) Pelton turbines

- There is information available which makes the development of this technology easier than in the case of Michell-Banki turbines. Nevertheless, during the execution of the project, complementary theoretical aspects were developed with regard to the handling of the general equation of the turbine, adimensional analysis, the processing of design data by means of minicomputers, a method for the analytical calculation of the angle of the buckets (instead of an estimate by graphic methods), evolute profile of the bucket edge, etc.

  Plans of turbines made by experienced manufacturers were also studied, and compared with their design specifications and operational efficiency, for the purpose of determining their empirical design elements.

- A mechanical design methodology was developed which permits the interchangeable use of a series of standardized buckets and discs, critical-speed verification of the axle, simplification of the design of the framework and chassis on a concrete base, parallel displacement of the deflector, etc.

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2/ "The Banki Water Turbine", C. A. Mochmore, Oregon State College.

3/ DOC. IM 72-29 - Colombia.

- At prototype level, experiments are being conducted on various cast materials for the buckets (13 per cent Cr steel, aluminium bronze, phosphorous bronze, cast iron, etc.), which will be bolted on to the disc of the runner, careful attention being paid to dynamic balance. Various materials are likewise being considered for the mouth of the nozzle, the point of the needle and the deflector.

  For the remaining elements only the use of carbon steel sheets is being considered.

(c) Industrial prototypes

A series of standardized turbines (Michell-Banki and Pelton) has now been developed; one of each type of these is being constructed as a prototype to be installed in the pilot plant to work with a 20 kVA alternator. The standardized series will be perfected on the basis of the experimental results of this second stage of the project.

5.6. Turbine/alternator transmission

The need to have available a standardized series of turbine runners (with given diameters) and their use with a wide range of heads has the result that the turbines will rotate at a speed which will depend on their specific application, which will conflict with the need for developing alternators for one or two speeds at the most, as we shall see further on.

To overcome this apparent contradiction in objectives, a speed transmission system must be available between the turbine and the generator.

For the capacities and speeds required by the range of application of the project, an analysis was made of the various alternatives such as gear transmission, which did not prove very economical for small reductions and capacities, chain transmission, which proved very limited as regards circumferential speeds, flat belt transmission, which did not prove very efficient, and finally the alternative chosen of employing V-belts of a special type, which allows for reductions up to 4:1 throughout the range of the project.

According to the experiments conducted at the pilot plant, the use of V-belts is a satisfactory solution, but their effective application requires an integrated design of the turbine/generator chassis, reducing distances between their centres to a minimum.

Relative standardization of the turbine pulleys was found to be possible, leaving the final dimensions of the generator pulley to be established for each hydroelectric micro-plant.

A specific methodology has been evolved for the selection of belts and the design of pulleys.

5.7. Speed regulators

The typical conditions of rural electrification permit variations of ± 2 hertz in the frequency (60 hertz), and even greater variations where applications are restricted to illumination; consequently, the problem of the turbine's speed regulator does not concern its precision but rather its stability, reliability and resistance under conditions of involuntary inattention, sudden load changes, humidity, lack of skill on the part of the operator, etc.

Some authors suggest as an alternative the dissipation of the excess energy resulting from operating continuously at full load. We believe this is only justifiable when economic use can be made of the dissipated energy (mini-fertilizer-plants, heating, etc.). Otherwise, dissipating energy in the surroundings becomes excessively costly in terms of rational use of the water, particularly when the latter is used for generating as well as irrigating.

Two technical alternatives are being developed in the project, the conventional oil-mechanical regulator and the electric/electronic regulator.

The former is being developed on the basis of adapting existing designs, paying careful attention to conditions of stability and reliability, compatible with the aim of keeping costs down.

The first prototype of an electric/electronic regulator is in process of being made and will subsequently be tested at the pilot plant. Its operation is based on sensing and amplifying electronically the changes in frequency so as to produce displacement of the system of regulation of the flow of the turbine by mechanical action operated by a triphase electrical motor, the dirction of whose rotation can be reversed.

If this electric/electronic system proves operable we would have a low-cost device which would be easy to replace. It should be noted that an air-conditioned design is being considered with ample capacity to resist excessive voltages.

In the case of the Pelton turbine the automatic regulator would only act on the deflector.

5.8. Alternators

In Peru the firm of ALGESA manufactures alternators of between 3 and 200 kVA for generator units.

This firm is carrying out an industrial technological research project complementary to the one being conducted directly by ITINTEC 4/ for the purpose of adapting their design to the most demanding conditions of racing found in hydroelectric power-stations (racing speeds approaching double the design speed), raising the integration level of the components and developing a more robust design for the voltage regulator.

The trials of the first prototype (4 kVA) have proved satisfactory. A new 20 kVA prototype will be installed during the second stage of the pilot plant.

For developing micro-power-stations within the range of the project (5-50 kW and conditions in the Sierra), only the use of two-pole and four-pole alternators (3,600 r.p.m. and 1,800 r.p.m. respectively) is considered, because it is not economically feasible to produce alternators with a higher number of poles domestically.

5.9. Asynchronous generators

The firm of DELCROSA makes squirrel-cage asynchronous electric motors.

To study their use as asynchronous generators, this firm has embarked on an industrial technological research project using 2 per cent of net income generated. 4/

The project has two purposes: first, to determine the limits of an asynchronous generator working parallel with an alternator, and, secondly, to evaluate the autonomous operation of an asynchronous generator with a special voltage regulator and its own exciter system, assuming the use of waterproof machinery.

A first 3.6 kW prototype has been satisfactorily tested at the pilot plant, operating autonomously. Subsequently (second stage) a second prototype will be installed to operate parallel with a 20 kVA alternator.

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4/ In Peru there exists a system of incentives for technological research by industrial firms using 2 per cent of their net income for that purpose: otherwise the sums concerned are added to ITINTEC funds.

Besides developing the technology of the regulation system, the project will establish the conditions suitable for the autonomous operation of an asynchronous generator.

Its operation in parallel with an alternator will make it possible to expand the installed generating capacity of a micro-power-station, with minimum additional investment.

The possibility of using waterproof machinery is also particularly interesting in the case of units installed without much environmental protection or when leaks occur in the plant.

An additional application of the technology developed concerns storage stations, where the generator would serve as a motor for pumping requirements.

5.10. Miscellaneous aspects

Technologies in some additional fields are being developed as part of the project:

- Design of low-voltage modular electric instrument panels for hydroelectric micro-plants.
- Design methodology for low-voltage transmission lines for rural areas, assuming the use of eucalyptus poles, bare conductors etc. It should be pointed out that for the range of capacities envisaged in the project it is mainly planned to use a low voltage; thus in the specific siting of a micro-plant careful consideration must be given to the distance between the plant and the village.
- Design for lightning conductors.

## 6. OPERATION OF THE PLANT

### 6.1. Operation

As is normal in isolated rural villages, the initial operation of the plant is from 5 p.m. to 11 p.m. In addition, the local bakery requires electricity (2 kW) in the early morning from 2 a.m. to 6 a.m.

As part of the agreement with the rural community, local operators are being trained. This is very important if one is to avoid the big effects on operating costs of recruiting a qualified operator from the town, or else run the risk of having to employ an unskilled operator.

### 6.2. Maintenance

With a pilot hydroelectric micro-plant routine maintenance requirements are minimal, limited to occasionally oiling the bearings, checking the adjustment of the belts, examining the generator and generally cleaning the plant.

The main components subject to wear by erosion are, with the Michell-Banki turbine, the injector, the entrance blade and the blades of the runner, and, with the Pelton turbine, the nozzle, the needle, the deflector and the buckets.

So far the pilot plant has had no repair problems, and no projections for the service life of any of the parts have been determined experimentally.

Routine maintenance and minor repairs must be carried out by the operator. The hydroelectric micro-plant has only minimal workshop facilities. An interesting possibility would be for the operator to perform minor electro-mechanical repairs at his village, thereby adding to his earnings without increasing the operating costs of the power-station.

The intake installation, the channel and the basin will need maintenance and periodical cleaning: this will not be very different from the requirements for maintaining an irrigation canal, normally taken care of by community work.

### 6.3. Rates system and controls

By the terms of the agreement the Obrajillo rural community is responsible for the electric service to the community. Installing electricity meters in the houses is not justified because of the high cost involved compared with the small quantities of energy consumed. The rates have therefore been set in accordance with installed consumer capacity. The community leaders are also responsible for checking and inspecting the installed capacity of each house.

6.4. Compatibility with irrigation requirements

Most of the irrigation take-off points are located upstream from the basin so that priority for irrigation is automatic.

For irrigation downstream from the basin normal requirements are less than 20 litres/second; considering that the maximum demand of the power-station is of the order of 61.5 litres/second, it can be seen that it will be sufficient to increase the canal's capacity to 80 litres/second.

However, in times of drought, when it is not possible to obtain the flows indicated and when it becomes necessary to irrigate at night, the hydroelectric micro-plant will be out of action or will operate at part-load (street lighting only). This will present no major problem since it is the rural community which itself decides on priorities, and conflicts can be avoided.

7. COSTS

7.1. Details of the cost structure of the pilot plant

Owing to the very nature of a research project, there can be no direct comparison between the costs incurred in constructing and equipping the Obrajillo pilot hydro-electric micro-plant and the costs of an investment project utilizing advanced technology, as can be seen from the points below:

(a) For experimental reasons two sets of tubing were installed (one made of PVC of 8" dia. and the other made of polyethylene of 4" dia.) whereas in an investment project only one would be needed. The sluice valves are also duplicated.

(b) The plant has three turbines where a single turbine would suffice.

(c) The plant has two alternators and two asynchronous generators where one would suffice.

(d) In addition to the minimal instrumentation of the panel, further instrumentation is required for research measurement purposes.

(e) Construction of various turbine runners to test different designs.

(f) Development of prototypes, modifications, individual production of parts, higher costs for design and computation, etc.

TABLE 1. SIMULATED APPROXIMATE COST STRUCTURE OF A HYDROELECTRIC MICRO-PLANT OF 19.2 KW

| ELEMENT | INVESTMENT WITH CONVENTIONAL TECHNOLOGY | INVESTMENT WITH NON-CONVENTIONAL TECHNOLOGY |
|---|---|---|
| Intake | Classical construction including a sand sluice.<br>$US 4,250 | Adaptation of the existing irrigation canal intake.<br>$US 650 |
| Lead canal | Excavating and lining a canal 3 km long.<br>$US 8,500 | Utilization of and improvements to an existing irrigation canal.<br>$US 850 |
| Basin or fore-bay | Concrete construction and steel sluices.<br>$US 1,700 | Lean concrete construction including sand-remover and wooden sluices.<br>$US 1,050 |
| Precision tubing | Imported 8 Sch. 40 steel tube sections joined with welded clamps (115 m long).<br>MATERIALS<br>Tube $US 8,100<br>Clamps $US 3,400<br>Expansion joint $US 450<br>Sub-total: $US 11,950<br>INSTALLATION<br>Anchorages $US 850<br>Assembly $US 3,200<br>Painting $US 1,050<br>Sub-total $US 5,100<br>TOTAL: $US 17,050 | PVC 8 class 10 tube made in Peru joined with pegs and sockets stuck on (115 m long).<br>MATERIALS<br>PVC tube $US 2,450<br>Clamps $US 450<br>Adhesive $US 200<br>Sub-total $US 3,100<br>INSTALLATION<br>Anchorages $US 850<br>Assembly $US 850<br>Coating $US 1,500<br>Sub-total $US 3,200<br>TOTAL: $US 6,300 |
| Sluice valve | $US 850 | $US 850 |
| Powerhouse | $US 3,400 | $US 1,700 |
| Electro-mechanical equipment and instruments (turbine, speed regulator, transmission, alternator and panel) | According to an up-dated quotation from an overseas supplier (including a complete modular unit with a Michell-Banki turbine).<br>$US 36,200 | Total cost of the Michell-Banki turbine, electro/electronic regulator, transmission by special V-belts, ALGESA alternator and modular wooden panel.<br>$US 7,650 |
| GRAND TOTAL: | $US 71,950 | $US 19,050 |

7.2. Simulated cost structure of an equivalent investment project and comparison with the use of conventional technologies

Taking as reference the specifications of the Obrajillo pilot hydroelectric micro-plant (19.2 kW), and excluding duplications required for an experimental plant, we can determine the approximate cost structure for an equivalent investment project, as shown in table 1.

For the estimates we have taken prices and costs prevailing in Peru in June 1979 and converted these into United States dollars at the current rate.

Although the costs given have a purely indicative value, not only because of their approximate nature but also because the amount of investment needed depends on the specific characteristics of each investment project, comparing the costs of conventional technology with the costs of the technology developed for the conditions in Peru shows an investment cost ratio of about 3.8 to 1 and, in the case of the main electro-mechanical equipment, advantages of 4.7 to 1 in favour of the technology considered for the project.

7.3 Production cost of electric energy

(a) Energy to be produced

With an installed capacity of 19.2 kW, two hypotheses are assumed:

TABLE 2. ENERGY GENERATED

| | Annual hours of operation | Average load (percentage) | Energy generated (kWh/year) |
|---|---|---|---|
| First hypothesis | 3,000 | 80 | 46,080 |
| Second hypothesis | 5,000 | 90 | 86,040 |

These results are calculated as follows:

$$\text{kWh/year} = P\ (\text{kW}) \times \text{hours/year} \times \frac{\text{average percentage load}}{100}$$

(b) Annual cost of production

In a hydroelectric micro-plant, annual costs are virtually fixed and almost independent of the amount of energy generated.

Given the conditions assumed for the investment structure indicated under 7.2., with the technology developed in the project, the total annual costs would be as follows:

(1) Interest and amortization in respect of loans

Assuming an interest, including commissions, of 10 per cent a year, payable for 30 years on the basis of ordinary annuities calculated on present value.

$$\text{Annuity} = \frac{\text{Present value x interest/100}}{\left[1 - \left(1 + \frac{\text{interest}}{100}\right)^{-\text{No. of years}}\right]} = \frac{19{,}050 \times 0.1}{\left[1 - (1 + 0.1)^{-30}\right]} =$$

$US 2,020.81

(2) Repairs

An amount of 1.5 per cent of investment is assumed. 0.015 x 19,050. $US 287.75

(3) Insurance

An amount of 1.2 per cent of the value of equipment is assumed. 0.012 x 7,650. $US 91.80

(4) Sundries

An amount of 0.3 per cent of investment is assumed. 0.003 x 19,050. $US 57.15

(5) Wages

An index of 1.4 is applied to take into account social benefits and bonuses.

1 worker x $US 65/month x 12 months x 1.4 $US 1,092.00

Wages paid in respect of maintenance and cleaning of civil engineering works (intake installation, channel and basin) are not taken into account because it is assumed that these are performed by community services.

TOTAL ANNUAL COST: $US 3,549.51

(c) Unit cost of energy

This is obtained as follows:

$$\text{Unit cost (\$US/kWh)} = \frac{\text{Total annual cost (\$US)}}{\text{Energy generated (kWh)}}$$

TABLE 3. UNIT COST OF ENERGY

| | Energy generated (kWh) | Total annual cost | Unit cost ($US/kWh) |
|---|---|---|---|
| First hypothesis | 46,080 | $ 3,549.51 | 0.077 |
| Second hypothesis | 86,040 | $ 3,549.51 | 0.041 |

In addition, there is an investment of $US 6,000 in respect of a three-phase low-voltage transmission and distribution line because the hydroelectric plant is located 200 m from the town. Assuming use of bare copper wires and eucalyptus poles supplied to the project by the community free of charge, and also assuming amortization over 20 years and an annual interest of 10 per cent, the implication for energy cost will be as shown in table 4.

TABLE 4. IMPLICATIONS FOR ENERGY COST OF INVESTMENT ON THE LOW-VOLTAGE LINE

| | Energy produced (kWh/year) | Annual cost of the wire (interest + amortization) ($US) | Additional unit cost ($US/kWh) | Total unit cost ($US/kWh) |
|---|---|---|---|---|
| First hypothesis | 46,080 | 661 | 0.014 | 0.091 |
| Second hypothesis | 86,040 | 661 | 0.008 | 0.049 |

## 8. PROSPECTS FOR USE

### 8.1. Advantages and limitations of electrification of isolated rural communities using small hydroelectric plants

In the case of Peru, the advantages are as follows:

(a) Wide availability of water resources which can be exploited on a small scale: high heads in the Andean range and large flows in the forest region;

(b) Low operating costs;

(c) Ease of maintenance;

(d) Proven technologies which require only diversification and adaptation to specific conditions;

(e) In the case of small capacities, it is possible to use the water for both irrigation and generation of electricity.

The main limiting factors are the following:

(a) High investment costs by comparison with the small capacities installed;

(b) High cost of excavation and inlet and channelling works, if used only for the generation of electricity;

(c) Inadequate development of domestic production of equipment; high price;

(d) High cost of feasibility and engineering studies;

(e) High cost of pressure tubing;

(f) Little knowledge of rural demand for electricity and the small-scale hydroelectric resources available;

(g) Difficulty of obtaining finance on easy terms;

(h) Shortage of skilled workers in rural areas.

### 8.2 Prospects for use of the technology developed

Chapter 5 indicates the main implications of the technology developed within the scope of the project under investigation, whose prospects for use are indicated by the following:

(a) A substantial reduction in the initial investment required has been achieved.

(b) It is possible to manufacture all the equipment for small hydroelectric plants domestically (with the exception of instruments), at competitive prices, ensuring adequate quality and prompt delivery. Additional industrial investment is not required.

(c) It has been possible to define parameters for the standardization of equipment components.

(d) Specialists and technicians able to cope with all aspects of the problems raised by small hydroelectric plants are being trained.

8.3. Existing government policies

Action required

(a) Technological development

The project described in this document is only one step towards the development of technology for the equipping of hydroelectric micro-plants, the study being confined to a range of capacities of between 5 and 50 kW and conditions of high heads and small flows characteristic of the Andean region.

In the short and medium term, the following technological research projects, *inter alia*, should be initiated under the responsibility of ITINTEC:

Small hydroelectric plants in the range of 50-500 kW, for conditions in the Andean region (high heads);

Hydroelectric micro-plants in the range of 5-50 kW, for conditions in the forest region (large flows and low heads);

Design and manufacture of hydraulic ram pumps;

Comprehensive study of demand for electricity and availability of hydroelectric resources in rural areas.

(b) The Ministry of Energy and Mining is taking action aimed at initiating a programme of rural electrification using small hydroelectric plants.

(c) Electrical interconnection

Peru is a country with an extremely irregular terrain, and its rural population is scattered in small, isolated villages with few inhabitants, making it impossible to carry out rural electrification by interconnection with the high-voltage grid because of the high cost of transmission lines and sub-stations to meet a small demand for electricity.

Nonetheless, for many rural uses, the establishment of a small medium-voltage interconnected system linking a group of neighbouring communities and making it possible to take advantage of the economic benefits of generation of electricity on a large relative scale is feasible.

8.4. Cost of energy

The sale of electric power is governed by a system of rates laid down at the national level which tends to balance out the higher cost of generation on a small scale, but also negatively influences the evaluations of feasibility studies which do not take into account all the problems of rural electrification, but consider only specific profitability with respect to an established rate.

For reference purposes, we would indicate that rates of around $US 0.025/kWh are charged by the small rural hydroelectric plants operated by ELECTRO-PERU (the State-owned electricity enterprise), those rates being heavily subsidized in relation to costs.

# ANNEX

## METHOD OF PRELIMINARY CALCULATION FOR THE DESIGN OF A HYDROELECTRIC MICRO-PLANT

This annex sets forth some basic design principles for establishing the specifications for a hydroelectric micro-plant and its prime movers, taking as reference the approximate calculations for the second stage of the pilot hydroelectric micro-plant at el Molino (the mill), Obrajillo.

(a) DETERMINATION OF THE INSTALLED CAPACITY OF THE MICRO-PLANT

For isolated rural communities in Peru, a typical peak demand of 20-30 W per inhabitant is estimated.

In line with the project specifications (4.2) for the second phase, installed capacity will be:

$$P = 16 \text{ kW}$$

(b) DETERMINATION OF THE GROSS DROP

On the basis of the levelling obtained from the topographical survey carried out, the gross drop from the basin to the level of the intake spindle of the turbine is as follows:

$$H_B = 56.5 \text{ m}$$

(c) DETERMINATION OF THE TUBING PROFILE

In accordance with the results of the topographical survey the length of the tubing is

$$L = 115 \text{ m}$$

Taking into account the losses of head in the accessories, for purposes of the calculation the following length is assumed:

$$L_T = 125 \text{ m}$$

(d) PRELIMINARY SELECTION OF THE ALTERNATOR

A domestically manufactured alternator (ALCESA), with the following specifications, is assumed:

60 c/s, 1,800 rpm (four poles)
20 kVA generated
Cos $\phi$ = 0.8 (assumed)
Efficiency = 0.85

(e) CALCULATION OF POWER

$$\text{Power generated} = \text{kVA} \times \cos \phi$$
$$= 20 \times 0.8$$
$$\underline{\text{Power generated} = 16 \text{ kW}}$$

Assuming an alternator efficiency of 0.85, the power transmitted at the generator will be:

$$\text{Power transmitted} = \frac{16}{0.85} = \underline{18.82 \text{ kW}}$$

Assuming V-belt transmission with an efficiency of 0.95, the power at the turbine brake will be:

$$P_T = \frac{18.82}{0.95}$$

$$\underline{P_T = 19.81 \text{ kW} = 26.34 \text{ hp}}$$

Assuming a mechanical efficiency of the turbine of .95, its hydraulic power will be:

$$P_{HYD} = \frac{19.81}{.95}$$

$$\underline{P_{HYD} = 20.86 \text{ kW} = 28.36 \text{ hp}}$$

Assuming a hydraulic efficiency of the turbine of 0.8, the power absorbed by the power-station will be:

$$P_{ABS} = \frac{20.86}{.80} = 26.07$$

$$\underline{P_{ABS} = 26.07 \text{ kW} = 35.45 \text{ hp}}$$

(f) CHARACTERISTICS OF THE TUBING

PVC tubing - class 10 (150 pounds)

| Nominal diameter (inches) | External diameter (mm) | Internal diameter (mm) | Thickness (mm) |
|---|---|---|---|
| 2 | 60.0 | 53.0 | 3.5 |
| 2 1/2 | 73.0 | 65.0 | 4.5 |
| 3 | 88.5 | 78.9 | 4.8 |
| 4 | 114.0 | 102.0 | 6.0 |
| 5 | 141.8 | 126.0 | 7.5 |
| 6 | 168.0 | 150.2 | 8.9 |
| 8 | 219.0 | 195.8 | 11.6 |
| 10 | 273.0 | 244.0 | 14.5 |
| 12 | 323.0 | 291 | 16 |

Length of sections = 5 m

Breaking strength (tension) (25°C) = 5-5.2 $kg/mm^2$

Breaking strength (bending) = 7-9 $kg/mm^2$

Breaking strength (compression) = 6-7 $kg/mm^2$

For operation under pressure, at 20°C, a safety factor of 5 is recommended.

Working strength = $\frac{5}{5}$ = 1.0 $kg/mm^2$

Density of material = 1.43

(g) CALCULATION OF LOSS OF HEAD BY FRICTION, NET DROP AND FLOW BY ITERATION

For each size and type of tube, the sequence followed is:

(1) Calculation of flow

$$Q = \frac{P_{HYD}}{9.807 \eta_{HYD} H_n}$$

$P_{HYD}$ = hydraulic power of the turbine (kW)

$\eta_{HYD}$ = hydraulic efficiency

$H_n$ = net drop (m)

Q = flow, $m^3$/second

Note: In the first iteration it is assumed that there are no losses of head.

(2) Calculation of speed in tubing, C (m/sec)

$$C = \frac{4 \times 10^6 Q}{\pi Di^2}$$

Di = internal diameter of the tubing (mm)

(3) Calculation of loss of head, $h_w$ (m), for PVC tubing

$$h_w = (0.4893 + \frac{0.8217}{\sqrt{Di}} + \frac{2.7209}{\sqrt{C\ Di}}) \frac{L_T C^2}{Di}$$

$L_T$ = equivalent length of tubing (m)

(4) Calculation of net usable drop, $H_n$ (m)

$$H_n = H_B - h_w$$

$H_B$ = gross drop (m)

(5) Iterate to point 1 with the new value of $H_n$, and so on, until Q has been ascertained to a given accuracy.

(h) ASCERTAINMENT OF MINIMUM THICKNESS, $e_{Min}$ (mm)

$$e_{Min} = 0.001 \frac{DiH_T}{2\sigma_D}$$

$\sigma_D$ = designed strength, kg/mm$^2$

$H_T$ = maximum equivalent height (m). For our purposes, we assume a water impact superpressure of 30 per cent, thus:

$$H_T = 1.3\ H_B$$

Simplifying and replacing $H_B$, we have:

$$e_{Min} = 0.00065 \frac{H_B Di}{\sigma_D}$$

Compare the minimum thickness with the real thickness of the tubing under consideration.

If $e_{Min} > e_{Real}$ scrap the tubing.

(i) CALCULATION OF WEIGHT OF TUBING, $W_T$ (kg)

$$W_T = \frac{\pi \rho_T}{1,000} L_T\ e\ (Di + e)$$

$\rho_T$ = density of tubing material

(j) DATA PROCESSING

Using a programme for micro-plants, the data in respect of the above points were processed for various sizes and types of pressure tubing.

($H_B$ = 56.5m, $P_T$ = 16 kW, $L_T$ = 125 m)

$\eta_H$ = 0.8, $\eta_m$ = 0.95, $\eta_{TR}$ = 0.95, $\eta_A$ = 0.85

PVC tubing - class 10 (150 pounds)

| Nominal disaster | Diameter (mm) | e (mm) | $h_v$ (m) | $H_n$ (m) | C (m/s) | Q ($m^3/s$) | $e_{min}$ (mm) |
|---|---|---|---|---|---|---|---|
| 5" | 126.0 | 7.5 | - | - | - | - | - |
| 6 | 150.2 | 8.9 | 4.82 | 51.68 | 2.903 | 0.05144 | 7.17 |
| 8" | 195.8 | 11.6 | 1.14 | 55.36 | 1.595 | 0.04802 | 9.35 |
| 10" | 244.0 | 14.5 | 0.376 | 56.124 | 1.013 | 0.04736 | 11.65 |

(k) SELECTION OF TUBES

This is based on economic optimization, minimizing the sum of the investments necessary for tubing together with the energy shortfall due to loss of head.

(l) FINAL SPECIFICATIONS

$P_{inst.}$ = 16 kW

Cent. = 0.6137

Gross drop $H_B$ = 56.5 m

With PVC (150 lb) tubing and 8" nominal dia.

Length L = 115 m (125.0 m for friction)

Loss of head hw = 1.1 m

Net drop $H_n$ = 55.36 m

Flow Q = 0.0480 $m^3$/second = 48.0 litres/second

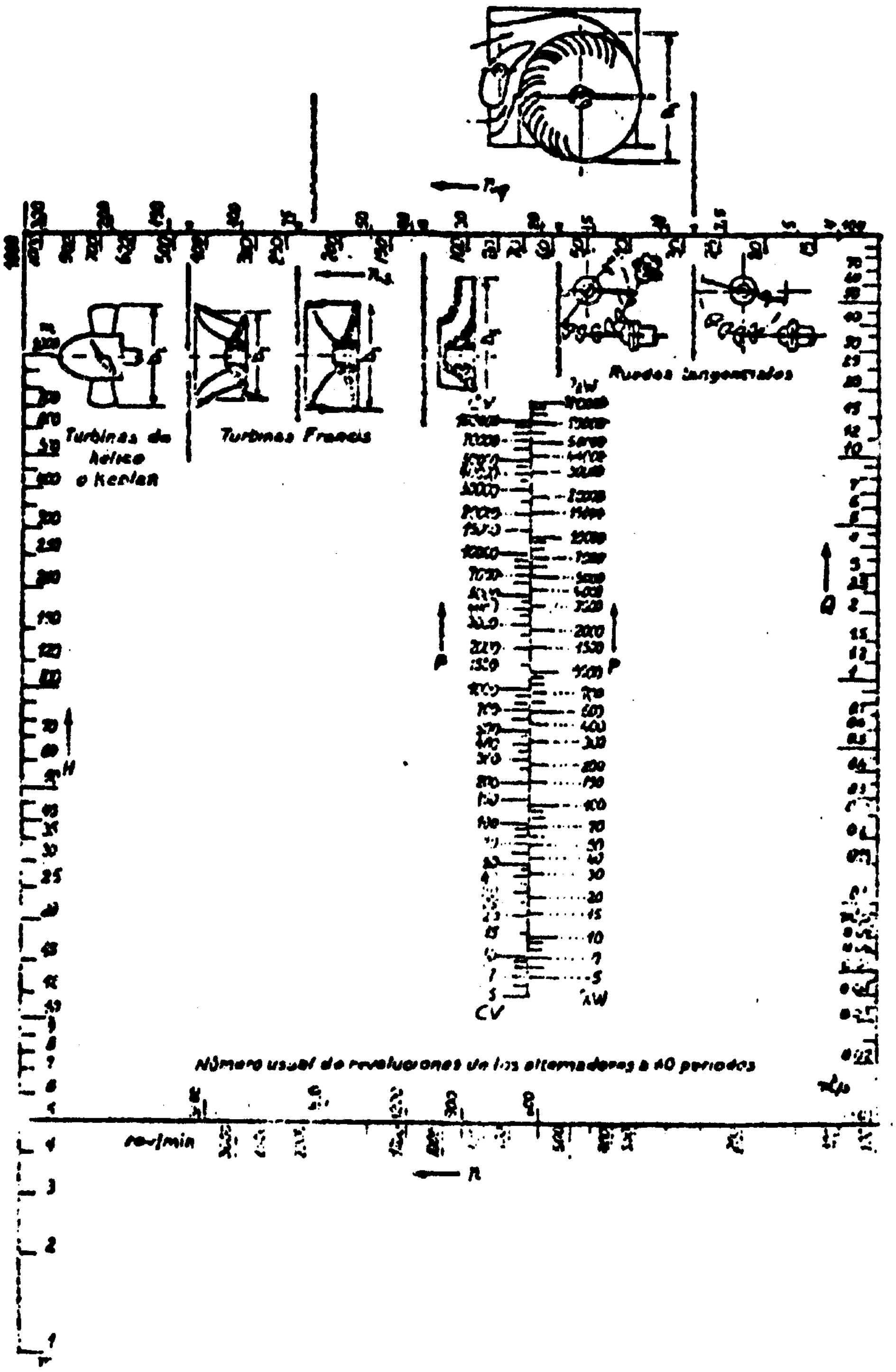
(m) SELECTION OF TURBINE

General considerations

The type of turbine to be used in each case is determined by the specific speed ($n_s$ or $n_q$) which corresponds to the operating conditions given by the capacity, head, speed (r.p.m.) and efficiency.

In figure A.1.1 a nomogram is shown for the selection of turbines in relation to their principal parameters.

**Michell-Banki turbines**




**For reference efficiency $n_t$ = 80%**

| TYPE OF TURBINE | $n_s$ | $n_q$ | $H_{max. adm.}$ |
|---|---|---|---|
| Pelton with single nozzle | 10-29 | 3-9 | 1,800-400 |
| Pelton with 2 or more nozzles | 29-59 | 9-18 | 400-350 |
| Michell-Banki | 29-220 | 9-68 | 400-80 |
| Slow Francis | 59-124 | 18-38 | 350-150 |
| Normal Francis | 124-220 | 38-68 | 150-80 |
| Rapid Francis | 220-440 | 68-135 | 80-20 |
| Propeller and Kaplan | 342-980 | 105-300 | 35-5 |

Figure A.1.1. Selection of the type of turbine according to operating conditions

There are two expressions for specific speed. The first is dependent on the efficiency of the turbine, its formula being:

$$n_s = N \frac{P^{1/2}}{H_N^{5/4}}$$

Where

$P$ = net capacity in hp

$H_N$ = net drop (m)

$N$ = Speed (r.p.m.)

The second specific speed allows us to establish similarity criteria independent of the output, and is shown as follows.

$$n_q = N \frac{Q^{1/2}}{H_N^{3/4}}$$

Where

$$Q = m^3/s$$

The following relationship between the two specific speeds can also be deduced:

$$n_s = n_q \sqrt{\frac{1000}{75} \eta \text{Hyd}}$$

In this formula:

$\eta$ Hyd = turbine efficiency (fraction)

In our particular case we consider:

$\eta_{Hyd}$ = 0.8, so that we have:

$$n_s = 3.266\ n_q$$

## The Michell-Banki turbine

This can be defined as a cross-flow, radial entry, partial-admission action turbine, an essential feature being that a large flow of water of rectangular section impinges on the rotor blades twice, in a double-effect action (see fig. A.1.2).

From the point of view of the specific number of revolutions, the Michell-Banki turbine covers the field comprised between the double-injector Pelton turbine and the slow Francis turbine.

With reference to the performance of the variable-load turbine, this has the advantage of operating efficiently within a broad range of flow, in a manner similar to the Pelton turbine.

As most of the applications derived from the project are characterized by substantial heads, we see no point in designing the turbine with partial suction tube, since the increase in useful head would be marginal, raising the cost and increasing the complexity of the machinery unnecessarily.

## The Pelton turbine

This is a classical example of a tangential-flow action turbine whose operation is characterized by the impulse provided by the jet of water expelled through one or more nozzles, which impinges on a series of buckets placed around the periphery of the wheel.

Its use is restricted to the lower ranges of specific speed.

As to its physical disposition, the axle may be vertical or horizontal. For high specific speeds and capacities the turbines are designed with two or more nozzles. This makes it possible to reduce the size of the runner but it increases its complexity, mainly in regard to the regulating system.

For the purposes of our project, we are only considering Pelton turbines with a single nozzle or injector and with a horizontal axle. See fig. A.1.3.

As to their adjustment, it is preliminary assumed that there will be automatic regulation by means of a deflector, and further manual adjustment by means of a needle valve.

## Calculation of the rotation speed of a Michell-Banki turbine

The ideal number of revolutions for a Michell-Banki turbine is obtained by the following formula:

$$N = \frac{39.79\sqrt{H_N}}{De}$$

where

N = rotation speed of the turbine (r.p.m.)

$H_n$ = net effective drop (m)

De = external diameter of the runner (m)

**Figure A.1.2. Michell-Banki laboratory turbine**
**Installed at Obrajillo - Canta**

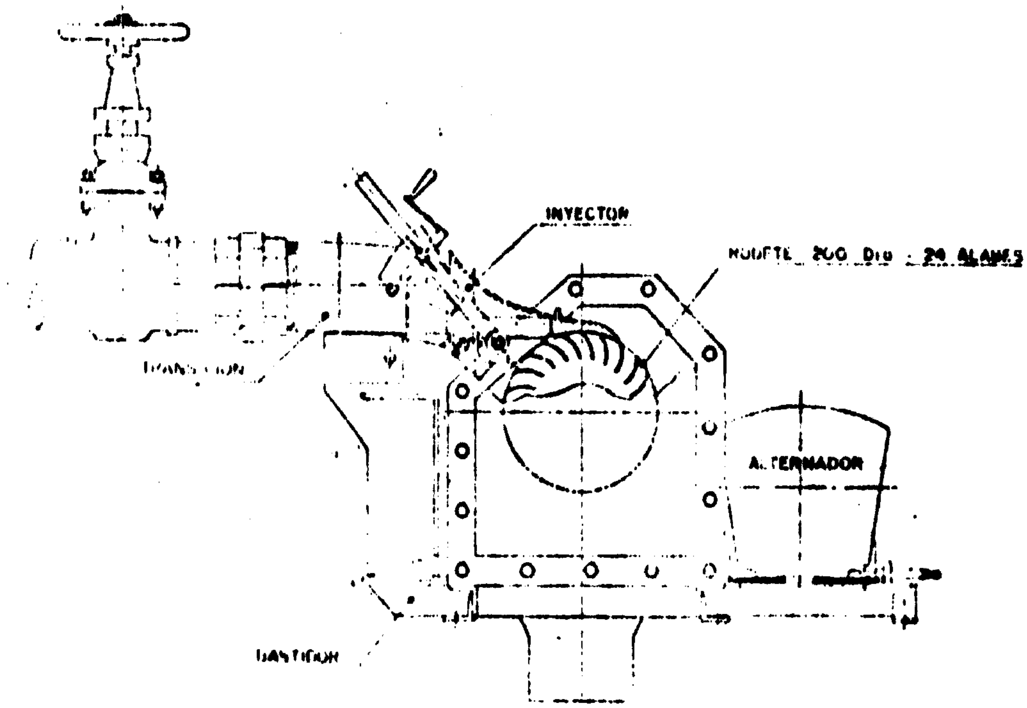
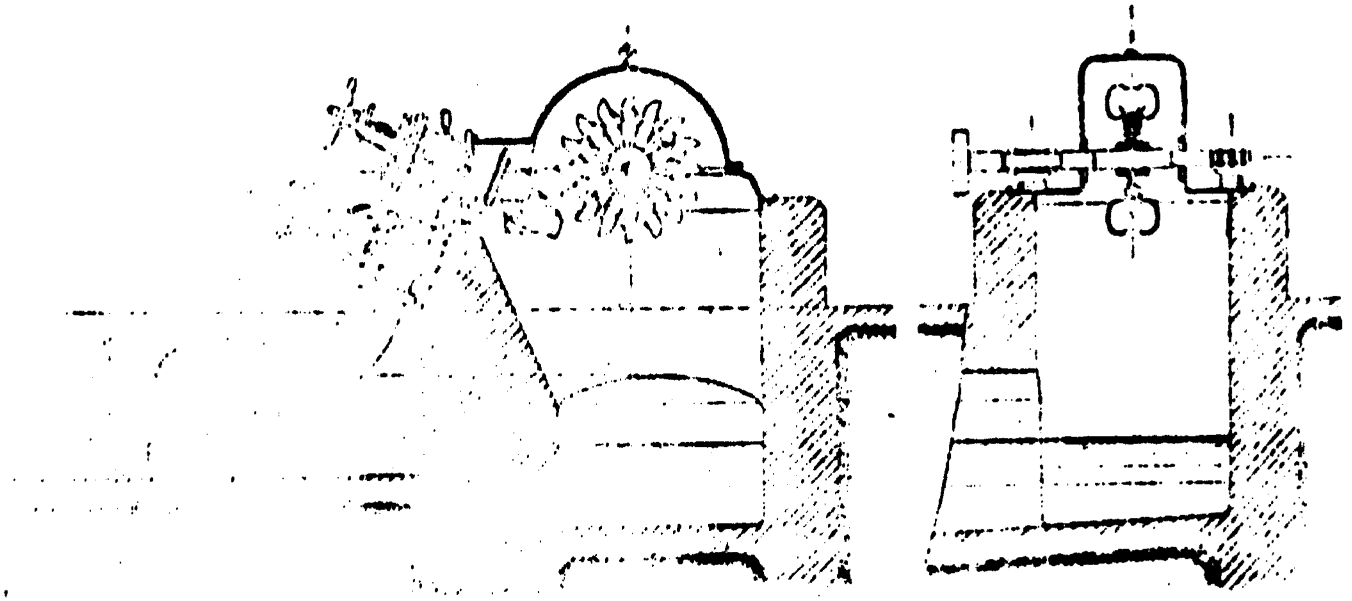



Fig. A 1 2

**Figure A.1.3. Single-nozzle Pelton turbine**



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This formula is derived from theoretical considerations relating the optimum speed to the net drop for a given angle of entry of the jet and typical experimental coefficients for the losses in the injector and the runner.

In the conditions of the project if we assume a standardized runner diameter of De = 0.2 m and a net drop of Hn = 55.36 m, the optimum rotation speed of the turbine will be:

$$N = \frac{39.79 \sqrt{55.36}}{0.2}$$

$$N = \underline{1,480 \text{ r.p.m.}}$$

With a 1,800 r.p.m. alternator we have a transmission ratio of 1.22 which is suitable for the use of belts.

Calculation of the rotation speed of a Pelton turbine

The optimal number of revolutions of a Pelton turbine is expressed by the following formula:

$$N = \frac{41.45 \sqrt{Hn}}{D_p}$$

where

$D_p$ = Pelton diameter (m)

This formula is deduced from the theoreticl considerations relating the optimum speed to the net drop and assuming typical experimental coefficients for the losses in the nozzle and buckets.

Under the conditions at the pilot plant, involving a net drop of $H_n$ = 35.36 m, and assuming a Pelton diameter of Dp = 0.6

$$N = \frac{41.45 \sqrt{55.36}}{0.6}$$

$$N = 514 \text{ r.p.m.}$$

With a 1,800 r.p.m. alternator we have a transmission ratio of 3.5 which is suitable for the use of belts.

Specific speed of turbines

In accordance with the specifications of the power-station and considering the rotation speeds selected, the specific speeds of the turbines will be:

Michell-Banki turbine

$n_s$ = 52.20

$n_q$ = 15.98

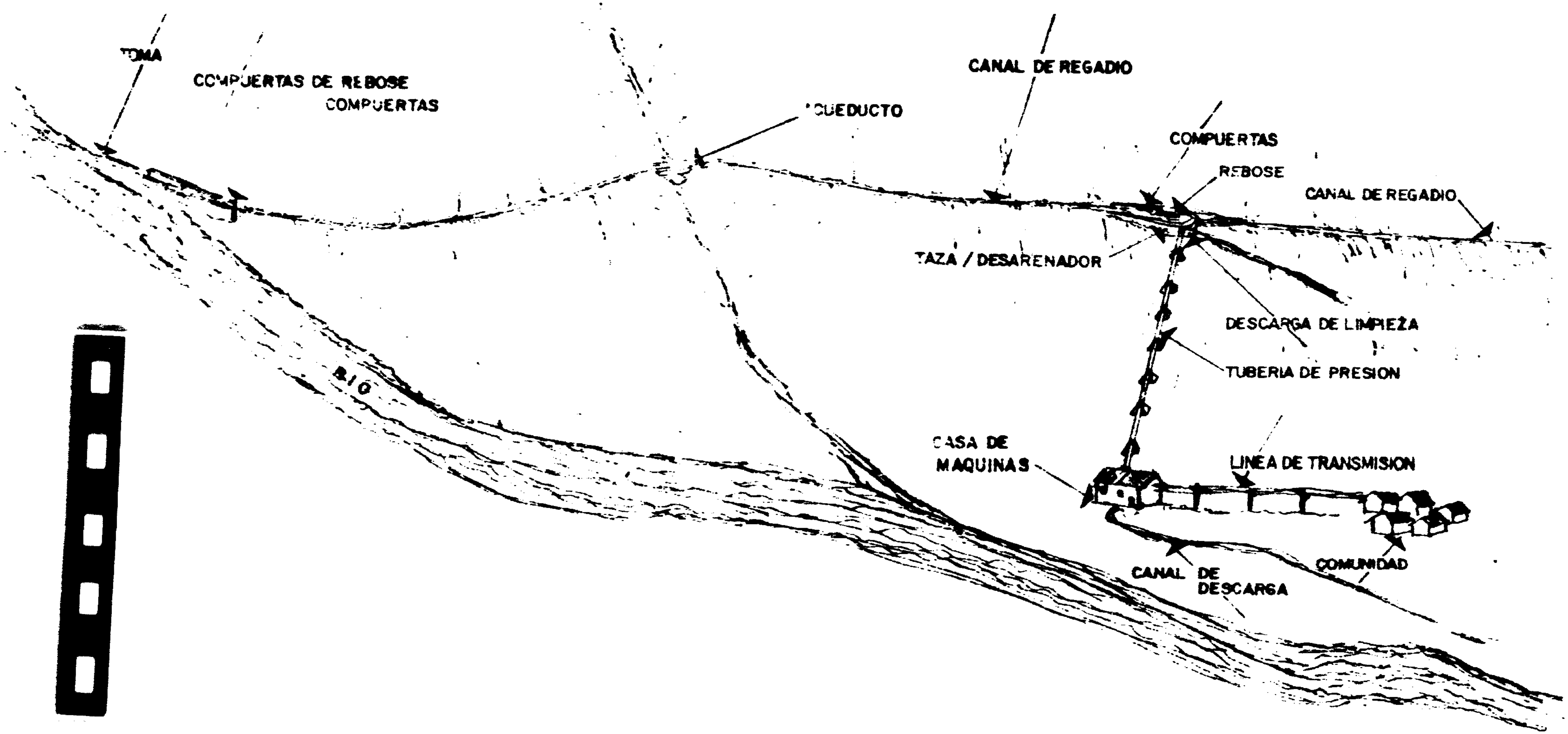
Pelton turbine

$n_s$ = 18.13

$n_q$ = 5.55

These are within the typical application ranges.

**Figure A.1.4. Schematic diagram of a hydroelectric micro-plant**



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