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SMALL-SCALE POWER SUPPLIES FOR RURAL COMMUNITIES IN DEVELOPING COUNTRIES

MARCH 1963

GENERAL ELECTRIC

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INTRODUCTION

This report describes and evaluates alternative small-scale power technologies for supplying electric energy to rural communities in developing countries. The principal objectives of the report are to appraise the technical suitability of currently available small-scale power supplies and to delineate near-term and far-term development opportunities for improved equipment systems.

Since the report largely restricts itself to technical considerations, the reader is cautioned against drawing conclusions with respect to the economic feasibility of alternative power supplies. The latter problem is considered in a separate report on Cost Analysis of Electricity Supply Systems for Rural Communities. Nevertheless, the report does draw on the findings of field investigations conducted in India, Colombia, Peru, and Chile for the purpose of formulating technical requirements. Accounts of the field investigations are available in Field Survey Reports for the above-named Countries.

It should also be noted, as brought out in the field surveys, that the supply of electricity, in itself, does not automatically bring about its productive application. Thus an effective utilization system, as well as a means of supply, needs to be established in order for electricity to have a development impact on rural communities.

The report is organized into three major sections. Requirements are discussed initially, followed by an appraisal of the merits of alternative technologies. The concluding section sets forth opportunities for research and development.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

A summarized evaluation of alternative small-scale power supplies for rural communities in developing countries is presented in matrix-form in Table 1. The power supplies tabulated are discussed in the Alternate Concepts section of this report. The principal conclusions of the report are presented below:

Diesel Engine-Generator

Diesel engine-generator plants are the most appropriate equipment for local generation of power where diesel fuels are economically obtainable. Their range of power levels, high performance, rugged reliability and general acceptance in field installations are already well proven. There is a need, however, for improved adaptation of diesel engine-generators to the rural environment. Possible improvements include:

- Simplified operating controls for starting and stopping.
- Ruggedized speed and engine control devices.
- Development of a "packaged concept" including factory installed accessories, weatherproof enclosure, etc., to minimize field installation requirements.
- Increased standardization of components and designs

Gasoline Engine-Generator

Gasoline engine generator plants are an alternate to diesel equipment in situations where their lower first cost, lower efficiency, higher fuel cost, and higher maintenance are acceptable. Power ratings below 1 kw are possible. Plant efficiency and cost are somewhat lower than diesels in general, although in many specific engine designs these are equivalent. The major drawback, relative to a diesel, is the increased frequency of maintenance, i.e., overhaul every 3500 hours compared to 5000 hours for the diesel.

Gas Engine-Generator

For situations where natural gas, bottled gas, or bio-gas fuels are available, consideration should be given to the "LP" gas engine which is a conventional gasoline engine in which the fuel intake and control components have been modified to accept gaseous fuel.

Hydroelectric Generator

Where there is a sufficient water resource both in head drop and flow rate, a hydroelectric plant consisting of conventional components should be given first consideration, particularly if the rural community contributes labor and indigenous materials to the construction of the dam, ditching, and the installation of equipment. Very careful site evaluation is necessary to determine adequacy of water flow rates, site topography and earthwork requirements.

An opportunity exists for standardized packaged hydro electric plants in the power range of 75 to 100 kw for the high head, low flow conditions characteristic of glacier fed streams in upland Peru and Colombia.

Wankel Engine-Generator

The Wankel engine may be successfully demonstrated as a reliable power plant for automotive application within the next five years. If this occurs, it should prove to be considerably lighter in weight, smaller, and cheaper than conventional gasoline engines. It also has possibilities of operating on both gasoline and diesel fuels. These advantages make it an attractive potential future candidate for rural electric plant engine drives.

Thermal Engine-Generators

Thermal engine systems using steam or other vapor as the working fluid will have limited applicability because of system complexities, bulk and weight, relatively low efficiency, and high first cost.

In the event of a requirement for an engine-generator capable of utilizing various indigenous fuels, a modular steam engine-generator, such as those manufactured in Germany for a rated power level as low as 25 kilowatts may be appropirate. An alternate concept based on the use of concentrated solar heat to run an hermetically sealed organic fluid turbine-generator is a possibility for power levels below 10 kw. Limited applicability is forseen for such generators.

Stirling Engine-Generator

The Stirling engine, now under development, is not considered a promising equipment for local power generation because of its very large bulk and associated cost relative to diesel engine equipment. The best possible design would utilize a helium or hydrogen working fluid

at 1000 psi, in which case its efficiency might equal that of a diesel. Equipment size, in this case, would be 2 to 4 times larger. For rural situations, air would be a more practical and safe selection as the working fluid, but the penalty would be a size 8 to 10 times that of the diesel, and performance would drop significantly. The Stirling engine would have the advantage of being able to use indigenous fuels, in the limited situations where this is required.

Gas Turbine-Generator

Gas turbines are available for power ranges above 30 kw. Gas turbines are operable on a variety of fuels, are extremely light weight, compact and easily operated. However, present design characteristics are oriented to special purpose applications such as marine propulsion and emergency power plants, and their maintenance schedules are similar to aircraft practice, with overhauls every 1000 to 2000 hours of operation. Furthermore, gas turbine-generators in the lower power range (below 100 kw) have no more than 10 per cent plant efficiency. Gas turbine technology is advancing steadily, however, and may have long-range implications for small-scale generators.

Wind Generators

Wind-power electric generators are available in the power range below 10 kw, and larger units up to 100 kw are being developed for supplementing grid systems. A wind generator plant for application to an isolated rural community would probably require a large and expensive electric storage capability to help regularize power availability. Furthermore, successful application is so dependent on a favorable wind regime, that the application opportunities in competition with other generation concepts are relatively few. The use of windmills for water pumping is an excellent opportunity for many rural areas, however.

Fuel Cells

Fuel cells using conventional hydrocarbon fuels and air are under development in many laboratories. Their high theoretical efficiency of 50 to 60 per cent and basic simplicity make them an eventual potential competitor of the internal combustion engine. However, a realistic evaluation of their suitability for rural power supplies must await the results of the technical development programs, which face many difficulties.

Photovolatic Cell and Thermoelectric Generators

Photovoltaic solar cells and thermoelectric generators are limited primarily to power levels below 200 watts. Currently the cost of solar cells varies from $500 to $2000 per square foot, which is prohibitively expensive for applications in rural areas of developing countries. Continued research and development will lead to cost reductions, although probably not sufficient for near-term applications in rural communities. A major breakthrough will be required to achieve the cost reductions required.

Thermoelectric generators will also be too costly for small power applications in rural communities in the foreseeable future. A significant cost reduction in this area will also depend upon a breakthrough in materials technology, which cannot now be predicted.

TABLE 1

SUMMARY COMPARISON OF SMALL SCALE ELECTRIC GENERATORS
(Qualitative Scale, Higher Numbers Indicating More Favorable Characteristics)

Type	Power[1] Range (KW)	Efficiency[2] Range (%)	Fuel	Size[4] (ft^3/kw)	Weight[4] (lbs/kw)	Equip. Cost[4] Range ($/kw)	Site Preparation	Maintain-ability	Status	General Applicability
Diesel Engine Gen.	10 - 200+	25 - 35	Diesel	1.4 - 6.0	40 - 140	100 - 320	4	4	Available	Yes
Gasoline Engine Gen.	1 - 150	20 - 30	Gasoline	1.7 - 5.4	50 - 170	90 - 350	4	3	Available	Yes
LP Gas Engine Gen.	1 - 150	20 - 30	Propane-Biogas	1.7 - 5.4	50 - 170	90 - 350	4	4	Available	Yes
Wankel Engine Gen.	3 - 200+	20 - 30	Diesel-Gasoline	2/3 of Gasoline Engine		< Diesel	5	3	Prod. Dev.	Yes
Steam-Vapor Engine	5 - 200+	3 - 6 (Open)[3]	Indig.[7]-Solar	6	400	750(5)	2	2	Available	Limited
Steam-Vapor Turbine	2 - 200+	10-25(Closed)	Indig. -Solar	600 ft^2 Solar Collector/kw		1000(6)	2	2	Prod. Dev.	Limited
Stirling Engine Gen.	Watts - 200+	15 - 35	Indig. -Solar	4 to 8 Times Larger than Diesel		> Diesel	3	3	Adv. Dev.	No
Gas Turbine Gen.	30 - 200+	8 - 16	Liquid - Gas	1	10 - 15	150 - 300	4	2	Available	Maybe
Hydroelectric Plant	1 - 200+	80 - 90	Water	Larger Than Diesel		(Equip. Only) 200 - 500	1	5	Available	Yes
Wind Generator	1 - 100	10 - 20	Wind	---	---	200 - 400	3	5	Available	Limited
Fuel Cell	1 - 200+	50 - 60	Hydrocarbons	.25	25		3	3	Adv. Dev.	Maybe
Photovoltaic Cell	< 200 Watts	5 - 10	Solar	600 ft^2 Solar Collector/kw		≈ 100,000[8]	2	4	Adv. Dev.	No
Thermoelectric Gen.	< 200 Watts	2 - 5	Indig. -Solar	2 - 5	50 - 100	3000 - 5000[8]	4	3	Adv. Dev.	No

1. Small scale power range includes up to 200 kw.
2. Range of efficiencies of typical equipments at full load operation.
3. Refers to type of cycle.
4. Higher values refer to lower power levels.
5. Values estimated for 10 kw closed cycle steam engine generator.
6. Dr. Tabor's 3-3/4 kw MCB turbine generator.
7. Indigenous combustible fuels.
8. Estimates of present fabrication costs.

RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT

Short-Range Equipment Improvement Opportunities

Diesel and Gasoline Engine-Generators

It is recommended that further evaluation of engineering adaptations of the diesel and gasoline engine-generator to the rural environment be undertaken with engine manufacturers. Possible adaptations include simplified operating controls and ruggedized speed and engine control devices, complete "packaging" of engine-generators, including accessories, and standardization of parts.

Medium-Range Equipment Development Opportunities

High-Head, Low-Flow Packaged Hydro Unit

Consideration should be given to the packaging of a high-head, low-flow hydro-electric unit. Such a concept would involve the packaging of already existing technology, including an 1800 rpm Francis reaction turbine coupled to a generator shaft. The equipment might be standardized for a power rating of 75-100 kw.

Wankel Engine-Generator

An agressive development effort is underway on the development of the Wankel engine as an automotive power plant. In the event that this effort is successful, the Wankel engine should be evaluated as an engine drive for small-scale rural power plants.

Thermal Vapor Turbines

It is recommended that a periodic audit be conducted of the development work on small-scale vapor turbines being carried on in Israel. This concept offers some promise where the fuel supply is restricted to solar energy.

Long-Range Equipment Development Possibilities

Fuel Cells

A periodic audit should be conducted of the development status of fuel cell technology. Of potential long-range interest as a rural power supply are fuel cells capable of utilizing common hydrocarbons as an energy input. When a practical demonstration of a fuel cell operating on conventional hydrocarbon fuel and air takes place, possibly within the next two-three years, the potential of the fuel cell as a rural power supply can be better evaluated.

Photovoltaic Cells

A periodic audit should be undertaken of the development status of photovoltaic cells with particular attention to their suitability as devices for supplying very small quantities - less than 200 watts of power.

REQUIREMENTS

This section is based on the field survey investigations carried out in India, Colombia, Peru and Chile in the Spring of 1962, on the Generation and Utilization of Power in Rural Communities of Developing Countries. The findings of these investigations with respect to requirements are set forth in terms of environmental considerations and engineering specifications.

ENVIRONMENTAL CONSIDERATIONS

At the outset of these investigations it was hypothesized that a compact, reliable, small-scale vapor engine-generator--ten to fifteen kilowatts--capable of utilizing alternative indigenous fuels would be an effective and economical means of supplying electricity for productive purposes to remote rural villages. This hypothesis was not borne out in the field investigations as will be discussed below with respect to generating capacity and fuel availability. Additional environmental considerations that have significance for the type of power supply suitable for rural communities include the availability of local technical skills and the use of contributed labor in installing local power supplies.

Village Size in Relation to Generating Capacity

In the limited number of instances where it was judged that the local generation of electrical energy could make a productive contribution at the village level (population 2000-3000), the field studies showed that a 50 kw unit would be the minimum size required. In addition, it would be advisable at the outset to install excess capacity for future load growth. Further, some reserve or standby capacity should be provided to assure a dependable supply. These requirements are well above those originally estimated, and have substantial implications for the alternative fuels that can be considered.

Fuel Availability

It was found that, in practically every case, supplies of local fuels such as wood, rice hulls, dung, straw, leaves, etc. were insufficient to meet the daily requirements of an engine-generator of adequate size on a dependable basis. Some of these fuels are seasonal in supply, e.g., rice hulls and straw, and are difficult to stockpile. Some have other uses besides fuel-agricultural mulch, fertilizers, building materials, or animal feed. Some are concentrated geographically,

for example coal in India, where the cost of transport into the villages is an effective deterrent to its widespread use. Wood is available in certain areas, as in the Indian State of Orissa or in southern Chile, but in general wood is either not available in the quantity required, or is too expensive.

Widespread distribution systems for diesel and gasoline fuels exist in both South America and India. Under these circumstances, reliable internal combustion engines would appear to be the most appropriate equipment for local energy generation. However, diesel power is usually too expensive both in terms of the ability to pay and existing rural electric rate structures. This is particularly true in India, where the price of high speed diesel fuel in rural areas ranges from 50 to 60 cents per U. S. gallon, reflecting the high tax designed to discourage consumption of imported petroleum fuels. It is less true in Colombia and Peru where domestically produced fuel is considerably cheaper, ranging from 10 to 16 cents per U. S. gallon.

The upland areas of Chile, Peru and Colombia in the Andes have many glacier-fed streams with a year-round hydroelectric potential of 50 to 500 kw. Because of their steep gradients (150 to 300 feet per mile) these streams are a potential source of locally generated electricity. This resource has been exploited to only a limited extent for rural electrification and many excellent opportunities exist.

Local Technical Skills

The field investigations revealed a general lack of mechanically trained individuals in village communities. Nevertheless, where diesel or gasoline engines have been installed for pumping and power generation in rural communities in India and South America the local operator has usually acquired a capability to maintain the equipment and to make simple repairs. However, there is a lack of qualified technicians to aid in on-the-spot installation and major overhaul efforts.

Finally the survey teams found no evidence that local workmen could not be trained to utilize modern tools and equipment. Rather the team members were impressed with the responsiveness of local workmen to minimal technical training.

Contributed Labor

Due to the surplus labor force which is characteristic of most of the rural communities investigated by the survey teams an opportunity exists to utilize unskilled contributed labor in the construction of earth

works, setting of poles, and building of structures. Such labor would be particularly helpful in the construction of small-scale hydro facilities on glacier fed streams in the uplands of Colombia and Peru. In this case contributed labor could assist in the construction of the dam, ditching, and foundation for penstock and equipment.

ENGINEERING SPECIFICATIONS FOR LOCAL POWER PLANTS

It is not difficult to list the desirable attributes of a small-scale power supply for a rural community. These would include:

- Reliable performance
- Long equipment life
- Low maintenance requirements
- Simplicity of operating and control
- Light weight and compactness
- Low operating and capital costs

The desirability or relative importance of these attributes for any particular power supply would have to be determined in part by a systems engineering analysis. Such an analysis would specify the trade-offs for the various parameters.

Nevertheless, it is useful to mention some of the practical specifications encountered in the field which must be kept in mind in designing or selecting a power supply. These include ease of equipment transport, voltage and frequency, and system stability.

Transportability

Since access to rural communities in newly developing countries is frequently quite limited, size and weight are often at a premium. In this connection the possibility of disassembly into self-contained units can be highly advantageous.

Voltage and Frequency

Many of the developing countries have established voltage and frequency standards that are based on either U.S. or European practice and in some South American instances vary within the same country. In general, India standardizes on 220 V phase to ground and 50 cycles. The major metropolitan centers in Colombia, Peru and Chile also use these

standards because of their reliance on European generating equipments. But several rural areas particularly in Colombia have 110 and 220 volt phase to ground systems at 60 cycles.

All the countries visited had well established national electrification programs standardized for 220 V at 50 cycles. Rural electrification by isolated plants should also reflect this standard.

Single and three phase equipments are available. However, if motors over 10 Hp are to be connected the three phase type are more readily available and less expensive. Also, three phase generators are relatively cheaper. Three phase distribution, with single phase laterals can ultimately transmit maximum power for the least cost, although initially it may not be well utilized. Consequently, single phase electric plants should not generally be selected; or at the most, they should only be considered for system capacities of less than about 20 Kw. Three phase plants should, in general, be the choice.

Typically, then, the output of an electric plant to serve isolated rural communities (India, Colombia, Peru, Chile) should be:

220-440 volts
3 phase
50 cycle

Electric System Stability

The size and character of the connected load relative to the electric plant rating determines the stability of the system. If only resistance loads, such as tungsten lamps, small radios or irons, are connected, then the total connected load may approximate the plant rating without serious inductive starting loads causing voltage fluctuations or ripple. If there are motor loads, such as are required for refrigerators, water pumping, small industries and workshops, then allowance must be made in sizing the electric plant to accept the starting loads without undue system instability. Typical motors require 2 and 3 times their rated running power for starting, and if there is even a single motor in the system of as much as 1/3 the plant rating system stability will be severely impaired if other loads are operating. As a rule of thumb system stability will not suffer greatly if the maximum individual motor size in the system is no larger than 1/6 of the total plant rating providing no more than one of these motors is started at a time.

ALTERNATE CONCEPTS

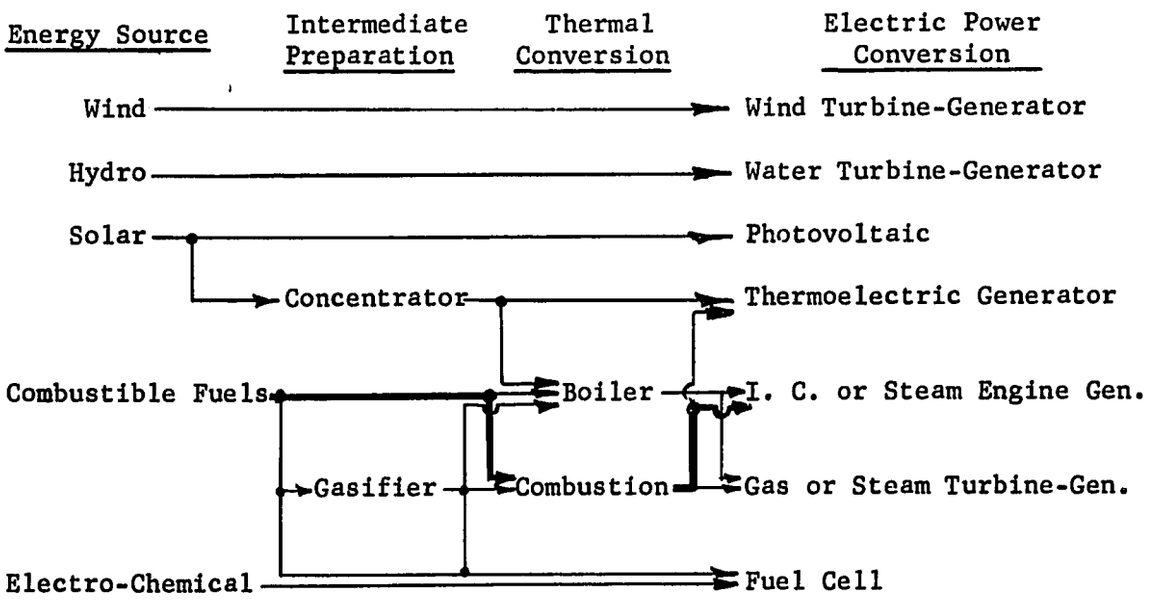
This section describes and evaluates a number of alternative concepts for the local generation of electric power, for rural communities, up to 200 kw in capacity. The major concepts considered are:

1 - Internal Combustion Engine Generators
2 - Small Scale Hydroelectric Plants
3 - Thermal Vapor Engine Generators
4 - Gas Turbine Generators
5 - Wind Generators
6 - Fuel Cells
7 - Photovoltaic Solar Cells
8 - Thermoelectric Generators

The first two categories include the bulk of available equipment currently in use. The remaining categories are of interest primarily from the standpoint of possible future concepts.

Electricity may be generated in a variety of ways from available forms of energy. The tabulation below indicates the pathways of conversion of energy to electricity of practical importance in this study. To illustrate, an energy source such as diesel fuel will liberate heat in a combustion process to produce electricity from an internal combustion diesel engine generator. The path is traced in a heavy line.

PATHWAYS OF CONVERSION OF ENERGY TO ELECTRICITY



The alternate concepts for generating electricity are discussed on the following pages.

INTERNAL COMBUSTION ENGINES

Internal combustion engines have undergone considerable development for 60 or more years, probably more so than any other type of energy converter. Their widespread application has resulted in equipments of innumerable ratings and configurations. As a consequence they serve as a benchmark for evaluating alternative concepts. Internal combustion engines are used as automotive or tractive power plants, for marine propulsion, as mechanical power generators for factories or process industries, as pump drives and for driving stationary or portable electric generation plants.

Low Power Diesel Electric Plants

Diesel electric plants are built in ratings from about 5 kw to tens of thousands of kw. The diesel cycle uses the compression heat of the intake air to ignite the fuel injected at the end of the compression stroke. This is known as compression ignition and is accomplished without the need of a spark or glow plug, providing sufficient compression ratio is built into the engine for the particular grade of fuel used. In some cases, diesel engines will include a spark or glow plug to cause ignition at a desirable point in the cycle. This modification is generally referred to as a mixed, combination or limited-pressure cycle.

The major characteristics of diesel engines are relatively slow speed to accept limiting combustion reaction rates, high compression ratios to achieve compression-ignition temperatures, and complex accessories for fuel pressurization, injection and control.

The ruggedness, size and speed of a diesel engine is generally a function of the type of fuel used. Heavier fuel fractions, such as so-called low speed and residual fuel oils are relatively inexpensive. Conversely, the heavier, higher compression ratio engines needed to run with these fuels are costly. These economic considerations must be considered in selecting engine generator equipment to optimize operating costs in relation to fuel grade availability in isolated areas.

Diesel Fuel Characteristics

In a very general sense almost any hydrocarbon fuel that may be ignited by compression heating can be considered a diesel engine fuel. In fact, it is not uncommon to operate on peanut oil, crudes, residuals, kerosene and poor grade gasolines, providing the engine compression ratios and engine speeds are adjusted to accept the fuel ignition and reaction rate requirements.

Within the context of this study the diesel fuels of particular interest are the three grades 1-D, 2-D, and 4-D as classified by the American Society for Testing Materials in ASTM D975. Residual oil, which can be classed as Fuel oil #5 in the ASTM D396-487 classification, is included as it may be pertinent for large engines in certain countries. The major characteristics of these fuels are listed in Table 2 and 3 below.

TABLE 2

SPECIFICATIONS FOR DIESEL FUELS

As classified by ASTM D975

Grade	1-D	2-D	4-D
Flash Point, min. deg. F (or legal)	100	125	130
Water and sediment, % of vol. max.	trace	0.10	0.5
Viscosity, SSU, 100°F			
minimum	1.4*	32	45
maximum	-	45	125
Carbon residue, % st. max.	0.15	0.35	--
Ash. % wt. max.	0.01	0.02	0.10
Sulphur, % wt. max.	0.50	1.0	2.0
Cetane number, min.	40+	40+	30

*Kinematic viscosity, centistokes
+During 1955 average cetane no. of these grades was above 50.

TABLE 3

SPECIFICATIONS FOR NO. 5 FUEL OIL (RESIDUAL TYPE)

As classified by ASTM D396-48T

Flash Point, min. deg. F (or legal)	130
Water and sediment, % vol. max.	1.0
Ash, % wt. max.	0.10
Saybolt viscosity, minimum @ 100°F	150 (Universal)
maximum @ 122°F	40 (Furol)

Cetane number - not applicable to residual fuels.

Heating values of petroleum oils which are a function of density, are shown in the following Table.

TABLE 4

HEAT VALUES OF PETROLEUM OILS

From Marks, Mechanical Engineers Handbook, 6th Ed.

Degrees API @60F	Density (lbs/gal)	Higher Heat Value (btu/lb)	Lower Heat Value (btu/lb)
10	8.337	18540	17540
20	7.787	19020	17930
30	7.305	19420	18250
40	6.879	19750	18510
50	6.500	20020	18720
60	6.160	20260	18900
70	5.855	20460	19020
80	5.578	20630	19180

Grades 2-D and 4-D, by comparison to the specification sheets in Appendix E are associated with the fuel qualities established for "high" and "low" speed diesel fuels used in India.

Associated engine characteristics may be delineated as follows: Fuels with high cetane ratings have high combustion reaction rates with clean efficient burning and are therefore applicable to high speed, high performance engines. Fuels with cetane numbers equivalent to the heavier oils require very slow speed engines, and in fact become sensitive to minimal cylinder sizes and cylinder power rating to operate effectively.

Diesel engines may be approximately classified in three groups dependent on grade of fuel used.

"High Speed" Engines

Fuel grades 1-D and 2-D with Cetane numbers of 40 and above.

Applicable to high piston speeds of 1800 ft. per minute and above to overload speeds of 2500 ft. per minute. There is no practical minimum limit on cylinder bore for efficient operation.

"Low Speed" Engines

Fuel grade 4-D with Cetane numbers of about 30.

Applicable to moderate piston speeds up to 1200 ft. per minute. There is no apparent penalty for limiting cylinder bore.

"Residual Fuel"Engines

Effective operating dependent on piston speed and cylinder bore. Typical parameters are piston speeds of 1000 ft. per minute of less and cylinder bores of 8 inches or more Modern locomotive diesels are operated up to piston speeds of 1800 ft. per minute, but this is perhaps the upper practical limit. Generally, these parameters are associated with engines of 2000 Hp and up, with minimum rated cylinder power levels of about 150 Hp.

General Motors manufactures a class of diesel engine that operates equally well on either "high" or "low" speed fuels. The GM 6-71 is a six cylinder engine with a piston displacement of 71 cubic inches, has a bore of 4.25 inches and a stroke of 5.0 inches.

When operating on "high" speed oil, the engine is adjusted to run at 1800 RPM with a piston speed of about 1800 ft. per minute, producing 37.5 Hp per cylinder. With minor changes in the fuel oil injector and timing, the engine is operated with "low" speed oil at 1200 RPM, and piston speeds about 1200 ft. per minute, producing about 25 Hp per cylinder.

Diesel Electric Plant Characteristics

Typical characteristics of available diesel electric plant equipments are shown in Table 5 . Tabulations of total price, specific price, weight, and volume on a per Kw basis, and Specific Fuel Consumption (SFC) are listed at rated power levels for 120/208 volt, 3 phase, 60 cycles, 1800 RPM equipments. Specific fuel consumption and engine generator efficiencies are not directly evident in catalog specifications, and it was necessary to estimate the SFC values by relationships described in Appendix A .

TABLE 5

DIESEL ELECTRIC PLANT CHARACTERISTICS

1800 rpm - 3 phase - 120/208 V

From 1962 Katolight Corp. Catalog

Rating, Kw	Price, $	$/Kw	Lb/Kw	Ft^3/Kw	SFC, Lb/Kw-Hr
10	3,165	317	140	6.0	0.88
15	3,675	245	130	3.4	0.85
25	4,600	184	84	2.6	0.78
30	4,715	157	85	2.3	0.78
40	6,010	151	66	1.8	0.65
50	6,360	128	65	1.6	0.67
60	7,735	129	63	1.4	0.67
75	8,915	119	63	-	0.67
100	10,000	100	53	-	0.67
125	13,300	107	49	-	-
150	15,500	103	47	-	-

Part load performance of diesel engine electric plants has been derived from 1962 catalog data of the Cummins Engine Company. The original data was in terms of gallons of fuel consumed per hour for equipment supplying 60 cycle power and includes losses for fans and standard accessories. This tabulation lists performance in terms of SFC in pounds per Kw-hr and overall efficiency for the case of using a diesel fuel having a density of 6.84 pounds per gallon and a H.H.V. of 19,000 Btu per pound.

TABLE 6

DIESEL ELECTRIC PLANT PERFORMANCE

Part Load Conditions

Plant Rating (kw)	100% Load SFC	100% Load Eff.(%)	75% Load SFC	75% Load Eff.(%)	50% Load SFC	50% Load Eff. (%)
40	0.71	25.3	0.80	22.5	0.90	20.0
50	0.67	26.8	0.73	24.6	0.88	20.4
60	0.62	29.0	0.64	28.1	0.74	24.3
75	0.57	31.6	0.58	31.0	0.66	27.2
100	0.62	29.0	0.62	29.0	0.69	26.0

Electric Plant Rating

An isolated electric plant must be sized to accept the total connected load with margin for starting loads of the largest single motor components in the system. A priority may be established in a small community so that no two large motor loads are started simultaneously. In addition, for the intended applications, it is probably acceptable to sustain some ripple and voltage fluctuations in order to minimize the plant rating, and hence its cost.

Resistance loads such as lamps, radios, irons, or the like do not produce a power surge and their total load may be made equivalent to the power plant rating. If there are motor loads, such as required for operating of refrigerators, irrigation pumps, or shop tools, the starting loads severely affect stability of the system voltage level. Typically, motors require two to three times rated power for starting, and this must be allowed for in determining plant rating, particularly if the motor size is a significant fraction of the plant rating.

A.G. Zakharin, in his paper A/162 to UNSCAT in February 1963 points out that 15 to 20 Kw squirrel-cage motors should not be placed onto a system capacity of less than 300 Kw in order to maintain a hard system frequency and voltage stability. This is undoubtedly true when the power is used simultaneously for other high quality needs. In the environment of an isolated community where electricity may be used for household illumination only, in the evening hours, some degradation in system quality may be acceptable for operating motor loads at other times, and a much softer system stability accepted. At a minimum, however, the plant rating should be at least 6 times the single motor size even if it is the only load placed on the line, i.e., a 50 Kw electric plant to illuminate a village of 2000 persons during the evening hours may during the daylight hours be capable of starting a single 8 Kw motor load.

Prices of Diesel Electric Plants

Figure 1 is a plot of the total price of a diesel engine generator equipment assembly as a function of power rating for five major manufacturers. These prices do not include necessary accessory or control components. High, low, and median curves are plotted through these points. It is apparent that they are linear, with the median intersecting the abcissa at $2000.

The resulting formulation for catalog list price, FOB, in the United States, is

$$C_e = 2000 + 76 \times Kw \text{ (list price, dollars)}$$

Accessory and optional equipment are required to operate the diesel electric plant effectively in generating electricity. Table 7 lists the minimal components needed and their typical list prices, FOB, in the United States. The curve in Figure 2 is linear and may be represented by the formulation

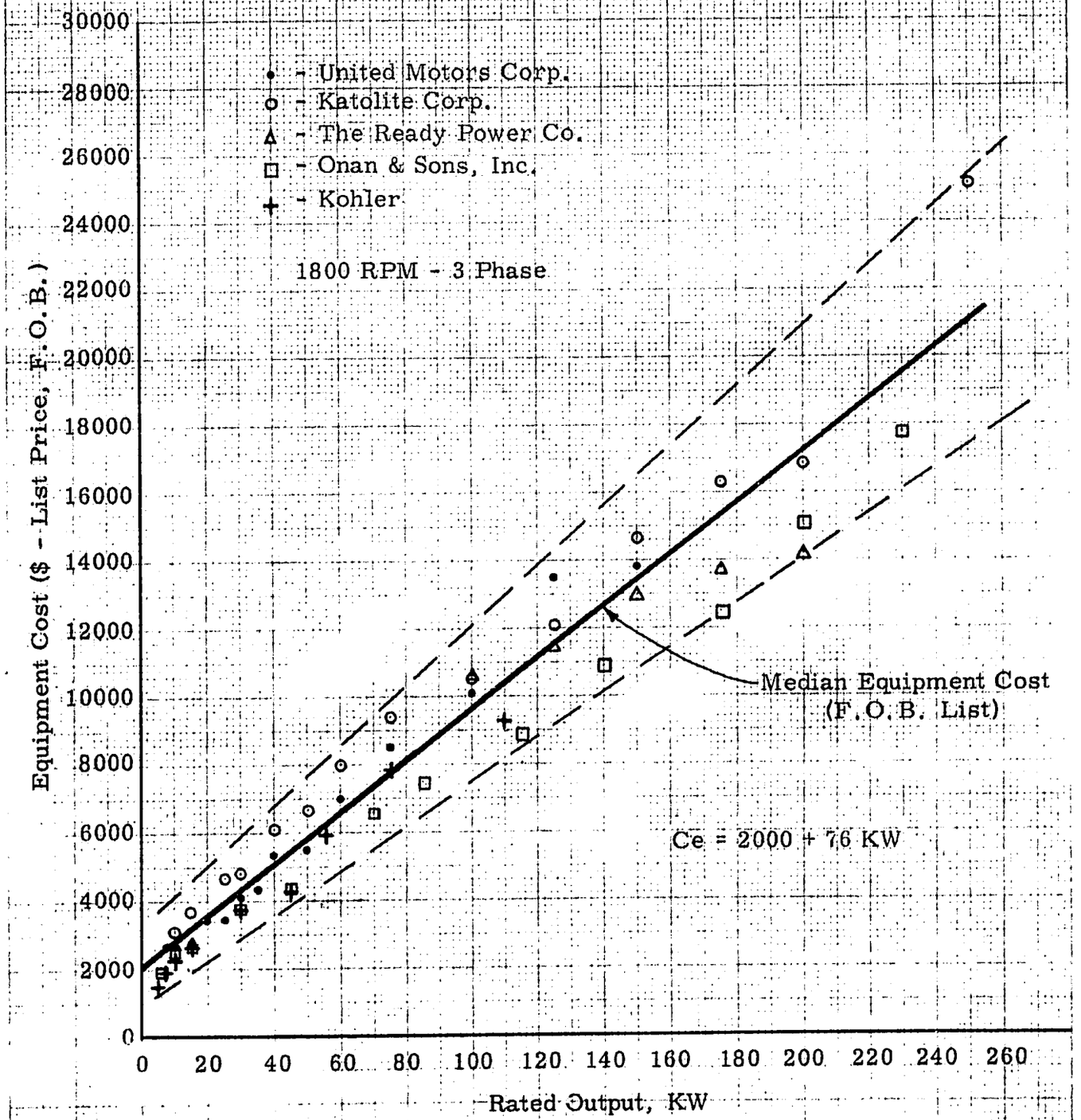
$$C_o = 600 + 51.5 \times Kw \text{ (list price, dollars)}$$

The total price of the representative diesel electric plant is the sum of these two expressions

$$C_t = 2600 + 127.5 \times Kw \text{ (list price, dollars)}$$

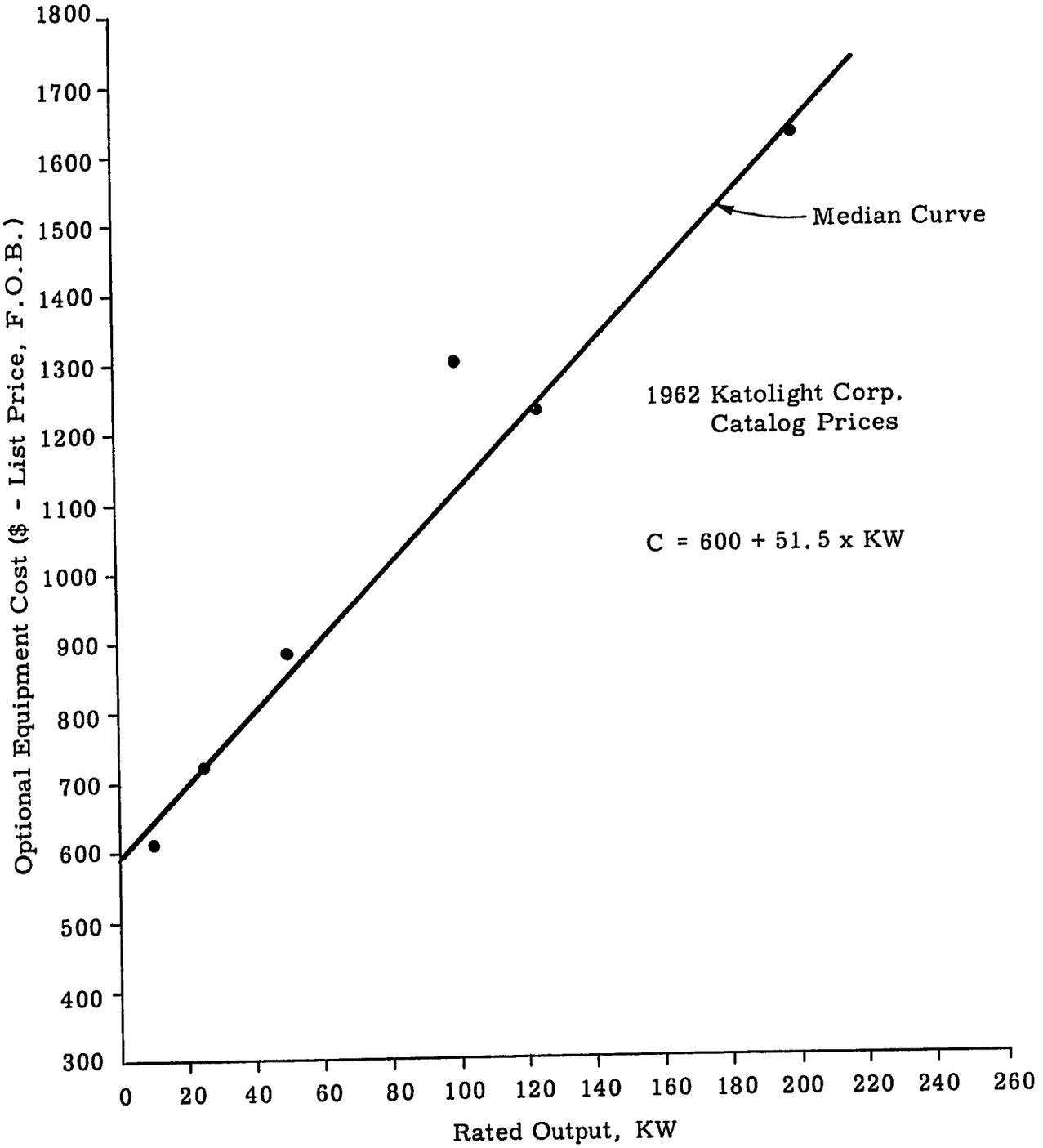
It is apparent that the accessory and optional components account for about one-third of the total price.

FIGURE 1



Diesel Engine A.C. Generator Equipment Costs.
F.O.B. - List Prices - 1962 Catalogs

FIGURE 2



Optional Equipment for Diesel Electric Generating Sets
3 Phase, 60 Cycle, 120/208 Volts

TABLE 7

OPTIONAL EQUIPMENT FOR DIESEL ELECTRIC PLANTS
3 Phase, 60 Cycle, 120/208 Volts - Minimal Selection

1962 Katolight Corporation Catalog FOB List prices

	Rated Output, KW					
Equipment	10	25	50	100	125	200
Instrument Panel	140	140	140	140	175	175
Time & Freq. Meter	65	65	65	65	65	65
Circuit Breaker	25	60	210	365	210	365
Main Line Fuses	25	35	50	105	140	250
Field Discharge Switch	85	85	85	85	85	85
Field Resistor	45	45	45	45	45	45
Overspeed Safety	75	75	75	125	150	150
Muffler	60	100	100	135	150	240
Skid Base	30	40	40	40	60	75
Radiator Guard	30	30	30	45	-	-
Battery	30	50	45	150	150	180
TOTAL PRICE	610	725	885	1300	1230	1630

Approximate price differences between high and low speed engines can be demonstrated by comparing the resulting price formulation for 1200 and 1800 Rpm equipment derived from the 1962 Katolight Corp. catalog. It should be noted that the 1800 Rpm equipment for this manufacturer has higher price figures than that shown as an average above. However, the price variations vs. speed for this Company's products are illustrative. Overall performance for moderate power levels approximates 25 to 30 percent, regardless of speed.

Diesel Electric Plant	Price Formulation
Katolight Corp.	
1800 RPM - water cooled (10 Kw - 150 Kw)	2400 + 87 x Kw
1200 RPM - water cooled (10 Kw - 150 Kw)	2000 + 126 x Kw
Avg. of Five Manufacturers	
1800 RPM - Water/air cooled (10 Kw - 250 Kw)	2000 + 76 x Kw

Diesel Electric Plant Maintenance

It is extremely difficult to obtain an explicit definition of diesel engine maintenance costs from available literature. However, it is felt the following is a reasonable estimate of maintenance costs as a function of power plant use on a yearly basis. This includes labor and materials.

Type	Running Time, Hrs.	Yearly Maintenance Charge % of Orig. Equipment Cost
Nominal		5-10
Minor Overhaul	5,000	20
Major Overhaul	20,000	35

The effective yearly maintenance charges are directly proportional to the amount of use made of this equipment. The following table presents the assumed rates.

Maintenance Rates

Run Time Hrs/yr	Use Factor %	Nominal %	Minor %	Major %	Maint. Rate-Net %
250	2.9	5	1	0.4	6.4
500	5.7	5	2	0.9	7.9
1000	11.4	7	4	1.8	12.8
2500	28.6	10	10	4.4	24.4
5000	57.1	10	20	8.8	38.8
7500	85.6	10	30	10.2	50.2

Equipment lifetime is estimated at 20 years, more from the standpoint of obsolescence rather than failure.

In an actual application, the power plant operator invariably performs maintenance labor, therefore, assignments of maintenance costs over and above operating wages would be for materials only.

In their "Power Packs for Peace" the Fairbanks Morse Company lists costs of maintenance materials to be 7% per year of the initial equipment cost. Maintenance labor is considered to be part of operating cost. This value, 7%, does not seem unreasonable at a plant operating factor of 20 to 30%.

Gasoline Engine Electric Plants

Generally speaking, diesel engines are the most appropriate type of internal combustion equipment for a rural electric plant. However, there are opportunities for the gasoline engine electric plant where gasoline fuels are more plentiful or maintenance experience with automotive equipment predominates. The general characteristics of gasoline engines are much the same as diesels. The following discussion highlights the major differences.

Gasoline engine electric plants operate on the spark ignition principle, inducting premixed air and fuel (by carburetion) into the cylinder, where it is burned at the end of the compression stroke by a spark discharge. These machines can operate at high speed, are of much lighter construction relative to a diesel engine due to lower compression ratios, and have relatively simple fuel controls. They generally require increased maintenance compared to the diesel because of their light construction, higher piston speed, and greater sensitivity to induct erosive particles into the cylinders. Gasoline engine generators have been built in ratings from several hundreds of watts to thousands of Kw.

Gasoline engines have found major application to automotive power plants, all manner of low-powered applications such as outboard motors, lawn mowers, and as emergency electric plants. They are used to a limited extent for stationary electric power plants in power ranges up to 150 Kw.

Table 8 presents specific characteristics of representative equipments as appearing in catalogs of the Homelight and Katolight Corporations.

TABLE 8

GASOLINE ENGINE ELECTRIC PLANT CHARACTERISTICS

Rating, Kw	Price, $	$/Kw	Lbs/Kw	Ft^3/Kw	SFC (lbs/kw/hr)	Eff (%)
Homelight Utility Line 3600 RPM - 1 - Phase, 115 V, Air Cooled.						
1	250	250	80	3.2	--	--
2	315	158	65	2.6	1.54	11.2
3	400	133	47	2.4	1.37	12.6
4	500	125	58	3.3	2.05	8.4
Katolight 1800 RPM 3 Phase, 120/208 Volt, Water Cooled.						
5	1775	355	170	5.4	--	29.8
10	1930	193	130	3.7	--	--
15	2400	160	97	4.0	.63	27.4
20	3125	156	82	2.6	.65	26.6
25	3250	130	68	2.6	.78	22.1
30	3775	126	88	2.3	--	--
100	9000	90	66	1.7	.70	24.7
125	11000	88	52	1.7	.71	24.3
150	13600	91	66	1.9	.81	21.3

This data results in a price formulation of,

$$C_e = 1200 + 81 \times Kw$$

Reference to the Katolight Corporation catalog shows that required minimal accessory and optimal equipment is essentially the same as that required for diesel electric plants of the same power rating. Refer to Table 7 and Figure 2 . This formulation is:

$$C_o = 600 + 51.5 \times Kw$$

The resultant approximate total price is the summation of the above two relations, or

$$C_t = 1800 + 132.5\ Kw$$

Price formulation and approximate range of gasoline engine electric plants not including accessory components are listed below.

	Price Relation
Model Airplane Engine Type	(less than 1 Kw)
*Ohlsson & Rice 6300 RPM Air Cooled	50 + 85 Kw
Light Duty Engine Type	
Sears Roebuck (1-10 Kw) 3600 RPM Air Cooled	50 + 85 Kw
Utility Engine Type	
Homelight (1-4 Kw) 3600 RPM Air Cooled	150 + 87 Kw
Katolight Corp. (5-20 Kw) 1800 RPM Air Cooled	1000 + 70 Kw
1800 RPM Water Cooled (5-150 Kw)	1200 + 81 Kw
1200 RPM Water Cooled (5-150 Kw)	1400 + 101 Kw

*For comparison purposes a 70 percent efficient generator costing $30 was hypothetically connected to an O & R engine. This engine also requires special fuels and will have increased maintenance requirements.

Maintenance requirements for gasoline engines requires a major overhaul at least every 3500 hours of running time. But as with diesel engine operating a value of 7 percent per year of original equipment cost for maintenance materials appears to be a fair rate for plant factors of 20 to 30%.

LP or Gas Engine Generators

The gasoline engine or spark ignition cycle is easily adapted to operate on gas, providing the gas has a sufficiently high octane rating. Many gases such as propane, butane and methane, meet this requirement and permit engine operation at as good or better efficiency than with gasoline. The adaptation consists of replacing the aspirating carburetor with a geseous fuel air mixing chamber. The most convenient way to handle the gaseous fuel is under pressure so that additional blowers to force the gas into the engine are not required.

The most important gaseous fuels of interest to operating engine electric plants in isolated areas will include:

Gas Fuel	HHV Btu/lb.
Propane	21560
Butane	21180
Bio-gas	8570

Propane and Butane are derivatives from petroleum refineries and must be delivered in pressurized containers in liquid form. Pressures are 167 psig and 49 psig at 90°F temperature for the two fuels.

Bio-gas, which is receiving considerable interest in India,* is a derivative from Aneorobic decomposition of cow dung, and other biologic wastes. Typically the raw gas emanating from the process has a methane content of 59%, the balance being largely CO_2 with minor constituents including nitrogen and hydrogen. Even in this form it may be used with success in operating a spark ignition engine. However, for much improved performance due mostly to the gas pumping power requirements, it is desirable to strip off the excessive CO_2 and water vapor prior to pumping the gas to usable pressures and for storage purposes. The resulting methane content may be increased to the 90% and better range with heating values approximately 20,000 Btu per lb. Methane may not be liquified at reasonable pressures such as is the case with Propane or Butane, and in order to optimize storage facilities it may be necessary to pressurize this gas to 3000 psig.

As an example of the storage difficulties four times as much energy is stored in a cubic foot of liquid propane at less than 200 psi than in gaseous methane (or purified Bio-gas) at a pressure of 3000 psi.

The price formulation for a light duty engine type without accessory components of about the 5 to 10 kw class operating at 3600 RPM is approximately

$$Ce = 130 + 85 \times kw$$

*See Appendix C - Cost Benefit Analysis of Bio-gas Plants in India

Wankel Engine

An alternate concept to reciprocating pistons in individual cylinders is the rotary engine. A variety of rotary types, including vane and gear have been developed, but the most promising is the Wankel design being developed in Germany by NSU Motorwerke and now being evaluated by Curtiss Wright in the 3 hp to 1000 hp range, for automotive application.

Basically, the Wankel engine consists of a 3 sided piston rotor turning in an epitrochoidal cylinder. The rotor is eccentrically operated within the cylinder to form a sequence of appropriate cylinder volumes and to obtain compression and expansion strokes as in a conventional piston engine. The eccentric action of the piston rotor drives the output shaft at up to 3 times rotor speed making it well matched for direct coupling to high speed electric generators.

The Wankel has a very simple structure, since the rotor replaces a number of pistons. It is consequently compact and light weight. Its efficiency may be somewhat less than comparable internal combustion engines due largely to friction and leakage losses at the rotor seals. Fairly high compression ratios are possible making the engine operable on diesel fuels or kerosene as well as gasoline. Manufacturing costs may be significantly less than gasoline engines, due to its simplicity and small size, providing it is mass produced.

The major unresolved technical problems include satisfactory development of long life, low maintenance seals on the piston rotor. Very complex face and cylindrical seals are required for the engine to operate efficiently. The configuration, surface speeds and forces require a major advance in sealing technology relative to that of the reciprocating piston engine. To date, these seals have experienced considerable wear and erosion with frequent major overhauls required.

It may be some years before these problems are solved for the satisfactory application of this engine to automotive use. When these difficulties have been overcome, however, the Wankel engine will be a contender for cheap, light weight, electric plants for rural communities.

SMALL SCALE HYDRO-ELECTRIC PLANTS

Electricity may be generated from the potential energy available in water flowing from a higher elevation to a lower elevation. The types of sites vary from dammed up streams and tidal flats to situations where only the velocity head of the flowing water in a stream or incoming ocean waves my be tapped.

The amount of power available in a water stream between two points at different elevations may be computed from the following equation:

$$\text{Water Horsepower} = \frac{WH}{550}$$

where

W = water flow rate (lbs. per second)

H = difference in elevation (feet)

Obviously, this is the gross power and does not take into account the losses due to conveying the water through pipes or weirs to the generating equipment and its associated machinery.

The type of equipment required to generate electric power varies with the conditions at the water resource. Generally, an on site inspection is necessary to determine available heads, consistency of water flow rates throughout the year, topographical features, distance from load center, availability of contributed labor and materials, etc. All these factors are needed to establish the economic validity, before finalizing the selection and design of a hydroelectric plant.

There are four general types of hydraulic prime moving equipments that are available. They represent a mature technology and have demonstrated high performance, long life, reliability, simple to operate and maintain. Their gross characteristics are listed in Table 9.

Figure 3 is a plot of estimated small hydroelectric plant efficiencies, not including penstock losses.

TABLE 9

CHARACTERISTICS OF HYDRAULIC PRIME MOVERS

TYPE	RELATIVE HEAD	RELATIVE FLOW RATE	RELATIVE SPEED	SIZE POWER	+SPECIFIC SPEED RANGE
Water Wheel	low 0 - 50 ft.	low	very low	very large	-
Impulse turbine (or Pelton)	very high *50 - 3000 ft.	low to moderate	high	low	3 - 7.5
Francis reaction turbine	low to high 5 - 1000 ft.	moderate to high	high	moderate	20 - 100
Propeller turbine (or Bulb)	low 0 - 50	high	high	large	100 - 175

*Dependent on flow rate and specific speed values

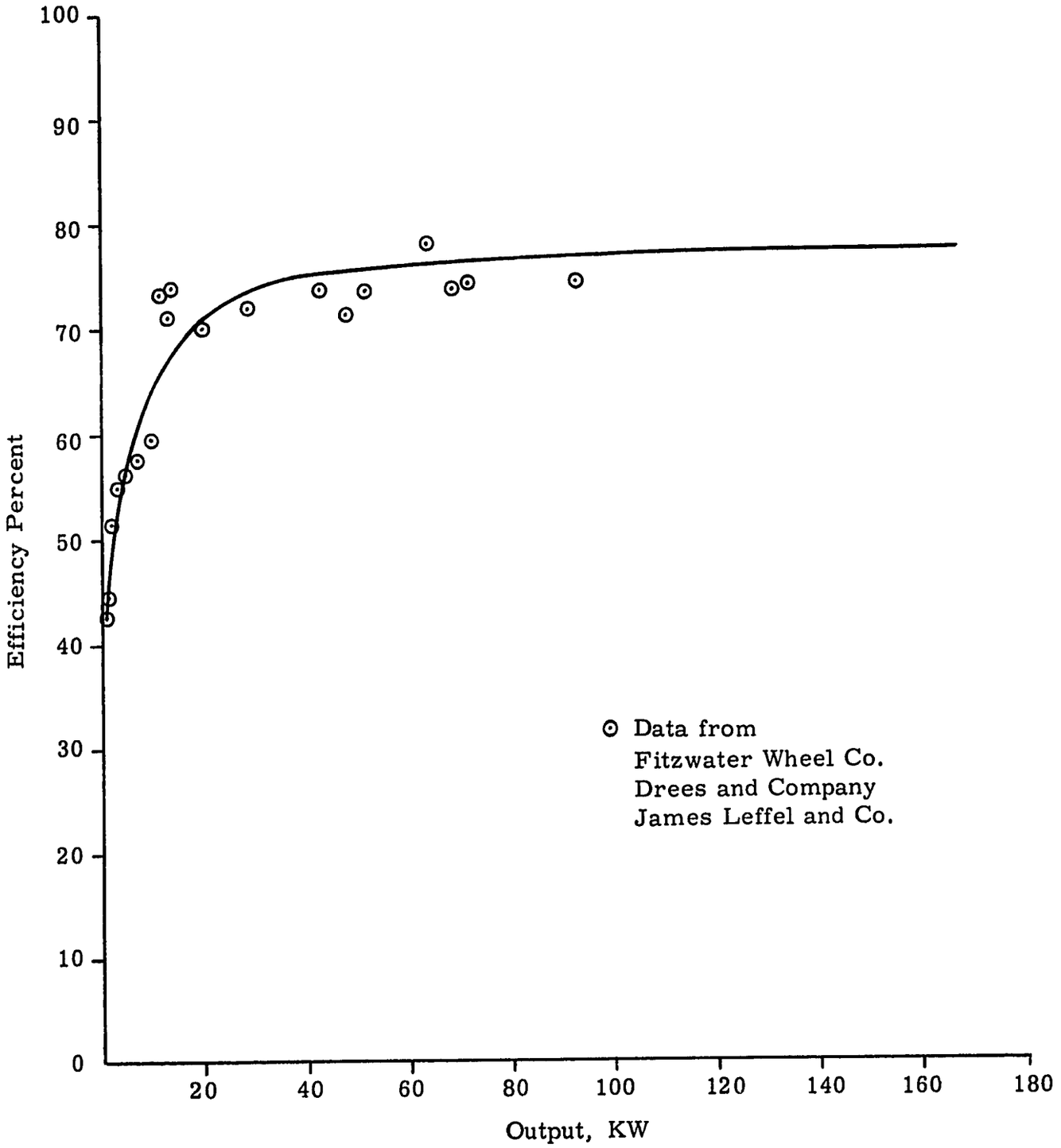
+Specific speed $= \frac{RPM \quad P}{H^{5/4}}$

RPM is pump speed (revs. per minute)

P is power (Horsepower)

H is head (feet)

FIGURE 3



Estimated Efficiencies of Small Hydraulic Turbine-Generator Power Plants.

In general, the peak efficiency of hydraulic prime movers approximates 90% with fairly good performance even at 1/3 load conditions.

Water Wheel Concept

For small streams with variable flow and non-freezing temperatures the water wheel is the most efficient. Water from the stream is directed over the wheel by means of a weir which can be controlled by a governor. Belts or gears are used to transmit the wheel motion to a suitable generator to furnish electric power. Because of the size of the wheel required most of these plants are limited to 15 kw or less. Their chief advantages are ease of erection and maintenance. In the case of the over-shot wheel they maintain reasonable efficiency as the stream flow changes due to seasonal conditions.

Hydraulic Turbine Concepts

For most communities having a water resource, a type of hydraulic turbine is appropriate. With the turbine all the generating machinery can be put undercover and the higher speed characteristics of the turbine may permit the generator and turbine to be constructed as a single unit. If more than one generator is connected to the bus the units may be operated in parallel using governors adjusted as required. This equipment, apart from minor maintenance such as lubrication, can operate continuously in most locations for 20 years or more before major replacements are necessary.

Hydroelectric Plant Installation

As for the equipment itself, some type of stone dam or spill-way must be built across the stream and so arranged that excess water can flow over it for by-pass or flood conditions. Water for the turbine may be inducted directly to the turbine located at the dam site or diverted by a canal or ditch to a location where the desired head is available. Water to the turbine penstock is controlled by a sluice gate made of cast iron or wood with steel hardware which can be opened or closed to admit water. Some type of screen is needed around the sluice gate to keep large floating objects from damaging the turbine blades.

The penstock is generally steel pipe or pipe made of wood with steel bands at short intervals strong enough to withstand the water pressure. It must be anchored and protected against damage. In some installations it may be more convenient to put a shut-off valve next to the turbine and use the sluice gate as a head control by varying the water over-flow at the dam.

Water flowing through the turbine does work on the rotor which rotates the connected generator to produce electricity. Discharge water is redirected into the downstream bed through an additional penstock or tail race. A suitable control must be used to limit the flow of water impinging on the turbine wheel. This is done by using a series of gates arranged around the Francis wheel so they can be opened and closed by turning a single shaft. The Pelton turbine uses a needle valve or deflector mechanism. If frequency changes are not objectionable as the generator load changes and no paralleling with another source of power is used in the electrical system, an automatic governor is not required. It is, however, necessary to change the gate control valve manually as the load changes, otherwise speed and voltage fluctuations may damage the electrical equipment. If the plant has an attendant he can change the valve settings occasionally as indicated by a generator voltmeter. Many isolated small power plants of this type do not use automatic governing.

In order to keep the generator small and its cost low and still have 60 cycle current it is necessary to drive the generator at a higher speed than the turbine. This can be done with belts and pulleys or some type of gearing. Some European manufacturers make a turbine, generator, and governor combination all operating at the turbine speed. These are packaged units including a weather-proof enclosure. Literature on this equipment shows their size limited to 70 kw. One manufacturer in the U. S. builds a similar unit but its size is limited to 10 kw.

The generator must be protected from line short circuits and over-loads so that a control panel containing circuit breakers is included in the plant. Most installations include a voltmeter for monitoring purposes and there is some voltage regulation in the generator circuit.

Finally, the generating equipment should be housed in a weather proof structure which will protect the machinery and yet allow access for routine maintenance. It is important that the alignment of the machinery does not alter with time causing bearing wear. Also the generating equipment should be isolated from the curious who might get hurt in the belts and shafts, or electrocuted by accidental contact with the electrical circuits.

Costs of Small Scale Hydroelectric Plants

The total installed cost of hydroelectric plants varies greatly and is largely dependent on the physical characteristics of the site. The dam, earthwork, tunnels and similar terrain sensitive components may account for one half to more of the total installation cost. Generally, for large rated installations the equipment, particularly the penstock and water turbine is uniquely dependent on head and flow requirements,

so it is difficult to determine a simple expression to represent installed cost as a function of plant rating. Large plants in the U. S. generally cost $200 and $500 per installed kw.

The Japanese have issued an article "The Present State of Small Hydraulic Power Stations in Japan" by Shiro Oda, World Power Conference, Belgrade, 1957, Vol. VI, p. 539, which presents an excellent discussion of both operating and capital costs for low power installations. Figure 1 represents a median curve of installed costs for conduit type plants vs. plant rating in U. S. dollars (1 yen = $.00252). Its representation appears to be:

$$C = 1000 + 350 \text{ kw}$$

Power plant manufacturers point out that installation costs of large scale plants are equivalent or somewhat greater than that experienced inside the U. S. In spite of low labor costs for on site erection there is a magnification effect due to the need for more low effectiveness workers, great transportation and material procurement problems, gross delays, import duties and taxes and the need to send qualified technicians at premium rates to supervise erection.

To document hydroelectric plant equipment costs, Table 10 was made up from quotes and catalog data for U. S. manufactured components for plants 20 kw to 150 kw rating. (Refer to Appendix B). These costs do not include labor and materials for the dam, ditches, land purchase, field installation, transportation costs, duties or taxes. For instance, in South America, much of the local labor and indigenous material may be contributed. This data is also shown in Figure 4.

An unsuccessful attempt was made to obtain equipment costs for packaged plants of the type manufactured in Germany. Some preliminary data showed prices to be in excess of that appearing in Table 10.

Hydroelectric Sites in South America

Upland Peru, particularly, has a wealth of glacier fed, continuously flowing streams. The steep valleys afford high head drops in only a few kilometers. In general, the streams are of low flow rates, typically about 100 cu. ft. per second so that for a 100 foot drop the potential terminal power from a hydroelectric plant, allowing for inefficiencies, is about 100 kw.

TABLE 10

ESTIMATED COSTS OF HYDRAULIC TURBINE POWER PLANTS

ITEM	Output KW 20	25	30	40	50	60	70	100	125	150	Remarks
Generator	82	80	75	65	59	53	47	40	37	34	1800rpm-25 kw 1200rpm-150kw
Turbine	92	89	83	78	73	70	66	63	61	61	40'head up to 45 kw 30' hd 45-75 kw 25' hd 75-150kw
Penstock 100 ft.	10.2	10.1	10	9.8	9.5	9.3	8.8	8	7.2	6.4	Prepared ends spiral weld pipe
Penstock Elbows (2)	5.1	5.1	5.1	5.2	5.3	5.5	516	6.2	6.8	7.5	Prepared ends for connecting
Sluice Gate Valve	9	9.4	9.6	10.2	10.6	10.8	11.2	11.3	11	10.4	Mountin equip't & hand wheel
Governor & Associated Equipment	142	138	134	126	120	110	100	80	62	42	Pumps,piping & linkage. No fly-wheel
Drive	7.2	8.6	9.0	9.6	10.5	11.4	12.7	15.4	18.5	21.6	V belts and pulleys
Electric Control	29	23.8	20	14.6	11.6	13.4	11.2	8.2	6.3	5.4	Meters & field control plus breakers.
House 20'x20'x10'	107.5	86	71.6	53.8	43	35.8	28.7	21.5	17.2	14.3	Roofing,floor, steel,cement, hardware
Total Cost $/kw	484	450	417.3	372.2	342.5	319.2	291.2	253.6	227	202.6	
Total Cost $	9,680	11,125	12,519	14,888	17,125	19,152	21,840	25,360	28,375	30,390	

These costs do not include construction labor, taxes, duties, transportation, or technical assistance charges. It is assumed that all buildings including the dam will be made from indigenous materials such as stone, wood, etc.

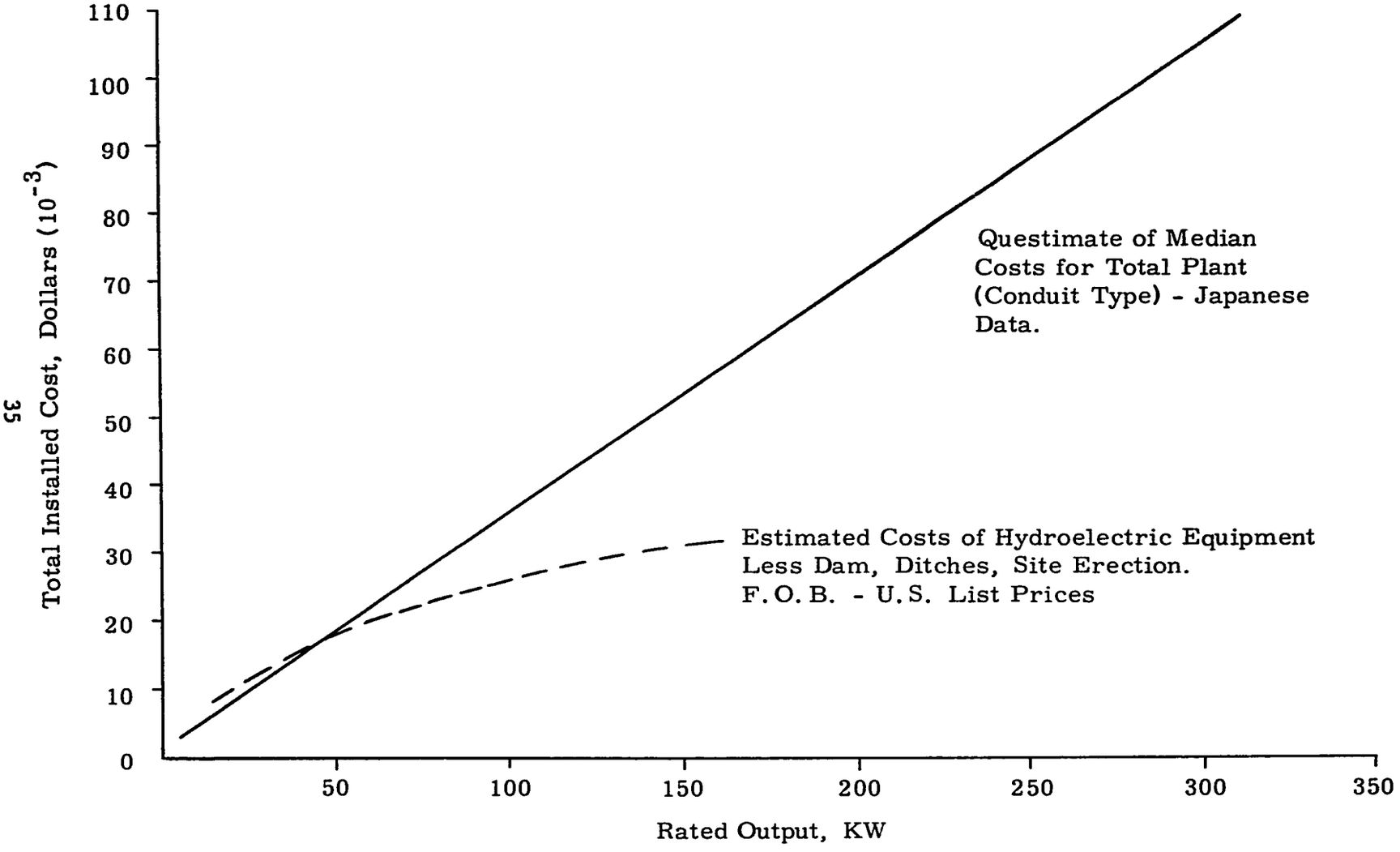


FIGURE 4

Hydroelectric Plant Costs

The installations would typically consist of a diversion and overflow control dam located upstream. It would never be more than 25 feet wide or higher than 5 feet. Water would be diverted to a ditch along one side of the valley to a point, perhaps 1 to 2 km downstream, where the fall to the stream is 100 to 150 feet. The valley sides typically slope up at 50 to 75° allowing for reasonable penstock installations. These heads and power conditions represent a specific speed of 60 for a 1800 RPM turbine rotor direct coupled to a generator. A Francis reaction type of rotor is indicated.

In that no truly packaged equipment for this character of installation is available, it is recommended that product development for indigenous installation be considered. There is need for a packaged self-contained plant rated at 100 kw and designed to operate with a head of 100 feet at a water flow rate of about 100 cubic feet per second. This package should be installable by community labor and not require additional structure other than a field installed pedestal foundation.

THERMAL VAPOR ENGINES

Thermal vapor engines represent a class of equipment in which the thermal energy of a fuel is transferred to an intermediate working fluid that acts the moving parts of an engine to produce mechanical power. Both open and closed cycles are used. The open type refers to the case in which the working fluid is expelled from the system after exhausting from the engine, whereas the closed cycle returns the exhausted fluid back into the system.

Typically, the cycle includes a furnace for burning the fuel, or a solar collector, a heat exchanger or boiler through which thermal energy is transferred to the working fluid, an engine, either a turbine or reciprocating type, and if it is a closed cycle system, a heat exchanger to condense the exhausted working fluid for reuse in the boiler. A boiler feed pump is required to pressurize the working fluid to engine intake pressure. The condenser usually rejects its waste heat to cooling water or ambient air.

Working fluids may include water, freon refrigerants or some newer selections such as mono-chlorobenzine, mercury, alkaline metals such as sodium and potassium and others.

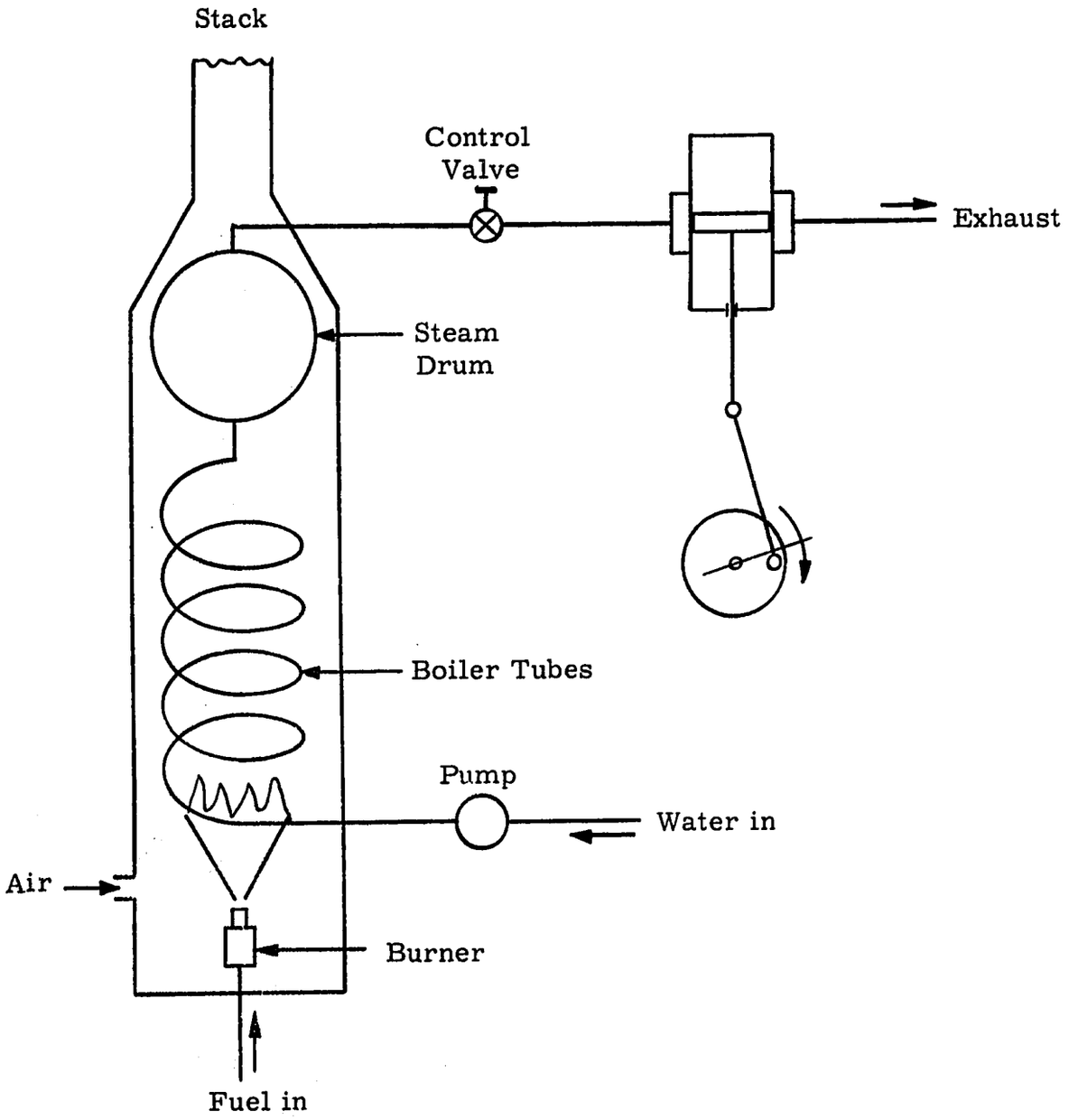
Reciprocating Vapor Engines

General Characteristics

Reciprocating engines using a vaporizable liquid such as water, freon, or other condensibles are probably the oldest type of thermal engines that have been developed. Steam engines have played a key part in the early industrial development of England and in the powering of early railroads, industries and farms of the United States at the turn of the century. Such machines were built to burn wood, farm wastes, coals and all manner of petroleum products.

Figure 5 shows the typical simple open cycle steam engine, consisting essentially of a boiler and steam engine. Water is supplied to the boiler under pump pressure, is heated in boiler tubes with hot gases derived from burning fuel and air, is converted into steam at saturated or super-heated temperatures and then delivered with suitable pressure and flow controls to the engine. Mechanical work is produced by the engine converting the expansion energy of the steam in the cylinders, and the expended steam is exhausted. Overall efficiency of this cycle is typically 3 to 6 per cent.

FIGURE 5



Simple Open Cycle Steam Engine Plant

Figure 6 represents a simple closed cycle steam engine with the addition of a heat exchanger to condense the exhaust steam from the engine for reuse in the cycle. Closing the cycle permits a drastic improvement in overall efficiency, particularly through decreasing the exhaust pressure on the last cylinder stage to below atmospheric levels. It also makes possible, from economic and performance viewpoints, the use of complex multi-expansion cylinder arrangements at elevated inlet pressures and high super heat conditions to the extent that plant efficiencies of up to 30 per cent are attainable.

Another feature is that a single, non-replenishable charge of water can be used in the cycle, and the water purity conditions can be controlled to minimize scaling and corrosion problems inherent in the open cycle. The use of a condenser, however, demands a heat sink for waste heat rejection, either to the surrounding air or to a body of water. In a practical sense, only closed cycle plants of very low power ratings can reject heat to the air successfully. The size of heat transfer surfaces and needed blowers makes air heat sink impractical for consideration at power levels much above 10 or 20 hp.

Steam engines represent a relatively old technology. Other cycles, such as the steam turbine and internal combustion engines with their much improved performance, convenience, compactness and low cost, have superseded them. The result is that steam engine development has been arrested as of 50 years ago. In fact, the typical steam engine one might procure today is largely unchanged from that available decades previously.

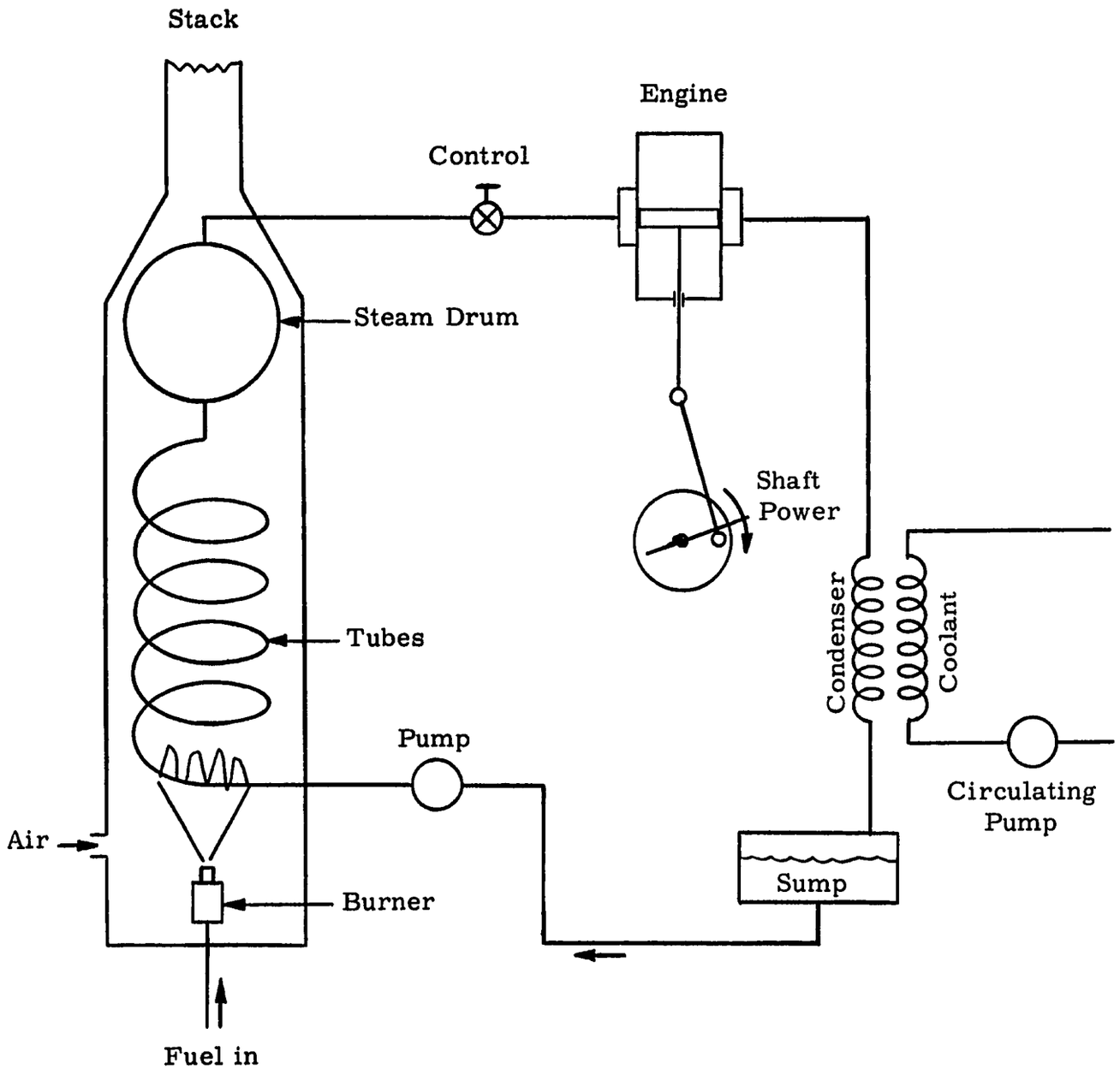
Currently Available Equipment

Conventional steam engines:

A closed cycle steam engine with typically available equipment for generating 10 kw would weigh close to 4,000 lb. and cost in the neighborhood of $7,500 for an assembled system. At the low boiler pressures considered -- 100 to 150 psig -- for safe isolated village application, the overall efficiency would approximate five to eight per cent.

The following tabulation lists typical physical characteristics of steam engines currently manufactured in the United States. These data are for vertical single-cylinder engines operating at an inlet steam pressure of 250 psi gage.

FIGURE 6



Simple Closed Cycle Steam Engine Plant

TABLE 11

CHARACTERISTICS OF CONVENTIONAL STEAM ENGINES

Power Rating hp	Speed rpm	Specific Weight lb/hp	Specific Volume cu. ft./hp
12.5	600	64	3.9
20	500	75	3.8
30	450	58	3.1
40	400	64	4.5
60	400	56	4.0
75	350	60	3.7
100	325	56	3.5
125	300	52	3.2
160	300	69	3.3
200	250	65	2.7

Modular steam engine:

German manufacturers such as Spillingwerk have developed a modular steam engine wherein engine assemblies from one to six cylinders with output of 40 to 240 hp are available. The single vertical cylinder engine runs at 1500 rpm and accepts a maximum inlet pressure of 200 psig and temperatures up to 750 F. Specific weight and volume characteristics are 2.3 lb. per hp and 0.09 cu. ft. per hp. Price estimates for the German engines have been obtained, delivered at U. S. docks. They are roughly as follows:

Cylinders	Dollars per hp
1	125
2	95
3	80

Alternative Development Possibilities

Automotive engine conversion:

It would be possible to adopt an in-line automotive- type engine to operate on steam, provided engine speed is no more than about 1,500 rpm, due to required valving. Special provision must be made for cylinder lubrication and sealing for steam operation. Crankcase heating would also be necessary to prevent undue condensation or corrosion affecting moving parts. Such a conversion would permit a nominally rated 100 hp auto engine to produce 20 hp with steam. This adaptation would permit open cycle operation only, with its attendant low overall efficiencies, perhaps as high as five per cent.

Closed cycle operation would be impossible due to oil entrainment into the condenser and boiler. Therefore, the principal advantages of adapting automotive-type engines would be a weight reduction in comparison with conventional steam engines and a potential reduction in capital costs per hp. Converted engine costs might approximate 25-50 dollars per hp.

Wankel engine conversion:

The conversion of a Wankel engine to steam operation is another possibility. Where the major problem of the Wankel is in wear of the sealing surfaces due to errosive action of combustion products, use of steam may minimize this difficulty. Seal surface velocities and pressures are within typical steam engine practice. The major difficulty lies in effective valving of the intake steam into the expansion chambers, and this is not readily achieved with the Wankel engine concept. Another major difficulty is the lubrication of the rotor eccentric, particularly in a steam environment. In summary, although such a machine would be of interest, the technical difficulties of valve and lubrication problems would entail gross development costs and little assurance of success.

Freon engine:

The concept of using a working fluid such as Freon appears of interest, particularly for application to boilers burning indigenous fuels. Wood, agricultural wastes, and other low quality heat sources including concentrated solar energy generally result in low combustion temperatures. The pressure and temperature characteristics of some of the Freon refrigerants are most appropriate at the low temperature regions, resulting in much improved overall cycle efficiency in comparison with steam, at the same temperature. There are, however, some specific limitations that must not be violated. Freon fluids are expensive, highly volatile, and in some situations toxic, and in these respects must be used in a hermetically, sealed system. This implies that the generator should also be physically placed within the hermetic casing along with the engine, as shaft seals are not entirely adequate seal against Freon vapor leakage, In addition, limiting temperatures of the Freon liquid in the boiler tubes should not exceed about 350 at the risk of chemical breakdown.

An evaluation was made of the possibility of adapting an electric motor-driven Freon refrigerator compressor into a Freon vapor engine generator, literally by running it backward to generate electricity.

In concept it is feasible. The particular refrigerator compressor unit considered, which represents the largest capacity made by the General Electric Company (motor rating about 12 hp) would probably generate a maximum of three kw of electricity when converted. In addition, the valves required for introducing high pressure Freon vapor to the cylinders would limit engine speed to 1,800 rpm (compared to 3,600 rpm original speed) and the inherent mechanical stresses would permit a possible life of only a few thousand hours. Its overall efficiency would be no more than 3%. Consequently, it was concluded that a useful adaptation of an available Freon refrigerator compressor to a Freon engine-generator was not practical.

Comparative Performance Estimate of Vapor Engine Cycles

Figure 7 plots estimated efficiencies of vapor engines as a function of boiler or evaporator temperature.

The curves marked with the Freon fluids F-11, F-113, and F-114 are for the hermetic closed cycle Freon vapor engine generator system, indicating maximum overall cycle efficiencies of 2 to 2.8 per cent at a limiting evaporator temperature of 300 F.

The curve marked "Closed Cycle Steam Engine" is for the case of condensing steam to a heat sink of 95 F and wherein the moisture content of the steam exhausting from the cylinder does not exceed 40 percent. This plot indicates an overall efficiency of 4.3 per cent at an evaporator temperature of 400 F, but crosses under the performance values of the Freon engine at 250 to 300 F. This implies that below these temperatures there may be a performance advantage to the Freon cycle.

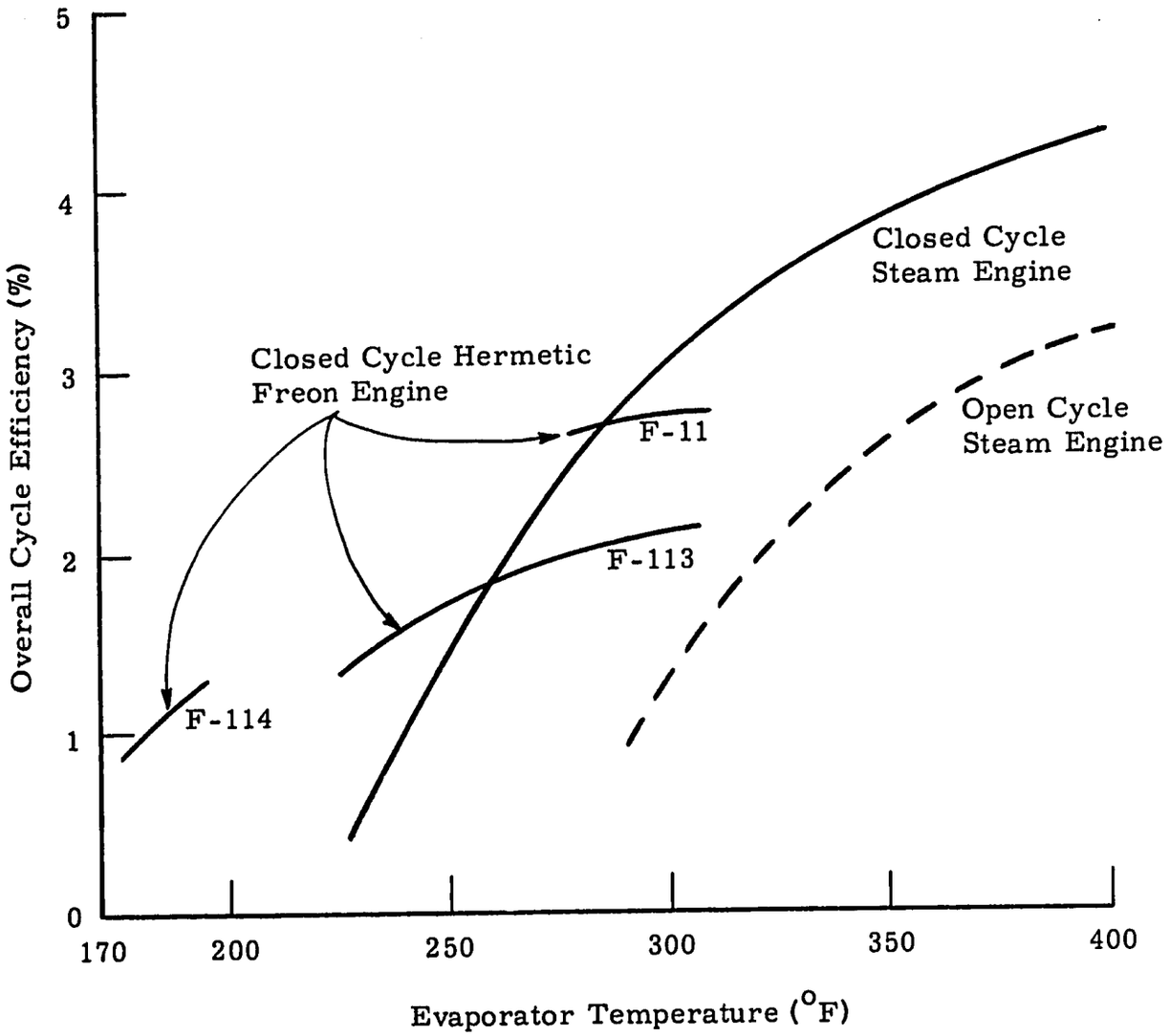
Of particular interest is the F-114 curve representing a Freon engine cycle using a solar heated saline pond as a heat source. Dr. Tabor of Israel is experimenting with large saline ponds and has measured temperatures up to 180 F. Even then, this temperature level permits only a one per cent overall efficiency.

For comparison, a dashed curve is shown of overall cycle efficiency of an open cycle steam engine generator. It approaches 3.5 per cent at a 400 F evaporator temperature. Below 300 F its performance is uninteresting.

To sum up, only at low evaporator temperatures -- perhaps when using a low-quality solar heat source -- would the Freon engine generator have relatively good performance. Steam engine generator performance -- both open and closed cycles -- can be achieved with

FIGURE 7

Overall Cycle Efficiency
Steam and Vapor Engine Generators



already developed equipment. A case can be made for adapting automotive engines to open cycle steam operation to minimize equipment cost and size. The latter possibility should undergo further evaluation if steam engine cycles are of interest to remote rural communities in the area of 20 hp.

Steam and Vapor Turbines

The vapor turbine cycles are identical to the vapor engine cycles except that a turbine is used instead of a reciprocating piston engine. As with the reciprocating engine, a variety of vapors, may be used, and cycle performance is dependent on boiler or evaporator temperature and type of working fluid used. Heat sources may, as with the reciprocating vapor engine be indigenous and concetrated solar heat.

Figure 8 is a plot of overall cycle efficiency as a function of evaporator temperature for three types of working fluids -- steam for open and closed cycles, Freons for closed cycle hermetically-sealed equipment, and mono chlorobenzine (MCB) for a hermetically-closed cycle. The open steam cycle produces low performance values and is improved by closing the cycle, going to many stages and incidentally of quite large diameter to accept the high specific volume of steam at low temperatures and pressures. At these conditions the number of stages may approach three or four, and be arranged in an axial flow path, with peripheral turbine blade velocities of 800 to 1,000 feet per second and requiring highly stressed high quality steel materials with diameters of two to three feet for even 10 kw ratings, but with good performance. The Freon cycles, on the other hand, having widely different pressure temperature characteristics, would be characterized by much smaller diameter rotors, running at peripheral velocities of 200 and 300 feet per second. The resultant stresses and aerodynamic characteristics would permit the use of cheap cost centrifugal rotors. Freon performances approach three and four per cent up to limiting evaporator temperatures of 300 F. It is interesting to note (although they are not exactly comparable) that turbine performance exceeds reciprocating engine performance at these temperature levels.

The performance estimate of about five per cent for MCB was derived from some preliminary data on Dr. Tabor's work with a solar heated MCB turbine plant.

In summary, the use of hermetically sealed Freon, MCB or equivalent turbines, with their relative simplicity compared to steam turbine types, for application to low quality heat sources such as solar energy, appears of interest. The technology is sufficiently well developed that successful technical development does not appear questionable.

Overall Cycle Efficiency
Vapor Turbine-Generator Plants

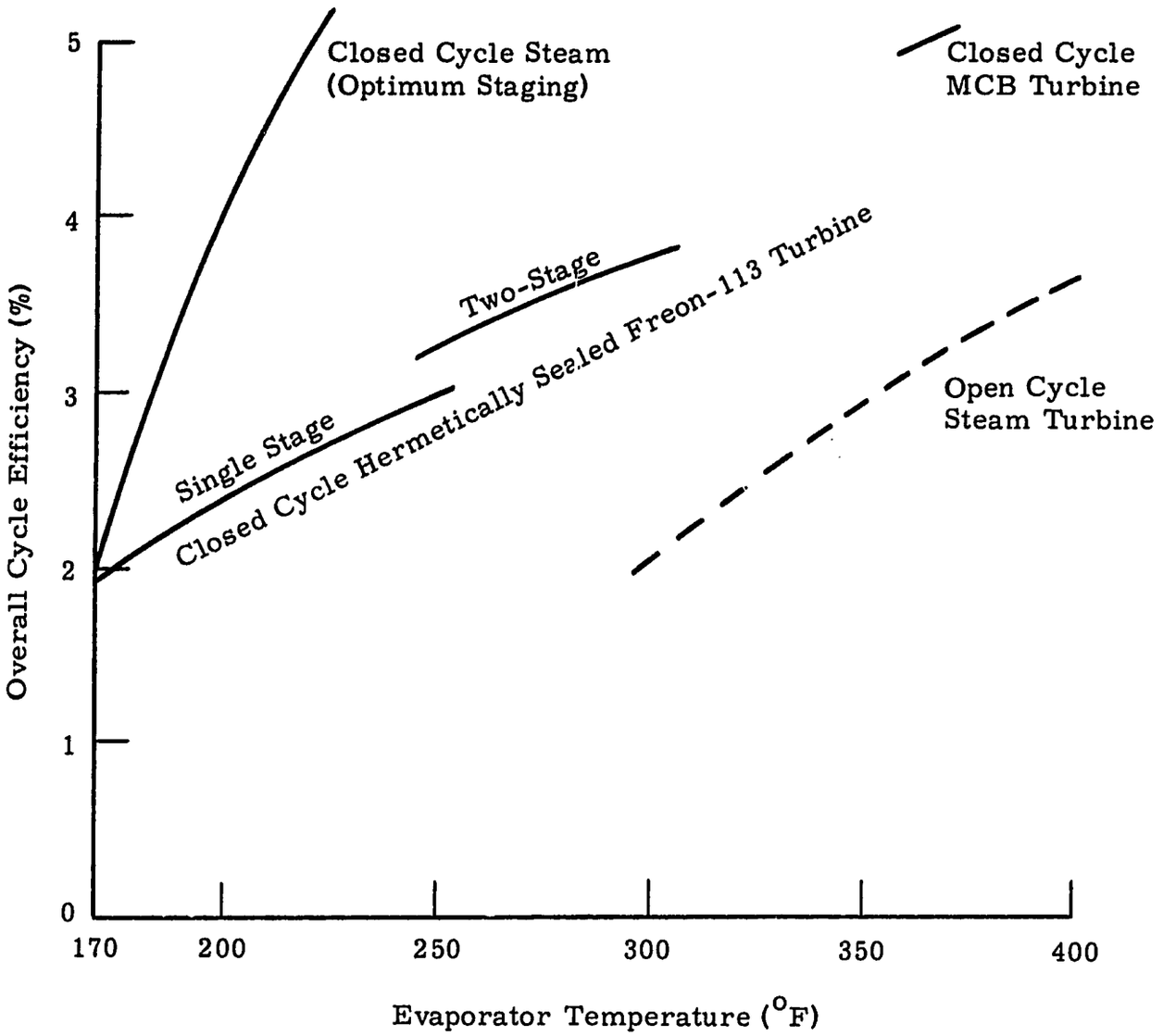


FIGURE 8

Stirling Engine

The stirling engine is an external combustion engine that operates with a hermetically sealed working fluid that successively receives heat from a hot chamber, expands in a cylinder to produce work against a piston, and rejects heat to a cold chamber for regeneratively heating the subsequent cycle. The mechanism and control of this engine to achieve expansion and compression of the working fluid in the correct sequence and for optimum performance is extremely complex. Inherently, the engine is very quiet and adaptable to any high quality heat source.

Developmental machines have been built, particularly in Holland by the Philips Research Laboratories and by the Battelle Memorial Institute in the U. S. A. for power levels of a fraction of a horsepower to hundreds of horsepower. It is claimed that their efficiency is as good or slightly better than that of conventional internal combustion engines, perhaps 30 to 35%. Fuels may be of any burnable type but care must be taken to develop furnaces and the required heat transfer surfaces, particularly if indigenous fuels are to be used.

Due to thermodynamic requirements, the piston speed for optimum performance approximates 500 ft. per minute, 1/3 to 1/4 that of diesel engine practice. Also, to achieve high efficiencies the mean effective pressures with helium or hydrogen are about 1000 psi.

A strong argument can be made for the use of air as the working fluid for remote community applications rather than hydrogen or helium. If this is the case, mean effective pressures may not exceed 50 psi even with supercharging, with a related penalty in efficiency. The resulting power per square inch of piston area then appears to be less than 0.5. Typical diesel engine practice approximates 2.0 horsepower per square inch implying that the basic stirling engine may be four fold the size of a diesel. Actually, it will be significantly larger than this, when allowance is made for the hot and cold chamber heat exchangers. Finkelstein, of Battelle, suggests that stirling engines may only be economically attractive for very special purposes such as military needs and for space. To date, no well developed application has been established.

In summary, it does not appear that the gross size of this equipment, at an estimated higher cost, and relatively poorer performance than IC engines (if air is used as the charge), would make the stirling engine an attractive candidate for rural electric plants, in spite of its probable ability to operate on indigenous fuels.

GAS TURBINES

Gas turbines are a class of thermal engines using the products of combustion directly to drive a turbine rotor. The unit consists essentially of a compressor to pressurize combustion air, combustion chambers for burning fuel with the compressed air and a turbine to extract mechanical power to drive the compressor and to supply shaft power. A regenerator can be added to preheat combustion air with waste heat from the exhuast, or intercooling and reheating can be introduced to improve plant efficiency. These additions, however, which increase the complexity of the cycle and add materially to its size and cost, are usually warranted only for large-scale applications.

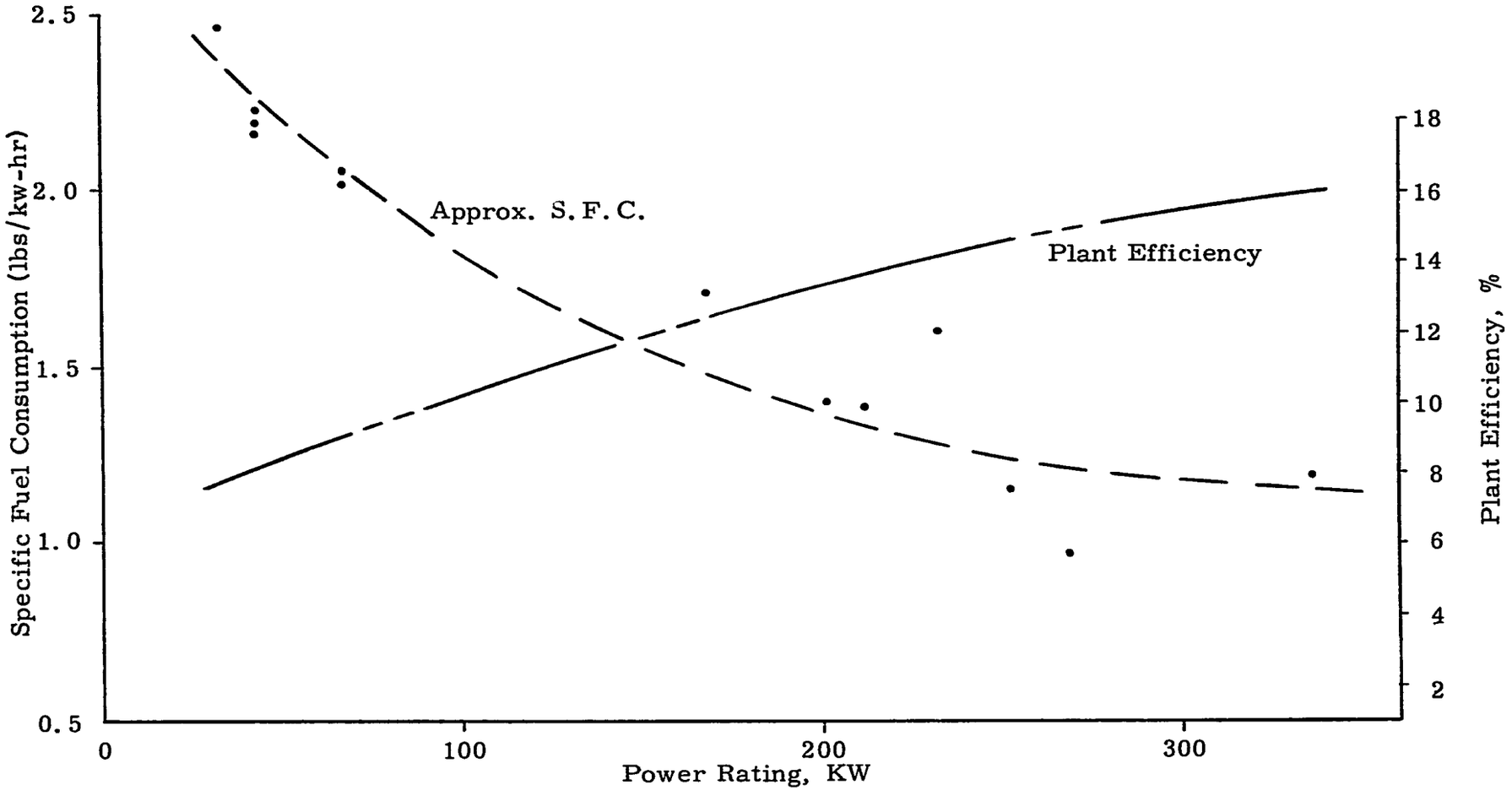
In its simple form the gas turbine is very light and compact, probably as little as 1/10 the volume and 1/20 the weight of an equivalently rated utility type diesel engine. Turbine generator plants have been developed and are being marketed for power ranges from 30 kw to 25000 kw. Available data from several manufacturers of equipments indicate Specific Fuel Consumption ranging from about 2.5 lbs/kw-hr at 30 kw to about 1.1 lbs/kw-hr at 300 kw power ratings. Plant efficiency ranges 8 to 16%. Figure 9 is a plot of this data with estimates of generator performance included. Specific electric plant weights approximate 10 to 15 lbs./kw and 1 cubic foot/kw or less.

No price data was available for low power rated equipments, but a 3500 kw gas turbine generator plant is priced at about 120 $/kw, a value lower than an equivalent diesel electric plant.

Most of the available equipments were initially developed for the aircraft industry with subsequent application to prototype automotive, prototype marine propulsion and special purpose power, pneumatic and portable water pump equipments. Consequently, initial design placed a premium on low weight, and their maintenance follows aircraft practice. Much of the lower power equipment must be overhauled every 1000 hours, although some manufacturers are striving for a 2000 hour goal.

There is no equipment presently available in the low power range having the ruggedness and maintenance free reliability to meet the continuous service called for on rural areas. From a technical standpoint, an equipment rated at 100 to 200 kw with a plant efficiency of about 10 to 12% could be evolved from existing technology by derating a present turbine, ruggedizing its structure and simplifying its controls. However, only if there were a large volume market for this type of equipment would development be worthwhile.

FIGURE 9



Estimated Performance of Simple Gas Turbine Generators.

WIND GENERATORS

Wind is an available resource at every possible site in the world, and its utilization for the generation of electricity or water pumping has been an accepted fact for many years. The wind regime at a given site, however, is highly variable during the season and during each day. For that matter, extreme wind variations occur over minutes of time. A site may experience an average wind velocity throughout the year, say of 10 miles per hour. The fluctuations go from a dead calm to over a hundred miles per hour.

Wind turbines are designed for a rated wind speed, with provision for cutting out at a minimum speed and feathering to prevent runaway at elevated speeds. This implies that only a small portion of the total power the wind generator could produce is available.

The analysis and evaluation of wind generators and site requirements may be found in excellent reports by many authors currently involved in this work.

Wind generators may be made in ratings from a few watts--such as the one made from a bicycle generator suggested at the 1961 Geneva Conference--to 1250 kw, the experimental machine developed at Grandpa's Knob in Vermont, U.S.A. In practice, however, the majority of units are in the ratings of 1 kw to 10 kw. The British, French, and Germans have been developing larger units up to 50 kw, and the Russians are designing a number of standard sizes up to 100 kw.

A great deal of this work is directed toward use of wind generators to supplement power generated by hydroelectric and thermal plants on large grid networks. Since the wind energy is "free", the resulting cost of electricity is quite low. E. W. Golding reports such costs as ranging from 1 to 2 pence per kw-hr, substantially lower than the costs of electricity produced by the more conventional plants.

The application of wind generators to this type of situation is apparently economically feasible where the grid system is operated at high utilization factors and where the ratio of the total power contributed by the wind generator to the system capacity is relatively low.

Applying wind generators to isolated rural communities, however, is a considerably different situation. Unless the people are satisfied to use the electricity only when adequate wind is blowing, a sizable electric storage facility will be required. The amount of storage will depend greatly on the site wind regime and load usage.

At typical rural community situations in Colombia and upland Peru, it was found that light winds blew during daylight hours and became calm at night. It was also found that electric power was used or desired only during the evening hours for household illumination. Daylight use of power could conceivably be for water pumping and small workshops.

As an example, the need for storage batteries to accumulate daytime power for just one night of use may increase electric generation costs three or more times. If greater storage allowance is made to account for successively calm days, costs obviously are significantly greater. An added disadvantage with electric storage batteries is the need for continuous semi-skilled maintenance.

It is because of this increased cost effect, the lack of substantial numbers of sites with appropriate wind regimes, and against the backdrop of ready availability of cheap petroleum fuels, particularly in the Colombia, Peru, Chile environment, that opportunities for wind generation in all probability do not appear economically feasible. Obviously, there are situations which can be found that are quite remote where the only alternative may be wind generation of any quality.

Without question, wind energy should, in the great majority of cases, be used to pump water directly in the rural community situation.

It is recommended, for isolated rural communities, that wind-driven water pumps be considered for irrigation of land or watering cattle, and that wind generators not be considered seriously, except in very unique and remote situations.

FUEL CELLS

All of the current methods for generating electrical power from fuel involve the combustion of the fuel. The over-all efficiency of these processes is limited by the Carnot cycle and varies from a low of 5 per cent for small, portable engine generator sets to a high of 45 per cent for large central power generating stations. Interest in fuel cells arose over 150 years ago as a means of by-passing efficiency limits set by the Carnot cycle, but progress was painfully slow and the interest level remained low. However, during the past decade, progress has been significant, and practical cells have been demonstrated recently.

Fuel cells are electrochemical devices capable of converting a portion of the chemical energy of a fuel directly into electrical energy. Under load, a single cell, which consists of two electrodes in contact with an electrolyte, generates 0.6 to 0.8 volt D.C. Higher voltages may be obtained by placing an appropriate number of cells in series.

The two electrodes of a fuel cell are known as the anode (negative electrode) and the cathode (positive electrode). Fuel is fed to the anode where its molecules release electrons which perform useful electrical work by flowing through the external load circuit to the cathode where its molecules gain electrons and enter the electrolyte as ions which migrate to the anode to react with the ionized fuel molecules. This completes the electrical circuit, and the two ions combine to form the fuel cell combustion products, water and carbon dioxide.

Some of the more important functional requirements for fuel cells are:

Reaction Zone - It is necessary to maintain an invariant reaction zone between the electrode, electrolyte, and fuel at each electrode.

Reaction Rate - The power output per unit of electrode area depends largely on the rate at which the fuel and oxygen can enter into the electron removal and acceptance step mentioned above. The exact mechanism by which these transfers are accomplished is not yet fully understood.

Reaction Product Removal - The continuous operation of a fuel cell system requires the removal of reaction products. For cells using hydrogen alone as fuel, the product is water. In those cells which use hydrocarbons as fuel, the reaction products are water and carbon dioxide. These must be removed to prevent dilution and neutralization of the electrolyte.

Heat Removal - The heat generated in the fuel cell comes from irreversibilities in the electrochemical reaction, the electrical resistance of the electrolyte and electrodes, and reversible heat, which is a function of the temperature at which the cell is operated.

Cell Types

At the present time, there are many fuel cell design concepts under development. These vary in electrode materials, electrode structure, type of electrolyte, method of retaining the electrolyte, fuel and oxidant used, and temperature of operation. A convenient classification, for purposes of discussion and comparison, is the cell operating temperature. Some of the more advanced systems are listed in Table 12.

Low temperature cells are best suited for operation with hydrogen as fuel. At high temperatures (500-1000 C), conditions are more favorable for the use of more practical hydrocarbon fuels such as natural gas (methane), kerosene, and unleaded gasoline. In order to avoid the severe materials problems encountered with high-temperature fuel cells, considerable development effort is being applied to the problem of developing low and intermediate-temperature fuel cells operating on hydrocarbon fuels such as propane, butane, and alcohol. The use of these fuels in these lower temperature fuel cells has already been demonstrated; however, the performance levels (efficiency) have been considerably lower than those attained with hydrocarbons in high-temperature fuel cells.

State of Development

The hydrogen-oxygen fuel cells are in the most advanced state of development. The Pratt and Whitney Company is currently engineering a boron-type fuel cell for power system use in the Apollo Project. The General Electric Company is engineering its ion-membrane fuel cell for use in the Gemini Project. Both of these systems are being designed to deliver several kilowatts of power.

In addition to these, the Allis Chalmers Company has demonstrated a prototype fuel cell powered tractor of approximately 15 kw rating, operating on hydrogen and oxygen. The General Electric Company has built a portable back power pack of 200-watt rating for the Bureau of Ships, operating on hydrogen and air. The first commercial application of a hydrogen fuel cell was announced by Pratt and Whitney in September 1962, with the installation of a 500-watt hydrogen fuel battery to supply power for electronic instruments at a gas compressor station operated by the Columbia Gulf Transmission Company.

TABLE 12

TYPICAL FUEL CELLS

	Reactants	Electrolyte	Electrodes Anode	Electrodes Cathode	State of Development
I. Low Temperature 100° C					
(1) Union Carbide	H_2-O_2	KOH	Carbon	Carbon	Advanced
(2) G. E. - Ion Membrane	H_2-O_2 or air	Acid Membrane	Pt	Pt	Advanced
- Liquid Electrolyte	H_2-Air	KOH or H_2SO_4	Pt, Pd	+ others	Moderately Advanced
(3) Justi - AFA Germany	H_2-O_2	KOH	Ni	Ag	Moderately Advanced
(4) Allis Chalmers	H_2-O_2	KOH-Asbestos	Ni	Ni	Advanced
(5) Shell - England	H_2-O_2	Acid	Pt	Pt	Advanced
II. Intermediate Temperatures 100-500°C					
(1) Bacon-Pratt-Whitney (200°C)	H_2-O_2	KOH	Ni	Ni	Advanced
III. High Temperature 500-1000°C					
(1) Molten Carbonates (500-700°C)	Hydrocarbons-Air	Alkali Metal Carbonates	Ni	Ag	Early
General Electric Texas Instruments Pratt-Whitney Illinois Gas Institute Broers, Holland Chambers, England					
(2) Ceramic Electrolyte (1000-1100°C)	Hydrocarbons-Air	ZrO_2 - CaO	C Pt	Ag Pt	Early
General Electric Westinghouse					

Hydrogen-air fuel cells, because of the relatively high cost of pure H_2, will probably be restricted to specialty applications where convenience, weight, silence, or some other factor outweighs cost as a prime requisite. One attractive potential commercial application for these cells is as a power source for fork lift trucks. The use of fuel cells as power sources could permit keeping these trucks in operation 24 hours a day, thus eliminating the 8-10 hour off-duty charging cycle.

On the basis of the current state of development, high-temperature fuel cells appear to be at least a decade away from commercial availability. On the basis of present experience, these types of systems appear best suited for generating blocks of power ranging from 1,000 to 50,000 kw. However, such fuel cells could be adapted to smaller ratings for service as remote site power sources.

Performance and Cost Estimates

Assuming continuing progress in the development of these devices and improvements in performance, commercial availability of hydrogen air cells is likely to occur in one to five years, and high-temperature hydrocarbon fuel cells in from five to ten years.

Performance and cost goals which appear attainable in the period 1970-1975 are given in Table 13. These are for D.C. power output. The cost of inversion to A.C. may add approximately $50 per kw.

A summary analysis of the significant technical problems to be overcome by the 1970-1975 time period is set forth in Table 14.

TABLE 13

PERFORMANCE AND COST GOALS

Type of Fuel Cell	Maximum Power Density KW/ft^3	Price - $/KW
Ion Membrane (H_2 - Air) 1970	2-3	1000 - 1200
(H_2 - O_2) 1970	4-6	800 - 1000
Alkaline Electrolyte (H_2 - Air) 1970	6-8	300 - 500
Acid Electrolyte (H_2 - Air) 1970	5-6	500 - 700
Molten Carbonate Electrolyte (Hydrocarbons-Air) 1975	4-5	85 - 100
Ceramic Electrolyte (Hydrocarbon-Air) 1975	4-5	85 - 100

SIGNIFICANT TECHNICAL PROBLEMS - TABLE 14

Type of Fuel Cell	Problem	Desired Solution	Probability of Achieving Solution by 1972	Alternate Solution	Probability of Achieving Alt. Solution by 1972	Comments
Ion Membrane H_2-O_2 H_2-Air	Catalyst cost.	Replace platinoid catalyst with inexpensive catalyst.	Moderate-difficult task to find as effective a catalyst.	Reduce amt. of catalyst used by a factor of 10 or more.	High; this is an empirical engr. task requiring patience and careful experimentation.	Cont. use of platinoid catalyst will keep price of ion membrane cell high and will require continued use of high purity H_2.
H_2-O_2 H_2-Air	Membrane life.	Extend to 5-10 year expected life.	Fair for organic membrane. Probability of developing suitable inorganic membrane is low.	Extend useable membrane life to 2-5 yrs.	Good	Long, reliable membrane life is required if ion membrane fuel cell is to attain general market penetration.
H_2-Air	Low power density	Increase power density by factor of 5.	Fair.	Increase power density by factor of2.	Excellent.	Thin membranes allow high power density but are susceptible to failure. Proper heat and mass transfer control can also significantly improve power density.
H_2-O_2 H_2-Air	Heat and mass transfer	Develop balanced heat & water invariance.	Good. This is an engineering design problem that appears soluble.	No alternative solution possible.		Need basic understanding of chemistry and thermodynamics involved.

Type of Fuel Cell	Problem	Desired Solution	Probability of Achieving Solution by 1972	Alternate Solution	Probability of Achieving Alt. Solution by 1972	Comments
Liquid Electrolyte / Basic Electrolyte	Electrolyte invariance	CO and CO_2 rejecting electrolyte	Good	Remove CO and CO_2 from the fuel.	Excellent.	A CO and CO_2 rejecting electrolyte is required for economic reasons. Removal of CO and CO_2 by scrubbers, etc. reduces system efficiency and increases fuel cell first cost.
Basic & Acid Electrolyte	Fuel purity	Operate cell on impure H_2 (containing CO, CO_2 and perhaps H_2S)	Low.	Fuel purification.	Excellent.	If full fuel cell market potential is to be attained, low cost fuel must be consumed. Ultrapure H_2 is overly expensive. Cost of purification can be reduced, but economic solution eliminates purification step.
Basic and Acid Electrolyte	Hydrocarbon fuel.	Operate cell directly on hydrocarbon fuel.	Very low.	Steam reform or partially oxidize hydrocarbons.	Good.	Converting hydrocarbons assumes that small, scaled down economic units can be developed that will produce H_2 of desired purity. Alternate solution results in lower power density, more expensive fuel cell. Thus limits achieveable market penetration

Type of Fuel Cell	Problem	Desired Solution	Probability of Achieving Solution by 1972	Alternate Solution	Probability of Achieving Alt. Solution by 1972	Comments
Acid Electrolyte	Expensive structural elements.	Find inexpensive corrosion resistant structural elements.	Good.	None.		There is no alternate solution because if materials of construction problem isn't solved, acid electrolyte fuel cell cannot be exploited.
Basic & Acid Electrolyte	Catalyst cost.	Catalyst cost of $100/Kw	Moderate			Catalyst cost figure must be achieved to attain significant market penetration.
Basic & Acid Electrolyte	Heat and mass transfer	Reliable control of temperature, water and air.	Good.	None		Temperature and H_2O must be controlled at electrode for high power density. Electrolyte temperature and concentration must be maintained. Impurities must be removed. IR and T S heat and generated H_2O must be removed.
High Temperature Molten Carbonate	Materials of construction	Select & develop materials capable of withstanding corrosiveness of molten carbonates.	Moderate.	Engineer cells around replaceable materials.	Good	Molten carbonates are extremely corrosive. However, cost of high temp. fuel cell with long lived matls. of construction should be less than one where high maint. costs are incurred replacing corroded structural elements.

Type of Fuel Cell	Problem	Desired Solution	Probability of Achieving Solution by 1972	Alternate Solution	Probability of Achieving Alt. Solution by 1972	Comments
Molten Carbonate	Electrode life.	Develop electrode structure capable of long term operation in this type of cell.	Moderate-operating conditions tend toward removal of catalyst from electrode.	Engineer replaceable electrode structures.	Good.	As above, alternate solution requires balancing maintenance costs versus first costs.
Molten Carbonate and Zirconia	Fuel conversion	Develop efficient self-contained fuel conversion unit to crack conventional fuels into consumable gases using waste fuel cell heat.	Good-requires top notch engr. to scale large scale efficiency cracking and reforming units into small, efficient, sizes and incorporate into fuel cell itself.	Develop separate fuel conversion unit.	Excellent. This solution requires only that existing H_2units be scaled down in size.	Alternate solution does not permit as efficient recovery of waste heat for fuel conversion. Capital costs would also be greater.
Molten Carbonate and Zirconia	Variable load operation	Maintain efficienc operation and cell temperature under low load conditions.	Good.	Operate fuel cell only under constant load conditions.	Excellent.	Alternate solution severely restricts market opportunity.

Type of Fuel Cell	Problem	Desired Solution	Probability of Achieving Solution by 1972	Alternate Solution	Probability of Achieving Alt. Solution by 1972	Comments
Zirconia	Electrodes	Develop long lived, high current density, inexpensive cathode. Eliminate platinoid materials.	Moderate-insufficient data is available to permit being overly optimistic about finding optimum solutions quickly.			
Zirconia	Invariant conditions	Maintaining invariant materials conditions under extreme temperature operating conditions	Moderate.	Engineer cells around replaceable materials.	Good.	Must compare high maintenance costs with high first cost.

PHOTOVOLTAIC SOLAR CELLS

The most familiar form of photovoltaic generator in use today is the silicon "solar cell" that is being used to convert the sun's energy to electrical energy on many of this country's satellites and space vehicles. The absence of moving parts, the lightness in weight, the simplicity and reliability of operation, and the indefinite life expectancy make these cells extremely attractive for space use and, except for their very high cost, may be attractive for very low power use in rural communities. At the present time, silicon yields the most efficient and most highly developed solar cells; for this reason the following description of the operating principles is given in terms of silicon cells. It must be emphasized, however, that there are many other materials that are capable of generating electric power under the influence of light, and that the hope for low-cost electricity from the sun lies in these other, less expensive materials.

Photovoltaic Generation Systems

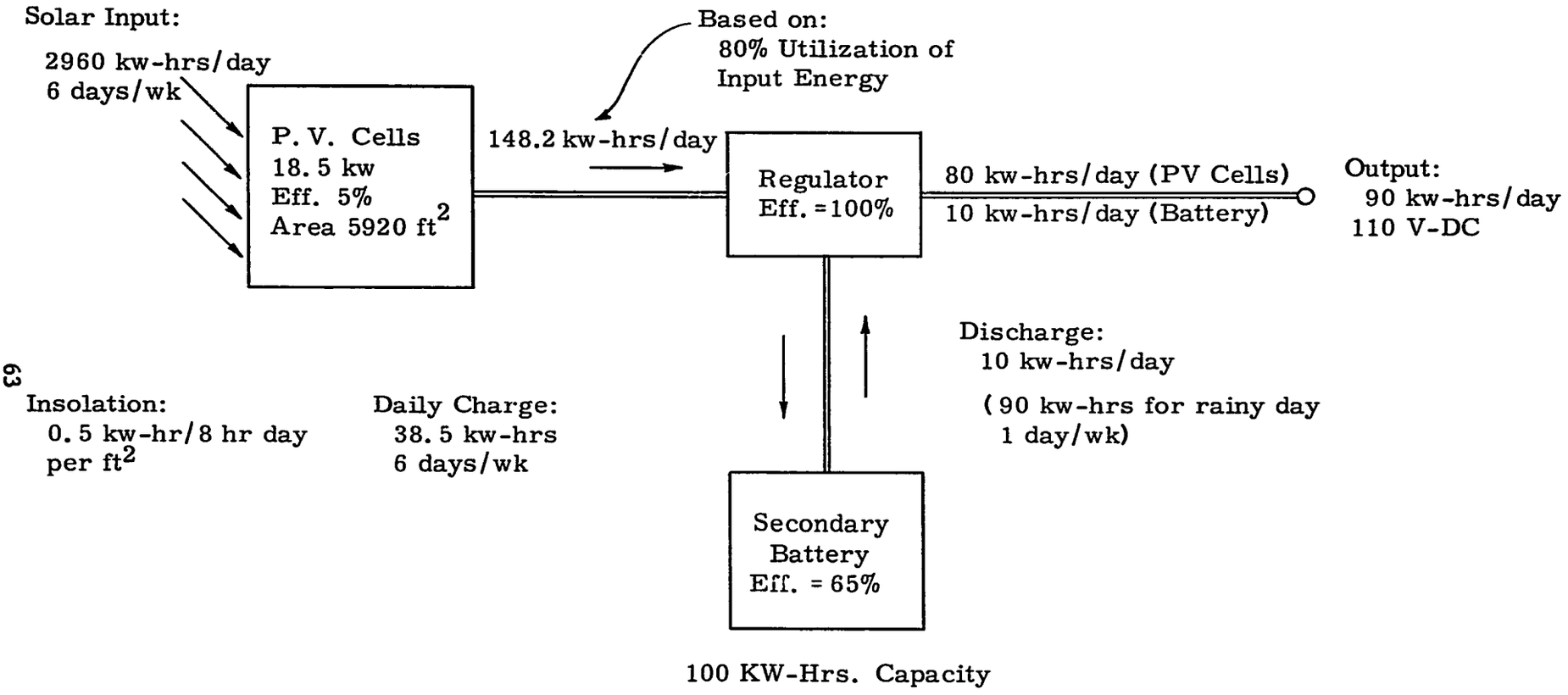
A schematic diagram of a typical photovoltaic generation system is shown in Figure 10. It consists of cells mounted on fixed panels tilted to receive optimum solar insolation at the particular latitude and variation of sun's altitude during the year. The power generated by the cells is controlled by a regulator where a portion is diverted to charge a secondary battery, the bulk of the power being available for load. The storage battery serves to accumulate power for night time loads and for operation during cloudy or rainy days.

A model has been analyzed for a nominal rating of 10 KW, although the analysis is equally applicable to other power ratings.

It is assumed that 10 KW may be delivered for the eight hours of practical impingement of solar insolation. In addition, it is assumed that 10 KW-hrs will be used during the evening hours. Therefore, the plant is nominally rated to deliver a total of 90 KW-hrs per day.

In addition, it is assumed that one day each week would be rainy and the total needs for one day would be supplied by the battery. On this basis, a 100 KW-hr storage battery would be needed. Then for cells having an efficiency of 5%, the solar input will be 2965 KW-hrs per day for 6 days per week, and the resultant overall plant efficiency is 3.55%.

FIGURE 10



Plant Efficiency: 3.55%
Plant Factor: 37.5%

10 KW Solar Cell Generator with 23.8% Battery Capacity.

The photovoltaic panel area, based on a solar insolation value of 0.5 KW-hrs/ft^2/8 hrs, is 5930 sq. ft.

If currently available silicon solar cells were used in the system described the total installed cost would be well over $100,000 per kw power output. 10% efficient silicon cells 1 cm by 2 cm in size cost about $3 to $4.50 each.

Performance Parameters

The General Electric Company has recently conducted a technical and economic study of photovoltaic power generation using thin film, large area cells which could be manufactured on a mass-produced basis and for less than 0.1% of the cost of silicon cells. Such cells, using thin films of cadmium sulfide and cadmium telluride are currently under development and efficiencies of 7% have been achieved in small samples and under carefully controlled conditions. The study analyzed the possible costs of such cells under mass production conditions and concluded that a selling price of $3.20 per square foot for 5% efficient cells could eventually be achieved.

Table 15 is a tabulation of equipment, and net cost of electricity for a photovoltaic system with a 100 kw-hr battery capacity for an output power rating of 10 kw. The prices of the cells were assumed to be $3.10 per square foot. Other assumptions made were:

Structure to mount the cells was 10% of cell cost.

Plant life of 20 years.

Heavy duty lead acid storage batteries would be developed, by the time photovoltaic systems were applicable, to sell at $40 per KW-hr of capacity.

Regulation, circuit switching and control and protection would vary from $130/KW at the 1 KW level to $50/KW at the 10 KW level. These values had been estimated for applications wherein severe solar insolation variations occur. For this example, it was assumed that a good source of reliable uninterrupted solar energy was available with consequent decrease in required regulator and control costs. Estimates of $110/KW at 1 KW to $30/KW at 10 KW were used.

TABLE 15

SYSTEM PARAMETERS AND COST OF PHOTOVOLTAIC ELECTRIC PLANT

AS A FUNCTION OF BATTERY CAPACITY AND UTILIZATION

(Based on 25% Plant Utilization)

Assumed cell cost	=	$3.10/sq.ft.
Cell efficiency	=	5%
Plant life	=	20 years
Daily load requirements	=	90 KW-hrs. (630 KW-hrs/wk)
Nominal plant rating	=	10 KW

BATTERY CAPACITY (KW-HRS)	0	10	100	180
Direct daily output (kw-hrs)	90	80	80	0
Daily battery output (kw-hrs)	0	10	10	90
Rainy day (1/kw) (kw-hrs)	0	0	90	90
Max. weekly battery utilization (kw-hrs)	0	70	150	630
Plant efficiency	4.00	3.81	3.55	2.60
PV cell area (ft^2)	4500	4720	5920	8070
Max. plant utilization (100% sun)	37.5	37.5	42.8	42.8
Max. plant utilization (85.8% sun)	32.1	32.1	36.7	36.7
Days capacity (0% sun)	0	.11	.11 to 1.11	1.0 to 2.0
Equipment cost ($/kw)	1555	1678	2449	3500
Equipment cost rate (mils/kw-hr)	168	181	264	377
Operation (mils/kw-hr)	72	72	72	72
Net cost (mils/kw-hr)	240	258	336	449

As shown on Table 15, the total equipment or capital cost for the photovoltaic system with 100 kw-hrs of batteries is about 2500 $/kw. Resultant electric generation costs are estimated at 3.36 cents/kw-hr. Figure 11 plots the estimated cost of generation for both 5 and 10% efficient cells over a range of solar cell costs, in the event cheaper fabrication processes are possible.

Problem Areas

It has been emphasized that the photovoltaic generating system costs are not based on existing cells, but on cells that must be developed. Considerable development effort must be spent in obtaining the required efficiency in large-area cells and in obtaining the required very low price relative to current prices for silicon cells. It is felt that the development of the cells described represents reasonably straightforward research and development and no major breakthroughs are required since the assumptions are modest extrapolations of the existing technology. The following problems must be solved, however, if these cells are to be achieved.

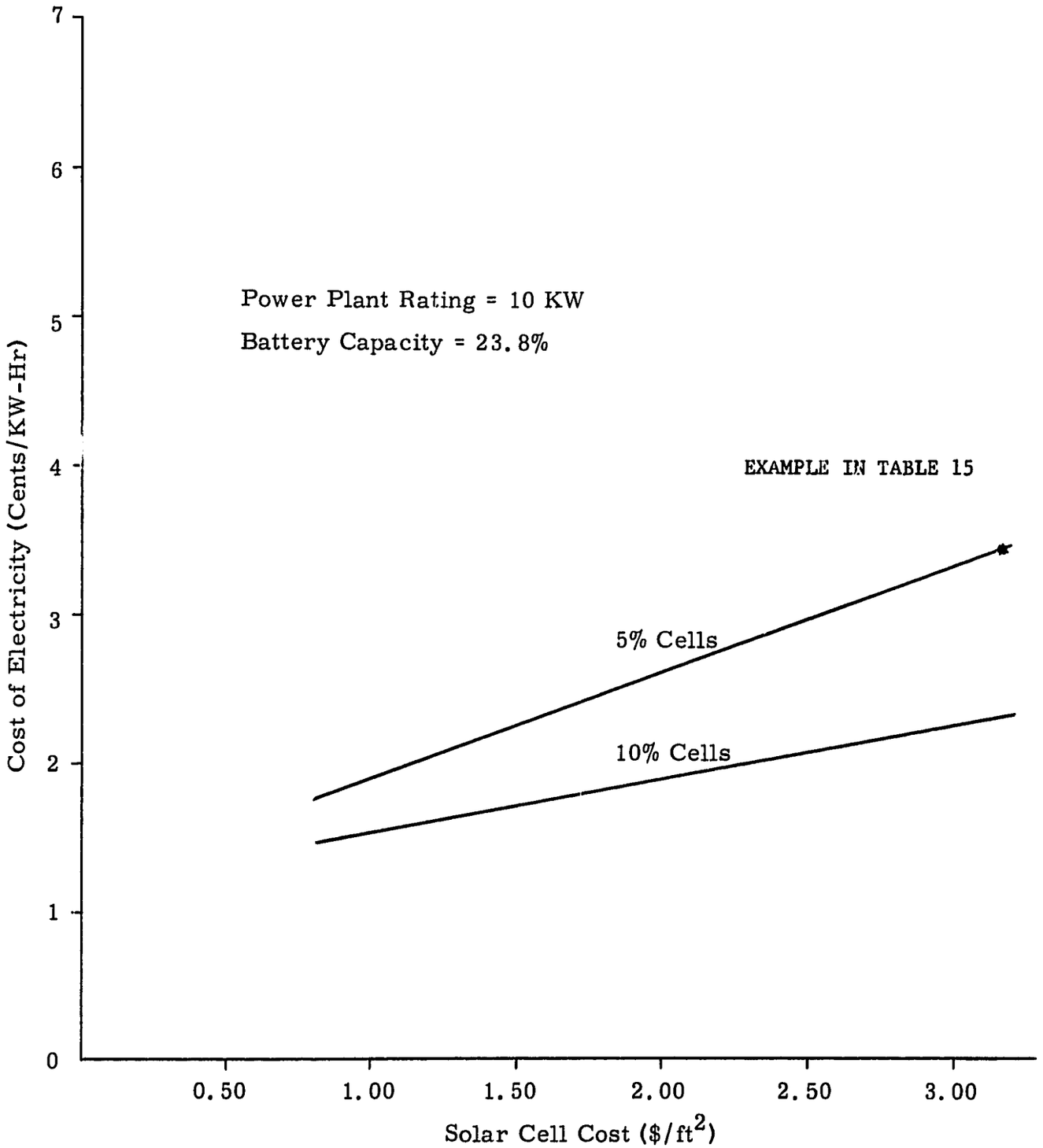
1. The cells must be designed using low cost materials insofar as possible and mass production techniques must be incorporated in order that the price of $3.20 per square foot or less can be achieved.

2. A method for depositing a uniform, high quality active surface (of probably cadmium sulfide or cadmium telluride) must be achieved in order that large (of the order of one square foot), 5% to 10% efficient cells can be produced with very low reject rates.

3. A method of encapsulating or otherwise protecting the cells from weather and other hazards without maintenace for a metter of years is required. In addition, high reliability must be achieved for the electrical connections which must also function without maintenance

4. It is essential that low cost storage batteries be developed for installation with the solar cell array, since the batteries represent a significant part of the total cost of the power system.

FIGURE 11



Cost of Generating Electricity with Solar Cells (Based on 25% Plant Factor).

THERMOELECTRIC GENERATORS

The thermoelectric generator is based on the familiar thermocouple, in which a voltage is generated across two junctions of dissimilar materials when the junctions are held at two different temperatures. These generators are made from carefully prepared semiconductor materials giving much higher efficiencies than the more conventional thermocouple materials. The power producing capability of a thermoelectric material is best indicated by the "dimensionless figure of merit" of the material, ZT, in which Z depends on the properties of the material and T is the absolute temperature of the material.

Since the thermocouple requires a temperature difference for its operation, a thermoelectric generator must provide for a heat source at the hot junction and a means of removing heat from the cold junction. On the other hand, we are at liberty to add the heat and remove it in whatever way best suits the particular application. Thus the generator does not require refined fuels as do gasoline or diesel engines, but can operate on indigenous fuels as might be available in isolated areas. In addition, because they contain no moving parts, thermoelectric generators can be made rugged, are maintainable with unskilled labor, and are portable.

Performance Capabilities

Presently, the best available thermoelectric material has values of ZT of 0.75, implying a generator efficiency of no more than 5%. Overall efficiencies are likely to be much less where indigenous fuels must be burned, since the efficiency of such burners is usually low as are the heat fluxes to the hot junctions of the thermocouples. Typically, designs of low power thermoelectric generators for operations with gasoline fuel have been made with specific weight and volumes of 8 watts/lb. and 13 watts/ft^3. Future designs of up to 20 watts/lb. and 40 watts/ft^3 are a possibility. Present day generators are expensive. A study indicates that prices for generators using lead telluride, the best presently available material, will be about $3 to $5 per watt in quantity production. A 100 watt generator would then cost $300 to $500. At these prices, it is obvious that thermoelectric generators will be attractive only where small amounts of power (up to perhaps 500 watts) are required and where the use of refined fuels or solar-powered generators is not feasible. Future improvements in fabrication techniques along with production may permit dropping costs to $1/watt with presently available materials.

Thermoelectric generators in above 500 watt sizes will probably not become practical in competition to other electric generation concepts until ZT values of 2.0 or higher are achieved. Such an improvement, coupled with better thermocouple junctions should result in increased efficiencies of 10 to 12%, and a cost decrease to $200 to $300 per kilowatt. A 500 watt generator then would cost $100 to $150. Generators in sizes to about 3 kilowatts might then be practical, in competition with gasoline or diesel electric plants.

Problem Areas

The major problem standing in the way of thermoelectric generators is that of cost. Costs of several thousand dollars per kilowatt do not make a 100 watt generator attractive for use in isolated areas. Although materials such as lead telluride are quite expensive, they do not contribute prohibitively to the cost per kilowatt -- rather it is the very poor efficiency that is primarily responsible for this. Some improvement can be achieved through significant reductions in the resistance at the junctions between the thermocouples and their conducting straps. A number of researchers are working on this problem with promise of practical solutions. This alone will not be enough, and a reduction in cost to acceptable levels will probably not be achieved until there is a significant improvement in the value of ZT. Progress in improving ZT has been slow. New materials have been discovered, but improvements in lead telluride make it still the best material available for the type of generators we are discussing. It is probably not unreasonable to expect that further slow progress will eventually increase the value of ZT to about 1.0, but it also seems safe to say that the required value of 2.0 will not be achieved through continued improvements in existing materials. In any event, if a value of 2.0 is ever achieved, it will be the result of a materials "breakthrough". It, therefore, appears very questionable whether thermoelectric generators will ever be used, except in rare circumstances, as power supplies in isolated areas.

EQUIPMENT DEVELOPMENT OPPORTUNITIES

This section reviews equipment development opportunities in these three classifications:

1. Short-Range Equipment Improvement Opportunities

   This category is restricted to improvements or adaptations of existing equipment which could be accomplished within a one to three year period.

2. Medium-Range Equipment Development Opportunities

   Equipment development opportunities which can be accomplished within a five-year development program.

3. Long-Range Equipment Development Possibilities

   Development possibilities which involve a period longer than five years for the development of practical equipment.

SHORT-RANGE EQUIPMENT IMPROVEMENT OPPORTUNITIES

The principal opportunities for improving existing small-scale power supplies, notably diesel and gasoline engine generators, lie in the area of adapting these machines to better meet rural environment application problems. Development opportunities in this area include the following:

1. Simplified operating controls for starting.loading and stopping. Current starting practice with conventional equipment involves complex setting of engine speed and switching into distribution line loads.

2. Ruggedized speed and engine control devices. Conventional speed governors, for example, require too frequent restting. Furthermore, the adjustment is usually too complex a task for the local operator.

3. Development of a "packaged concept" including factory installed accessories, weatherproof enclosure, etc., so as to minimize field installation requirements.

4. To secure maximum interchageability with other internal combustion engines in use, it is recommended that improved standardization of parts be considered.

MEDIUM-RANGE EQUIPMENT DEVELOPMENT OPPORTUNITIES

Packaged Hydro-Electric Plants

Numerous steep-gradient, glacier-fed streams in the upland areas of Peru and Colombia offer possibilities for installing standardized packaged hydro-electric plants. Glacier-fed streams in Peru typically have a dry season flow rate of 100 cubic feet per second and a head drop of 100 feet or more per kilometer. The estimated kilowatt capacity of hydro sites on these streams varies from 100 to 200 kw.

The foregoing situation indicates wide opportunity for a high-head, low-flow hydro-electric plant. The proposed installation would take the form of a small dam located upstream, with overflow for by-passing surplus or flood water. A horizontal ditch, lined with stone, would transport the water to a location having the required head. The penstock and generator equipment are installed almost vertically from the end of the ditch down the slope of the valley wall to the stream-bed below.

The equipment concept that is envisioned is a completely packaged unit which is integral with a section of the penstock and foundation pads. Such a concept would involve the packaging of already existing technology, including an 1800 rpm Francis reaction turbine coupled to a generator shaft. The equipment might be standardized for a power rating from 75-100 kw to benefit from lower production costs. In the event that additional capacity were required two or more of these units could be placed in series, where total head permits, or in parallel where flow rate permits.

The overall concept permits use of local contributed labor for the construction of the dam, ditching and foundations, installation of penstock, generator equipment, and distribution lines. This local contributed construction and installation work would permit a substantial reduction in over-all capital costs.

Wankel Engine Generator

The Wankel engine is currently under aggressive development as an automotive power plant. A confident evaluation of its real potentiality should be possible within several years. In the event that successfuly development is achieved, (difficult seal problems remain

to be overcome) and it is subsequently placed in mass production it would be a strong contender as an engine drive for a rural electric plant in the 100 kw range. Its potential advantages relative to a conventional diesel engine electric plant would be lighter weight, lower investment per kw, and an ability to utilize alternate liquid fuels including gasoline and diesel fuels.

Thermal Vapor Turbines

For a power range of 1-10 kilowatts, the development of vapor turbine generators using working fluids like monochlorobenzine offers some promise where the fuel supply is restricted to solar energy. Currently such a concept is under development in Israel. There is a considerable development opportunity for mechanical simplification and cost reduction, such that capital costs which are currently estimated to be $1000 per kw, might be significantly reduced.

LONG-RANGE EQUIPMENT DEVELOPMENT POSSIBILITIES

Fuel Cells

Molten carbonate and solid oxide electrolyte fuel cells currently under development show promise having eventual merit as small-scale power supplies for rural communities. These cells would utilize conventional hydrocarbon fuels as an energy input. Other cells under engineering development require hydrogen, or other exotic fuels which are unlikely to be economically or conveniently available in rural communities.

The former type of fuel cell may attain commercial feasibility within ten years. These cells may then offer a variety of generating sizes up to 1000 kilowatts, high reliability, low maintenance, and highly efficient operation (over 50%) on common hydrocarbons.

Stirling Engine Generator

The stirling engine, which is currently under development, is not a promising contender as an engine drive for a rural electric plant. Its size and weight are considerably greater than diesel equipment. Moreover, if its operation is restricted to air as a working fluid, its efficiency will be less than that of a diesel. The single advantage it would have for operation in rural communities is its ability to use alternate indigenous fuels, and for this reason it might find local application in rare cases.

Photovoltaic Solar Cells

Photovoltaic cells will have severe limitations as a local power supply for the foreseeable future. The only conceivable application for rural communities is where power requirements below 200 watts are involved for communications equipment. For example, the generation of 200 watts of power currently requires a cell panel area of approximately 60 square feet with energy storage included costing about $15,000. The likelihood that costs will be substantially reduced over the next 5-10 years will be dependent on the development of new photo sensitive materials and their fabrication into thin films. This critical problem offers some development opportunities.

Thermoelectric Generators

Thermoelectric generators, like photovoltaic cells, will continue to be restricted to the generation of very small quantities of power, e.g., less than 200 watts. Furthermore, the cost of a 1 kw thermoelectric generator today would approximate $3000 to $4000. It is conceivable, based on known materials, that a significant cost reduction could be achieved within 5 years. However, unless a significant materials breakthrough is achieved, thermoelectric power supplies will continue to be prohibitively costly for any conceivable application in rural communities.

A P P E N D I C E S

A. Estimation of Engine Generator Performance

B. Hydroelectric Equipment Cost

C. Cost Benefit Analysis of Bio-Gas Plants in India

D. Energy Content of Alternative Sources

E. Specifications of Diesel Fuels Available in India

APPENDIX A

ESTIMATION OF ENGINE GENERATOR PERFORMANCE

Catalogs or other specifications generally indicate engine performance in terms of fuel consumption in gallons per hour at a rated engine horsepower and speed. Unfortunately, this power rating is not that required to handle the generator load. A relationship is presented to correct this engine fuel consumption to the actual generator output, assuming the SFC remains reasonably constant, regardless of engine output, but at constant engine speed.

$$\text{SFC (lb/kw-hr.)} = \frac{Q_F \times w}{0.746 \times p \times e_g}$$

$$e_t = \frac{3413}{\text{SFC} \times \text{HHV}}$$

where

SFC = specific fuel consumption of engine generator in (lb./kw-hr)

Q_F = fuel consumption of engine in (gallons/hr.) at horsepower rating p

w = specific weight of fuel (lb./gal.)

p = horsepower rating of engine (hp)

e_g = generator efficiency (per cent)

e_t = over-all engine generator efficiency, ratio of electric power output to fuel energy input (per cent)

HHV = higher heating value of fuel (btu/lb.)

Generator Efficiency Values

For purposes of this estimate, typical values of generator efficiency are listed in the tabulation below. These are for 1800 rpm - three phase - 240 volt equipment.

Generator Rating, kw	Full Load Efficiency
10	0.805
15	0.81
20	0.835
25	0.86
30	0.86
40	0.87
50	0.885
60	0.885
75	0.895
100	0.90
125	0.91
150	0.915

Fuel Characteristics

Typical and consistent values of specific weight and higher heating value for two fuels are:

Fuel	Spec. Wt. (lb/gal.)	HHV (btu/lb.)
Diesel fuel-Grade 2-D	6.84	19,000
Gasoline	6.15	20,750

EXAMPLE

Estimated performance of 50 kw diesel generator set produced by KATOLIGHT CORP.

Engine type:	Continental TD 427
Power rating:	96 hp @ 1800 rpm
Fuel consumption:	6.2 gallons per hour
Generator efficiency:	0.885 (see Table above)

$$SFC = \frac{6.2 \times 6.84}{0.746 \times 96 \times 0.885} = 0.668 \text{ lb/kw-hr.}$$

$$e_t = \frac{3413}{.668 \times 19{,}000} = 26.9 \text{ per cent}$$

APPENDIX B

HYDROELECTRIC EQUIPMENT COST

Because of the difference in the requirements for each installation, it is impossible to determine a fixed equipment cost. In this investigation, we found a general reluctance on the part of manufacturers to quote on hydraulic turbines without specific data on the water supply, head, location, etc. Although many European manufacturers were solicited, none furnished cost information. As a result, assumptions were made to obtain representative component costs from manufacturers in the U.S.

We assumed a range of power generation equipment from 20-150 kw. The cost figures shown do not include transportation out of the U.S. or discounts for equipment re-sale and quantity. It was assumed the equipment would be shipped in pieces readily transportable by light truck or mule. Crating for overseas shipment was not included, nor were import duties or technical assistance for purchase or installation. A four wire, 3 phase, 60 cycle, A.C. power output was assumed. Only one company in the U.S. sells a complete package unit, and this is limited to 10 kw. Therefore, to obtain representative cost data, each component making up the plant was considered as a separate item as follows:

Dam or Equivalent

This can be built by native labor out of indigenous materials such as stone, rubble, cement, etc. No labor or transportation charge was assumed. It is our impression that if the local population can build a stone house or church, they can build a small dam and mount a sluice gate and penstock inlet. We assume the screen can be made of wood and maintained so as to prevent damage to the equipment.

Sluice Gate Valve

It is possible to make this component from wood and purchase or make the necessary hardware for actuating it. However, we have considered it as a manufactured self-contained component. The price data includes the necessary attaching bolts and hand wheel. A curve showing representative cost and weight data is shown on Figure 1.

Penstock

The penstock in most installations would be a very difficult piece of equipment to fabricate by local labor. In most cases, it would be a purchased item. It can be mounted on, or in the ground, but must be properly supported. We have assumed a lightweight steel pipe with two elbows and connection preparations suitable for bolting together at

the site. Approximate costs and weights for this equipment are shown on the curve on Figures 2 and 3.

Turbine and Governor

This equipment must be purchased so that it fits the conditions present at the site. Turbine sizes depend upon the volume and head of the available stream. Their cost is not only dependent upon physical size but also the type of mounting and water pressure. The cost data shown on the curve on Figure 4 is limited to turbines suitable for heads up to approximately 100 feet.

If an automatic governor is required in this equipment, it must be matched to the installation especially in sizes above 50 kw. Generally, the governor consists of a speed or load sensing unit with an oil pump and piping actuating a suitable servo device. The servo mechanism then by mechanical linkage operates the turbine gates, deflector, or inlet valve mechanism. If electrical paralleling and frequency stabilization are required a flywheel may also be needed. Cost data on the governor and its installation is considered a rough estimate. This is shown on curve 5.

Generator

For this study we have assumed the generator will be a belt driven, brushless, AC, enclosed unit. It is a packaged unit complete with exciter and silicon rectifiers. Mounting can be vertical or horizontal. Output voltage will be controlled by a manually operated field rheostat. The efficiency of these generators over the 20 - 150 kw range is about 94%. For obtaining cost data we assumed the following speeds: 10 - 25 kw, 1800 RPM and for 30 - 250 kw, 1200 RPM. Cost and weight data is shown on curve 6.

Generator Drive

Except in a single shaft turbine-generator unit the generator must be driven either by gears or belts. In underdeveloped countries a belt drive is the most easily maintained. Also because of the large pulleys needed in the larger size machines a considerable flywheel effect is present. This helps to stabilize output. Curve 7 shows costs for this type of equipment.

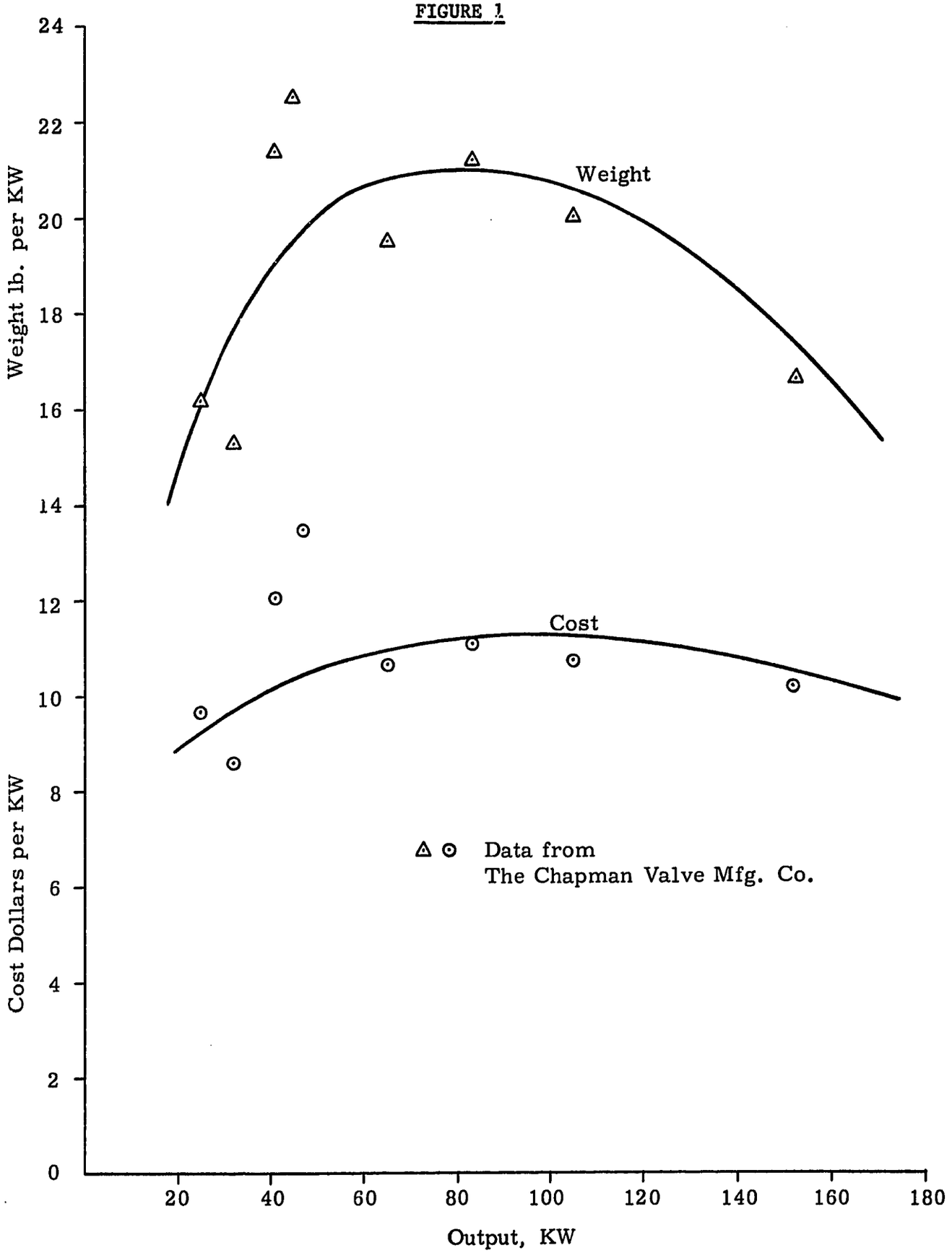
Electric Power and Generator Control

Even in the most elementary power supply some equipment is needed to disconnect the generator from the power lines and protect it from over-load. Included in the control is a generator field rheostat and a voltmeter. The cost data is shown on curve 8.

Power Plant Housing

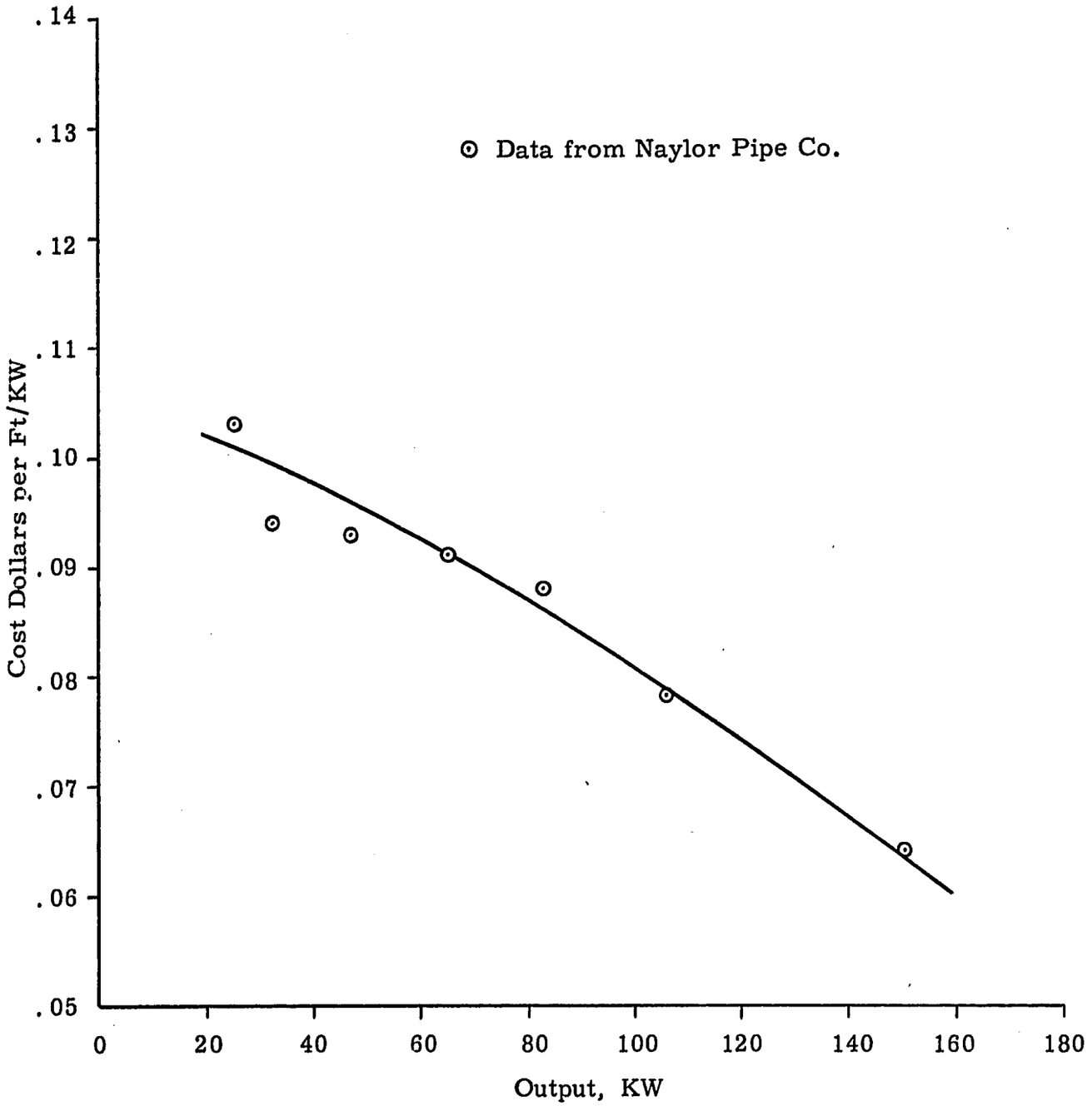
Except in the small sizes the integral hydraulic turbine-generator must be housed to protect the machinery from the weather and to furnish a satisfactory support for the machinery. In this investigation a simple sturdy building was designed and costs of the materials estimated. Basically, the building is a square structure with sloping walls made of stone. The floor on which the machinery is placed is assumed to be 20 ft. square. It would have a sheet metal roof, one window, and a trap door large enough to allow the component parts to be hoisted through. Costs include lumber, cement, steel supporting beams for the machinery, and miscellaneous hardware. We assumed indigenous materials would be used for the walls and no labor costs are included. Curve 9 shows the estimated cost of the above materials if purchased in the U. S. It is a reasonable assumption that some if not all of these materials would be available in the country where the plant would be installed. Because it is impossible to fix a height for such a building suitable for all installations the curve shows estimated costs for various heights. The floor area which is assumed 10 ft. below the roof remains constant.

FIGURE 1



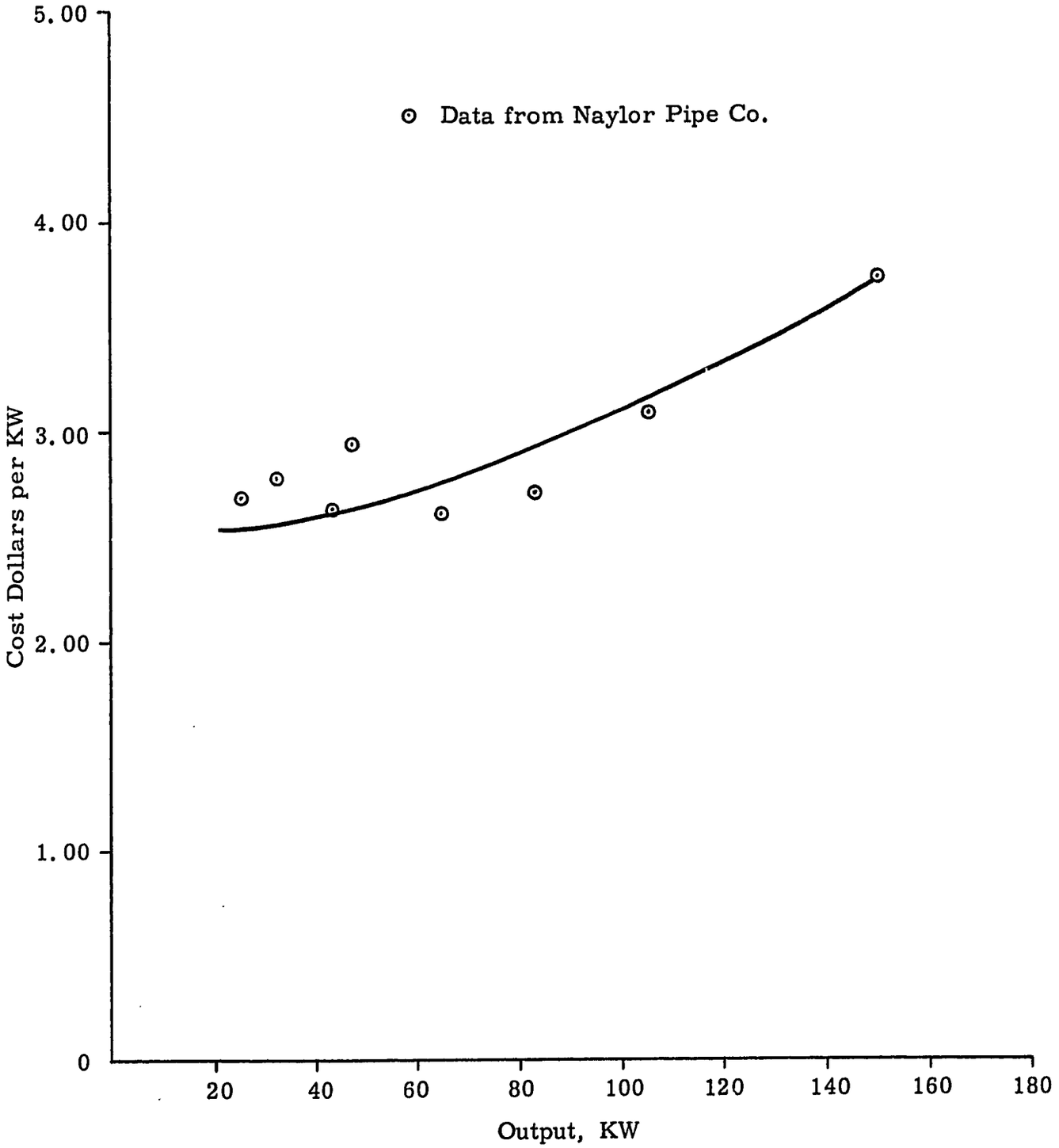
Cost and Weight of Cast Iron Sluice Gates.

FIGURE 2



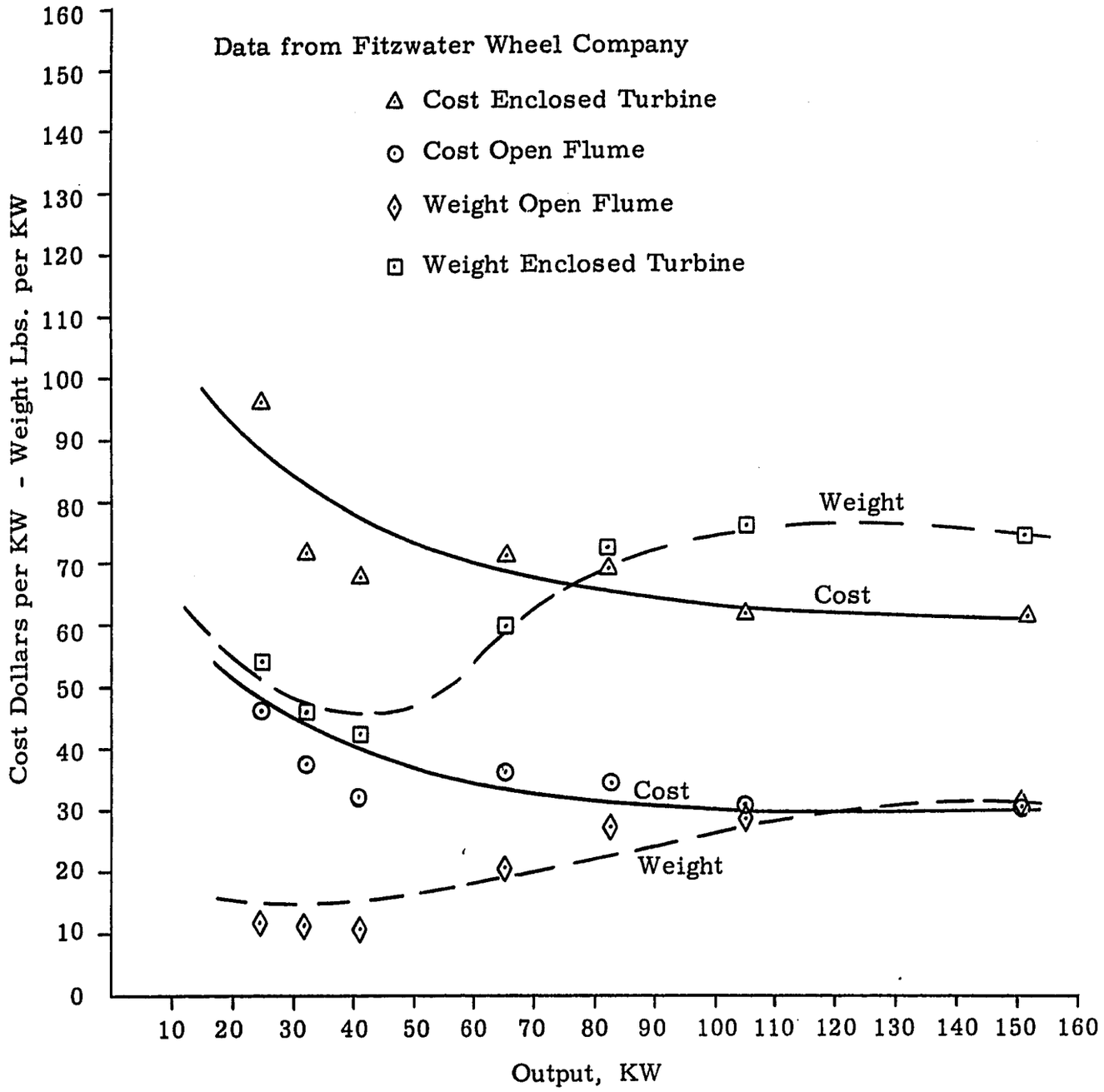
Cost Per Foot per KW of Steel Penstock Pipe Suitable for Low Head Small Hydraulic-Generator Power Plants.

FIGURE 3



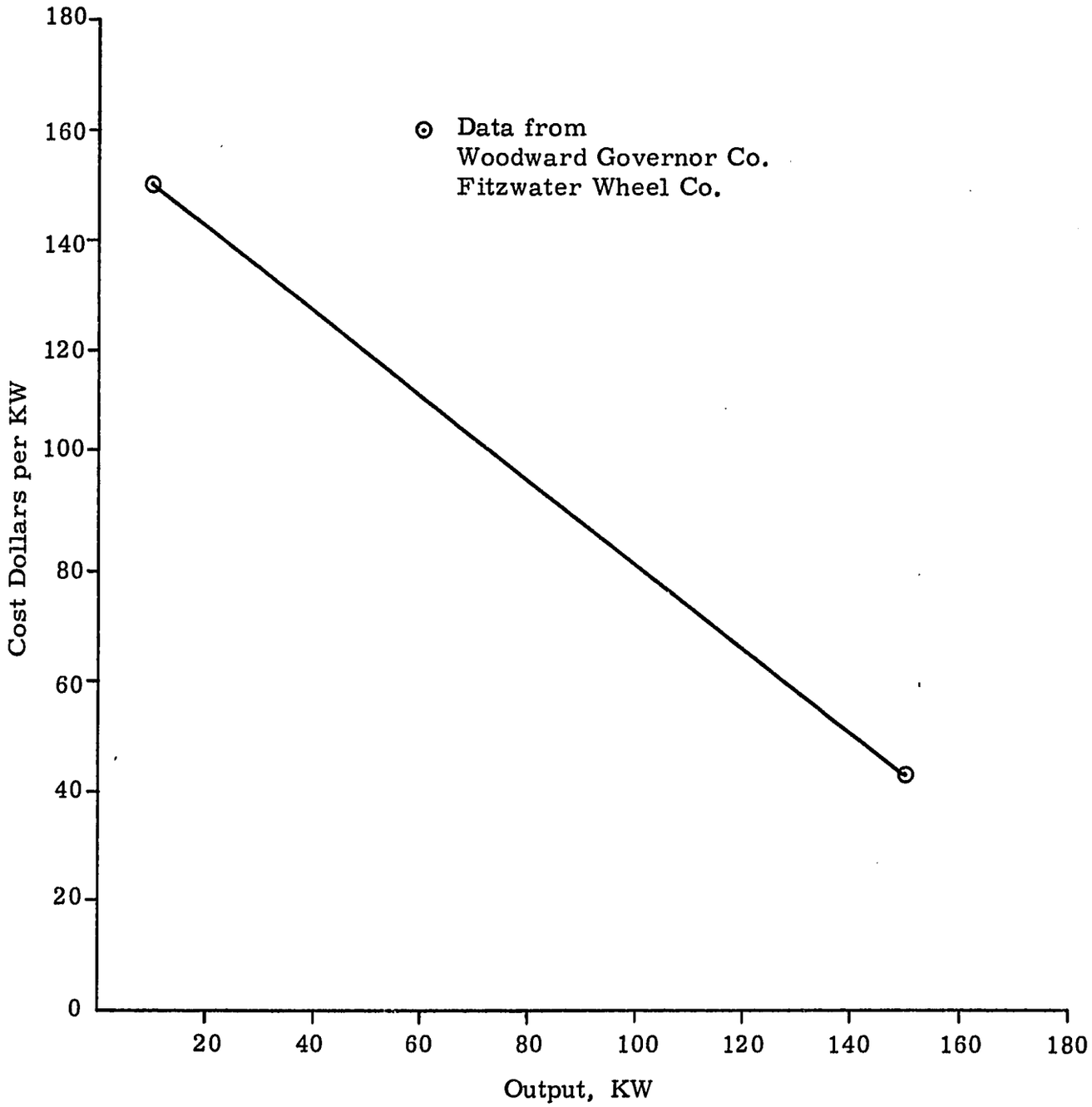
Cost of 90° Steel Pipe Penstock Elbows with Coupling Preparation.

FIGURE 4



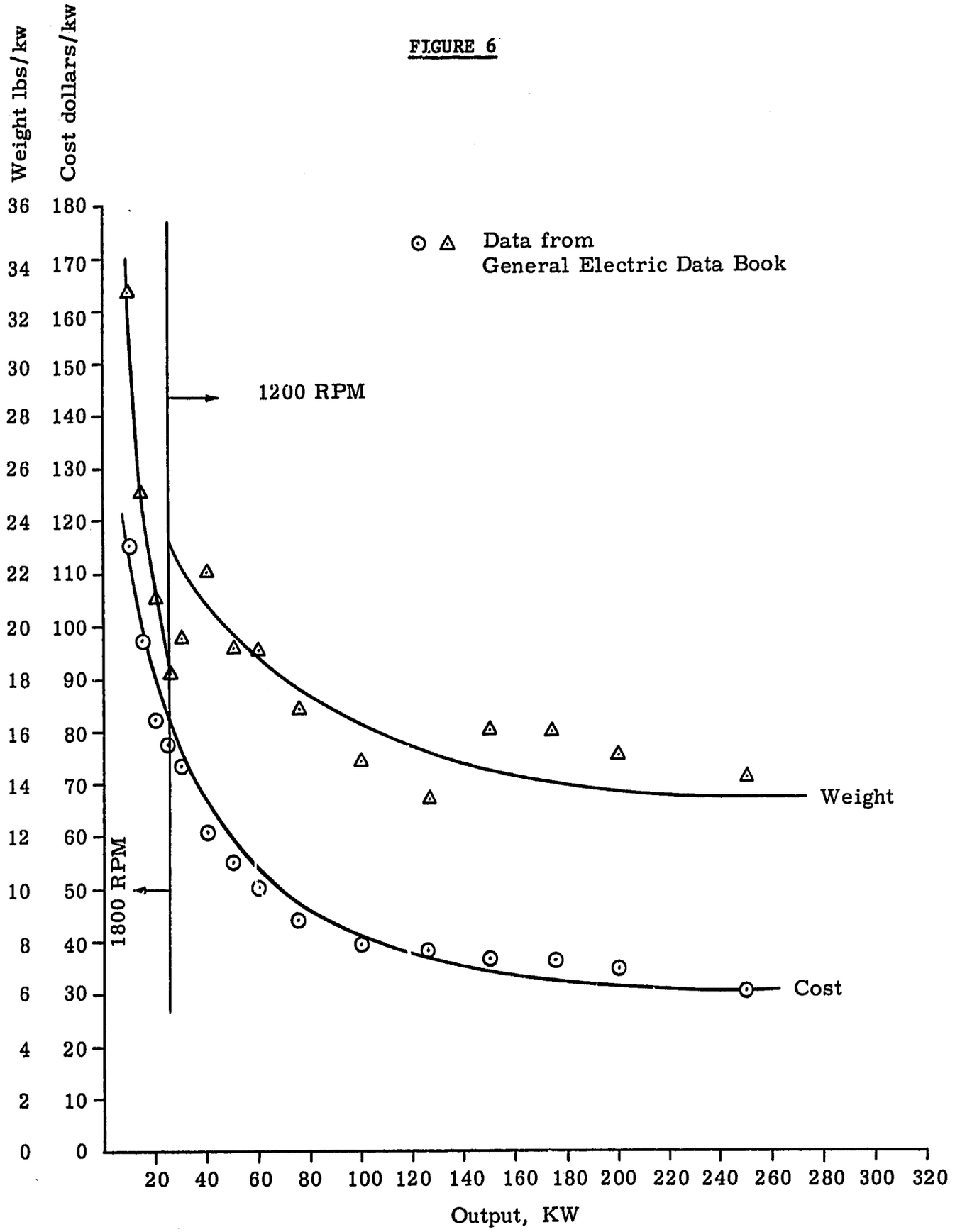
Estimated Cost and Weight of Hydraulic Turbines for Heads Less Than 100 Feet.

FIGURE 5

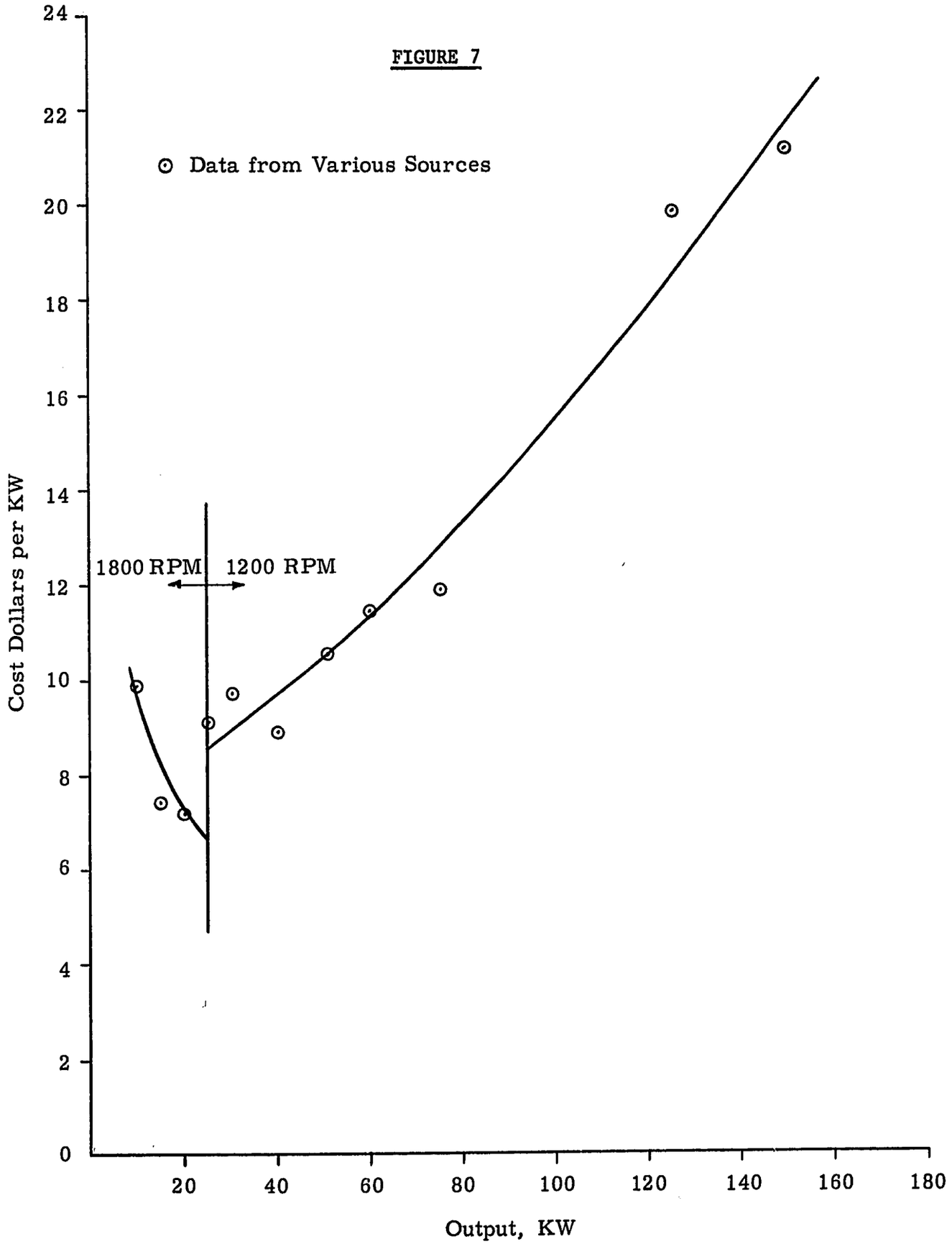


Estimated Cost of Governor Control System for Small Hydraulic Turbine Generators.

FIGURE 6

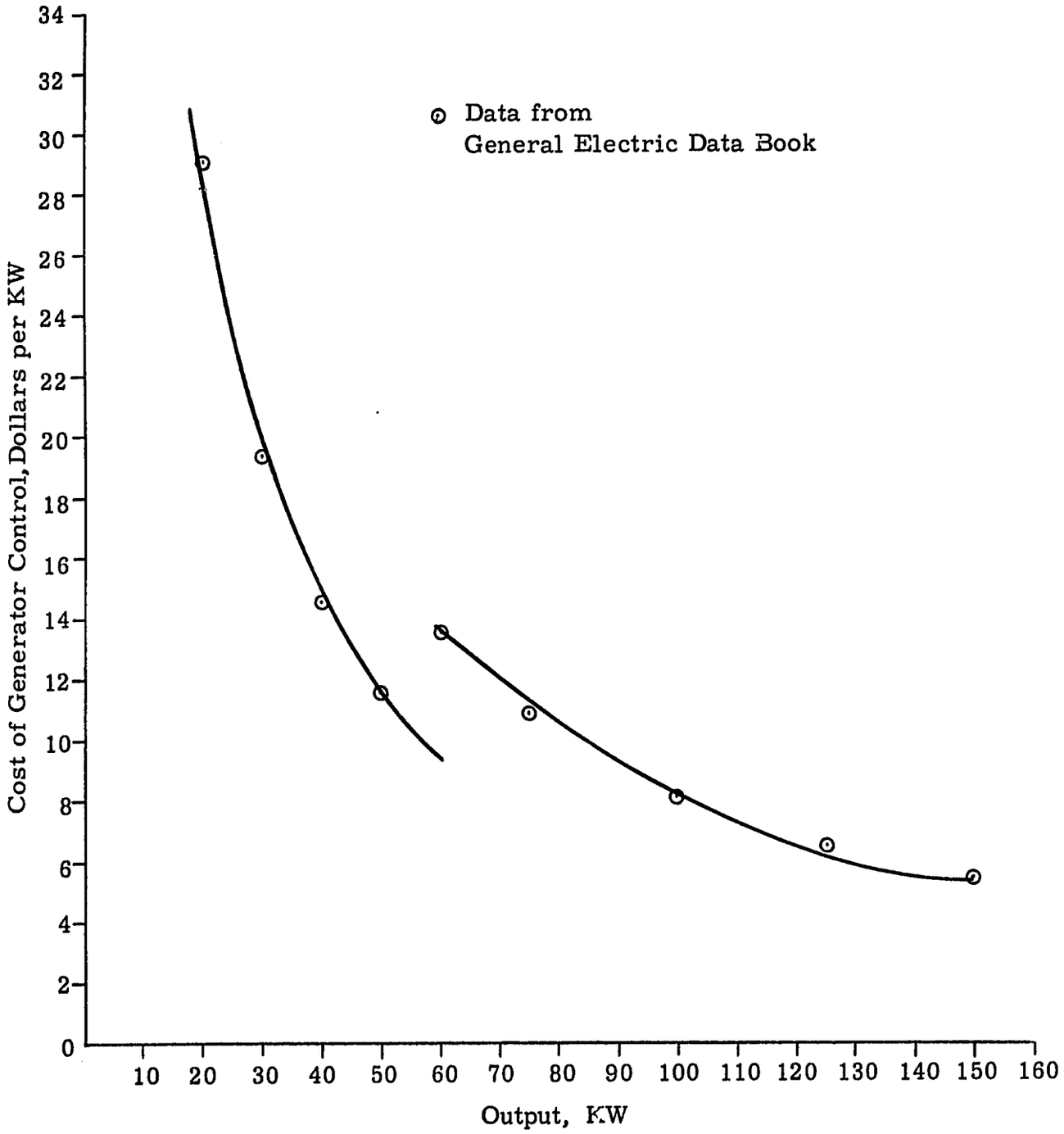


Cost and Weight of Belt Driven Packaged A. C. 3-Phase Generators.



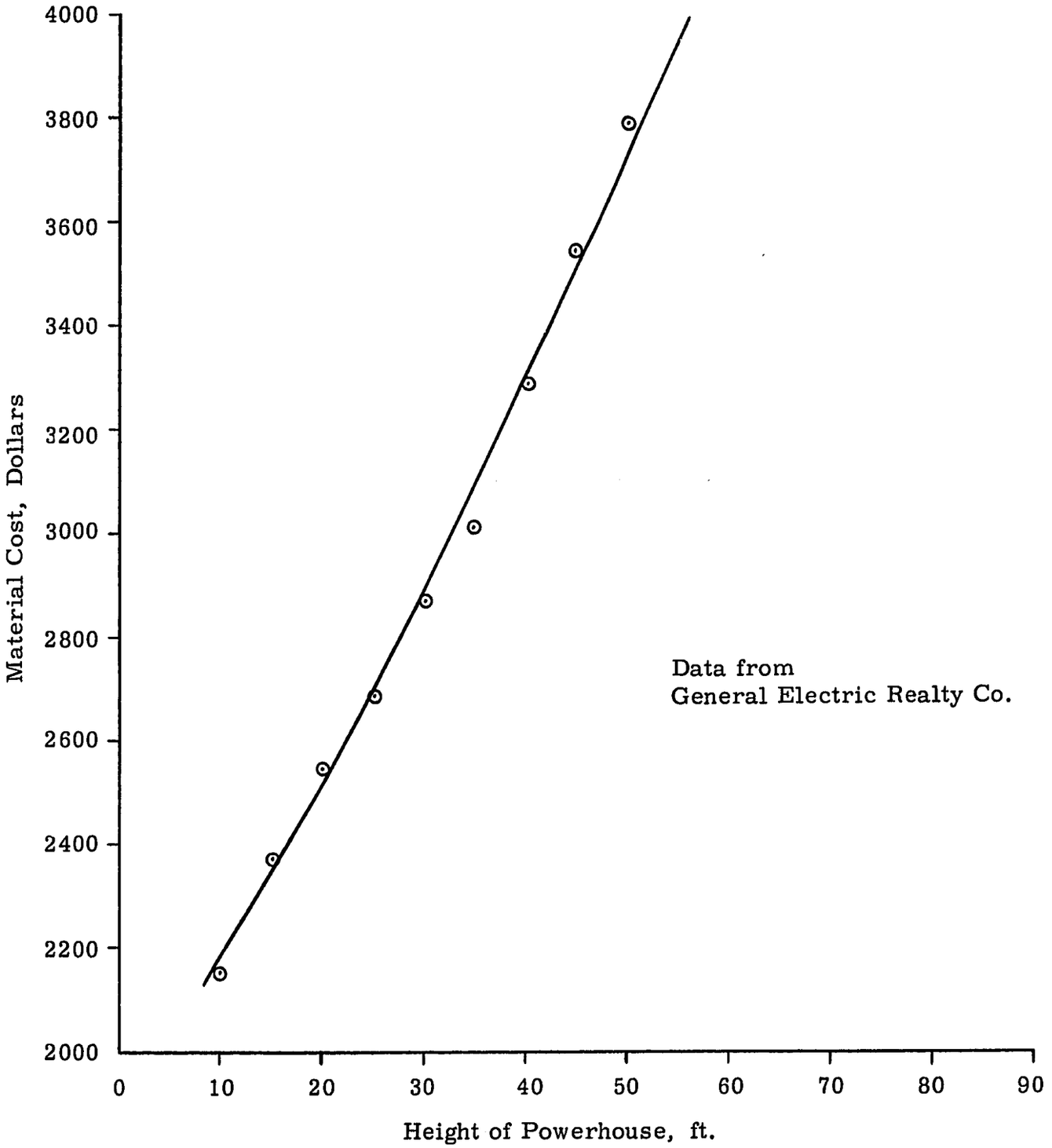
Cost of Pulleys and Belts for Vertical Turbine Driven A. C. Generators

FIGURE 8



Cost of Packaged Electrical Control for Three-Phase A.C. Generators (Includes Breakers, Meters, Field Rheostat).

FIGURE 9



Material Cost Less Stone for 20 ft. x 20 ft. Water Turbine-Generator Powerhouse

APPENDIX C

COST BENEFIT ANALYSIS

of

BIO-GAS PLANTS IN INDIA

Prepared by

CENTER FOR INTERNATIONAL STUDIES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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COST BENEFIT ANALYSIS OF BIO-GAS PLANTS IN INDIA

INTRODUCTION

The General Problem

Animal dung constitutes nearly 45 percent of the domestic fuel in rural India. This is equivalent to about 300 million tons of wet dung per year, roughly 27 percent of the total dung production in rural India (14)*. This dung would be much more valuable as a fertilizer, provided a substitute fuel for rural domestic use is available.

Bio-gas plants have been suggested as an answer to this problem. In a bio-gas plant, dung is fermented anaerobically to obtain gas. This gas contains about 57 percent of methane by volume and can be burnt as a fuel for heat and light. On the other hand, the digested dung (or 'sludge' as it is called) obtained as a residue is as good a fertilizer as dung. Thus, bio-gas plants can be used to retrieve the fertilizer value from the dung burned as fuel and the fuel value from the dung used as fertilizer.

Scope

The technological feasibility of simply operated bio-gas plants of various capacities has been demonstrated. Thus study presents an economic evaluation of these plants. Estimates of the costs and benefits accruing to the national economy assuming village-wide adoption of these plants are made. The initial capital cost is compared with the present discounted value of the benefits, and the benefits are measured in terms of the additional foodgrain production and the savings in firewood that result from the adoption of bio-gas plants. In addition, cost of bio-gas as a source of power is compared with the costs of diesel oil and petrol.

BIO-GAS PLANTS

Description of Plants

Essentially, a bio-gas plant is a closed well for fermentation with a floating drum to collect the gas. Dung, diluted with water, is fed in to the plant daily. Along with dung, other agricultural wastes and night-soil

* Numbers in the parentheses refer to the references in the Bibliography.

can also be used. A continuous supply of gas, which can be burned directly, is obtained provided dung is fed in regularly. However, the quantity of gas produced varies with the temperature and hence with the seasons.

A bio-gas plant suitable for the production of 100 ft. of gas per day needs about 100 lbs. of wet dung every day. This would meet the daily fuel requirement of a family of four or five and would correspond to the outturn of dung of four to five animals. Depending upon the season (i.e. temperature) 0.6 to 1.4 ft. of gas is produced from a pound of wet dung.

It is claimed (9) that more and better manure is obtained from a bio-gas plant as compared with the standard compost-pit method. Digestion of dung also increases its humus content and eliminates the weed seeds. However, the digested slurry contains 2 to 3 times as much water as dung and a large, well-drained compost-pit is required.

For running such a plant, either a co-operative would have to be set up or buying of dung and selling of manure would have to be organized. Organizing the buying (either with money or goods) is not a simple problem. Since the weight of dung varies with water content, weight as well as density would have to be measured. Whereas this can be overcome by preparing charts and measuring the volume as well as the weight, the problem of evaluating the nitrogen content of dung still remains. The effectiveness of dung as a fertilizer varies with its nitrogen content which in turn depends significantly on the feed fed to the animals, the preservation of urine along with dung, and the freshness of dung.

Moreover, a village level plant would require a system for distributing gas to the various households. Such a distribution may be carried out by laying a network of pipes (which introduces the need for measurement of gas consumed by various households) or using distribution containers, e.g. steel cylinders or plastic balloons. On the other hand, the gas may be used for running engines for some village industries or for a village powerhouse.

Availability of Dung

Varying estimates are given for the production of dung in India. The most sophisticated of these appears to be the one given by the NCAER study (14). Based on the Ministry of Food and Agriculture census and on a daily outturn of dung at 40 lbs. for cattle, 50 lbs. for buffalo and 20 lbs. for young stock, the average outturn per animal for the country is estimated at 5.8 tons (wet) per annum. This is equivalent to 35 lbs. wet or 7 lbs. dry dung per day per animal.

Based on the 1956 livestock census, 5.8 tons per year per animal gives 1110 million tons wet (222 million tons dry) annual outturn of dung for rural India. Assuming a 75 percent rate of collection, the available dung per year becomes 832.5 million tons wet (165.5 million tons dry). (12, page 42).

Availability of Agricultural Wastes*

Agricultural wastes can also be used in a bio-gas plant to obtain gas by fermentation. However, the availability of agricultural 'wastes' for this purpose is very questionable. In this section, the various agricultural wastes are examined in turn.

a) Rice and Wheat Straw: This is used in India as a cattle feed and as such is not a waste.

b) Corn Stalks: The principal use of corn stalk is for cattle feeding and whatever is left uncut is ploughed back into the fields where it has an important fertilizing value. It also seems highly unlikely that the expenditure of labour in retrieving the uncut stalks for a bio-gas plant would be worthwhile.

c) Linseed Stalk: From nearly 4 million acres under linseed, it is estimated that 1.5 million tons of linseed stalk are available.

Whereas an item by item analysis does not seem to indicate the availability of substantial agricultural wastes, the NCAER study estimates that in rural India, every year 18.5 million tons of coal-equivalent of waste wood (dried leaves, twigs, agricultural wastes) is burnt. At 2000 KCal/lb. for wood and 2700 KCal/lb. for coal, this corresponds to 18.5 x 2700/2000= 25 million tons of waste wood.

This is a small percentage of the available quantity of dung. It is, therefore, neglected in this study.

COSTS AND BENEFITS

Initial Costs

The Plant

In evaluating the cost of the plant, the total cost is divided in to three parts: (a) initial cost of the plant, (b) the cost of the accessories, and (c) operating costs.

* Most of this section is based on (3).

The benefits of the bio-gas plant are the bio-gas and the fertilizer. The value of bio-gas as fuel is measured by the amount of solid wood that is saved and the value of sludge as a fertilizer is measured by the additional production of foodgrains.

Table 1 shows costs and subsidies for various size plants approved by the Khadi and Village Industries Commission.

Accessories

Each household using bio-gas for cooking would require at least 2 burners. At Rs. 6.00 per burner this would come to Rs. 12.00 per household served.

For lighting purposes gas lamps are available. However, at present they are inefficient and costly. They burn considerable gas and the costly gas mantles have to be replaced at least five times in a year. Furthermore, rooms become too hot in summer when gas lamps are used. It appears that at least for the present, bio-gas would not be used for lighting purposes. As dung is not used for lighting purposes in any case, this does not affect the usefulness of bio-gas plants.

Since the digested slurry from the bio-gas plant has a higher water content than fresh dung, the slurry is more than twice as bulky. The larger compost-pit required for a family unit plant, is assumed to cost no more than the usual compost-pit for fresh dung, since the land and labour involved are small.

In the case of a community plant, a drying bed might be required. The rent of this land can be considered zero as any unproductive piece of land can be used for this purpose.

Operating Costs

Significant operating costs are not involved in a family size plant. Although a regular collection of dung is required, this is no different than if the dung were collected for direct burning or composting. The feeding of dung and the occasional stirring required involve little time and labour. This labour is free and can be neglected in cost calculations.

In the case of a larger community unit a plant attendant is required. At Rs. 50 per month, the attendant would cost Rs. 600 per year.

Fuel

Thermodynamic considerations indicate that a 100 cubic ft. per day plant should meet the requirements* of at least five families of an

* Reference (14) estimates 0.25 million tons of coal equivalent (coal = 2700 Kcal/lb.) of annual per capital rural requirement for energy. This is equivalent to 0.25 x 2240 x 2700/365 = 415 Kcal per day.

TABLE I

Costs of Alternative Size Bio-Gas Plants

Production Capacity Cubic Feet Gas Per Day	Total Cost Rs.	Construction of Digester Rs.	Construction of Gas Holder Rs.	Laying of Gas Pipes Rs.
100	900/-	450/-	360/-	90/-
150	1,300/-	650/-	520/-	130/-
200	1,700/-	850/-	680/-	170/-
250	2,000/-	1,000/-	800/-	200/-
300	2,400/-	1,200/-	960/-	240/-
350	2,700/-	1,350/-	1,080/-	270/-
400	3,000/-	1,500/-	1,200/-	300/-
450	3,250/-	1,625/-	1,300/-	325/-
500	3,500/-	1,750/-	1,400/-	350/-
600	4,000/-	2,000/-	1,600/-	400/-
700	4,550/-	2,275/-	1.820/-	455/-
800	5,000/-	2,500/-	2,000/-	500/-
900	5,400/-	2,700/-	2,160/-	540/-
1000	5,750/-	2,875/-	2,300/-	570/-
1250	6,875/-	3,437/50	2,750/-	687/50
1500	7,875/-	3,937/50	3,150/-	787/50
1750	8,750/-	4,375/-	3,500/-	875/-
2000	10,000/-	5,000/-	4,000/-	1,000/-
2500	12,500/-	6,250/-	5,000/-	1,250/-
3000	15,000/-	7,500/-	6,000/-	1,500/-

NOTE: The Khadi Commission provides funds for the construction of these plants on a half-grant, half-loan basis. The loans are repayable in 9 equal installments over a 10-year period.

average size of 5.5 members each. On the other hand, experience with pilot plants suggest that 10 to 15 cft. of gas is required to cook meals for one person (9). This indicates that 100 cft. gas is just enough to meet the fuel needs of a family of 5 to 6. This discrepancy may be due to inefficient burners.

Since in an average village there is 0.5 to 0.6 animal per capital, if we assume that a 100 cft. plant is used by one family only, then there is just enough dung to provide bio-gas fuel for about 60 percent of the families. This would release just enough firewood for the remaining families to substitute firewood for dung. Hence, on the fuel side, there would be no savings made.

On the other hand, if we assume that a few 100-cft. plants provide the entire domestic need for fuel in the village, the saving of firewood has to be considered as a benefit of the bio-gas plants.

Table 2 shows the estimated savings in firewood under various conditions based on a per capital annual energy consumption of 1.5 million K-calories.

Fertilizers

Since no dung is wasted as a fuel, more fertilizer is produced when a bio-gas plant is used. The quantities of compost and sludge and their effectiveness as fertilizers are considered in this section.

The percentage of dung burned varies from state to state. It varies from 4.1 percent (of the dung collected) for Madhya Pradesh, to 71 percent for West Bengal in comparison with a national average of 36 percent. A 100 cft. plant requires 33 lbs. of dry dung per day. Of the 33 lbs. fed daily into a plant 11.8 lbs. (33x.36) would have been burned in the absence of a plant. The remaining 21.12 lbs. of dry dung would have given 0.72 x 21.12 = 15.2 lbs. of compost, with a total nitrogen content of 15.2 x .021 = 0.319 lbs. On the other hand, 33 lbs. of dung fed into the plant give 33 x 0.72 = 23.76 lbs. of sludge with a nitrogen content of 23.76 x 0.021 = 0.5 lbs. This is equivalent to 8672 lbs. of dry sludge per year with 182 lbs. of nitrogen in it. In Table 3 these calculations are shown for the different states.

Experience in India indicates that a pound of nitrogen supplied in the form of green manure increases the yield of rice by 10 lbs. An increase of 15 lbs. of rice occurrs for every pound of nitrogen supplied in the form of oil cakes (18). Agricultural evidence (7) in India indicates that a treatment of farm yard manure (compost from dung) gives

TABLE 2

ESTIMATED PER CAPITA SAVING OF FIREWOOD DUE TO USE OF BIO-GAS PLANTS 1

Region	Per capita* dung outturn (dry) tons/yr.	Percent* of collected dung burnt	Coal equival. of wood burnt tons/yr.	Coal equival. of wood burnt tons/yr.	Total Wood Burnt tons/yr.	Solid wood burnt (56 o/o of total) tons/yr.
Andhra	.721	27.2	.018	.118	.159	.089
Assam	.642	5.4	.014	.236	.317	.177
Bihar	.544	49.0	.111	.139	.187	.105
Bombay	.741	32.0	.099	.151	.204	.144
Madras	.524	60.0	.131	.119	.161	.090
Madhya Pra.	1.234	4.1	.020	.230	.311	.174
Orissa	.700	8.2	.024	.226	.305	.171
Punjab	.792	45.0	.148	.102	.137	.077
Uttar Pra.	.668	66.7	.186	.064	.086	.048
W. Bengal	.252	71.0	.179	.071	.071	.038
Jammu & Kashmir	.530	4.4	.010	.240	.324	.181
Mysore	.796	33.0	.119	.131	.177	.099
Rajasthan	1.202	17.0	.085	.165	1.223	.125
Kerala	.240	51.5	.052	.198	.268	.150
India	.292	36.0	.106	.144	.144	.081

* Reference (14) page 42

1 Based on

a) .25 tons of coal equivalent of energy requirement per capita per year.

b) 75 percent dung collection rate

c) coal = 2700 Kcal/lb., wood = 2000 Kcal/lb., dung = 1500 Kcal/lb.

TABLE 3

QUANTITIES OF COMPOST AND SLUDGE FOR A 100 CFT BIO-GAS PLANT

(DRY BASIS)

State	Percent of collected dung burnt	Total Dung fed in the plant lbs/yr	Amount of compost lbs/yr	Amount of nitr. in the compost (4) x 0.21 lbs/yr	Amount of sludge (3) x 0.72 lbs/yr	Amount of nitr. in the sludge (6) x .021 lbs/yr	Add'l nitr. (7)-(6) lbs/yr
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Andhra	27.2		6320	133	8672	182	49
Assam	5.4		8200	172	"	"	10
Bihar	49.0		4920	103	"	"	79
Bombay	32.0		5890	124	"	"	58
Madhya Pra.	4.1		8310	174	"	"	8
Madras	60.0	33x365	3470	73	"	"	109
Orissa	8.2	=12045	7960	167	"	"	15
Punjab	45.0		4770	100	"	"	82
Uttar Pra.	66.7		2890	60	"	"	122
W. Bengal	71.0		2515	53	"	"	129
Jammu & Kashmir	4.4		8300	174	"	"	8
Mysore	33.0		5800	122	"	"	60
Rajasthan	17.0		7200	151	"	"	31
Kerala	51,5		4210	88	"	"	94
India	36.0		5550	116	"	"	66

a response of 5 to 15 lbs. per pound of nitrogen depending upon the nature of soil, watering and other factors. This range of 5 to 15 lbs. of additional foodgrains production per lb. of nitrogen is used in evaluating the benefits.

Only nitrogen has been considered here, since most Indian soils are deficient in nitrogen and phosphorous but not in potash, and since nitrogen affects the yield much more significantly.

ANALYSIS

Shadow Prices

Even though the market rate of interest in India is as low as 4 1/2 percent, Chakravarty (2) has estimated the shadow rate of interest for India, for maximizing the rate of growth, to be within 8 to 12 percent.

The prices used for foodgrains and firewood are the market prices, since these are considered not too different from their shadow prices. Any changes that might be brought about in these prices by a large scale adoption of bio-gas plants are neglected.

Costs of Alternative Schemes of Bio-Gas Plants

Bio-gas plants can be introduced in a number of ways in a village in order to save dung for manurial purposes. The representative village has a population of 550 with 100 families. It has a livestock population of 300 animals. At 7 lbs. per animal, the daily outturn of dung is 2100 lbs. (dry). However, a collection rate of 75 percent is realistic, since some loss on the pastures is unavoidable. This reduces the daily outturn to 1575 lbs. for the village or 5,25 lbs. per animal. The total gas production would be 1575 x 3.0 = 4725 cft. per day.

The costs and their present discounted values for various schemes of introducing bio-gas plants in this village are shown in Table 4. Schemes 1b, 1c, 2b and 2c are feasible only if more efficient burners are designed. Schemes 1a, 2a, 1b and 2b cover only half the village families. The other half of the families can switch over to burning wood completely since enough wood is released. In schemes 1c and 2c the entire village takes to bio-gas and the solid wood saved is counted as an additional benefit in these schemes.

Value of Benefits

The entire dung collection of the village (75 percent collection rate assumed) will be diverted to fertilizing purposes. The increase in food production for the village is calculated from Table 3 in Table 5 for the states. In evaluating the value of the foodgrain a price of Rs. 0.25 per

TABLE 4

COSTS OF ALTERNATIVE BIO-GAS SCHEMES

	Initial Costs Including Plants, Distribution pipes & burners Rs.	Skilled Labour Operating Costs Rs/yr	Total Costs Present Discounted Value (30 years) Rs. 4.5%	Rs. 8%	Rs. 12%
1a. One plant per family - 50 units					
i. with labour*	46,000	0	46,000	46,000	46,000
ii. without labour	43,700	0	43,700	43,700	43,700
1b. One plant per 5 families-10 plants					
i. with labour	13,600	0	13,600	13,600	13,600
ii. without labour	12,920	0	12,920	12,920	12,920
1c. One plant per 5 families-20 plants					
i. with labour	27,200	0	27,200	27,200	27,200
ii. without labour	25,840	0	25,840	25,840	25,840
2a. Two 2500 cft. plants for 50 families					
i. with labour	31,000	600	40,750	37,750	35,830
ii. without labour	29,450	600	39,200	36,200	34,030
2b. One 100 cft. plant for 50 families					
i. with labour	8,675	600	18,525	15,425	13,505
ii. without labour	8,242	600	17,992	14,992	13,072
2c. One 2000 cft. plant for 100 families					
i. with labour	16,000	600	25,750	22,750	20,830
ii. without labour	15,200	600	24,950	21,950	20,030

*Unskilled labour charges; assumed at 5% of the Initial Cost.

lb. is assumed. Table 5 also shows the present discounted value of this additional foodgrain production for different discount rates.

No wood is saved in Schemes 1a and 1b. However, in 1c, the entire village population changes over to bio-gas and a saving in the consumption of wood occurs. The consequent annual savings are calculated from Table 2 and their present discounted values are shown in Table 6.

In calculating the present discounted values, a life of 30 years for the bio-gas plants is assumed.

Comparison of Costs and Benefits

From Table 4 it is seen that if a paid plant foreman is required for a larger community unit, the expenses involved substantially offsets the economics of scale in the plant construction. Still, the cost of Scheme 2a is less than the cost of Scheme 1a. However, the difficulties involved in the organization of a community plant may favour Scheme 1a over Scheme 2a.

The cost of Scheme 1b is so much lower than the cost of Scheme 1a, that it becomes of the utmost importance to ascertain how many families can be served by 100 ft. of gas. Research for an efficient utilization of bio-gas should be given top most priority in bio-gas plant development. If 100 ft. of bio-gas can serve five families, then Schemes 1b, 1c, 2b and 2c become feasible. Tables 4 and 6 indicate that the value of wood saved justifies the additional expenditure involved for Scheme 1c and 2c over the cost of Schemes 1b and 2b respectively, even at a discount rate of 12 percent.

From a comparison of Table 4 and 5, it is seen that for the states of Assam, Madhya Pradesh, Orissa, Jammu and Kashmir (all having high per capita forest area and consequently less burning of dung) bio-gas plants are uneconomical. This is so even at the low interest rate of 4 1/2 percent, let alone the shadow interest rate, and even when maximum productivity of 15 lbs. per lb. of nitrogen for fertilizers is assumed.

For the states of Madras, Uttar Pradesh, West Bengal and Kerala, bio-gas plants are strongly suggested. Even with the assumption of low productivity of 5 lbs. of grain per lb. of nitrogen and with a discount rate of 12 percent, bio-gas plants are economic in these states.

A discount rate of 4 1/2 percent and a fertilizer productivity of 5 lbs. of grain per lb. of nitrogen for a discount rate of 12 percent and a fertilizer productivity of 10 lbs. of grain per lb. of nitrogen would justify bio-gas plants in the states of Andhra, Bihar, Bombay, Punjab and Mysore. For Rajasthan, however, a fertilizer productivity of 10 lbs.

TABLE 5

ADDITIONAL ANNUAL FOODGRAINS PRODUCTION FROM USE OF DUNG AS A FERTILIZER AND ITS PRESENT DISCOUNTED VALUE IN A REPRESENTATIVE VILLAGE

State	Add'l nitro. for 6 animals (from table 3.4.3) Lb. /yr.	Add'l nitro. for village (300 animals) Lbs/ yr.	Add'l food grains pro-duced per lb. of nitro. Lb/yr.	Total Add'l food grains pro-duced Lb/yr.	Value of add'l food grains at Rs. 0.25 per lb.	Present Discounted Value (30 Year Stream) @ 4 1/2% Rs.	@ 8% Rs.	@ 12% Rs.
Andhra	49	2450	5	12,250	3,062	49,800	34,500	24,700
	"	"	10	24,500	6,125	99,500	69,000	49,400
	"	"	15	36,750	9,187	149,000	103,500	74,100
Assam	10	500	5	2,500	625	10,150	7,030	5,030
	"	"	10	5,000	1,250	20,300	14,050	10,060
	"	"	15	7,500	1,875	30,450	21,100	15,090
Bihar	79	3950	5	19,750	4,937	80,200	55,500	39,800
	"	"	10	39,500	9,875	160,500	111,000	79,600
	"	"	15	59,250	14,812	240,500	166,500	199,400
Bombay	58	2900	5	14,500	3,625	59,000	40,700	29,200
	"	"	10	29,000	7,250	117,000	81,500	58,400
	"	"	15	43,500	10,875	175,500	122,000	87,600
Madhya	8	400	5	2,000	500	8,100	5,620	4,020
	"	"	10	4,000	1,000	16,200	11,250	8,060
	"	"	15	6,000	1,500	24,300	16,780	12,090
Madras	109	5450	5	27,250	6,812	110,500	76,500	55,000
	"	"	10	54,500	13,625	221,000	153,000	110,000
	"	"	15	81,750	20,437	332,000	230,000	165,000
Orissa	15	750	5	3,750	937	15,200	10,500	7,550
	"	"	10	7,500	1,875	30,400	21,100	15,100
	"	"	15	11,250	2,812	45,600	31,600	22,650
Punjab	82	4100	5	20,500	5,125	83,400	57,700	41,250
	"	"	10	41,000	10,250	166,500	115,000	82,500
	"	"	15	61,500	15,375	250,000	173,000	123,750

Uttar Pradesh	122	6100	5	30,500	7,625	124,000	85,700	61,400
	"	"	10	61,000	15,250	248,000	171,500	122,800
	"	"	15	91,500	22,875	372,000	257,000	184,200
W. Bengal	129	6450	5	32,250	8,062	131,000	90,800	64,800
	"	"	10	64,500	16,125	262,000	181,500	129,600
	"	"	15	96,750	24,187	393,000	272,000	194,400
Jammu Kashmir	8	400	5	2,000	500	8,100	5,620	4,030
	"	"	10	4,000	1,000	16,200	11,250	8,060
	"	"	15	6,000	1,500	24,300	16,870	12,090
Mysore	60	3000	5	15,000	3,750	61,000	42,200	30,200
	"	"	10	30,000	7,500	122,000	84,400	60,400
	"	"	15	45,000	11,250	183,000	126,600	90,600
Rajasthan	31	1550	5	7,750	1,937	31,500	21,800	15,600
	"	"	10	15,500	3,875	62,000	43,600	31,200
	"	"	15	23,250	5,812	94,500	65,400	46,800
Kerala	94	4700	5	23,500	5,875	95,400	66,000	47,200
	"	"	10	47,000	11,750	191,000	132,000	94,400
	"	"	15	70,500	17,625	286,500	198,000	141,600
India	66	3300	5	16,500	4,125	67,000	46,400	33,200
	"	"	10	33,000	8,250	134,000	92,800	66,400
	"	"	15	49,500	12,375	201,000	139,200	99,600

TABLE 6

ANNUAL SAVING OF WOOD AND ITS PRESENT DISCOUNTED VALUE IN A REPRESENTATIVE VILLAGE (550 PERSONS)

State	Per Capita Annual Consumpt. of solid wood Tons/yr.	Total wood consumption of the village Tons/yr	Price of solid wood[1] Rs/ton	Total value of wood saved Rs/yr	Present Discounted Values (30 Year Stream) @4 1/2% Rs.	@8% Rs.	@12% Rs.
Andhra	.089	49	55	2,700	44,000	30,400	21,700
Assam	.177	97.3	45	4,370	71,000	49,200	35,200
Bihar	.105	57.7	65	3,750	61,000	42,200	30,200
Bombay	.114	62.7	55	3,450	56,000	38,800	27,800
Madras	.090	49.5	75	3,710	60,500	41,700	29,900
Madhya	.174	95.7	40	3,730	60,700	42,000	30,000
Orissa	.171	94	45	4,230	69,000	47,700	34,100
Punjab	.077	42.8	60	2,560	41,700	29,800	20,600
Uttar	.048	26.4	80	2,110	34,300	23,700	17,000
W. Bengal	.038	20.9	85	1,770	28,800	19,900	14,250
Jammu Kasmir	.181	99.5	40	3,980	64,700	44,800	32,000
Mysore	.099	54.4	55	2,990	48,700	33,700	24,100
Rajasthan	.125	68.7	50	3,440	56,000	38,700	27,700
Kerala	.150	70	70	5,770	94,000	65,000	46,500
India	.081	44.6	60	2,680	43,500	30,100	21,600

[1] Prices of wood estimated from prices in Delhi, Bombay and Calcutta. Deductions for transportation were made and per capita forest areas were considered.

of grain for a discount rate of 4 1/2 percent or a fertilizer productivity of 15 lbs. of grain for a discount rate of 12 percent are required before bio-gas schemes become economically feasible.

Alternatives To Bio-gas Plants

The essential feature of bio-gas plants is that they permit the use of dung as a fertilizer by providing a substitute domestic fuel for rural India. The same result can be obtained, though at different costs, by providing conventional fuels as substitutes to dung. Such fuels would be: a) electricity, b) kerosene, c) coal, or d) wood.

A planned program of growing firewood might offer the cheapest answer to the rural fuel problem. With a six year period of growth, fuel would be available from the seventh year. A yield of 20 tons* of wood per acre. At 2000 kcal/lb. this amounts to nearly 90 million kcalories per acre every six years. For a village of 550 people, an annual per capita energy requirement of 1.5 million kcalories gives 550 x 1.5 x 6/90 = 55 acres as the land required for wood growing. This estimate, admittedly very rough, compares with that of Pal (15) who estimates a land requirement of 50 acres.

The cost of providing this wood, however, depends upon the availability of land for wood growing. If fifty acres of fallow land which is too unproductive for any other use, are available, then the cost of land can be neglected. If, on the other hand, productive land has to be dirverted to wood growing, then the costs might be substantial. Assume that land which is being used exclusively for growing 'jowar' (sorghum) is diverted to wood growing. However, jowar is a second crop and no land is exclusively given over to jowar cultivation. The cost of land, calculated on the basis of the loss of jowar from the land, would thus be the lower limit of the cost of land. The yield of jowar from 50 acres would be 250 x 50 = 12500 lbs. At a price of Rs. 20 per 100 lbs., this amounts to 125 x 20 = Rs. 2500.00. Once again assuming that surplus labour is available and that land is the only scarce factor, Rs. 2500.00 would be the cost of 50 acreas of land (classical Ricardian rent) per year. In the worst case, when rice growing land is diverted to firewood growing, 500 x 50 = 25000 lbs. of rice is lost per year. At a price of Rs. 25.00 per 100 lbs. this amounts to 250 x 25 = Rs. 6250 per year.

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* Estimate made as follows:
1 acre will have 225 trees at 200 sq. ft. per tree. Trees will have a girth of 2 ft. in 6 years. (Gamble, J.S. "A Manual of Indian Timbers", p. 292, Sampson, Low and Company, 1902). For acacia arabica, at 55 lbs/cft, a height of 12 to 15 ft will give nearly 225 x 15 x 55/2240 = 20 tons per acre.

To compare the cost of growing wood with bio-gas schemes, the present discounted values for the costs of wood growing are shown in Table 7.

TABLE 7

COST OF GROWING WOOD FOR FUEL

Available Land	Lost Production Per Annum	Present Discounted Value (30 years) 4 1/2%	8%	12%
a. Fallow, otherwise unproductive land	0	0	0	0
b. Jowar growing inferior land	2500	40,700	28,150	20,100
c. Rice growing land	6250	101,500	70,400	50,300

From Table 7, it is clear that if otherwise unproductive land is available, growing wood for use as a domestic fuel is a preferable alternative to bio-gas plants. However, under no circumstances would diversion of rice growing land to wood growing be cheaper than bio-gas schemes. When jowar growing land is available, growing wood on this land is equal to bio-gas Scheme 2a if the discount rate is 4 1/2 percent. However, since benefits for the first six years are lost, it cannot be considered an economic alternative to Scheme 2a. With a 12 percent discount rate, the cost of wood growing is Rs. 20, 100 as opposed to a cost of Rs. 34,030 of Scheme 2a. But since at 12 percent the present discounted value of the first six years' benefits constitutes 44,7 percent of the total value for 30 years' benefits, bio-gas Scheme 2a would still be preferable. Thus, diverting even the least productive land which is under cultivation to firewood growing is uneconomic.

Bio-gas as a Source of Power

It has been suggested that bio-gas plants be used to generate bio-gas to run an engine for either mechanical power or electrical power. Without going into the details of the economics of village electrification or of village industries, a comparison is made here of the cost of bio-gas with that of diesel or petrol fuel as an engine fuel.

For the representative village discussed above, the total gas production was 4725 cft. per day. On the basis of a domestic requirement of 100 cft. per day per family, this can serve nearly 50 families. Nothing would be left for funning a gas engine. If a gas engine has to be run, a substitute domestic fuel would be required. In regions where locally grown wood can be an economical substitute for a bio-gas scheme, a gas engine can be run on bio-gas.

On the other hand, if 20 cft. of gas per day were enough for a family, then 1000 cft. of gas would serve 50 families. This would leave 3725 cft. of gas for running a gas engine.

A gas engine consumes 15 to 16 cft. of gas per brakehorse power hour. On this basis, 3725 cft. of gas per day can deliver 3725/15.5 = 240 horse-power hours per day. This means a 30 horse power engine can be run eight hours a day.

The initial cost of a gas engine is the same as that of a petrol engine which is lower than the cost of a diesel engine. One gallon of petrol is equivalent to 225 cft. of bio-gas, and one gallon of diesel oil is equivalent to 250 cft. of bio-gas.

For evaluating the relative economics of fuel supply a 2500 cft. bio-gas plant is considered since this plant has the lowest cost per cft. capacity. The cost would be as follows.

1.	one 2500 cft. plant	Rs. 18,750
2.	connections to gas engine	Rs. 100
3.	total cost	Rs. 18,850
4.	less unskilled labour charges at 5 percent	Rs. 850
5.	Total cost excluding unskilled labour	Rs. 18,000

Since the mechanical power would be used by an industrial organization, the labour of the plant foreman can be considered already available and his wages need not be considered.

2500 ft. of gas per day is equivalent to 4000 (= 2500 x 365/225) gallons of petrol per year and to 3650 (=2500 x 365/250) gallons of diesel oil per year. The present discounted values of these two for a 30 year period is shown in Table 8.

From Table 8 it is clear that bio-gas is an economical alternative to diesel oil or petrol for generating mechanical power. Whether this mechanical power can be economically used in a village is a different question.

TABLE 8

PRESENT DISCOUNTED VALUE OF PETROL AND DIESEL EQUIVALENT TO 2500 CFT. PER DAY OF BIO-GAS

Item	Price Rs/gal.	Annual Value	Present Discounted Value (30 years) Rs. 4 1/2%	Rs. 8%	Rs. 12%
a) 4000 gallons of petrol per/yr.	3.00	12000	195,000	135,000	96,500
b) 3650 gallons of diesel oil per/yr.	2.00	7300	118,700	82,200	58,800

CONCLUSIONS

a) Bio-gas schemes are not justified for the states of Assam, Madhya Pradesh, Orissa and Jammu and Kashmir, which have a high per capita forest area and consequently less burning of dung.

b) For the states of Madras, Uttar Pradesh, West Bengal and Kerala, bio-gas plants are strongly recommended.

c) For Andhra, Bihar, Bombay, Punjab and Mysore, bio-gas plants are justified if (i) the discount rate is 4 1/2 percent or if (ii) the productivity of manure is 10 lbs. of additional grain per lb. of nitrogen.

d) In the case of Rajasthan, a manurial productivity of 10 lbs. of grain per lb. of nitrogen for a discount rate of 4 1/2 percent of a manurial productivity of 15 lbs. of grain per lb. of nitrogen for a discount rate of 12 percent are required to justify bio-gas plants.

e) Two large bio-gas plants for the village are slightly cheaper to many small plants. However, since the small plants are also economical and since the difference is not substantial, institutional reasons may prompt a choice of the smaller plants.

f) Growing wood on the side of the village to obtain a substitute fuel for wood is a preferable alternative to bio-gas plants, only if otherwise unproductive land can be used for this purpose. Diverting even jowar growing land for growing firewood is uneconomic.

g) Bio-gas is an economical alternative to diesel oil or petrol

for generating mechanical power. Whether this mechanical power can be economically used in a village is a different question.

h) A more efficient utilization of bio-gas than is currently done can cut down the cost of bio-gas plants to about one fourth their present cost. Research for an efficient utilization of bio-gas should be given topmost priority in bio-gas plant development.

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APPENDIX D

ENERGY CONTENT OF ALTERNATE SOURCES

R E S O U R C E

A. Animal Power — Horsepower

Man — 0.5 hp practical max. for few min.

0.1 hp probably max. for 8 hr.

Beasts

	Eff. (%)	Drag (lb)	Velocity (ft/sec)	Horsepower (for 8 hr. period)
1 Horse	100	99	3.0	0.54
2 Horses	98	194	3.0	1.06
4 Horses	80	317	3.0	1.73
8 Horses	49	388	3.0	2.12
1 Ox		132	2.0	0.48
1 Mule		66	3.0	0.36
1 Ass		31	2.6	0.15

B. Indigenous Fuels — BTU/Lb. Fuel

Wood	7,750
Charcoal	13,530
Agricultural wastes	
Bagasse	8,000 - 9,000
Straw	5,000 - 6,000
Dry Cow Dung Cakes (India)	4,000 - 6,000
Bio-gas (from Cow Dung) HHV	8,570 but/lb.,585 btu/ft.^{3}

C. Hydrocarbon Fuels (HHV)

	BTU/Lb. Fuel
Peat (air dried)	7,000 - 9,000
Bituminous coals	9,500 - 14,000
Anthracite coals	12,000 - 13,500
Coke	13,000
Fuel oils	18,000 - 20,000
Diesel fuel	18,500 - 20,000
Gasoline	20,000 - 21,000
Kerosene	19,400 - 20,200
Propane	21,560
Natural gas	1,129 btu/ft^3

D. Other Energy Sources

Solar insolation above earth's atmosphere	442 btu/hr. per sq. ft.
Solar insolation - avg. rate for proposed "roof day" unit	221 btu/hr. per sq. ft.
Wind	Stream power, kw = 5.3×10^6 AV^3
Hydraulic	2.54×10^{-4} stream hp/gpm/ft. head
Nuclear	Approx. 4×10^{13} btu/lb.
	(A reactor converts about 10^{10} btu/lb.)

HHV = Higher Heating Value

APPENDIX .E

SPECIFICATIONS ON DIESEL FUELS AVAILABLE IN INDIA

	"LOW" SPEED DIESEL OIL	"HIGH" SPEED DIESEL OIL
Specific Gravity at 15°C/4°C	.920	min. 0.820/ max. 0.870
Flash Point PMCC, min. °F	150	131
Viscosity (Redwood I) secs. @ 100°F, max.	50	45
Sediment by extraction, % wt. max.	0.02	0.01
Water, % wt. max.	0.25	0.05
Pour Point (Upper), max. °F	50	40
Ash, % wt. max.	0.02	0.01
Carbon Residue (Conradson) % wt., max.	1	0.05
Sulphur (Quartz tube), % wt., max.	1.5	1.0
Calorific value H. H. V. Btu/lb.	18500	19000
Acidity (Inorganic) mg KO H/g	Nil	Nil
Diesel Index (Cetane No.) min.	23	48
Distillation-Recovery @ 366°C., % Vol., min.	-	90
ASTM equivalent*	4-D	2-D

*By Comparison