PN-AAS-758 40053

COST IMPLICATIONS OF SMALL HYDROPOWER SYSTEMS

by

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Presented at

A workshop on Small Scale Hydropower in Africa
Abidjan, March 1-5, 1982

being jointly sponsored by:

The African Development Bank

The Union of Producers, Conveyors, and
Distributors of Electrical Energy in Africa

The United States Agency for International Development

The National Rural Electric Cooperative Association

proj. # 936-5715

Abstract

Of all renewable energy technologies presently available to developing countries in search of indigenous energy development opportunities, small-scale hydropower may be the most economic option due to its reliability, accessibility, and low cost. Costs of small hydropower systems vary widely and are dependent on site characteristics, size, the development approach, and the end-uses of the energy, in terms of the delivered cost. The ultimate cost of a project is chiefly a function of whether the design is suitable to the need for the plant, the resources available to implement it, and the means of managing it.

Conventional small hydro cost data indicate that predictable economies of scale prevail whereby the unit cost increases as the size of the installation decreases. Recent experience with this technology at the lower end of the capacity range in a number of developing countries, however, tends to contradict conventional thinking with respect to economies of scale. This experience suggests that, due to the scarcity of equipment, materials, and technical and manufacturing expertise in most developing countries, per-unit costs tend to be greater with larger-sized small hydro plants. These plants typically require more complicated engineering, and larger and more sophisticated equipment than plants at the lower end of the scale which afford greater opportunity for non-conventional approaches using local materials, equipment and technology.

Biographical Information

Mr. Clark has acted as Training and Information Specialist for NRECA's Small Decentralized Hydropower Program since February, 1981. He previously served with the U.S. Senate Budget Committee for four years, where he advised Committee members on fiscal and monetary affairs pertaining to national economic policy. He was also Legislative Assistant to U.S. Senator Gary Hart of Colorado for economic, energy and foreign affairs from 1975 to 1977. Mr. Clark has an MA in International Studies focusing on economic development from the American University in Washington, D.C. and a BA in Political Science from the Colorado College.

1. INTRODUCTION

Why Hydropower?

Unlike thermal-based power generation, hydropower systems are not subject to continuous cost escalation—indeed, they are essentially inflation-proof, once built. They carry no energy (fuel) cost, and since their useful lives can be more than twice as long as thermal plants, this is significant. Moreover, they usually incur none of the environmental costs associated with thermal systems. The advantage of this technological choice are enhanced when one considers that, apart from these cost advantages, hydropower can provide secondary benefits that are not possible with other energy technologies, such as irrigation, public water supply, and flood control.

Why Small Hydropower?

Another advantage of hydropower technology, when considered for small-scale applications, is that it is accessible to most parts of the world where technical and financial capabilities may foreclose the option of utilizing more expensive and complicated technological solutions, including large-scale hydropower development.[1] Apart from the enormous complexity of building large storage hydro facilities, it should also be borne in mind that the long lead-time that must be allowed for its planning and construction, including longer procurement schedules, can reach 10-15 years, which bears with it a considerable cost to the project. Smaller scale hydropower development is also more adaptable to incremental, or staged, development, allowing for earlier pay-back on the investment.[2]

Other reasons may be offered which favor the development of small hydro systems as an alternative to large central power stations, particularly for purpose of providing energy to dispersed rural regions, which consume roughly one-tenth as much energy as urban areas.[3] The cost of building transmission facilities over long distances, particularly in mountainous regions, can be very high, ranging from $15,000 to $25,000 per km in the U.S., and maintenance costs may be considerable. Yet rural energy demand is typically very low,

particularly during daytime hours. Thus, large centralized powerplants generally cannot compete successfully with small plants where loads are small and widely scattered. Moreover, it should not be overlooked that grid extensions do not eliminate the need to generate new power to meet rural loads. This is especially significant where the grid power is based on thermal generation. Finally, environmental costs, both with regard to human and natural environments, are more likely to come into play. Grid extensions may nevertheless be more economical if distances are not excessive, the terrain is compatible, and the energy demand warrants them. The choice between isolated development or interconnection with the central grid to serve rural needs depends on these, and a number of other criteria which are discussed below, that must be viewed on a site-by-site and country-by-country basis in terms of identifying the least-cost option.

Point-of-Departure

A great deal of literature is available on the costs of small hydro development within the industrial nations of North America and Europe which goes back for a century or more. Economic and cost analysis of more recent experience with this technology in a number of developing countries, however, is almost non-existent. Information on direct costs of installation are available to some degree, but data relating to reliability, efficiency, and durability of these systems, as well as specfic information relating to intangible costs, is difficult to attain. Yet it is this experience that may be more relevant here, and more revealing as to the true costs of small hydro technology in remote rural regions of Africa.

For a number of reasons, some of which have already been alluded to, this paper does not attempt to provide a specific costing methodology for small hydropower development. While cost tables and cost curves are abundant in this field, it is generally inadvisable to suggest that any of these indices can be applied generally--indeed, an important conclusion of this paper is that they should not. General cost parameters can be offered, and a number of examples are presented to give the reader some idea of the actual costs that

are associated with small hydropower plants. Costing of small hydro plants is dependent on a large number of variables that are site-specific; there are virtually as many cost indices for small hydro plants as there are sites. Rather, the purpose of this paper is to present some views on factors that tend to influence costs. Further efforts are needed in developing a comprehensive costing methodology that takes into account some of the cost-influencing factors presented here, and which is adjustable to reflect the relevant technological conditions pertaining to small hydropower development that exist in different parts of the world. This paper is offered as a brief introduction to some of the key issues involved and a preliminary assessment of what the existing experience reveals.

For purposes of this paper, the term "small hydropower" refers to any size of plant with the range of 1 kW to 1,000 kW unless specifically indicated otherwise. Further, it will generally avoid the question of whether rural energy development--be it in the form of mechanical or electrical power--is worth the cost of investment. In a discussion of costs, one can quickly become embroiled in a debate on the merits of rural electrification. While this question is well worth debating, in light of the high costs of electrification, the relative merits of energy versus other investments is not considered.

2. GENERAL COST HISTORY

It would be misleading to suggest that a general statement on the costs of small hydropower installations can be made. Costs will vary from case to case since labor, equipment, terrain, and technical experience, to name but a few of the criteria, are highly variable. Moreover, it is hazardous to attempt to directly apply the data and experience developed in certain countries to other regions of the world where the same conditions and assumptions may not apply. Indeed, much of the published data (see tables given in Appendix A) are based on cost indices that are drawn from large hydrosystem development which has been scaled down to smaller sizes, leading to distortions that tend

to make small hydropower appear overly costly. Costing achieved by this method cannot only prejudice the decision-maker against the small hydro option, but more importantly may influence the choice of development approach which may be inappropriate—and needlessly costly.

It is therefore perhaps more valuable to take a quick look at some cost data that have been drawn from actual experience in a number of developing countries where small hydro development has taken place in recent years (see Fig. A). Again, caution is advised in accepting these figures into the record. The numbers shown here have been taken from published and unpublished sources without any critical evaluation, and therefore may not reflect the true costs of the cases given. Moreover—and this can be said of virtually any source—these costs typically reflect

Country	Capacity	Head	Cost/kW[1]	Equipment as % of Cost	Comments
Thailand	800 kW	40 m	$2850(80)	15%	concr. construction for civil works
Ecuador	400 kW	40 m	$2200(79)	36%	lined canal; imported equipment
Ecuador	400 kW	19 m	$2700(79)	30%	lined canal; direct intake; import. equip
Nepal*	200 kW	58 m	$ 900(80)	36%	part. lined canal; loose-packed rock dam
Nepal	120 kW	14 m	$ 900(80)	21%	masonry-lined headrace
Indonesia	120 kW	15 m	$1300(77)	58%	no headrace; local turbine
Thailand	100 kW	79 m	$ 950(80)	21%	concr. construction for civil works
Philippines*	100 kW	27 m	$ 750(80)	38%	local construction materials and turbine
Indonesia	90 kW	10 m	$1050(78)	54%	concr.-lined headrace
Nepal	80 kW	16 m	$1650(80)	23%	local materials and turbines (2)
Nepal	80 kW	14 m	$1050(80)	31%	local materials and turbines (2)
Nepal	25 kW	22 m	$ 650(80)	28%	existing irrigation works
Indonesia*	15 kW	22 m	$ 600(80)	30%	no headrace or governor, used alternator
Thailand	15 kW	10 m	$2350(80)	31%	earth dam and headrace
Thailand	10 kW	6 m	$1500(80)	27%	lined canal; local turbine
Pakistan*	10 kW	**	$ 270(78)	51%	local materials and equipment
Nepal	9.5 kW	9 m	$ 600(80)	46%	local materials and equip. except penstock
Pakistan*	7.5 kW	**	$ 320(78)	60%	local materials and equipment

[1]not including transmission and distribution costs; figures correspond to dates given in parentheses

*projects implemented and managed locally

**precise heads unknown, but generally between 3-10 m.

Fig. A. Installation Costs for Small Hydro Plants in Developing Countries.

Sources: Thailand (NEA); Philippines (NEA); Indonesia (PLN); Nepal (BYS); Pakistan (ATDO); Ecuador (INECEL).

only direct costs associated with the construction of small hydro plants, and do not take into account indirect or "intangible" costs that inevitably occur in the development process, which may take the form of subsidies, "experience-building" costs that occur over many years of a program, or socio-cultural costs that may occur at the site, which are certainly real costs, but are difficult to quantify and are therefore overlooked.

In terms of identifying an acceptable cost-range for small hydro plants, notwithstanding the World Bank's target of $2,000-$3,000/kW installed,[4] it is similarly inadvisable to toss out numbers that do not take into account important considerations such as the energy demand characteristics (both in quantity and quality terms) of the region served, the fuel transportation costs to the area, the distance from the existing grid, and the physical characteristics of the site itself, among others. Clearly, what determines the acceptable cost-range for a small hydro plant will depend on the relative costs of alternative energy options. To provide the reader with a very general rule-of-thumb, the graphs in Fig. B. give an idea of the range of cost of a small hydro plant which makes it a relatively attractive investment compared to a similarly-sized diesel plant. Note that as the load factor increases, the cost of the hydro can be higher and still remain competitive. This is due to the longer life-span and the lower operation and maintenance cost of the hydro as compared to the diesel.

3. UNDERLYING ISSUES

Matching Technology to Need

As mentioned earlier, costs taken out of context can be misleading, since the data are frequently incomplete or not quantifiable, and since market values are quite different from country to country or even between regions of the same country. Moreover, analyses that are based on cost alone, or even the partial cost of an installation, such as the equipment and civil works, cannot give an accurate picture of the value of a project since there are so many variables that determine the economy of a project. The economic attractiveness of a project is a function of both the cost and the end-use of the energy

produced. While it is certainly appropriate to consider factors that can reduce the input variables (i.e. costs), perhaps even more significant will be efforts to maximize the use of the energy. It is generally easier to reduce the delivered cost of energy by means of load enhancement, the economist's function, rather than by means of reducing input costs, the function of the

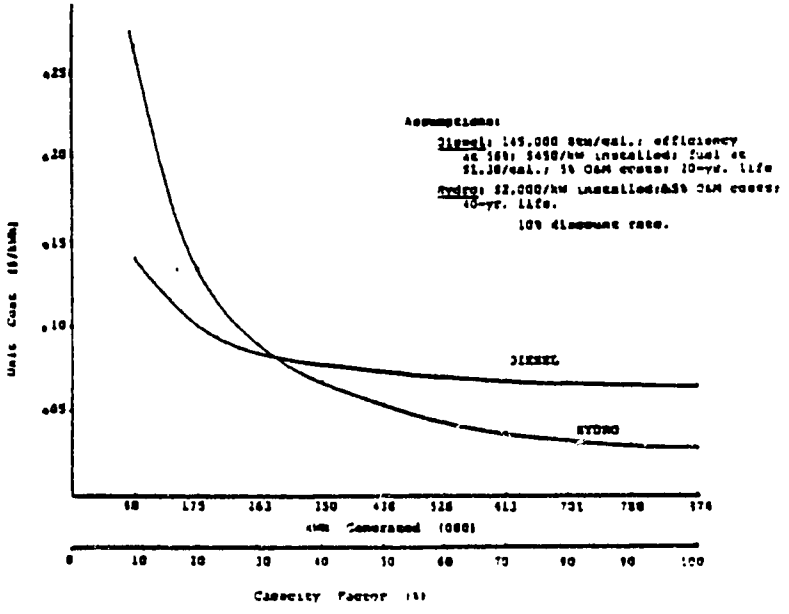

Fig. 8(1). Annual [illegible] for 100kW Diesel and Hydropower Installations.

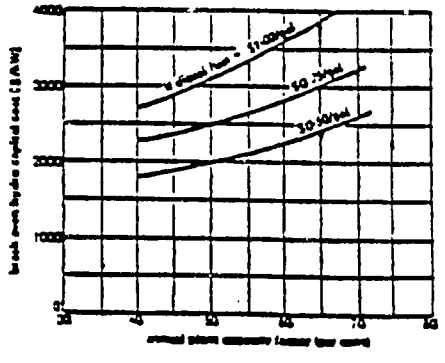

Fig. 8(2). Break-even Costs for 170kW Hydro Plant Compared to Diesel Assuming Benefit/Cost Ratio even for both.

Source: King (1979)

Fig. 8. Comparison of Diesel and Small Hydropower.

engineer. For this reason load planning is critical to the ultimate cost of the energy produced. This will be a function of how well the technology is matched to the consumer's energy needs in terms of both efficiency and capacity of the plant, and the tariff policy.

First, the energy form must be appropriate. Complex energy solutions for simple needs, in the rural context, implies higher costs to the consumer. A table is offered in Appendix B which can be helpful in matching energy technologies to the appropriate energy requirements. Please note that cost is an important criteria in the matching process. A corollary to this question of appropriateness is the matter of timing. Since small-scale hydro systems typically operate intermittently due to flow variations, the time-factor of energy supply can be critical. For example, if the energy demand does not coincide with the seasonal flow characteristics of a site, it should be borne in mind that storage requirements that may be necessary can add enormously to the costs of building the plant.

Second, capacity considerations are important. It is generally thought that plant factors should reach at least 20-30% in order for hydro to compete successfully with alternative energy technologies.[5] Domestic loads are typically very low in most of these regions, so it is important to emphasize day-time industrial uses, or "productive" end-uses, especially where existing demand is currently served by more expensive thermal generation, or where new industrial demand can be served which otherwise cannot be achieved economically by traditional energy means. Once an industrial load is established, domestic service can be provided at more feasible rates, as studies show that once modern power sources are introduced to an area and take hold (i.e. industrial uses), power demand from the general sector increases rapidly.[6] The tables shown in Fig. C. demonstrate the relationship between the load factor and the costs of producing the energy. Note that the cost of the delivered energy is reduced as the load factor increases. Fig. C(1). indicates that higher load factors allow a larger margin for capital costs at a standard tariff rate.

A key element here is that initial development of a new, isolated energy source must be scaled to the rate of demand in order to keep unit costs

sufficiently low to the consumer to permit the demand growth process to begin. This can be achieved both by designing the system to permit staged development, and by means of tariff policies which induce consumption.

Load Factor (%)	Capital Cost/kW ($)
10	212
20	675
30	1,150
40	1,613
50	2,075
60	2,537
70	3,000
80	3,475
90	3,938
100	4,400

Fig. C(1). Comparison of Load Factor to Capital Cost for Typical 50kW plant in Uttar Pradesh State, India.

(assumes standard U.P.S. tariff rate and full capital recovery)

Project	Average Load Factors (%)	Average kWh Cost (¢)
Gupekashi	23.6	7.0
Ganti-Charra	20.3	9.3
Tilwara	22.3	10.1
Koti	10.7	27.5
Deoprayag	4.1	62.5

Fig. C(2). Comparison of Load Factors to Generating Cost for five 200kW projects in Uttar Pradesh State, India.

(assumes full depreciation over 6 years)

Fig. C. Relationship of Load Factor to Capital and Generating Costs

source: ITIS (1980)

Costs and Benefits

In general, costs and benefits are judged in terms of what costs one is avoiding by either doing nothing (e.g. loss of forest cover, cost of diesel fuel), or investing in some alternative project (e.g. transmission costs), as

compared to the costs of electing the small hydro project, whose components are summarized in Appendix C.

In order to do an economic and financial analysis of a project, ideally the full range of costs and benefits associated with the investment must be quantified in some form, usually in monetary terms. This is true for virtually any analytical tool, whether one is seeking to find the internal rate of return, or the ratio of benefits to costs over the project's useful life, or if monetary calculations are not possible, by some means of imputed mass analysis. Although benefits calculations are an important part of assessing a project's worth, particularly in comparing different sector investment options, public infrastructure projects such as usually is the case with power generation are commonly analyzed by first setting a target in terms of a rate of return or a stream of benefits to establish the minimum desired result, and applying a least-cost analytical methodology which is often called the life-cycle costing method. What one is attempting to do by this method is to quantify all costs involved over the life of a project and to discount their values to present worth using an interest rate that reflects the opportunity cost of the investment. This is discussed in a previous paper but it worth noting that, as the discount rate used in the calculations increases, the value of the project declines. Moreover, an artificially low discount rate tends to favor capital-intensive approaches, which may not be appropriate for rural development projects.

4. MAJOR COST-INFLUENCING FACTORS

Small hydropower costs can be affected by numerous factors pertaining to the site, the scale of development, the technological approach, and the purpose of the project. For this reason it is difficult to present a uniform set of costs that can be applied simply and universally. The costs of individual components of a system are more easily defined, but even these depend largely on these same factors. The following is a brief discussion of each of the four major categories of cost-influencing factors.

A. Site Characteristics

Selecting the site is critically important to the ultimate cost that will result. The chief aspects of site selection which will affect cost are:

(1) its relation to the load center;

(2) the availability of head and flow, particularly the former;

(3) the river slope and hence the distance over which the head must be concentrated; and

(4) the degree of access to the site.

Relation to Load--Interconnected or Isolated. First, the plant must be located in a place where the energy can be used. Unless it is a site that can be grid-connected, all-important capacity factors may be very low if the site does not have a sufficient load center nearby. The energy must not only be appropriate, but it must be affordable. Sites that can be interconnected are certainly best, depending on the power capacity available, since load factors would theorectically be 100% of the convertable energy and since the need for expensive asynchronous frequency control equipment could be avoided by using induction generators. This cost-savings would be mitigated somewhat, of course, by the additional cost of voltage step-up equipment and transmission lines. Again, this depends on the capacity that is available at the site, and the distance from the grid.

Hydraulic Characteristics. Site selection is important also in terms of the type of scheme to be developed--whether low-head or high-head, and whether run-of-river type or storage (impoundment) type, which depends on the availability of natural head and flow.

Given the choice between run-of-river schemes and those requiring the construction of new dams, it is generally wise to avoid sites requiring the latter due to the high cost of dam construction and maintenance, particularly for low-capacity plants (see Appendix A-4 for dam construction costs). Moreover, the can:

(1) entail considerable environmental and health problems;

(2) cause enormous damage in the case of failure during peak flows;

(3) add considerably to the construction period;

(4) result in relocation of buildings or entire communities up-river;
(5) interfere with the use of the river for navigation and fish migration.

Dams are also susceptible to silting problems, which can complicate the design and up-keep of the intake structure, and can eventually render the dam worthless if used for impounding water.

An alternative approach for sites with higher natural heads is to build a low diversion weir to direct a partial flow of the river into the intake, as have been described in detail elsewhere. They are easier to construct and maintain in remote rural settings, and need not be of permanent construction, but could be formed by placing rocks and boulders across the stream that can be easily replaced following each peak-flow season. This would be the most simple design for a weir for a very small scheme, but permanent structures for larger sites can also be built at substantially lower costs than for an impoundment structure. Care should be take in selecting the placement of the diversion structure to avoid silting and erosion, which can add considerably to the cost of keeping the intake servicable.

Generally speaking, the degree of head available to a small hydro site is the single most important determinant of cost, since the amount of water needed to create a given amount of energy is reduced with higher heads, yielding cost-savings in both the turbo-generating equipment and potentially the civil works as well, depending on the slope of the river and the terrain. However since most siting opportunities will occur on rivers and streams with gradual gradients, the distances along which the water must be conducted to achieve significant heads may be considerable, perhaps several kilometers. Thus, the civil works costs for higher head schemes may often be the highest cost component. In short, for the greatest cost-effectiveness, sites should be selected to allow the highest head possible covering the shortest distance from the intake to the turbine

Low-head sites tend to be more expensive due to the large size of the machinery--which can account for up to 65% of the total cost[7]--and since dam structures are often required. Total costs for low-head plants (20m or under)

can be as much as two to three times as great as schemes with higher heads.[8] A final note--for very small micro schemes requiring less flow, heads need not be above what is generally presented as the low-head range in order to achieve the most cost-effective scheme. This is one reason why micro plants using local labor and materials appear to offer the best economie

Finally, flow considerations are also important in terms of the annual cost of energy supplied by the small hydro plant where flows are intermittent and varied, as found in many countries of the West and Central African region. If flow needed to operate the plant is available for only a few months of the year, per kWh costs may make the plant uneconomical. For this reason the quality of hydrologic calculations can be critical to the ultimate cost of the plant, particularly if the capital costs are high.

Access Considerations. Finally, the degree of access to the site may be important, particularly for larger schemes where equipment and materials may be large or heavy, requiring roads. Frequently the best high-head sites are found in areas where the terrain is inhospitable or the forest-cover dense. It therefore may be best to reserve these sites for very small schemes where equipment and materials do not require motorized transport, since the cost of building roads can be extremely high, about $50,000 per km in the U.S.,[9] and since population densities are likely to be low.

B. Economy of Scale Factors

Size of the Plant. The record is not clear on the question of economies of scale with respect to small hydropower. Conventional wisdom is that as the size of the plant decreases, the per-unit cost goes up. Certain costs which are relatively fixed such as the feasibility analysis, the engineering design costs, training, and the "experience-building" costs mentioned earlier, do tend to make lower capacity plants less competitive with larger plants; moreover, for low-head schemes requiring larger, more sophisticated equipment and impoundment structures, the economies of scale rule applies more readily.

Where design and construction techniques for small projects follow from modern technology that has been developed for conventional large hydropower, this rule generally holds true. However, if a different, non-conventional

approach is taken, based on smaller-sized plants emphasizing simpler designs and local expertise and materials, good economies can be achieved. More will be said on this later, but it is evident that reverse economies occur with this approach, where unit costs increase with the size of the plant above a certain level.

Programmatic Considerations. Economies of scale are also evident in the size of the program, whereby multiple development—especially when performed in the same river basin—can reduce the impact of fixed costs mentioned above by spreading the costs out amoung several projects. Overall costs can be reduced by as much as 10% in this manner.[10] Moreover, it may be particularly advantageous to consider establishing regional grids under such an approach to improve load factors, and to limit the number of plants that must be built. If multiple development is possible, thought should be given to standardizing the techniques used, the general design, and the equipment, although over-standardization can reduce cost-effectiveness. Since conditions from site to site are likely to be different, the civil works design should be flexible enough to allow innovation that is appropriate to each site. The greatest cost-effectiveness can be achieved by selecting sites with similar characteristics (i.e. head and flow) and standardizing equipment packages, particularly in the case of low-head sites, to operate within that range of conditions. Standardization of the turbo-generating equipment in this fashion will not only reduce the design and fabrication costs, but would shorten delivery time and minimize the need for spare parts inventory, which can be shared among various sites. Project costs can be reduced by 10-15% where standardization of equipment is possible.[11] It should be noted that over-standardization of equipment can reduce operational efficiencies of plants, so care should be given to the use of turbines that can operate under wide head and flow conditions, such as are possible with cross-flow types and converted centrifugal pumps used in multiple-unit configurations.

Timing of Development. Finally, economies of scale can be improved by approaching site development of an isolated plant on an incremental basis rather than developing the full energy potential of the site at the outset, in order to save on the ocst of the equipment or civil works. Again,

this is a function of the load factor, which is typically low during the initial stages of operation. With incremental development in mind, the headworks and penstock should be initially designed to capture the full amount of head feasible and so that larger flows could be accomodated for future capacity growth, assuming there is adequate water supply. The penstock should be sized to withstand larger volume and pressure than are initially required, or may be fitted with a bifurcation tee at some point along its length, if multiple units are feasible. Additional turbines may then be added as load growth warrants. Allowances should be made in the excavation depth and floor space of the powerhouse for these future additions. The principal reason for this approach is to avoid retarding the demand growth process by making the power cost to consumers excessively high initially. Staged development also in a programmatic sense permits "experience-building" to occur at a relatively low cost risk and can allow for experimentation with design innovations without laying too much money on the line. The decision of plant sizing and the timing of additional development should, of course, be predicated on the socio-economic feasibility study. However, since load growth is often difficult to predict in isolated regions of developing countries, the incremental design approach may be especially appropriate.

C. Use Criteria

Multiple Uses. With low-head sites, priority should be given to projects where power generation can be one component of a multi-purpose project. For example, installing a plant on existing irrigation works or an existing dam used for flood control, fish-breeding, or recreational purposes can vastly improve the cost-effectiveness of a project. Similarly, new multi-purpose water projects which include power generation as one component can yield better economies than a project where the only benefit is energy. Although costs would be greater for multi-purpose projects in absolute terms, since they can be shared among the various purposes, including municipal water supply, irrigation, flood control,fish-breeding, navigation and recreational uses, the unit energy costs would be significantly lower. Cases where the water supply can be attributed to irrigation and power generation, which is

frequently the case in China and Indonesia, offer the best configuration for multi-purpose projects since the irrigation works can reduce the cost of the power, while the power can be used to reduce the cost of distributing the water. Please note, however, that timing and design circumstances can lead to competitive uses of the water, indirectly raising the cost of the other water use (e.g. power generation when the water is diverted to irrigation.)

Project Purpose. Use criteria can also be viewed in terms of whether the purpose of the project is for fuel-substitution or for rural development (i.e. rural energy supply). This is not to suggest that these two criteria are mutually exclusive. Even for small isolated plants, where fuel substitution is minimal in the national scale of things, cash-savings achieved by reducing the need for kerosene and diesel fuel can be the most important benefit, aside from the rural development considerations of such a project. In this sense, small hydro technology may only be economical where the cost of fuel is particularly high due to transportation costs over long distances. However when the primary objective of the project or program is to effect reductions in the trade deficit, issues of plant capacity and the size of the program, hence the technological approach, become critical. It has been seen in Fig. A. that the greatest economies are achieved under conditions which permit the development of very small plants based on non-conventional technology. Yet import-substitution from a national perspective is limited due to the low aggregate capacity of even a large number of such sites.* It is only with much larger sites, where cost-effectiveness may not be as great, that this objective is better served. The point here is that, as an import-substitution technology from a national perspective, cost-effectiveness may at present only be achieved in a size-range above 1 MW, where the economies of scale rule applies more readily.

Tariff Policy Considerations. Lastly, tariff policies can be an important

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*Taking the Ivory Coast as an example, we see that over 1 million MWh of thermally powered electricity is now produced each year. If fifty 25 kW plants were installed throughout the countryside, assuming a relatively high capacity factor of 50%, the annual yield of fuel substitution that could be achieved would amount to only 5,500 MWh, or only 0.5% of the total currently produced.

determinant of the per-kWh cost of an isolated plant. Since there is no fuel cost associated with hydropower generation, unlike thermal stations, high capacity utilization reduces unit costs, whereas it tends to have the opposite effect with fuel-based generation. Hence, the objective should be to: (1) match the installed capacity to the peak-load factor on an incremental basis (design function), and (2) maintain a high load factor (tariff function). In other words, tariff policies should be set to encourage energy consumption and demand growth. Therefore the key element with small-hydro plants is to keep installation costs low, since operation and maintenance costs are minimal, in order to allow low unit costs to the consumer, which in turn improve load factors. Even with low installation costs, moreover, it may be necessary to provide power below cost for a period sufficient to induce demand growth during the critical period following the introduction of power, and to increase the capacity factor of the plant. This is particularly true for remote rural regions of developing countries, where, as one has put it, "it is not easy to get the consumer to pay for a service he is not used to having and that is foreign to his social behavioral patterns,"[12] and where, of course, people are usually too poor to pay much for such a service.

Experience has shown that it is best to rely on non-domestic uses in order to achieve economic success with isolated small hydro projects. Power stations where power is generated for industrial uses (often mechanical drive, not electrical applications solely) have shown plant factors to be twice as high as those where electricity is used for domestic and public lighting.[13] On this point it might be also be suggested that domestic consumers be charged on the basis of a flat-rate tariff (e.g. x amount per light bulb per month), as has been done in Nepal and Pakistan, to encourage consumption growth and to avoid costly metered connections for unit-pricing.

D. Development Approach

The foregoing discussion of cost-influencing factors with respect to site characteristics, economies of scale, and end-uses raises a number of fundamental issues that reflect two general approaches to small hydropower, particularly in terms of the technological approach that is used. On one

side of this dichotomy, the approach can be said to be conventional; that is, employing standards established in the construction and management of large hydroelectric powerplants and scaling the designs down to smaller sizes. In developing countries, this approach is more often associated with programs initiated and managed by central agencies, frequently using imported equipment, and predominantly permanent materials such as cement and reinforced steel for the civil structures. On the other hand, the approach may be of a non-conventional form, usually initiated and managed locally, where the designs are simpler, using locally-supplied equipment and civil engineering based on techniques already familiar to villagers for irrigation and primitive hydraulic energy. A key difference between these two approaches which reflects a fundamental trade-off in terms of cost and performance, is that conventional development tends to emphasize resource maximization, meaning the use of permanent structures and more sophisticated machinery based on designs that attempt to extract the most energy possible from a given site. Unconventional designs, on the other hand, are based on minimal needs, implying less effort in the feasibility analysis, but less efficient and less durable construction. Yet, contrary to conventional thinking, it may not be cost-effective to attempt to squeeze out every ounce of efficiency from a plant, since the greater costs implied with this approach may not be worth the additional energy conversion that is achieved, particularly for smaller isolated plants. Fig. D. presents a general description of the elements typical to each of these two approaches.

The more non-conventional approach, while being constrained in size by the limited capability of local resources to produce the larger and more complicated machinery and structures needed for systems over 100 kW, offers cost savings since:

(1) the technology is simpler, and can be easily grasped by villagers;
(2) greater innovation in design is possible;
(3) maintenance is simplified since the materials are provided locally; and
(4) community participation, upon which this approach is based, will reduce labor, engineering and management costs, and will provide greater assurance of long-term success.

	Type A.	Type B.
Scale	Over 100 kW.	Under 100 kW.
Type of System	All types, but more frequent incidence of impoundment and low-head with large flows.	Run-of-river, both high and low head, using low flows.
Technological Approach	Conventional hydro; emphasis on efficient imported equipment for resource maximization.	Non-conventional, innovative engineering; emphasis on local techniques and materials, volunteer labor, based on "as good as needed" approach.
Use of Energy	Electricity for large rural centers or grid-connection.	Mechanical and/or electrical power for small towns and villages.
Project Purpose	Imported fuel-substitution, rural electrification.	Basic energy needs, rural development.
Management	Central agencies, national utilities.	Local villages, cooperatives, entrepreneurs.
Tariff Policy	Conventional unit-pricing based on marginal cost.	Flexible rate setting; flat-rate structure for consumption enhancement.

Fig. D. Two Types of Small Hydro Development in Developing Countries.

The importance of the last point cannot be over-stressed. Apart from the cost-savings gained by eliminating the need for constant supervision by a remote central agency, self-generated local involvement improves the chances from the outset that the project will be better designed to serve the local population's needs, since it will participate in its design and construction, and that the powerplant will be something that the people are both able and willing to pay for, and keep running.

5. COST TRENDS

Taking into account the major cost-influencing factors, particularly those relating to size and the development approach, the historical cost

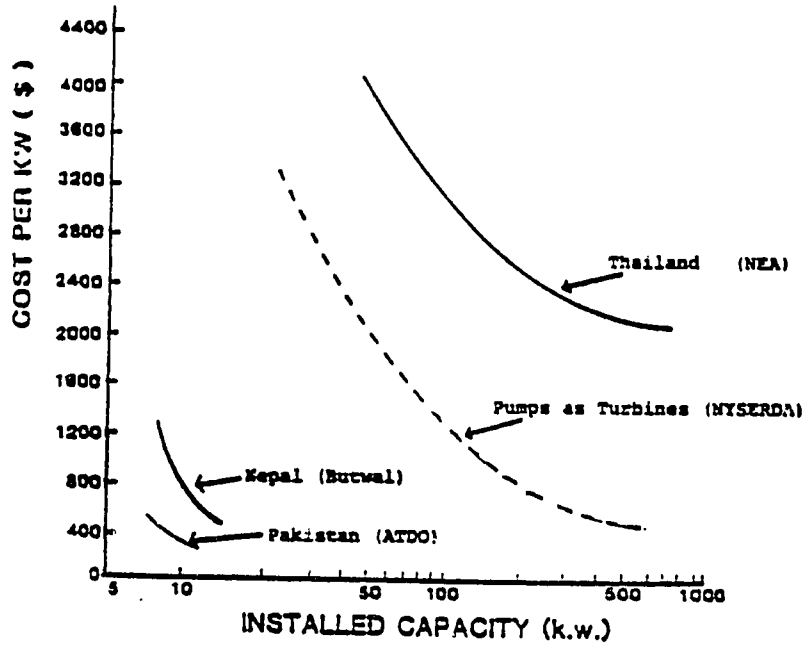


Fig. E(1). Comparison of Different Approaches to Development

source: Pakistan (ATDO); Nepal (Butwal); Thailand (NEA); New York State Energy Research and Development Authority

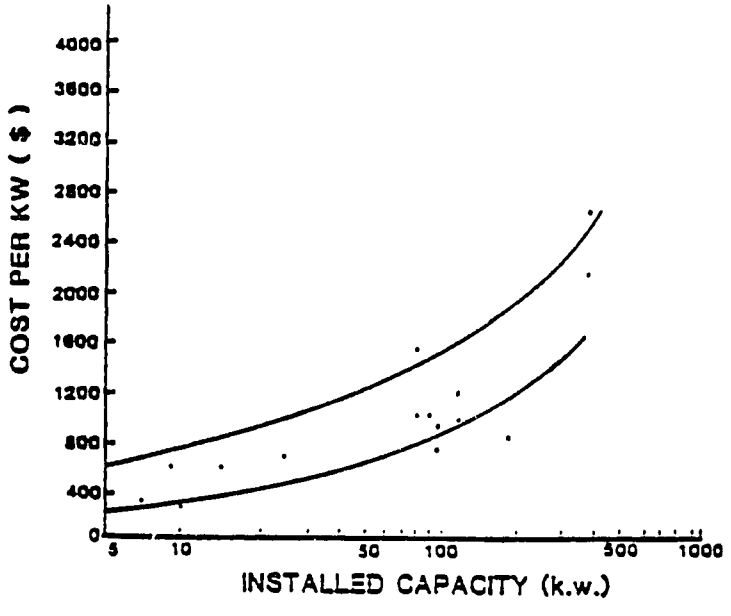


Fig. E(2). Cost Trend for Small Hydropower Plants in Developing Countries.

source: Curve plotted from figures given in Fig. A.

Fig. E. Cost Trends for Small Hydropower Plants.

data available to date suggest some interesting trends. Fig. E(1). gives a series of cost curves covering a range of sizes and approaches to development. At the lower end of the capacity scale, costs are considerably lower for schemes emphasizing local approaches to development, such as are found in Pakistan (Appropriate Technology Development Organization) and Nepal (Butwal), as compared to the costs of similarly sized plants under the more conventional approach, such as in the case of Thailand (National Energy Administration). Falling between the two general categories is a curve showing the costs of plant designs where civil structures are generally of a conventional nature but the turbo-generating equipment is not conventional, using centrifugal pumps run in reverse and standard, off-the-shelf generators. Note that each curve shows economies of scale where the unit capital costs decline as the size increases. But taken together, the curves show that as the capacity increases, so do the unit installed costs, or that reverse economies of scale occur.

Fig. E(2). plots the unit capital costs of the plants given in Fig. A. The resulting curve, or "envelope," since that data present only a general trend, from this sampling of actual costs tends to confirm the reverse economies theory. It should be acknowledged, however, that the local approach shown here only applies to very small capcity plants, due to the limited manufacturing capabilties of small workshops and the difficulties of using traditional village civil engineering techniques to accomodate larger water flows generally required for larger schemes.

The general conclusion one might derive from Fig. E. is that where hydraulic conditions permit the development of only very low capacity plants, of 100 kW or under, conventional development approaches are not as cost-effective as non-conventional approaches. As you move toward larger capacity schemes, above 500 kW, economies are not as great but nonetheless, may certainly be worth undertaking, depending on the cost of alternative solutions, and particularly if the plants can be interconnected with an existing national or regional grid. What is left is the least economical range, between 100 kW and 500 kW, where local technologies are presently difficult to apply, but economies of scale with more conventional approaches tend to auger against the small hydro option. For this range of plant, it may be best to consider

adapting certain aspects of civil works used in local schemes that avoid the use of extensive materials such as concrete and steel, and substituting standardized pumps and generators for custom-made turbo-generating equipment as proposed by the New York State Energy Research and Development Authority.

6. CONCLUSION

In summary, the costs of small hydropower plants are widely variable, and are subject to a host of interrelated technical, economic, and institutional factors. Least-cost solutions are more likely when all are considered as a whole. A technically ideal project may result in a misuse of resources if socio-economic factors have not been sufficiently taken into account. Is the energy appropriate to the need, and will it be available when it is needed? Is it affordable, and if so, are the people willing to take responsibility for making it economically viable? Can it be maintained? Local community participation that exists in the project right from the start—in the design, the collection of technical information, the construction, and the management and maintenance of the system—can lead to cost-effectiveness of a small hydropower project both in terms of the capital cost and in terms of extending its useful life.

Small hydropower technology, as with rural electrification in general, should not be viewed as an objective, but as a means; nor should it be "pushed" at any cost. In some cases, particularly where the goal is import-substitution, it may not be warranted as the most cost-effective option. The capacities of these plants may not be great, and therefore may not be worth the cost of capital-intensive development using a conventional power management approach aimed at maximizing the power potential of a site.

As an alternative to the conventional approach, the record to date suggests that small, micro-sized (below 100 kW) hydropower systems, based on:

- maximum use of local expertise and materials;
- acceptance of a lower, but acceptable, standard of reliability; and

— simple, and easily maintained machinery,

may offer be the best hydro solution for very remote rural areas where energy demand is initially low. The reason is that conventional development, which relies on imported equipment and foreign engineering standards, and substantial use of expensive materials for civil works such as steel and cement, do not allow as much opportunity for flexibility in design and construction. This is not to say that larger mini-hydro systems, where conditions are right (e.g. retrofitting existing dam structures; easy interconnection with the grid; opportunities for standardized "fits"), cannot be a cost-effective means of expanding a national power system. However, the cost-competitiveness of this approach in the medium size-range has generally not been proved, not only in developing countries, but in the United States as well. However, when significant economies of scale can be achieved at high load factors—in a range generally above 500-1,000 kW—the technology fares bettter economically. Again, it should be stressed that there is a fundamental trade-off between cost, on one hand, and operational reliability and efficiency on the other hand, in selecting the development approach. However, plants that are constructed simply are also relatively easy to operate, maintain, and replace. The same cannot be said for plants based on more complicated technology in parts of the world where technological infrastructure is not yet fully developed.

FOOTNOTES

1. Conferees at the United Nations Conference on New and Renewable Sources of Energy in Nairobi last summer ranked hydropower first among all other technologies on the basis of its economy and technological accessibility.

2. In a recent study examining the net energy ratios (output/costs) of small vs. large, conventional hydropower plants, small schemes showed a mean ratio more than twice as high as large plants, even without the additional cost of transmission included. Oak Ridge National Laboratory (U.S. Dept. of Energy), Net Energy of Seven Small-Scale Hydroelectric Power Plants (July, 1981).

3. Goldenberg, Jose, "Energy Consumption and Decentralized Solutions", Energy and the Developing Nations, Electric Power Research Institute (March, 1980).

4. Energy in the Developing Countries, World Bank (1980)

5. Small Hydroelectric Powerplants, NRECA (1981), and Small Hydropower for Asian Rural Development, NRECA (1982)

6. Dickinson, H. and Whittington, H.W., Rural Electricity Supplies, University of Edinburgh School of Engineering Science (June, 1978).

7. Standardization of Hydroelectric Generating Units for Low-Head Hydro, Allis-Chalmers (1979).

8. Meier, Ueli, Local Experience with Micro-Hydro Technology, Swiss Center for Appropriate Technology (1981).

9. Simplified Methodology for Economic Screening of Potential Low-Head Small Capacity Hydroelectric Sites, Electric Power Research Institute (1981).

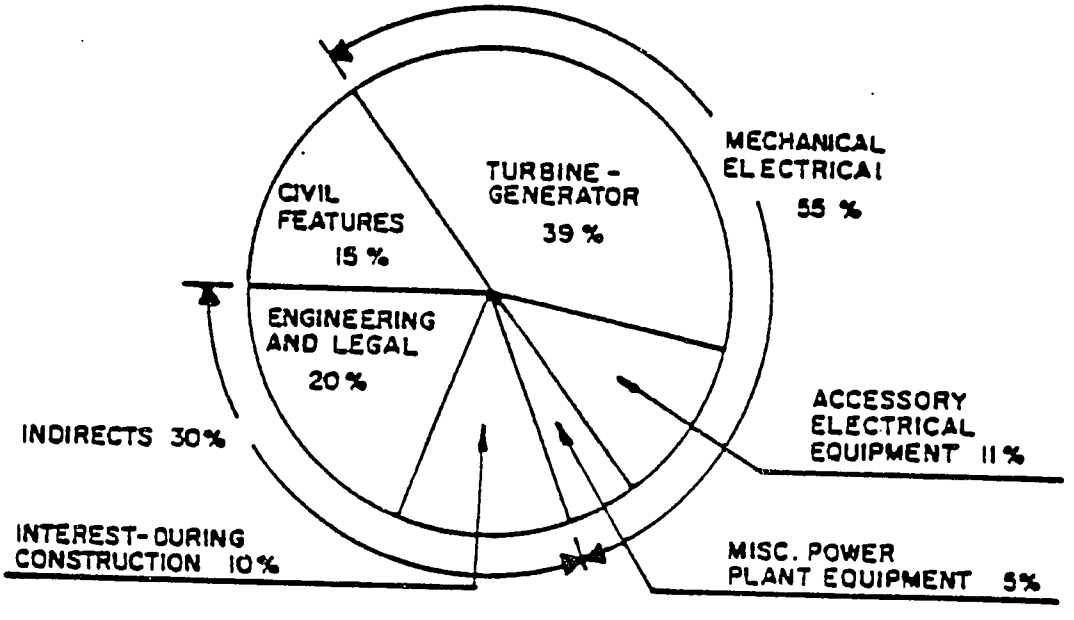
10. Allis-Chalmers, op. cit.

11. Ibid.

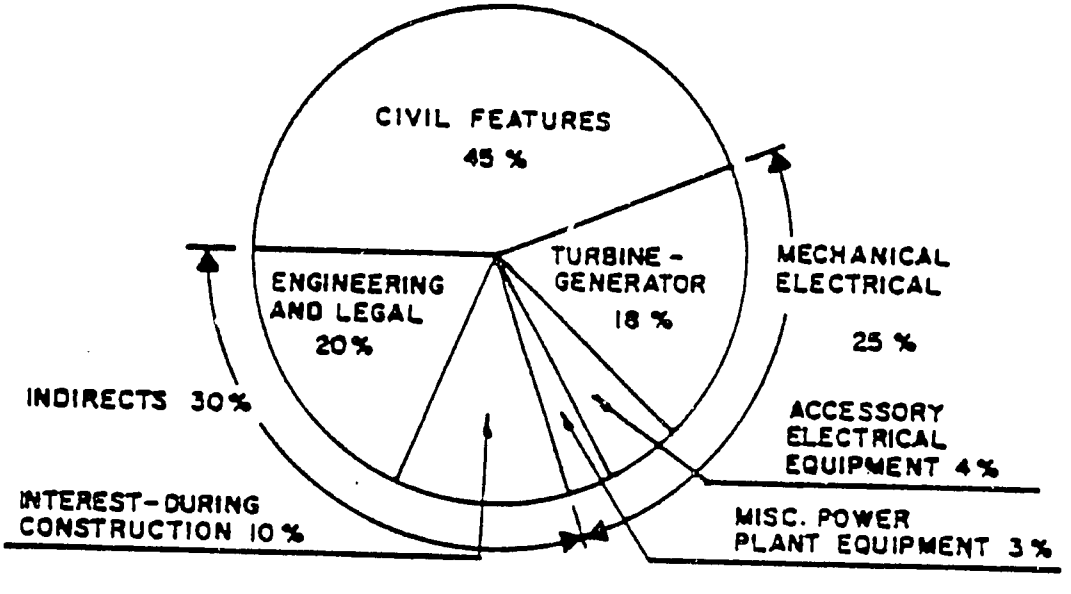
12. Small Hydroelectric Powerplants, op. cit.

13. Mohammed Abdullah (ATDO), in a conversation with author regarding experience in Pakistan (NWFP) with micro-hydro projects (1982).

Appendix A-1. Approximate Proportion of Project Capital Costs for Conventional Development



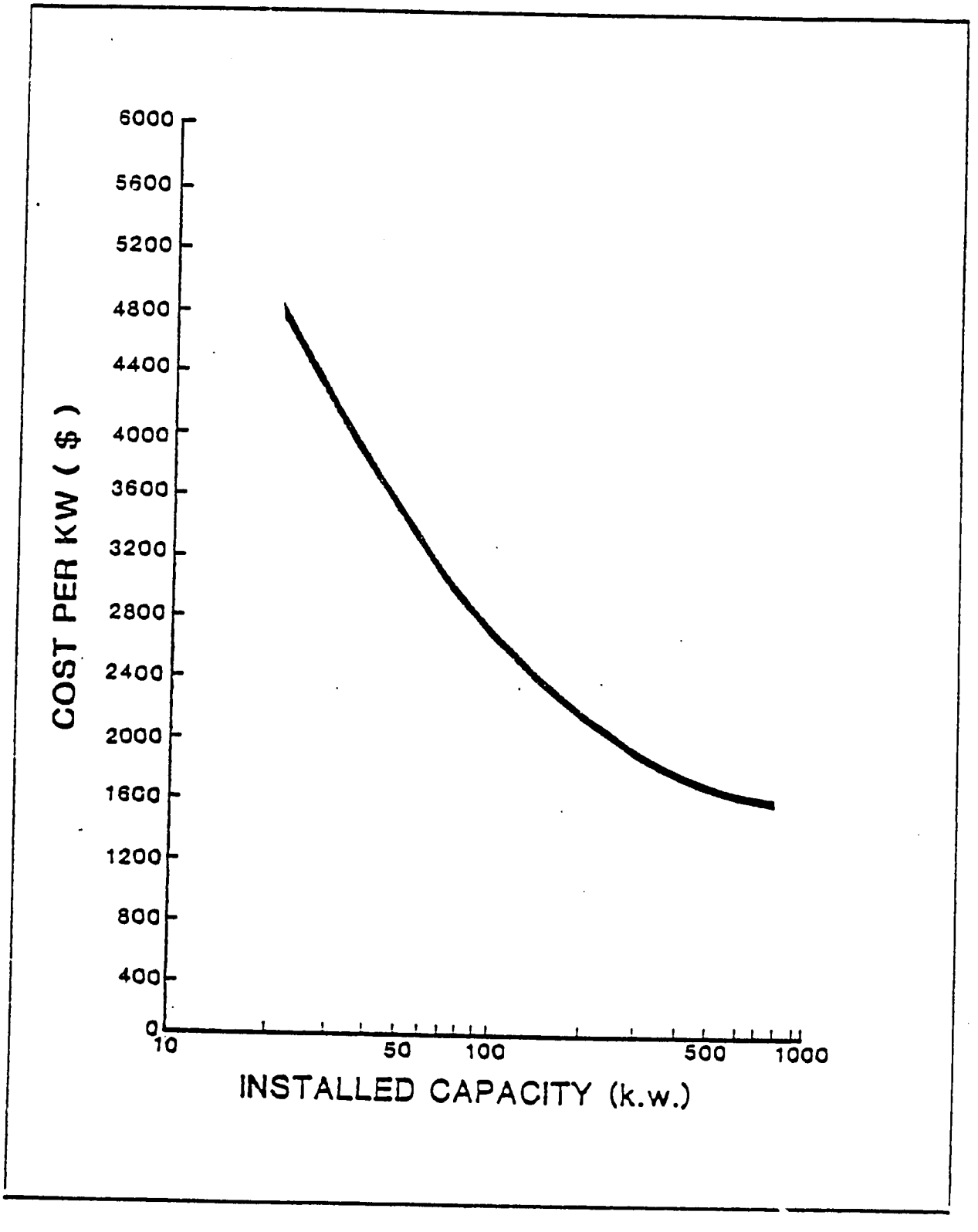
MINIMUM CIVIL FEATURES COSTS



MAXIMUM CIVIL FEATURES COSTS

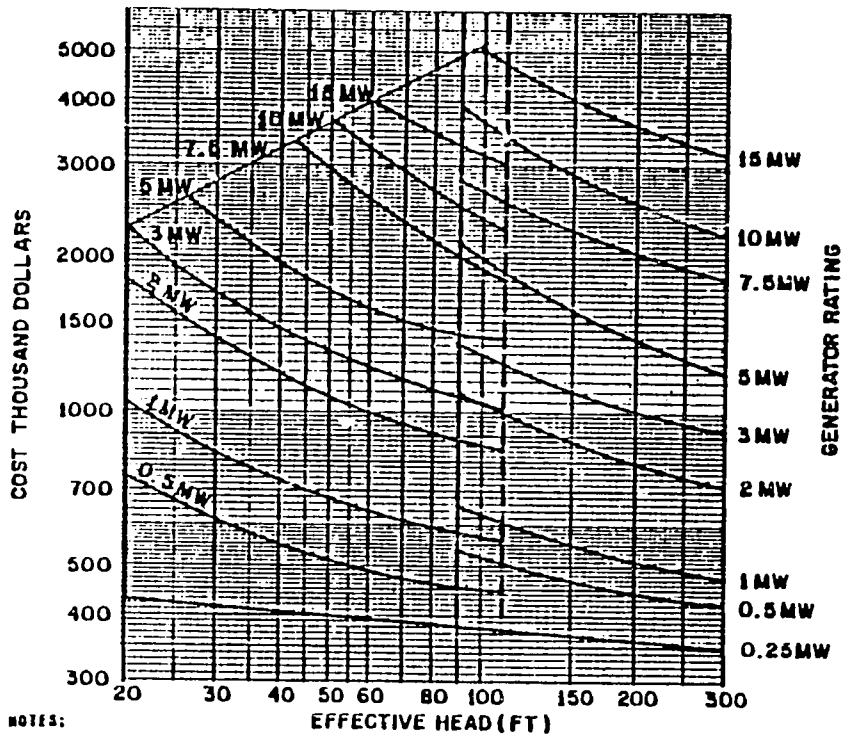
Source: U.S. Army Corps of Engineers (1979)

Appendix A-2. Base-line Cost Curve for Conventional Small Hydro Plants



source: New York State Energy Research and Development Authority (1981)

Appendix A-3. Cost Guide for Conventional Small Hydro Plants.



NOTES:

1. Estimated costs are based upon a typical or standardized turbine coupled to a generator either directly or through a speed increaser, depending on the type turbine used.
2. Costs include turbine/generator and appurtenant equipment, station electric equipment, miscellaneous powerplant equipment, powerhouse, powerhouse excavation, switchyard civil works, an upstream slide gate, and construction and installation.
3. Costs not included are transmission line, penstock, tailrace construction and switchyard equipment.
4. Cost base July 1978.
5. The transition zone occurs as unit types change due to increased head.
6. For a Multiple Unit powerhouse, additional station equipment costs are $20,000 + $58,000x(n-1) where n is the total number of units.

Source: U.S. Army Corps of Engineers (1979)

TABLE 4-2
MISCELLANEOUS RECONNAISSANCE ESTIMATE COSTS*
(Cost Base July 1978)

PENSTOCK COST

Effective Head (Ft)	10	20	50	100	200	300
Cost Index (CI)	1,800	745	285	145	70	50

Installed cost = CI x Penstock Length (ft) x Installed Capacity (MW)
Minimum Penstock Cost is $50 per linear foot

TAILRACE COST
Construction Cost = $15,000 fixed plus $200 per linear foot

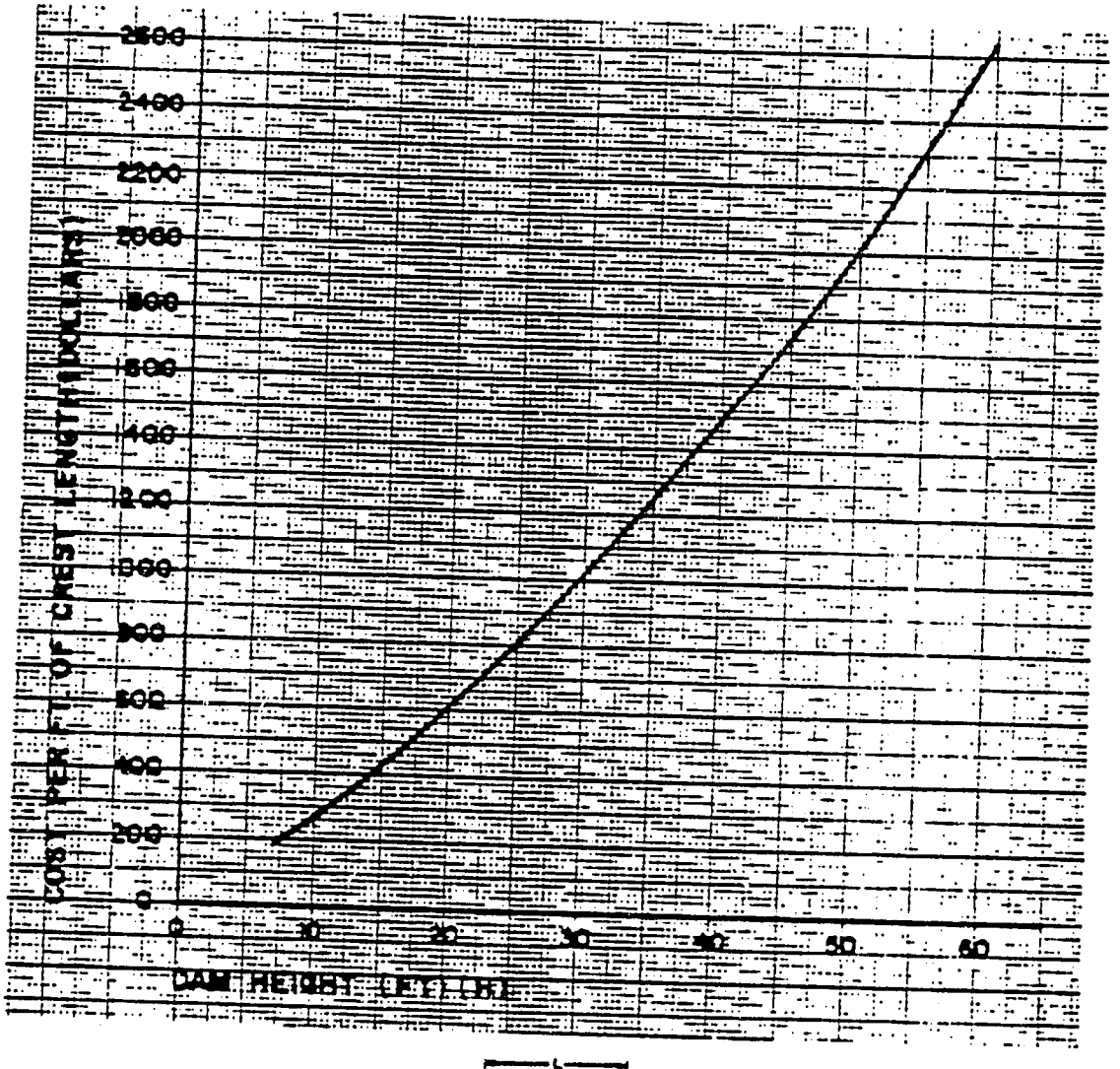
SWITCHYARD EQUIPMENT COST
(Thousand Dollars)

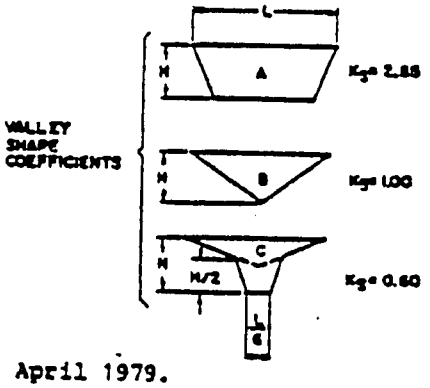
Plant Capacity	Transmission Voltage 13.8	34.5	69	115
1 MW	50	60	110	160
3 MW	85	100	120	175
5 MW	110	125	150	210
10 MW	150	170	210	280
15 MW	185	220	250	320

TRANSMISSION LINE COST
(Thousand Dollars)

Plant Capacity	Miles of transmission line 1	2	5	10	15
0.5 MW	30	60	150	–	–
5 MW	45	80	160	320	500
10 MW	60	100	180	380	600
15 MW	80	140	230	460	700

Appendix A-4. Embankment Dam Costs



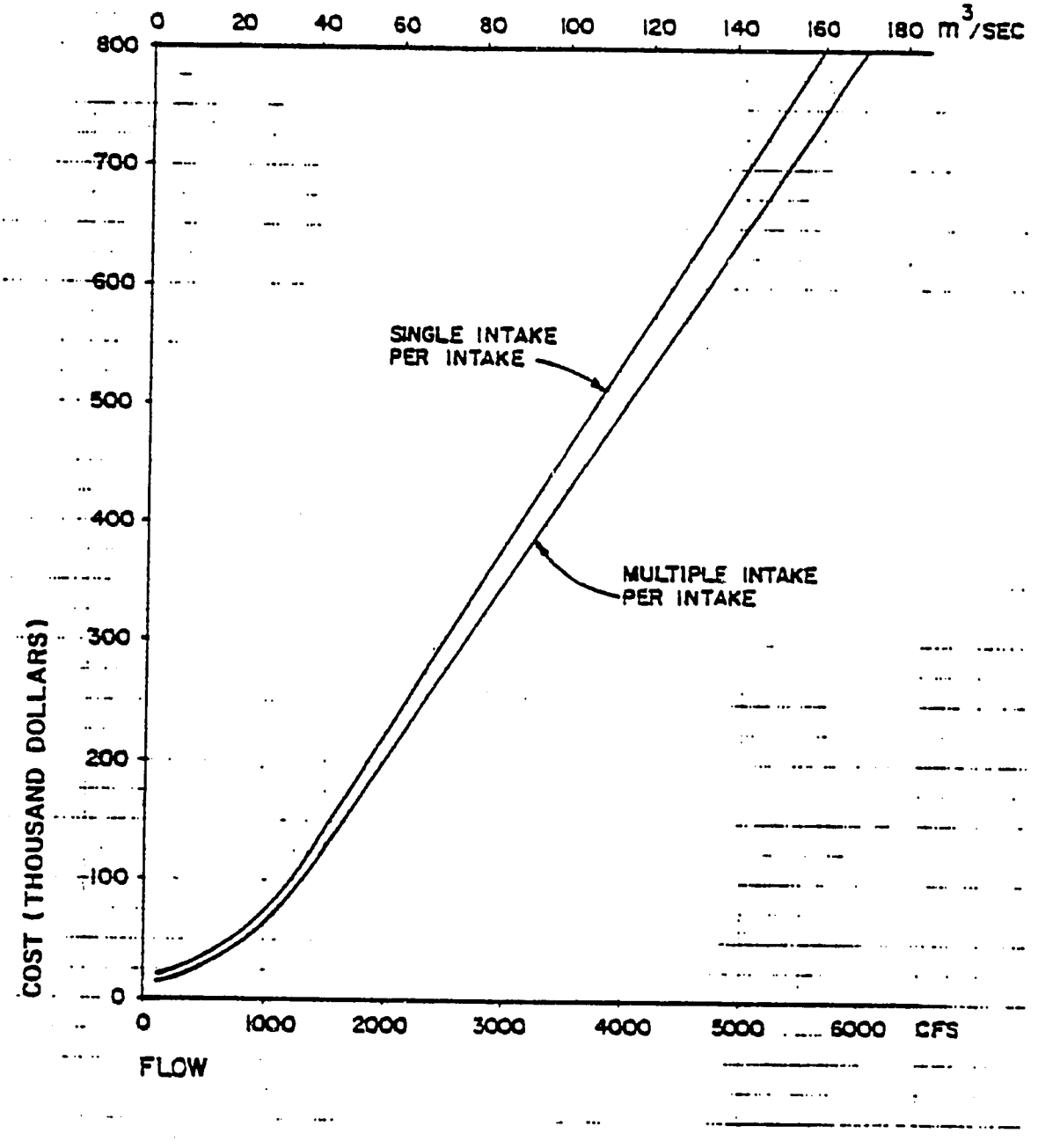


NOTES:

1. Date of costs is April 1979.
2. Total costs obtained by multiplying the cost per foot by the dam crest length.
3. The cost must be multiplied by the valley shape coefficients shown. See also Figure A-2.
4. The cost is based on a unit price of $10 per cubic yard for embankment fill.
5. Costs include 20 percent for excavation, foundation treatment, drainage and other minor items.

source: Electric Power Research Institute (1981)

Appendix A-5. Intake Costs

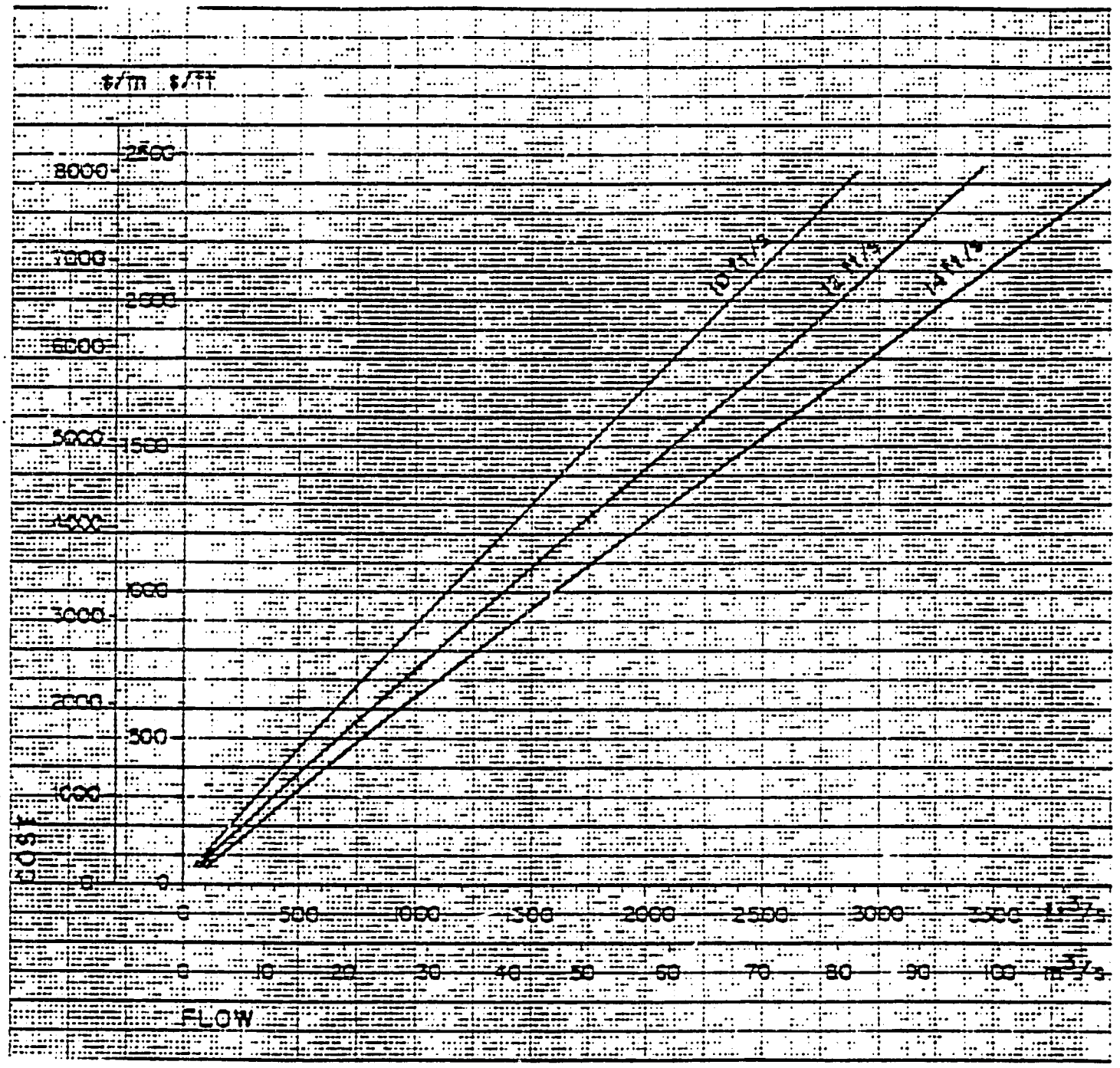


NOTES:

1. Date of costs is April 1979.
2. The estimated cost includes excavation, concrete, reinforcing steel, backfill, trash rack, miscellaneous metal and embedded metal.
3. No cost is included for an intake gate. The gate cost can be obtained from Figure 4-6.

source: Electric Power Research Institute (1981)

Appendix A-6. Steel Penstock Costs for Conventional Low-Head Plants

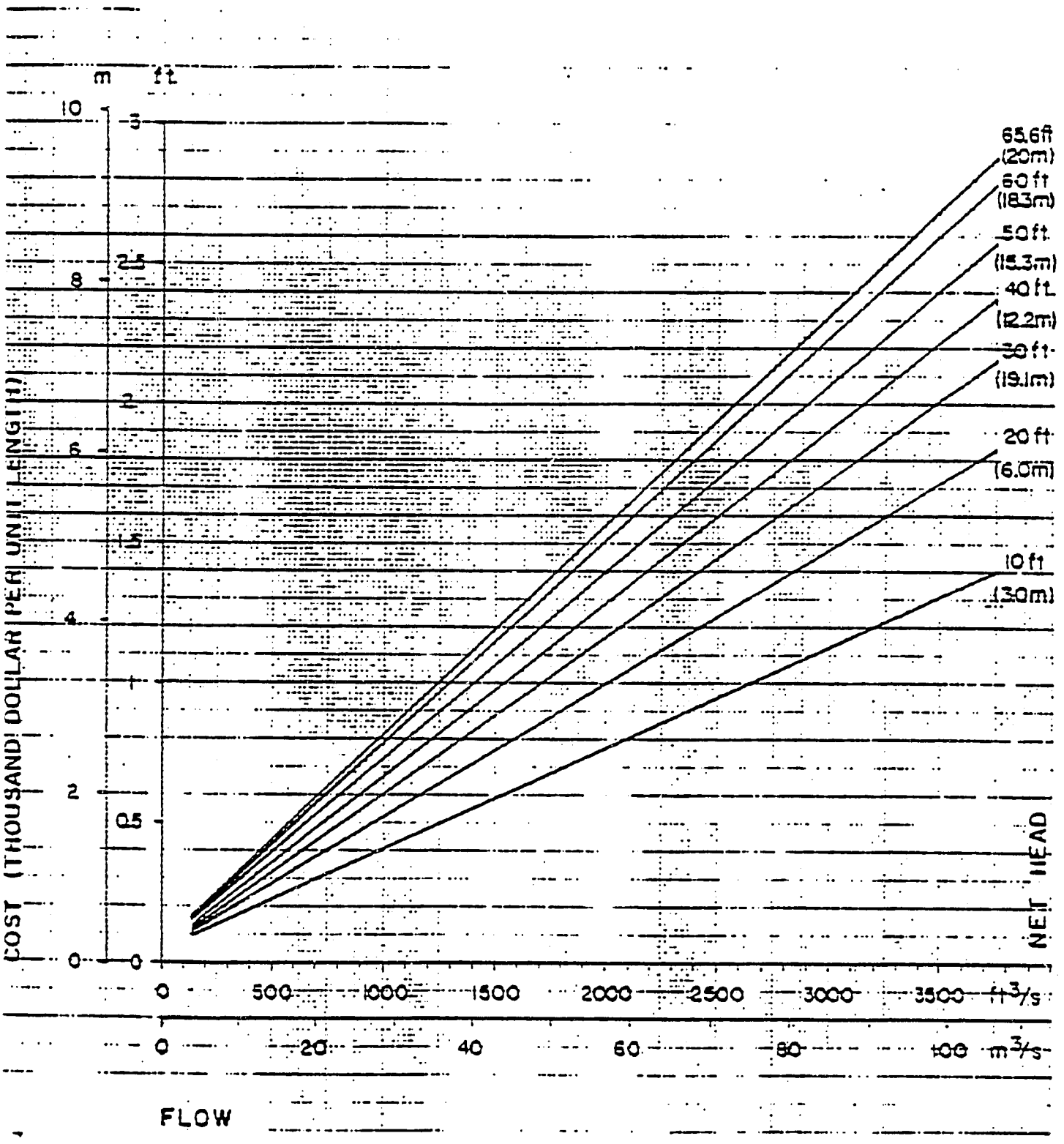


NOTES:

1. Costs based upon minimum handling thickness and a maximum net head of 65.6 ft (20m).
2. If the penstock gradient is greater than 15°, add 1% of total cost for each degree greater than 15°.
3. Costs include a steel penstock, supports, site clearing and excavation.
4. The cost of valves and bifurcations and anchor blocks are not included.
5. Cost base is July 1978.

source: U.S. Department of Interior (1980)

Appendix A-7. Concrete Penstock Costs for Conventional Low-Head Plants

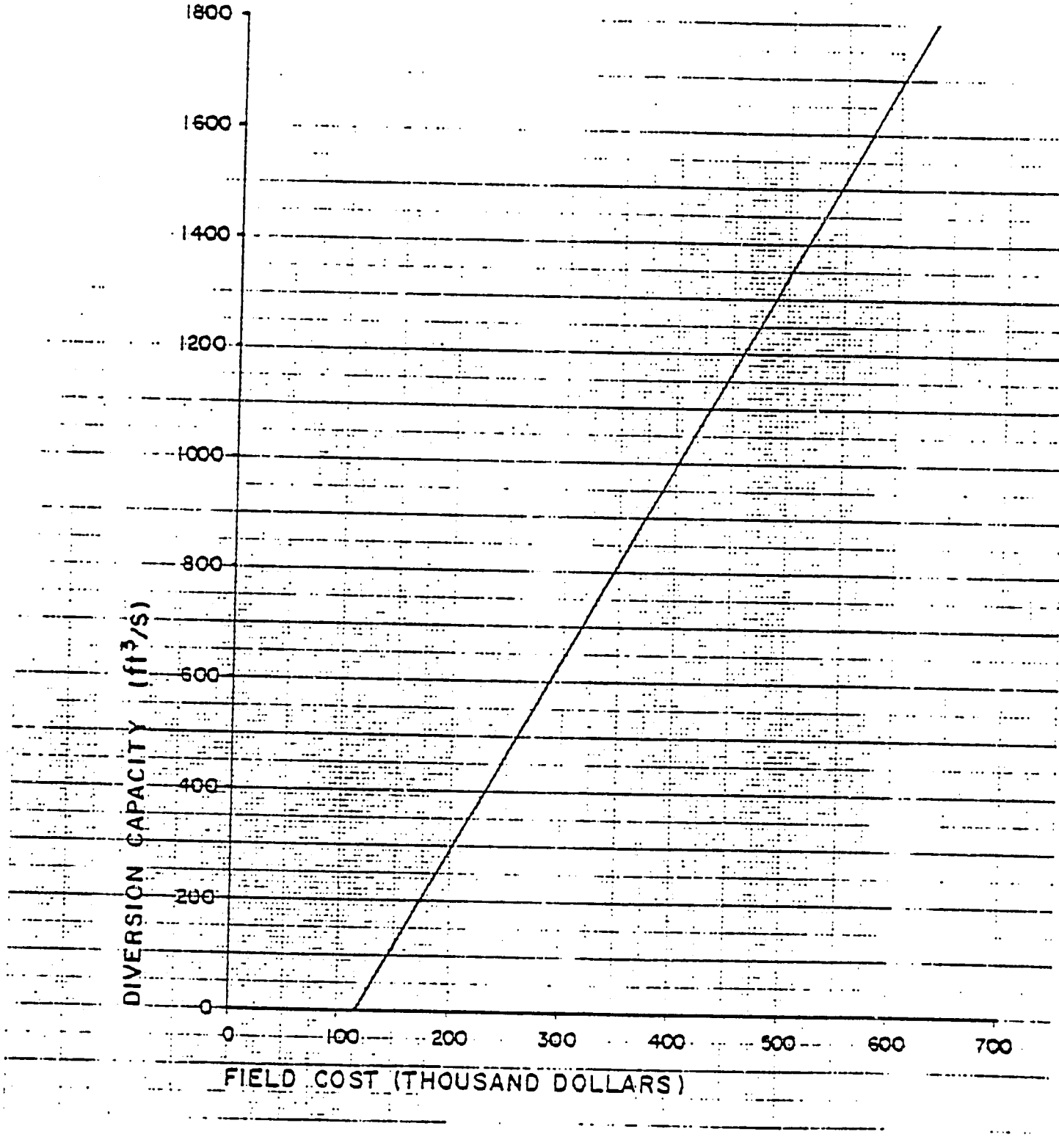


NOTES:

1. The curves give the cost per unit length of a reinforced concrete box section culvert at net heads in the range 10 to 65.6 ft. (3 to 20m).
2. Cost includes concrete, reinforcing steel, excavation 50% rock, 50% common), compacted backfill, foundation preparation, drains and filters.
3. Costs are for a penstock flow velocity of 10 ft/s.
4. Cost base is July 1978.

source: U.S. Department of Interior (1980)

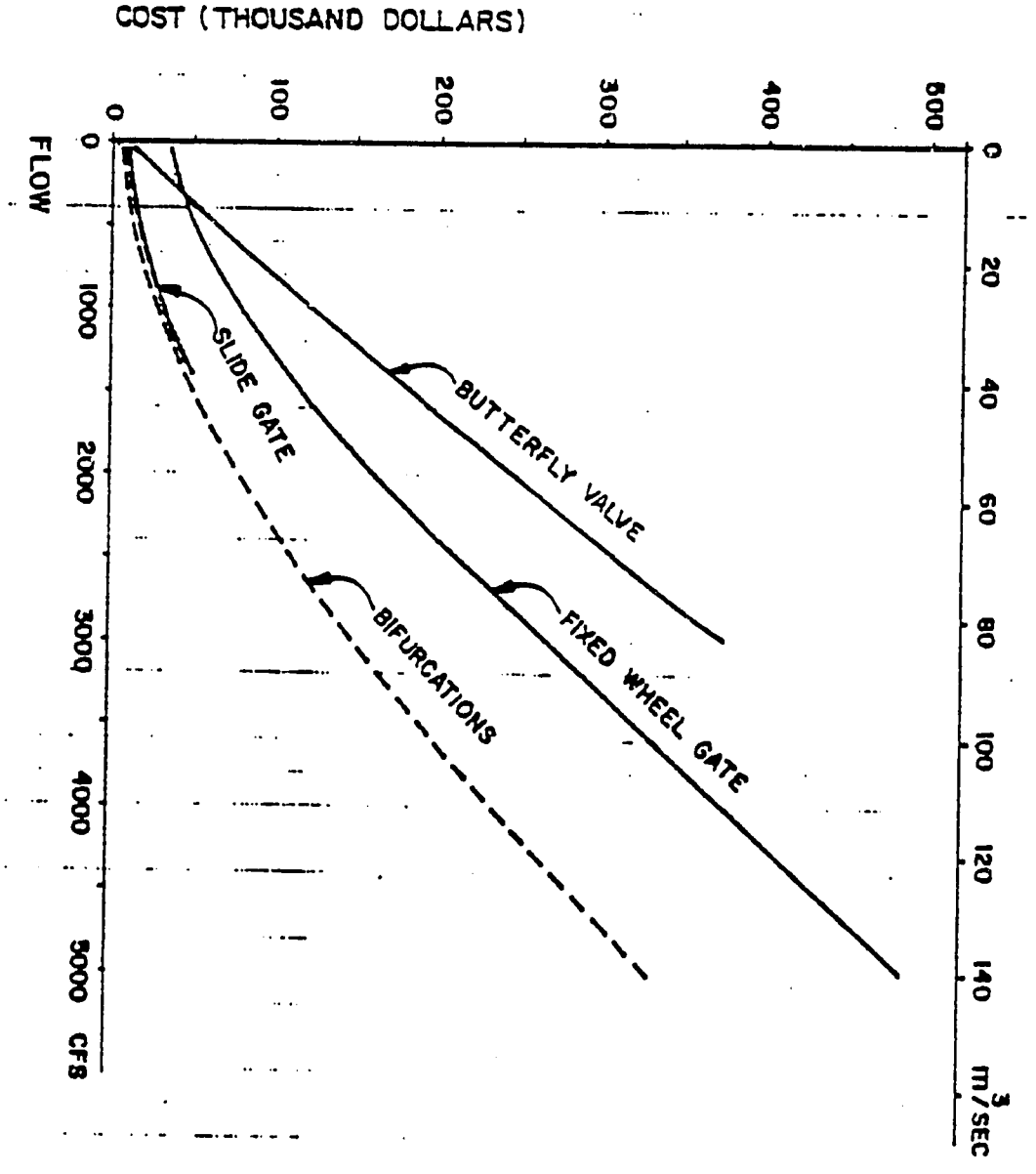
Appendix A-8. Diversion Dam--Field Cost of Canal Headworks, Discharging into Open Canal



NOTE: Cost base is July 1978.

source: Department of Interior (1980)

Appendix A-9. Valve, Bifurcation and Gate Costs

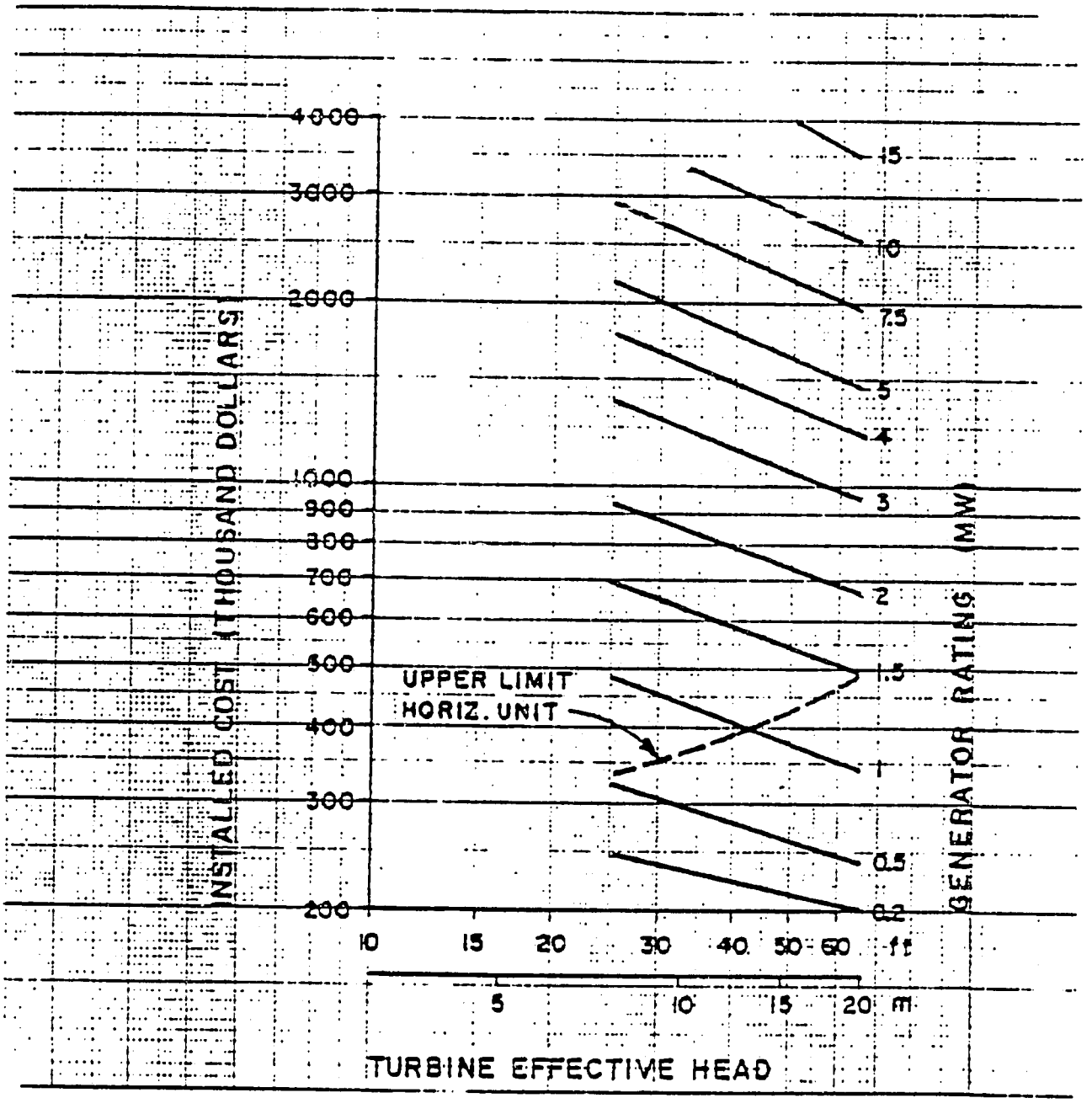


NOTES:

1. Date of costs is April 1979.
2. The estimated cost of the fixed wheel gate includes a hoist, gate frame, guides and installation.
3. The estimated cost of the slide gate includes an operator, gate frame, guides and installation.
4. The estimated cost of the butterfly valve includes a hydraulic operator and installation.
5. The bifurcation cost must be added to the cost of the equivalent length of steel penstock.

source: Electric Power Research Institute (1981)

Appendix A-10. Francis Turbine Costs

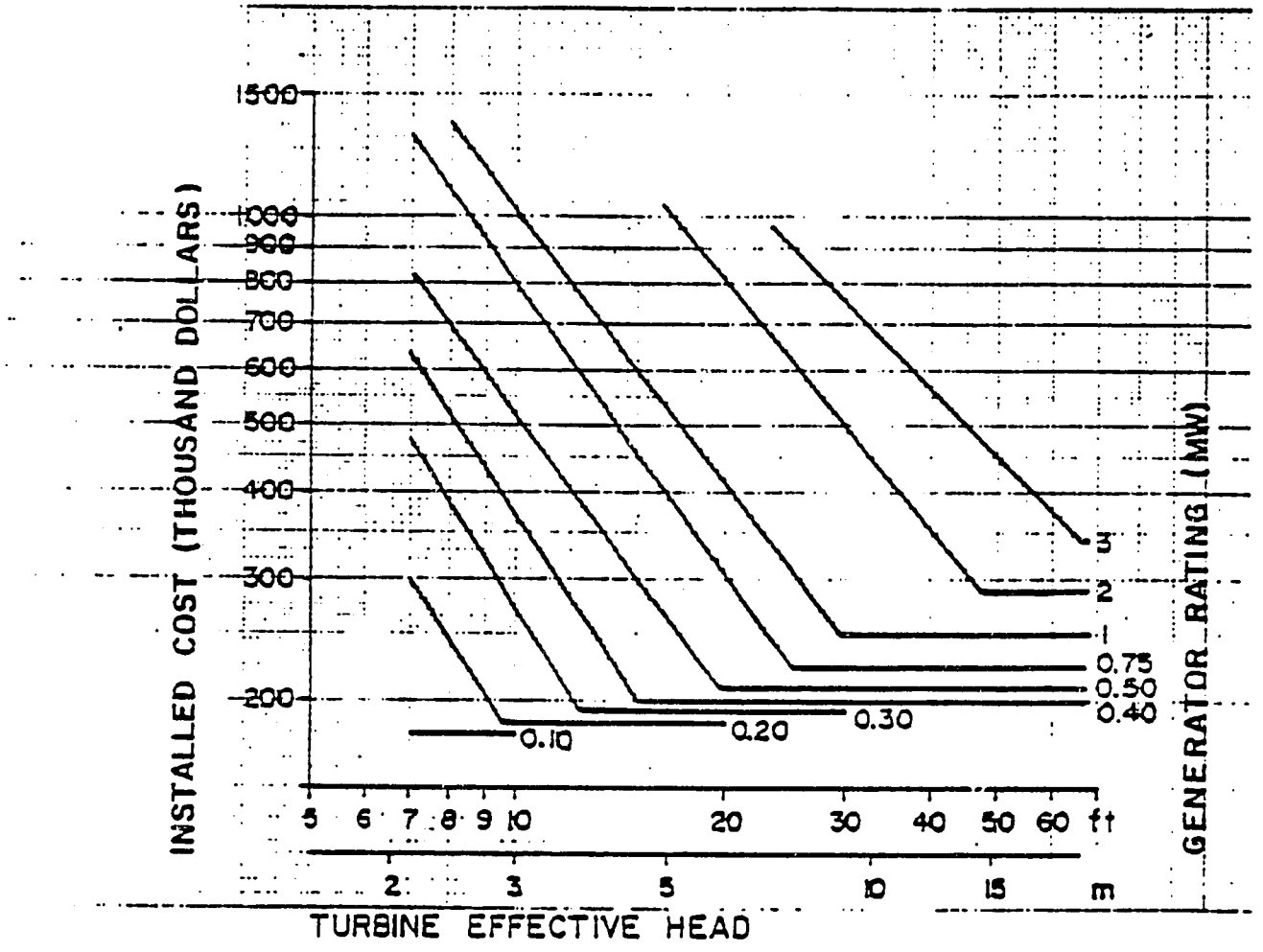


NOTES:

1. Estimated costs are based upon a typical vertical Francis turbine direct coupled to the generator.
2. Costs include a turbine, synchronous generator, inlet valve, non speed regulating governor and installation.
3. Installation costs are estimated at 15% of the total equipment cost.
4. Add $60,000 for speed regulating governor.
5. For horizontal mounting, deduct 7% of cost.
6. Cost base is July 1978.

source: Department of Interior (1980)

Appendix A-11. Closed Flume Turbine Costs

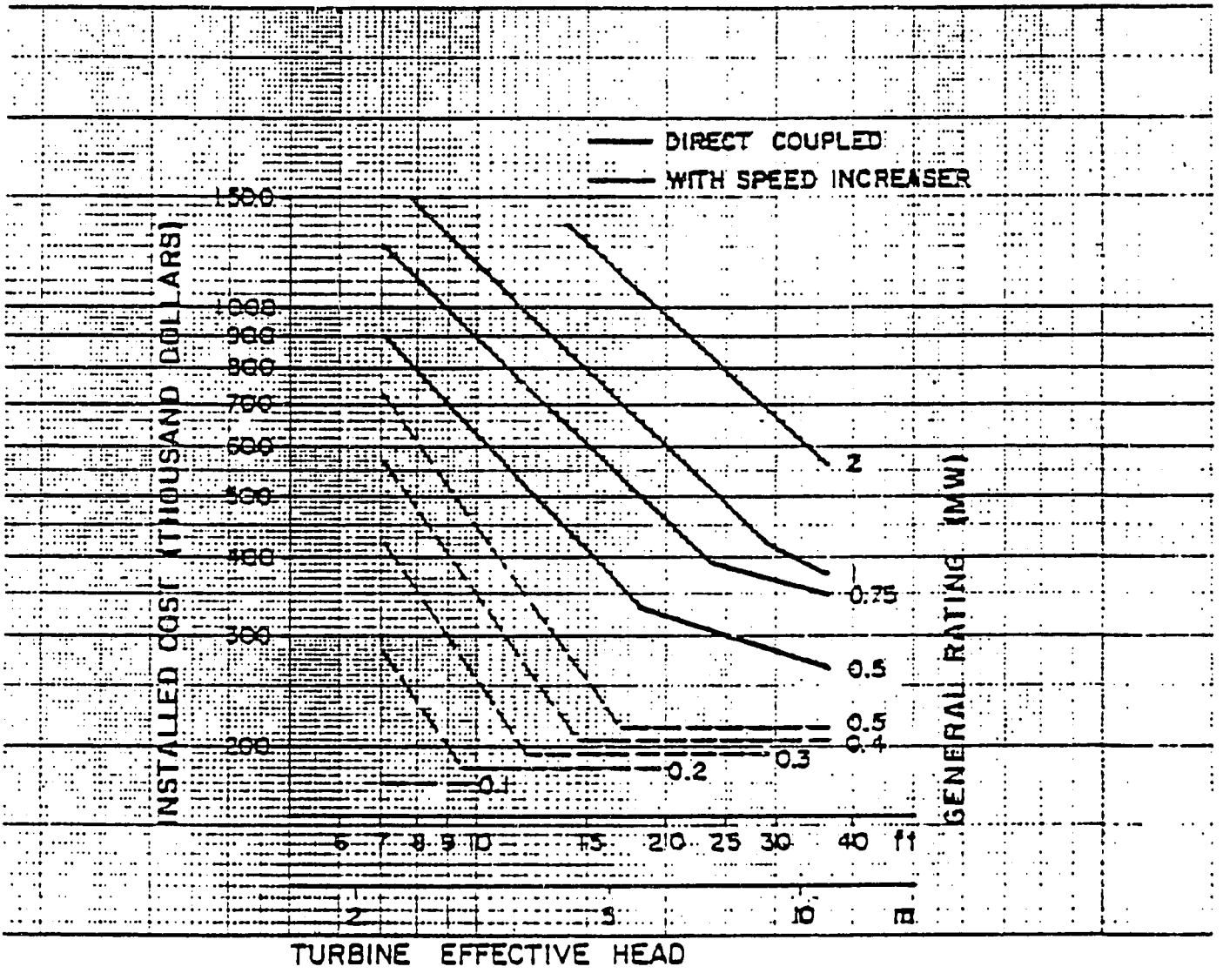


NOTES:

1. The estimated costs are based upon a typical horizontal turbine of either the propeller type coupled to the generator through a speed increaser.
2. Costs include a turbine with fixed blade runner and wicket gates, synchronous generator, speed regulating governor, speed increaser, steel spiral case and installation.
3. Installation costs are estimated at 15% of the total equipment cost or $40,000 minimum.
4. For vertical units, add 7% of cost.
5. Cost base is July 1978.

source: Department of Interior (1980)

Appendix A-12. Open Flume Turbine Costs

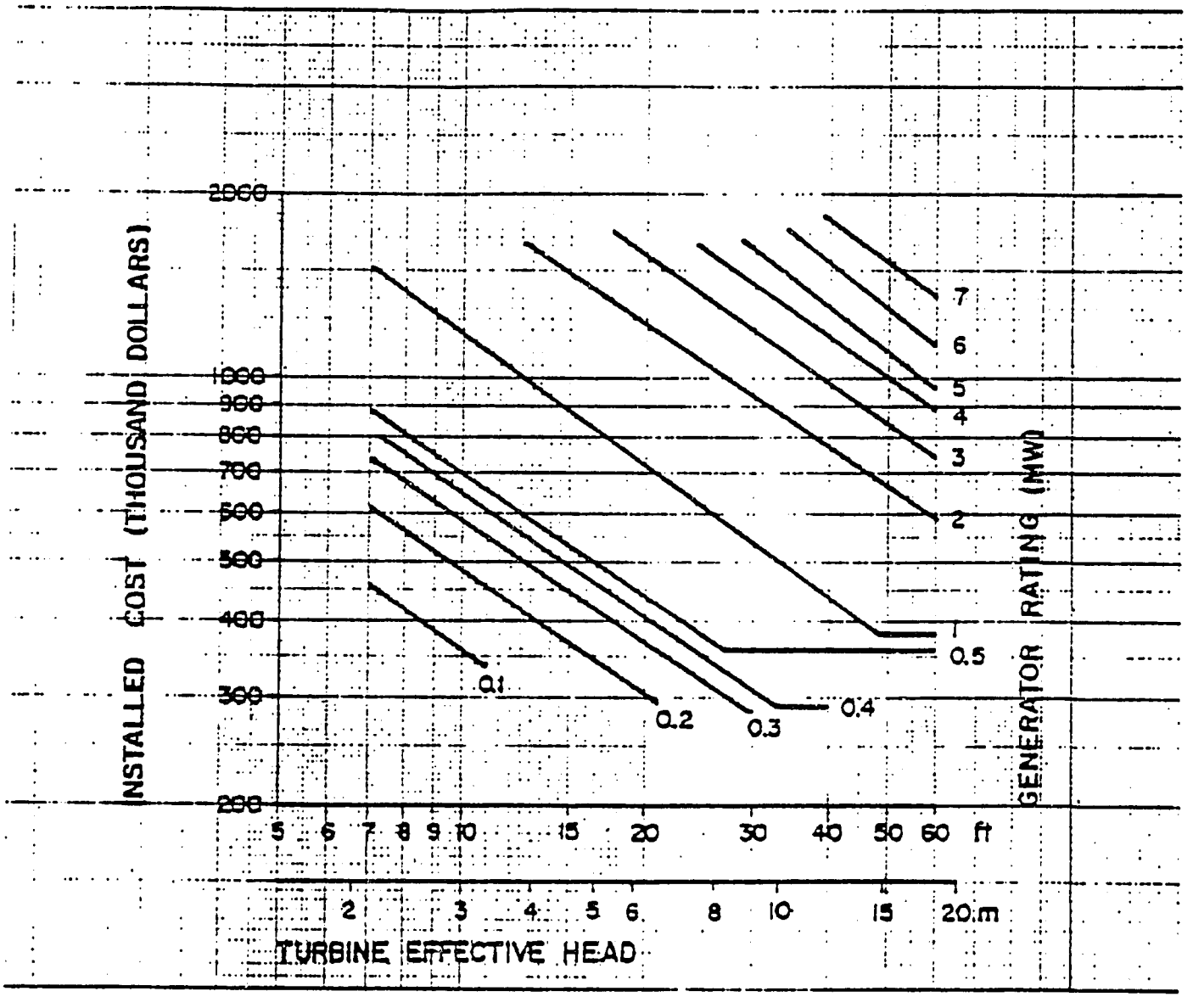


NOTES:

1. The estimated costs are based upon a typical vertical propeller turbine, coupled to the generator through a speed increaser.
2. Costs include a turbine with fixed blade runner and wicket gates, synchronous generator, speed regulating governor, speed increaser and installation.
3. Cost base is July 1978.

source: Department of Interior (1980)

Appendix A-13. Standard Tubular Turbine Costs

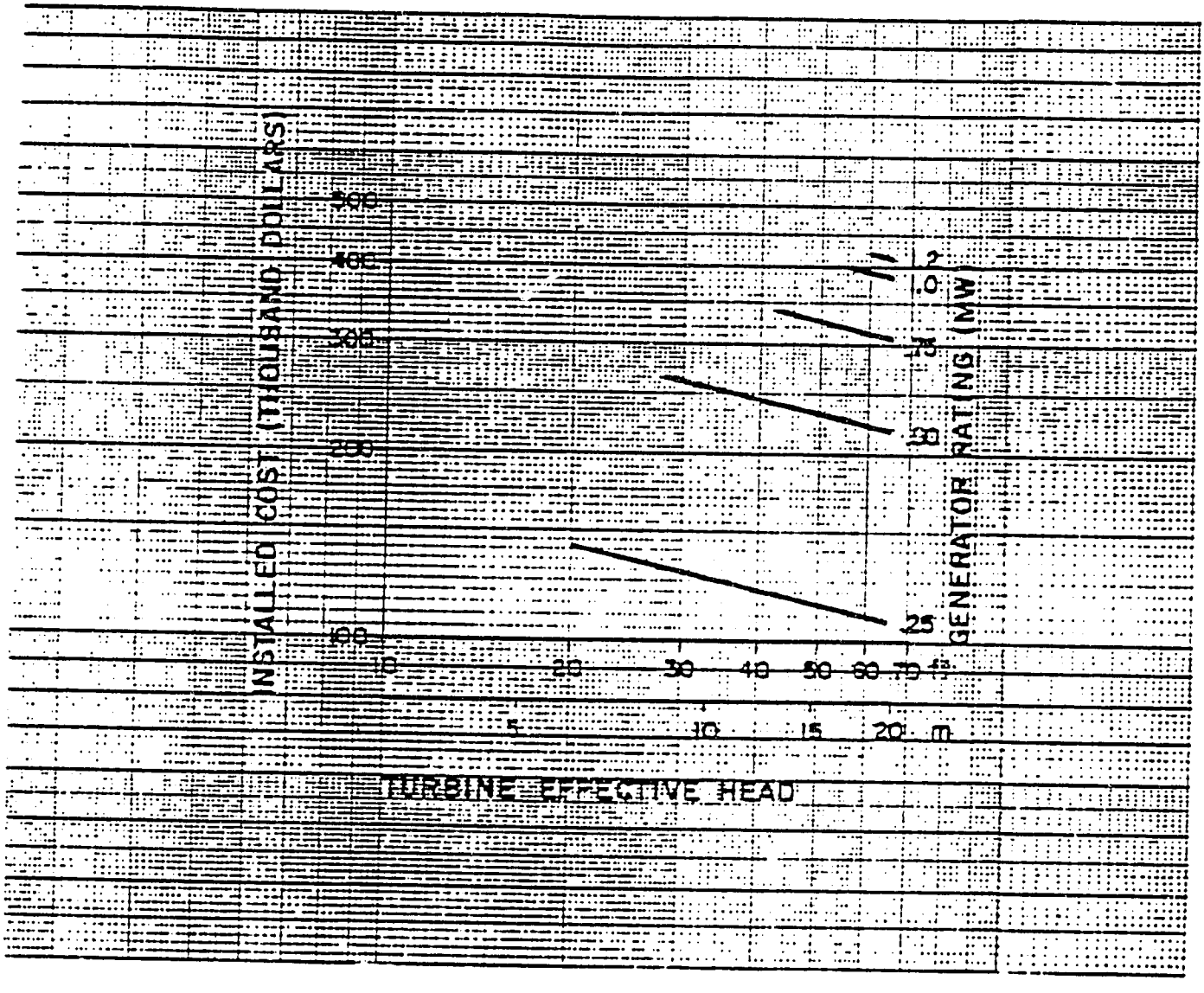


NOTES:

1. The estimated costs are based upon a standardized tubular turbine. coupled to the generator through a speed increaser.
2. Costs include a turbine with adjustable runner blades and fixed guide vanes. inlet butterfly valve. speed increaser. synchronous generator. speed regulating governor and installation.
3. Installation costs are estimated at 15% of the total equipment costs.
4. For fixed blade units. deduct $27,000.
5. Cost base is July 1978.

source: Department of Interior (1980)

Appendix A-14. Crossflow Turbine Costs for Conventional Plants

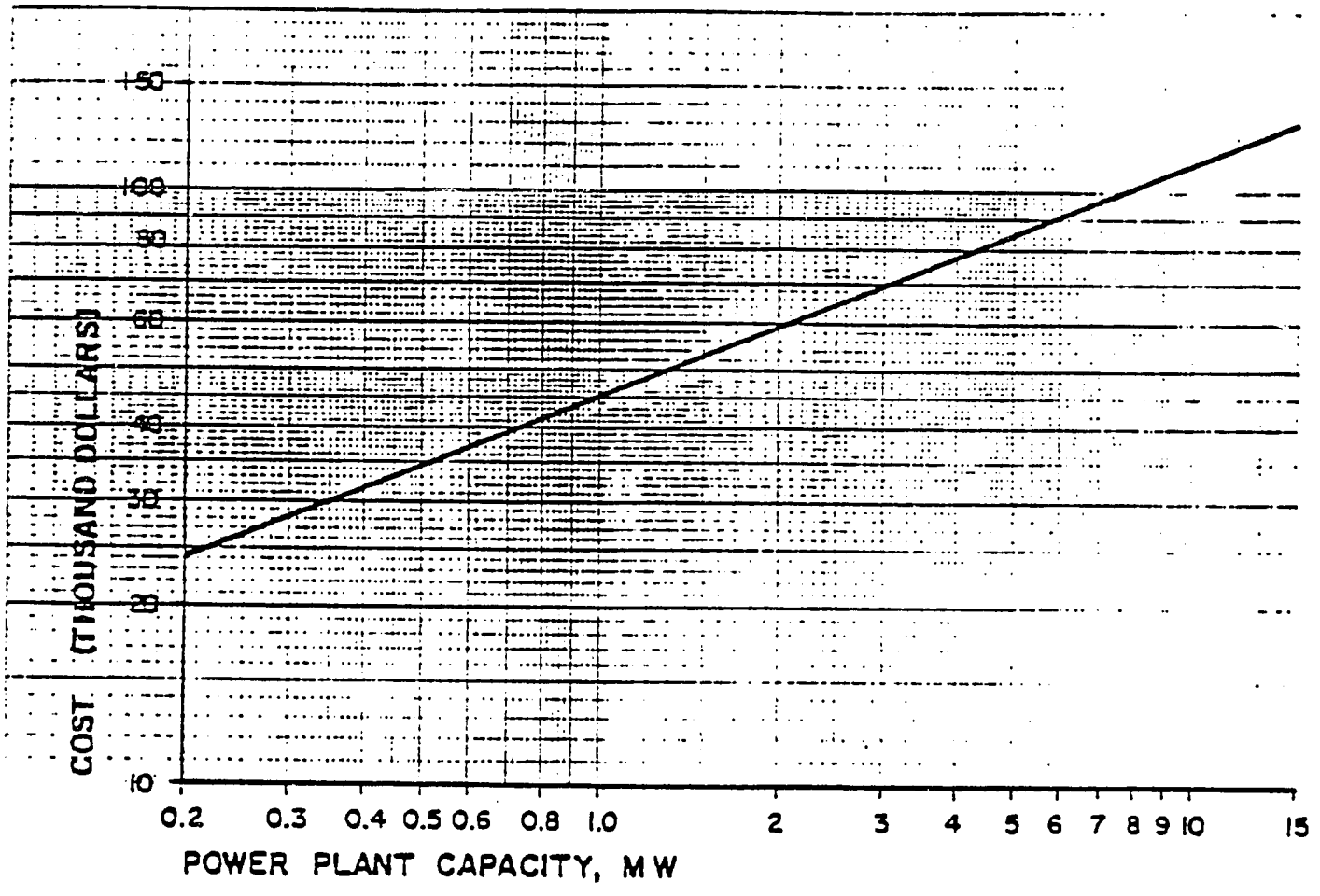


NOTES:

1. The estimated costs are based upon a typical crossflow turbine coupled to the generator through a speed increaser.
2. Costs include a turbine, synchronous generator, speed increaser, inlet valve, non speed regulating governor and installation.
3. For speed regulating governor, add $60,000.
4. Cost base is July 1978.

source: Department of Interior (1980)

Appendix A-15. Miscellaneous Power Plant Equipment Costs



NOTES:

1. The major miscellaneous power plant equipment is listed below:
   a. Ventilation equipment
   b. Fire protection equipment
   c. Communication equipment
   d. Turbine/generator bearing cooling water equipment
2. Communication equipment includes supervisory and radio facilities for unattended remote control of unit; further cost figures should be obtained for very remote locations or integration with complex communication networks.
3. All figures shown include 15 percent for freight and installation.
4. Cost base is July, 1978.

source: Department of Interior (1980)

Appendix A-16. Station Electrical Equipment Costs

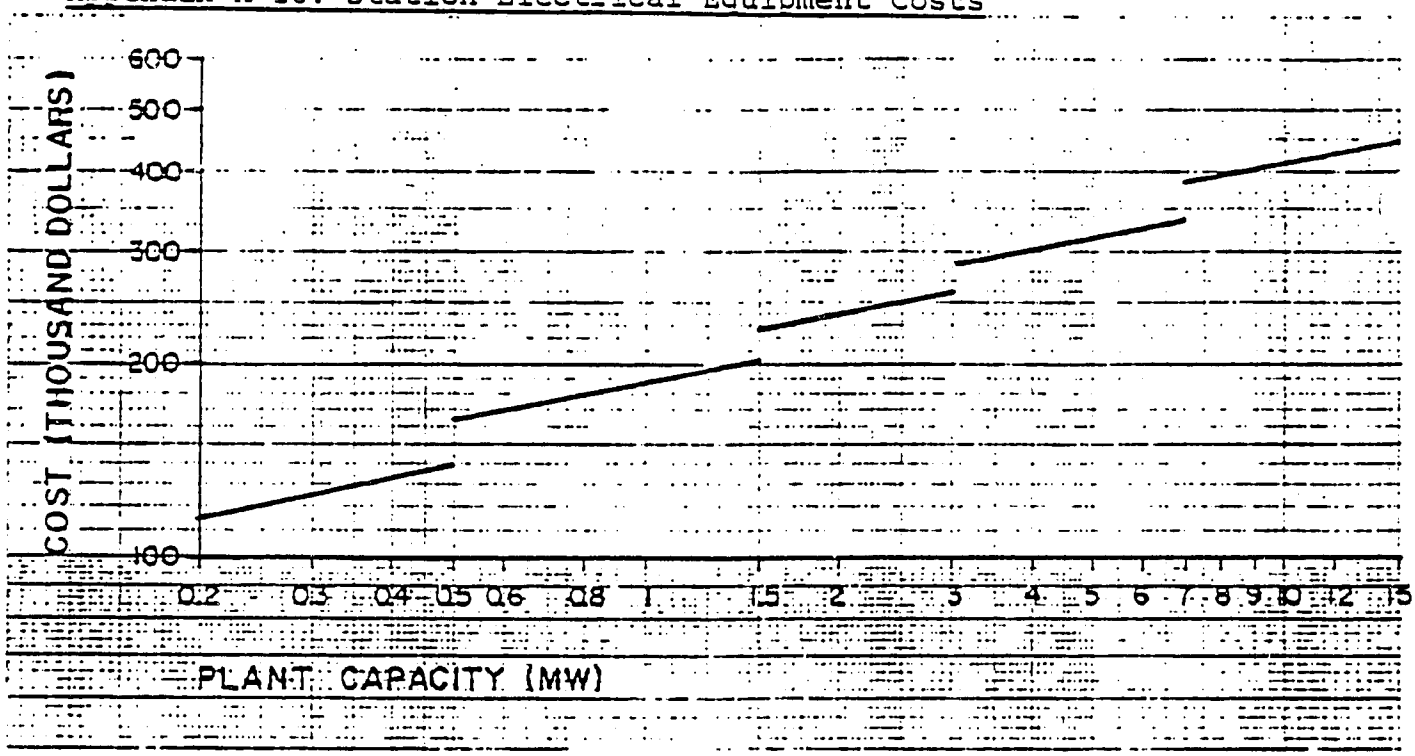


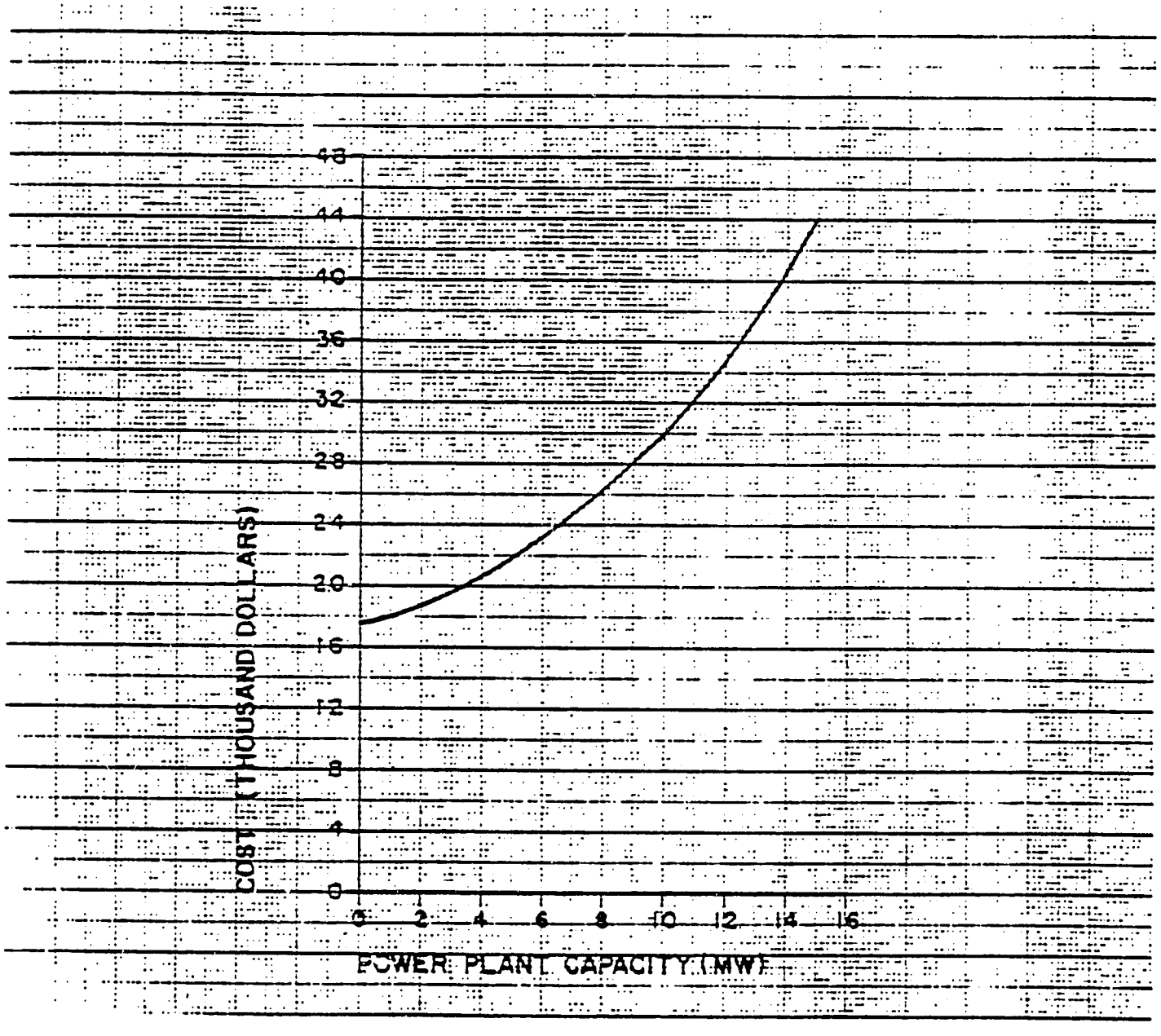
TABLE A	
MW	COST
0.2 - 0.5	25,000
0.5 - 1.5	35,000
1.5 - 3.0	45,000
3.0 - 7.0	60,000
7.0 - 15.0	95,000

NOTES:

1. The equipment and systems for which costs are included are:
   a. D-C switchgear and batteries.
   b. Station service transformer and switchgear.
   c. Main control switchboard.
   d. Wire and cable system.
   e. Conduit system.
   f. Grounding system.
   g. Lighting system.
2. Costs include freight and installation.
3. Costs are shown for a single unit plant.
4. To determine costs for a plant with multiple units:
   a. Determine cost from curve for plant capacity.
   b. Subtract cost from Table A for plant capacity.
   c. Add cost from Table A for unit capacity times number of units.
5. Cost base is July 1978.

source: Department of Interior (1980)

Appendix A-17. Switchyard Civil Costs



NOTE: Cost base is July 1978.

source: Department of Interior (1980)

Appendix C. Cost Summary for Small Hydro Projects in Developing Countries

A. Project Planning and Feasibility Assessment

1. Project Site Selection.
   a. hydrologic investigations.
   b. geologic and topographical investigations.
   c. environmental assessment.
   d. socio-economic and financial studies.
   e. socio-cultural and institutional studies.

2. Project Design.
   a. overall project design.
   b. technical design of power station.

3. Administration and Management.
   a. administration.
   b. management structure.
   c. training.

B. Project Implementation and Construction

1. Direct Costs.
   a. civil works.
   b. turbo-generating equipment.
   c. control equipment.
   d. station electrical equipment.
   e. transmission and distribution.
   f. unskilled labor.
   g. construction management and technical assistance.
   i. transportation of material, equipment and workforce.

2. Other Direct Costs.
   a. access system.
   b. construction equipment and tools.
   c. construction period interest.
   d. land, land and water rights.
   e. contingencies.

3. Indirect Costs.
   a. relocations.
   b. subsidies.
   c. foreign currency
   d. environmental costs.
   e. end-use requirements (forward linkages).
   f. indigenous resource development requirements (backward linkages).

C. Recurring Costs

1. Operation, Maintenance, and Replacement.

2. Financing Charges.

Author's note: A number of these items are relevant only in terms of the economic analysis of a project, and may not appear in the financial analysis; they might even appear as benefits (e.g. subsidies) in terms of the financial analysis. It is also recognized that some of these costs might not be considered as adding to the costs of a project, but would be costs that may be incurred whether the project is undertaken or not (e.g. hydrologic investigations, administrative costs). By the same token, this list may not be fully comprehensive, depending on the circumstances of a given situation. Further, it should be pointed out that some items, such as end-use requirements, may only apply for isolated projects undertaken for a specific purpose.

Appendix B. Characterization Criteria for Matching Renewable Engery Technologies to Village-Level Needs

Criteria	Basic Needs	Renewable Energy Technologies	Unit of Measure
	I. Discrimination Criteria		
Type of output	Form of energy that can satisfy demand	Form of energy produced	Not applicable
Temperature of output	Level of heat to perform required work	Range of temperature of energy system output	°C
Spatial dispersion	The number of locations per village needed for the performance of the basic need task	Capability to distribute the energy output produced by the technology	Number of sites per village required
	II. Site-Specific Temporal & Climatic Criteria		
Seasonality	Time of year when the energy demand occurs	Time of year when the resource produces useful energy output	Growing season, non-growing season, or all year long
Time of day	Time of day when energy is required to perform the basic need task	Time of day when the useful energy is produced	Morning, daytime, night, or 24-hour day
Duration	Duration of time per day required to perform the basic need task	Duration of time the technology provides useful energy during the day	Number of hours per day
Sensitivity to interruption	Length of time the performance of the task can be halted	Variability of output of the energy source	Can be interrupted or cannot be interrupted / Variable or not variable
	III. Site-Specific Social/Cultural/Environmental Criteria		
Usage by type of person	Persons participating in the basic need task affected by changing the energy source	Persons likely to be involved in operating the renewable energy technologies and their various skills	By sex, age, and class
Historical, social, & religious influences	Historical, social, and religious requirements/customs that affect how basic needs are met	Traditional patterns that could create resistance to the use of the energy technology and energy use	Description of the historical, social, & religious customs that affect basic needs
Traditional energy sources used	Sources of energy used to satisfy village requirements	Traditional use of renewable energy sources Traditional technologies used to protect renewable energy sources	Units consumed per capita or per task (kilograms of firewood, charcoal, dungs, etc.)
Environmental and ecological factors	Climatic and resource conditions that limit local ability to satisfy needs or that alter relative importance of basic human needs	Factors that influence energy system performance, durability, maintenance requirements, etc.; also factors that are affected by the installation of an energy system or the reallocation of resources	Qualitative descriptions
	IV. Cost Considerations		
Cost	The cost limits for new energy technologies (given the monetary, labor, and social costs of traditional and conventional energy used for basic need requirements and the financial resources available to the village)	Costs of the technology's local application	Costs given in dollars (and/or person days) per unit of work or per unit of output; social cost qualitatively described

source: SERI, U.S. Department of Energy (1980)