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DIGEST OF EQUIPMENT FOR CONVERTING SOLAR, WIND, AND GEOTHERMAL --ETC(U)

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INTRODUCTION

This document constitutes a catalog (i.e., an enumeration of principal requirements arranged systematically) of self-sufficient equipment that may be installed at select USN shore sites to convert solar, wind, or geothermal energy into utilizable electric power. The equipment is limited to devices that are being actively considered by CEL in the USN shore energy research and development program.

The data presented herein are for use by CEL systems analysts who, after establishing the mathematical model for economic analysis, formulate the energy problem for solution by digital computer. The model is used to determine which mixture of alternative energy-conversion systems offers the highest benefit/cost ratio for any USN geographic location ashore (1).* Subsequently the final product (a manual of procedures for using environmental factors) facilitates selection of proper energy-conversion equipment by NavFac planners and estimators confronted with the task of determining the most cost-effective (i.e., most economical in terms of tangible benefits produced by money spent) method of converting natural energy at a specific site ashore.

GENERAL

Fossil fuels represent stored solar energy which has accumulated throughout aeons. Reliable estimates by various authorities indicate that within a comparatively short period in history this stored energy will be consumed, after which the world's total expenditure of energy can be no greater than the daily input of solar energy reaching this planet unless energy is extracted from other sources. Excluding nuclear fission

*Underlined numbers within parentheses indicate reference numbers.

and fusion and the tides and waves in the oceans, wind and geothermal heat represent energy sources other than direct solar input and thus are considered the principal non-solar alternatives for USN purposes ashore. Solar, wind, tidal, and wave power provide variable supplies of energy. Nuclear and geothermal sources provide constant supplies of energy and accordingly are the most promising sources if energy is consumed at a greater rate than is provided daily by direct solar radiation.

Energy consumed by all USN shore facilities currently costs over $400,000,000 per year. At remote shore facilities, energy from commercial sources is unavailable and so self-sufficiency becomes imperative in view of increasing costs of petroleum-derived fuels. Achieving self-sufficiency ashore, relative to usable energy, ensures not only more fuel for USN forces afloat but possibly less cost in operating the facilities ashore. Self-sufficiency energywise at any USN shore facility may be accomplished if available natural energy forces are utilized gainfully. How soon this will be accomplished is debatable because there are many more questions than answers; the technology of converting solar, wind, and geothermal energies into electricity is complex and involves diverse engineering disciplines.

DIGEST

The compilations herein are digests of financial requirements, physical characteristics, and potential outputs of solar, wind, and geothermal energy-conversion systems currently under development as part of the USN shore energy program. The tabulated data are the result of collating information, available at CEL, relative to the requisite equipment for obtaining the indicated energy outputs; listed are the technical (electrical, hydraulic, mechanical, structural, and thermal) and financial requirements for producing the output by means of each conversional system. The compilations complement the separately developed environmental data mentioned below.

Environmental factors (meteorologic, geographic, specific power demands, etc.) representing dependent and independent variables peculiar to each of the three alternative systems, together with the economics and logistics involved therewith, influence the operation and output of each self-sufficient energy system. Such factors, which are documented by other CEL investigators, must be selected before the mathematical model can be used in revealing the optimal mixture of alternative energy systems that satisfies the energy needs at any given USN shore facility and minimizes the total costs thereof throughout a specified planning period.

SOLAR ENERGY

Background

The sun is the greatest and richest supply of available energy. The total solar energy reaching the continental United States during any day is more than 500 times the total energy consumed that day. Since there is a daily and seasonal variation in intensity, coupled with the adverse effects of clouds and dust particles, the problem is to develop means of harnessing this energy so as to ensure steady and uninterrupted flow of electricity. The data provided in subsequent paragraphs of this section identify the technical and financial requirements involved in two methods of converting solar energy to electicity: (1) high-concentration solar collectors coupled with a thermal engine and (2) direct conversion through photovoltaic solar cells. Emphasis is placed on small systems that are self-sufficient and essentially transportable.

Solar Collector Coupled With Open-Brayton-Cycle Engine

The total system consists of (1) the open-Brayton-cycle engine driving an open-cycle air-turbine generator and (2) a tracking concentrator to focus solar radiation directly into a receiver which provides heat for the engine. Such a combination conforms to the concept of a small mobile system for generating electricity at Naval shore sites, particularly advanced bases (2).

The solar heated open-Brayton-cycle engine has several advantages: (1) no water-cooled or air-cooled heat rejection and no heat exchanger (a condenser would be required with a Rankine-cycle engine); (2) no need for a sealed system (as required by Rankine-cycle, Stirling, or closed-Brayton-cycle engines) since air is the working medium; (3) small Brayton-cycle engines are used in projects sponsored by DoD and NASA (2, 3, 4); and (4) a high-concentration solar collector yields high temperatures to ensure thermal engine efficiency (10 percent is achieved at temperatures above 1,000^{o}F).

Concentrator and Receiver

The reflective point-concentrator is a parabolic dish in circular form (i.e., a paraboloid of revolution) which directs the solar energy through an aperture into a receiver. Figure 1 depicts the conceptual design of the solar collection system. The receiver chosen as most representative is an open-cavity black vessel into which reflected radiation is concentrated. For an open-cycle system, ambient air is the energy medium which passes through tubes within the cavity. The receiver essentially takes the place of the combustion chamber in a fuel-fired Brayton-cycle engine. Figure 2 depicts the receiver. Figure 3 is a typical plot of collection efficiency as a function of temperature. Figure 4 is a typical plot of the variation of collection efficiency as a function of radiation level.

Open-Cycle Air-Turbine Generator

In the usual fuel-fired version of the open-Brayton-cycle engine, ambient air is compressed, heated by combustion of fuel mixed with compressed air, expanded to produce shaft power, and exhausted to the atmosphere. After deducting the power needed to run the compressor, the remaining power is used to drive the generator which produces electricity. In the solar powered version, ambient air is heated by solar energy instead of by the combustion of fuel. Figure 5 is a schematic flow diagram of the solar powered open-Brayton-cycle engine system. Figure 6 depicts engine characteristics of various turbine inlet conditions and the design point selected as the basis for data presented in this section. Figure 7 depicts the efficiency of the total system as a function of receiver temperature. Figure 8 depicts the engine power output as a function of solar flux. Figure 9 depicts typical estimated engine output as a function of time for two latitudes at different dates.

Summary

Table 1 identifies various technical and financial requirements for converting solar energy into electricity by means of a solar collection system coupled with a thermal engine driving a generator. Performance figures are based on an open-Brayton-cycle engine that uses only ambient air as the compressed gas. In the financial analysis, consideration is also given to a hybrid system where fuel oil is burned when solar energy is unavailable; this yields higher turbine temperatures (not presented), but the output is assumed the same. The assumption is that by operating day and night the hybrid produces nearly triple the power output of a wholly solar unit in a one-year period and results in lower cost per kWh. This can be expected as long as fossil fuel is readily available, but time will narrow this difference as fossil fuel becomes scarce and consequently more expensive.

Direct Conversion of Solar Energy by Photovoltaic Cells

Converting sunlight into electricity by photovoltaic action is most desirable since this technique requires no moving parts, no prior conversion to heat, and no evacuated vessels. In theory, the two requisites are: (1) a material to create a photovoltaic junction and (2) the electrodes to withdraw the direct current which is produced. Arrays or panels of photovoltaic cells can be connected in series and parallel to adjust the current and voltage. The technique is not widely used because fabricating the photovoltaic junction is inordinately expensive.

Photovoltaic solar cells are utilized as electric power sources in space satellites. Since these power systems are not commercial ventures, emphasis is not on cost of the cells, but on reliability, resistance to deterioration, and high power-output per unit weight. A price of $2,000 per W_e is reasonable for space satellites. To compete in large-scale terrestrial applications, the present cost of photovoltaic devices requires reductions from about $11 to about 50¢ per W_e (5).

All photovoltaic materials are categorized as semiconductor solids. Semiconductors are materials in which electric conductivity ranges between that of a conductor and that of an insulator; in other words, nearly metallic at high temperatures and nearly nonconductive at low temperatures. The electric conductivity of such solids (e.g., germanium) is comparable to that of metals if sufficient energy is supplied in the form of photons or light quanta. Semiconductors may be intentionally altered to incorporate atoms of impurity which alter the electric characteristics described above. The addition of impurities, known as "doping", can cause a semiconductor to become either a "p" or "n" type. The juxtaposition of a "p" type and an "n" type semiconductor will create a "p-n" junction. The p-n junction is the source of the photovoltaic effect; essentially, the junction allows electrons, which are liberated by light, to be accelerated across a potential gradient into an external circuit to perform work (5). Although the p-n junction is at the central element of the photovoltaic cell, electrodes are required to conduct electrons through the external circuit; this is accomplished by using a metallic grid fastened to the back of the cell. Additionally, the cells are encapsulated in a rigid and transparent polymeric material for protection against thermal, mechanical, and chemical deterioration.

Materials commonly used for photovoltaic cells are silicon doped with elements such as boron, arsenic, and phosphorus to create the required "p" or "n" type quality. Gallium arsenide is another material for photovoltaic usage. Cadmium sulfide in contact with copper sulfide forms a so-called heterojunction photovoltaic cell (5,6,7).

The following constitutes a brief discussion of the physical state of the materials used in photovoltaic cells. The term "single crystalline" refers to material that is continuously grown from a single seed crystal and possesses no defects in the crystalline structure. The term "polycrystalline" implies a material composed of many randomly aligned single crystals. The term "thin film" refers to the deposition of photovoltaic material, in layers ranging in thickness from 0.00004 inch to 0.00200 inch, over a substrate material (5, 6). In semiconductor materials the electrons are in a bound state (the valence band); to establish conduction, the electrons must be unbound and capable of free motion through a crystal. In conductors, a number of electrons are normally in this free state (the conduction band). In semiconductors, electrons may absorb energy (e.g., light quanta) in order to move into the conduction band. Difference in energy between the valence and conduction bands is known as the "semiconductor energy gap" (denoted by "E"). For use in photovoltaic devices, semiconductors must have energy gaps that are within the energy range of the photons contained in sunlight. Silicon and germanium are in this category (5,6). Figure 10 illustrates the case where pure silicon is doped with either arsenic or boron. In pure silicon an extra electron is found in the valence band; this electron is easily removed to the conduction band, leaving behind a fixed positive charge. If silicon is doped by boron, an electron is lost from the structure; this absence is designated a "hole". When another electron moves into the hole, it also leaves another hole behind, thus generating "apparent hole motion" (positive charge). Movement of the hole leaves behind a fixed negative charge. These two types of doped silicon are referred to as "n" and "p" (negative and positive) respectively. In n and p silicon, the electrons and holes are termed the majority carriers (5,6). When p and n silicon are placed in contact, they form a "p-n" junction. Electrons from the n side and holes from the p side are free to flow across the junction. Figure 11 shows the situation when this occurs. An equilibrium situation is finally attained whereby the fixed positive charges from the n side meet the fixed negative charges from the p side, thus creating a junction potential. This situation inhibits electron flow from the n to the p side, and hole flow from the p to the n side; however, if holes were to be generated on the n side and electrons generated on the p side, the potential of the junction (diode) would aid the passage of the charge across the junction. Electron hole pairs are created if the junction is exposed to radiation; these are not due to the doping elements, but due to electrons from the bulk material (e.g., silicon) crossing the energy gap into the conduction band; electrons created in this manner are given an impetus to cross the junction from the p to the n side, and vice versa for the holes. Figure 12 shows the relationship of current density (j) versus the potential difference (v) across a load for different degrees of illumination (7); the power available from such a system is the product of current and voltage, and point A (in Figure 12) indicates the point of maximum power output for a given degree of illumination.

The overall efficiency of a photovoltaic cell is determined primarily by the following factors: (1) efficiency of surface penetration by light, (2) efficiency of light absorption within the cell, (3) efficiency of electron hole-pair generation within the cell, (4) current efficiency, and (5) voltage efficiency. Penetrative efficiency of light may be increased by anti-reflective coatings (e.g., either silicon oxide or tantalum oxide) (5,6). Loss due to reflection is thus reduced to a small percentage of total incoming radiation. The efficiency of light absorption depends on the type and thickness of the material exposed to radiation. All of the available solar energy is not absorbed, and all of the absorbed energy does not create electron-hole pairs; some of the energy is absorbed by the atoms of the crystal lattice and produces an increase in the temperature of the material, consequently increasing the electric resistance to an undesirable level. After electron-hole pairs are generated, some may recombine before reaching the external circuit; this phenomenon yields a drop in current efficiency. Thus, a successfully separated electron will quickly lose most of the excess energy which remains after its transition to the conduction band; this loss of energy is caused by collisions with lattice atoms and leads to a loss of voltage efficiency. Given all of these potential efficiency losses, a realistic overall efficiency for terrestrial applications may approach 20 percent; experimental solar cells are known to have efficiencies close to this value (7), but 10 to 12 percent is typical of commercially available silicon cells at present.

Silicon Cells

While thin-film silicon cells are in the experimental phase, the technologies that are currently workable are single crystal and slightly polycrystalline wafer cells. The following brief discussion is limited to these two technologies.

A typical silicon wafer solar array consists of the following components: (1) the basic material is a doped silicon wafer having a thickness of 0.00080 inch, (2) a conductive metallic grid-type electrode overlays the wafer (silver is used presently to avoid corrosion) and a metallic layer-type electrode underlies the wafer, (4) the wafers are conductively connected and are laid on a board composed of glass-fiber-reinforced epoxy resin, (5) the entire array is covered with a protective layer composed of glass-fiber-reinforced transparent plastic, and (6) a nonreflective coating of either silicon oxide or tantalum oxide is applied to the array. Figures 13A and 13B show the configurations of silicon wafers, panels, and free standing arrays. The panels depicted by Figure 13 are mounted on anodized aluminum stands protectively coated with enamel. Solar panels can be mounted on buildings and other suitable structures in the form of large arrays.

Cadmium Sulfide Cells

A typical cadmium sulfide (CdS) solar cell is manufactured as follows

(5,6,7): (1) a conductive electrode coating (e.g., either copper or tin) is applied to glass substrate; (2) a thin (few microns) CdS film is deposited over the electrode by either vacuum deposition or spraying; (3) a thin cuprous sulfide (Cu_2S) film is deposited over the CdS by spraying, dipping, or electrolytic plating; (4) a metallic grid, composed of copper and other base metals, is deposited over the Cu_2S by either electroplating or vacuum deposition; and (5) the whole device is hermetically sealed in glass after which an antireflective coating may be added. Figure 14 is a schematic diagram of a manufactured CdS solar cell.

Gallium Arsenide Cells

Gallium arsenide (GaAs) is also under consideration for use in photovoltaic devices. When used in the concentrating mode, single crystal GaAs cells may be applicable to generation of electricity at a central station in view of their relatively high overall efficiency which is about 17 percent (7). Figure 15 illustrates the construction of a single crystal GaAs cell. A p type GaAs substratum, 0.01 inch thick, is produced by manual pulling while under a pressure approximating 100 atmospheres. A stratum of n type GaAs, 10 microns thick, is grown epitaxially in the liquid phase immediately above the substratum. The second stratum, 9 microns thick, consists of aluminum gallium arsenide. The third stratum, 1 micron thick, is metallized GaAs; gold is currently considered in this application, although aluminum may be a more desirable alternative. Finally, an antireflective coating is applied over the cell to minimize reflection of incident solar radiation. The efficiency of this type photovoltaic cell is expected to approximate 20 percent (5,6,7).

Fresnel Lens

Research and development of a tracking Fresnel lens, constructed of methyl methacrylate, is currently underway because inexpensive mirrors cannot attain the concentration levels necessary for efficient operation (5,6). The goal of this effort is to achieve a concentration factor of 500. The efficiency of the Fresnel lens is expected to approximate 85 percent, in which event the efficiency of an overall array approximates 17 percent.

Cooling the cells is necessary because of the contemplated high concentration. In the Fresnel lens described above, cooling is accomplished passively by creating a thermal bond between each cell and the structure which supports the array; thus, heat is dispersed throughout the supportive structure by conduction, and cooling is effected by convection and radiation to the atmosphere. The cells are kept within the 122°F to 212°F (50°C to 100°C) thermal range by utilizing this method of cooling (5,6).

GaAs cells intended for residential applications are constructed of polycrystalline "thin films". These do not require concentration; rather, they are deployed in a flat-plate array. Thin-film GaAs cells display lower efficiency (about 7 percent) than do single crystal cells. Figure 16 illustrates the construction of a thin-film antireflection-coated metal oxide semiconductor (AMOS) solar cell incorporating GaAs (7). Figure 17 is a schematic of the process for producing thin-film cells; vacuum deposition is the method used in applying the GaAs. Because of mechanization in the process, producing thin-film GaAs cells requires less manual labor than does the single-crystal variety which must be pulled manually to form a thin ribbon.

Recent information (8) indicates that the Solarex Corporation is preparing to manufacture photovoltaic devices incorporating the tracking Fresnel lens. The devices are for use in the solar energy plant being built for the Department of Energy at Mississippi County (in Arkansas) Community College. Cost per peak watt (1977 dollars) is less than half that of photovoltaic equipment sold to date. The major reason for this price decrease is that concentrator arrays utilizing the Fresnel lens require only one-twentieth the number of photovoltaic cells per watt as do flat plate arrays.

Based on recent conversations (9,10), the Fresnel-type concentrator array generates electricity at a cost of $6.50 per peak watt, provided the array is mass-produced in batches of at least 1,000 units. The Solarex Corporation has firm bids for supplies of components constituting the arrays, thus ensuring achievement of the above unit cost. The college's specifications require these solar cells to be not less than 12 percent efficient at 131°F (55°C). The $6.50 per peak watt excludes the monetary value of the 1.5 mW of produced thermal energy which serves in heating the college building. Credit for this byproduct results in an adjusted cost of somewhat less than $2.00 per peak watt. The Solarex installation at the college requires 288 arrays, a total which is rated at about 250 kW_e and which requires nearly three acres of unobstructed land. Since the system is modular, airdrops of the solar units can be made at remote sites.

Summary

Table 2 identifies the various physical characteristics of photovoltaic assemblies and the costs of converting solar energy into electricity. These cells presently do not offer great economic advantage despite the introduction of the Solarex units. If productional technique could be simplified, the cost could be lowered to a level where photovoltaic electricity could be economical. Using present designs, at least 150 square feet per photovoltaic module or panel are required to generate one kW_e. If the unit cost of the solar cells could be reduced to less than 50¢ per watt of electricity, and if annual production of the cells were sufficient to provide 500,000 kW_e, the national energy problem would be considerably alleviated.

WIND ENERGY

Background

Wind energy is the cheapest of all the recurrent or so-called "renewable" sources of energy developed to date. About 60 percent of the cost of a wind-turbine generator is accounted for by its principal components. (11)

The electric output of wind-turbine generators normally is greater during the winter, when stormy weather generally prevails and power demands usually are greater, than in the summer. Although wind is a recurrent and nonpolluting source of energy, the disadvantages associated with wind-turbine generators are the intermittent nature of wind, the large areas of land required for wind farms, and possible civic problems related to noise generation.

Wind-Turbine Generator (Horizontal Axis)

Description

The principal components of the typical wind-turbine generator are: (1) the rotor turbine, (2) the gearbox, (3) the alternator, and (4) the tower. The wind causes the bladed rotor turbine to rotate at low speed about the horizontal drive shaft that is always parallel to the force of the wind. The drive shaft delivers the energy to an assembly of transmission gears in the gearbox where low speed (less than 200 rpm) is increased to high speed (about 1,800 rpm) which is necessary for the shaft driving the alternator. The gearbox and alternator are contained within a weathertight nacelle which is swivel-mounted atop the tower. The aerodynamic configuration of the nacelle permits yawing so that the horizontal shaft of the rotor turbine is always parallel to the wind forces; see Figure 18 which is derived from (12). Note that the Dunlite wind-turbine generator is devoid of a nacelle, but incorporates a tail to ensure yaw; see Figure 19 which is derived from (13).

Wind-turbine machines wherein the shaft of the rotor turbine rotates about a vertical axis have merit also, but are not considered in this document.

Efficiency

The theoretical maximum efficiency of wind-turbine generators is usually taken to be 59 percent. This limit is based on two factors: (1) getting power from wind involves slowing the wind while it flows through the area swept by the rotor blades and (2) the inherent kinetic energy of wind is proportional to the density of the atmosphere and the cube of the wind speed. The apparent implications are that extremely windy sites are most desirable and the design should be based on using the most intense winds that develop; the first is generally true, but the second is misleading. From the economic viewpoint, the optimum production of energy is obtained when the rated wind speed for the machine is between 1.5 and 2.0 times the average wind speed. Note that high wind speeds cause excessive stresses which can result in destruction of the entire installation (supportive tower and all equipment mounted thereon). A good design provides protection against severe gusts.

Specific power output (SPO), which is a measure of performance at a given location, is the ratio of total annual output to rated output and is expressed as (kWh per year) ÷ (kW). Calculating the value of SPO requires available data regarding the frequency of wind and the power output (of the wind-turbine generator) as a function of wind speed. For planning purposes, to determine SPO one needs to know rated windspeed, rated output, and average annual windspeed. Figure 20, which is based on (14), depicts this relationship if the wind-turbine generator is the Elektro model WVG-50. The value of SPO indicates the number of hours of rated output per year; a high value obviously is preferred.

Horizontal axis wind-turbine generators produce electricity having variable voltage and frequency in view of the intermittent nature of wind and variations in wind speed. The power delivered to the user must have constant voltage and frequency. The automatic load-matching system developed at CEL, in conjunction with small capacity (5 to 10 kW_e) wind-turbine generators, achieves this objective and involves no storage batteries. The Elektro and Dunlite wind-turbine generators are equipped with this system.

Summary

Table 3 summarizes the various technical and financial requirements of four wind-turbine generators representing rated outputs from $2kW_e$ to 1,500 kW_e inclusively.

GEOTHERMAL ENERGY

Background

The heat beneath the Earth's crust is a utilizable energy resource. This energy is available in geothermal regions which receive their heat from pockets of magma or molten rock, but extracting heat directly from the magma is impractical because temperatures as high as 2,200°F are encountered. The U.S. Government is encouraging the development of geothermal energy; about 1,700,000 acres of federal land have been leased for exploration since 1974. This action follows the advances of other nations (23): (1) Iceland where hot water for heating was instituted in the 1930's and pipes deliver hot water (265°F) at a total cost per household of currently $160 (American equivalent) or less per year in an area adjacent to the Arctic Circle, (2) Italy where the first development of geothermal power (the Larderello Field) began in 1904, (3) USSR where geothermal energy is currently under development for electricity as well as for nonelectric uses, (4) Japan where geothermal electric power generation began at Beppu in 1924, and (5) New Zealand where geothermal energy is used for hot-water heating in air-conditioning systems (in Roturua). About 90 percent of all U.S. geothermal resources are situated in the western continental states, Alaska, and Hawaii.

Geothermal systems are situated in those portions of the Earth's crust that contain hot water capable of extraction for use in energy converting equipment. Geothermal resources can be divided into three geologic types: (1) large artesian basins of platform areas, (2) small artesian basins of intermountain areas, and (3) crystalline massifs with thermal water in fissures or veins. Each of these types can be subdivided into what are termed the hearth subtype (hot water migrating from steeply dipping fracture systems into near-surface aquifers) and the stratal subtype (aquifer fluid heated directly by conduction from the aquifer rocks through which it flows). The hearth subtype, in which radical changes in temperature and permeability can occur over short vertical and horizontal distances, offers small targets for explorative drilling. The stratal subtype offers comparatively large targets of rather constant temperature and permeability, but of proportionally less worth because an attribute of the hearth subtype is the higher temperature normally encountered at shallow depths. Permeability is an acute problem only in hot-water fields, as opposed to dry-steam fields, because a much smaller mass of fluid is required in dry-steam fields per unit of power produced. Statistically, the probability of successfully evaluating the capacity of geothermal wells is about 50 percent in hot-water fields as opposed to 90 percent in dry-steam fields (24). Among all productive geothermal fields, only four are of the dry-steam variety: (1) The Geysers in California, (2) the Mt. Amiata group in Alaska, (3) the Larderello group in Italy, and (4) Matsukawa in Japan. In summary, three factors determine whether or not a geothermal well will be economically successful: (1) temperature, (2) permeability, and (3) reservoir depth.

Although six producible geothermal fields have been discovered in America, legal problems have hindered development of all except The Geysers in Northern California, and the Niland Facility in the Imperial Valley near the Salton Sea in Southern California. The others are Casa Diablo in California, Beowawe and Brady's Hot Springs in Nevada, and Yellowstone National Park in Montana, Wyoming, and Idaho. Based on relatively recent discoveries, potential areas are: (1) Steamboat Springs in Nevada; (2) Valles Caldera in New Mexico; (3) Surprise Valley and Clear Lake in California; (4) the Cascade mountain range in Oregon and Washington; (5) the Aleutian Island in Alaska; (6) the interior basins in Oregon; (7) portions of the Island of Hawaii; and (8) various areas in Idaho, Wyoming, Montana, Utah, and New Mexico. The areas at Steamboat Springs and Clear Lake, however, are not likely to be developed because of problems relative to disposal of waste water.

The Geysers is the only American geothermal location where electric power is presently generated in significant commercial quantities; installed capacity early in 1970 (directed exploration began in the early 1920's) was 83,000 kW_e, with a total steam reserve of over 1,000,000 kW_e (25). Note that The Geysers is essentially an area of dry-steam production (a rarity among geothermal locations). Of greater importance in the overall geothermal situation are: (1) numerous untapped resources of hot-water locations (where temperatures from 350° to 450°F, at drilling depths of 1,000 to 5,000 feet, have been observed) and (2) the brine fields at the Salton Sea in Southern California (where maximum temperatures of 680°F, at a depth of 8,100 feet, have been experienced). If the Niland Facility (Salton Sea) of the San Diego Gas and Electric Company continues to meet expectations, commercial power development in that area could reach a level between 50,000 and 75,000 kW_e by 1981 (26). Additionally, a 10,000 kW_e plant (expected to be operational by mid-1978) is the initial stage in developing a capacity of 65,000 kW_e in the East Mesa area of the Imperial Valley (in Southern California). The U.S. Geological Survey recently estimated (27) that the energy potential of the Imperial Valley's geothermal resources is 8,000 mW_e, which is about four times the present capacity of all the San Diego Gas and Electric Company's facilities. There is little doubt regarding the potential impact of geothermal power as an alternative energy source. Nevertheless, there will be three types of attendant problems: (1) legal nature of public land leases; (2) financial nature of investing capital throughout long and risky explorations to completion of power stations; and (3) disposal of waste water and geothermal brine, and corrosion and scaling of pipe systems.

Technical Requirements

The engineering and the associated design of a geothermal electric power plant differ considerably from those of an ordinary fossil-fueled electric power plant. The most significant differences are related to the characteristics of the geothermal steam and the absence of a boiler into which steam condensate is returned. The disposal of waste water accordingly is of major importance and consequently a plan for dealing with this problem must be developed before any decision is made to install a geothermal electric power plant. The necessity of this approach cannot be overemphasized since, for example, the quantity of waste water at a geothermal plant using flashed steam from hot water may be about four times the steam supply, without accounting for the waste water (from the steam condensate) which amounts to 20 percent of the steam supply. Statistically, a 50,000 kW_e unit, using flashed steam, produces waste water (including condensate) amounting to about 8,400 gpm (28).

At this point, it is appropriate to establish the basic differences in the known types of geothermal resources and briefly mention their attendant operational uses, advantages, and disadvantages. Perhaps the simplest, and the least common, is the dry-steam type of geothermal power plant. In America, the best known power plant of this type is The Geysers wherein the dry steam directly operates a turbo-generator for the production of electricity.

Most geothermal power stations do not use dry steam, but instead use either a mixture of steam and water (respectively 20 percent vapor and 80 percent liquid) or entirely hot water (i.e., the geothermal fluid is extracted from the well by either flashing or pumping).

The vapor pressure of the fluid inside the geothermal reservoir is much higher than atmospheric pressure; if allowed to flow upward freely through the well, some of the liquid vaporizes due to the combined effects of reduced frictional pressure and change in potential energy during the upward transit; this process results in flashing. When such fluid flow through the well is due to natural forces, some of the dissolved solids precipitate during flashing and are deposited as scale or incrustation on the interior surface of the well. If the solids content is high, a pump must be used (in forcing out the liquid) to prevent flashing; in such event only liquid (hot water) is available as the source of geothermal energy. When the mixture of water and steam is available, normal procedure at a geothermal power station is to pass the separated steam from the well through the high-pressure stage of the turbine, then flash the separated hot water for turbine use in a low-pressure stage. The remaining hot water is usually wasted unless transferred to a commercial consumer of low-grade heat.

To overcome this waste, and to utilize hot water alone as the energy source, use is made of a secondary fluid (i.e., another liquid, having a low boiling point, is utilized as the working fluid). In this case, the primary geothermal liquid is passed through a heat exchanger which converts the secondary fluid to a vapor which then passes to the turbine where the vapor is condensed to a liquid and thence returned to the heat exchanger. The primary advantage of this system is that more power can be obtained from any given mixture of geothermal steam and water, thus resulting in an optimal design that requires fewer wells for a given power output and consequently reduces capital investment.

There remains, however, the everlasting problem of waste water containing sodium chloride and possibly chemicals such as arsenic, fluorine, boron, and other mineral compounds leached from underground deposits. These minerals, even in concentrations as low as 2 ppm, are harmful to plant life (29). Accordingly, an adequate disposal system design is mandatory.

A commonly used approach is reinjection; this method is costly because it requires drilling extra wells (if no previously drilled and unsuccessful exploratory wells are convenient) and additional pumping power. The vapor-turbine cycle, utilizing isobutane as the working or secondary fluid, appears to be the technical answer to the problem of tapping and converting the heat beneath the Earth's crust into electricity, and doing so in an economic manner without pollution of either the atmosphere or nearby inland waters. Patented as the Magmamax Process, and used in electric power plants currently under operational evaluation, the schematic of the vapor-turbine cycle is illustrated in Figure 28 which is derived from (30). Although several acceptable working fluids may be used in this system, isobutane is preferable because of its high density and high vapor pressure under operational conditions, high critical temperature, good thermal conductivity, and comparatively lower cost; isobutane is noncorrosive and nontoxic, but is flammable and so must be handled as carefully as petroleum-derived fuel used in a gas-fired power plant.

A plant incorporating the Magmamax system is presently operating at the Salton Sea as a research and development project in conjunction with the San Diego Gas and Electric Company. Current output is 11,000 kW_e (31). Proposed improvements to the basic binary system are designed to take advantage of the potentially higher efficiencies available through the use of regenerative techniques. In this case, the superheated exhaust vapor (from the turbine) passes through a regenerator where the condensate is heated before it enters the main heat-exchanger. This process ensures that: (1) the condenser, cooling-water pump, cooling tower, and main heat-exchanger are each significantly reduced in size; and (2) the discharge temperature is noticeably higher than that of the basic cycle. This latter effect permits the heretofore wasted heat to be utilized for the production of freshwater for agricultural irrigation and for replenishing water-hungry areas in geothermal regions such as the brine fields of the Salton Sea. Figure 29, which is derived from (32), is a simplified version of Figure 28 and serves as a schematic of the basic isobutane cycle devoid of the preheater which is necessary in the Magmamax system. Figure 30 illustrates the regenerative isobutane cycle incorporating a multi-effect evaporator. Figure 31 depicts the differences in calculated heat-rejection rates for various turbine throttle-pressures. If the well output is a vapor-liquid mixture (instead of hot water alone), a regenerative two-stage heating cycle is feasible as depicted by Figure 32 in which the evaporator is omitted for purposes of clarity. Using either hot water or water vapor, input-regenerative performance offers improved electric power outputs (Figures 33 and 34) for various turbine throttle-pressures; these graphic data should not be interpreted as: (1) indicative of the limitation of geothermal input and power output, and (2) representative of optimum design requirements.

Improved thermal efficiencies are attained by adding a regenerative heat exchanger to the basic cycle; the total cost of power plant is consequently increased about 32 percent (32), but results in appreciably lower unit cost of electric power generated throughout the plant's lifetime.

With regard to the use of geothermal energy for hot water space-heating, there is minimal incentive in America for development in this direction because the supply of nongeothermal fuels (i.e., natural gas and liquid hydrocarbons) is currently available at a cost that is not excessive; this application of geothermal energy will expand as the availability of nongeothermal energy dwindles during the next 20 years. The only American operation of considerable size is located at Klamath Falls in Oregon where about 400 buildings are heated by over 350 wells, using a unique cost-competitive technique. The wells are about 490 feet deep and the bottom temperatures are slightly above 212°F. A perforated casing is installed in each well, a vertical pipe in the form of a narrow U is inserted, and the well is sealed. Cool water, flowing through the pipe, absorbs heat from the hot geothermal fluids within the well and, by means of thermo-syphon action, is delivered through insulated pipelines to hot water radiators (33). The formation of scale on the interior surfaces of pipe-lines and the adverse effects of a lowered water-table are thus precluded.

A final design requirement, herein considered last because discussion thereof can only be based on limited knowledge of past experience, pertains to size of geothermal field per desired power output, spacing of wells, drilling techniques, and related factors, all regardless of the geothermal fluid state and regardless of the conversion process utilized. There appears to be no consensus, among engineers proficient in geothermics, as to optimal spacing of wells; recommended values range from 20 to 40 acres. A 55 mW_e power plant is considered to require a minimum of eight wells (32), a number apparently based on rule-of-thumb since geothermal well temperature and turbine throttle-pressure are related to power output (as shown above). Taking the conservative 40-acre spacing and assuming a 50 percent reserve or steam surplus (equivalent to four additional wells), calculations reveal that nearly 500 producing-acres are required to support a 55 mW_e power-generating plant. General guidance in site selection accordingly would indicate at least 25,000 acres when doing exploratory drilling in a previously undrilled area and at least 2,500 acres in areas adjacent to productive geothermal fields (33).

Financial Requirements

To be economically competitive as an alternate energy source, geothermal power production must reach a state of refinement and sophistication in order to ensure low unit cost in comparison with the unit of power commonly produced currently from hydrocarbon fuels. The key factors affecting this unit cost are considered below.

Experience shows that 98 percent of the gross cost of generating electric power is proportional to the cost of constructing the power plant. Experience also shows that three key factors contribute to a low unit cost (net) of power produced: (1) minimum cost of construction, (2) high utilization of power plant, and (3) small power requirement for operating the plant (34). The larger the rating of the plant's power output, the lower the power cost. This relationship is illustrated by the curve in Figure 35, wherein a 90 percent utilization factor and an 8 percent power factor (for in-house service) are applicable. Note that the cost per $kW_e h$ becomes essentially constant when a rating of about 65 mW_e is achieved. The curves represent data from Reference (34) and are based on construction costs that range from \$340 (American) per kW_e (for a 10 mW_e unit rating) to \$125 (American) per kW_e (for a 70 mW_e unit rating). The analysis, in terms of percentages of total cost, is shown in Table 4. Figure 36 illustrates cost versus depreciation, and is based on a weighted average cost of wells, pipelines, related equipment, and buildings. Figures 37 through 42 respectively illustrate the relationship of cost to turbine inlet-pressure, well spacing, well output, gas content, and pipeline lengths. Although these data are from a single source, they may be considered representative of the order of magnitude of anticipated costs.

Exploration

Data from various United Nations Special Fund projects for geothermal exploration indicate that costs approximate \$3,000,000 (American) for installed plants having power outputs ranging between 5 and 200 mW_e (35). Another study (36) established a unit cost ranging between \$150 and

$300 (American) per kW_e (based on a 55 mW_e plant), but this range included field development. Cost of exploration depends on current labor rates, and also on other influences not solely associated with geothermal energy.

Drilling

If one assumes that in America the average cost of drilling a geothermal well is $40,000, that one-third of the wells is unsuccessful, and that each of the effective wells produces an average of 2,440 kW_e, then the average cost per useful well would be $60,000 (35). Drilling costs at The Geysers averaged $40,000 per well (depths from 900 to 4,000 feet) and $150,000 per well in the 5,000 to 8,000-foot range (37).

Power Plant and Pipelines

One accepted approach (35) is that these costs (in American dollars) may be estimated by means of a formula: $C = (1125)\ (kW_e)^{0.85}$ where C is the estimated cost and kW_e is the installed capacity. For example, if the installed capacity is 100,000 kW_e, the unit cost of the output is $200 per kW_e.

For a stated output, the cost of geothermal energy is primarily related to the lengths and diameters of pipe required, which in turn are influenced by the number of collection points as determined by the mass flow and steam/water ratio of geothermal fluid from individual wells. Additionally, costs of pipelines for waste materials must be considered, if applicable, because variations in cost are related to thickness of pipe and thermal insulation. Figures 41 and 42 are guides to pipeline cost and are based solely on geothermal power plant output. (Note that output reflects flow, temperature, and pressure). Available data for dry-steam plants indicate that the diameters of main pipelines range from 10 to 30 inches, the diameters of branch lines range from 8 to 16 inches, and the thickness of wrapped insulation (composed of asbestos and fiber glass) is 2 inches; the estimated total cost of such pipe system is \$8 to \$10 per kW_e of installed power capacity (37). At the Otake geothermal power plant (in Japan) the pipe diameters range from 16 to 24 inches, and the corresponding cost ranges from \$34 to \$114 (American) per lineal foot, including concrete foundations (34).

Reinjection

The least productive, and possibly the most disadvantageous, economic factor in converting geothermal energy into electricity is waste disposal through reinjection techniques. Where necessary, a disposal well could cost from \$20,000 to \$250,000 (depending on size and depth) plus an additional cost of \$1 per 1,000 gallons of fluid. This is equivalent to a cost of 3 to 5 mills per kW_eh (27).

Operation and Maintenance

Costs of this type are best represented by the economic data available for The Geysers (in California) and Otake No. 1 Unit (in Japan). Maintenance may be expected to range from 1.0 to 1.4 mills per kW_eh if pipelines, pumps, or other equipment suffer significant damage during the financial year, and as low as 0.6 mills per kW_eh throughout an average year if the geothermal fluid contains a relatively corrosive gas content (34). Operational cost at The Geysers during the period 1966 through 1968 decreased from 0.77 to 0.45 mills per kW_eh, while cost of fluid increased from 2.28 to 2.66 mills per kW_eh (37).

Summary

Analysis of data based on The Geysers, shown in Table 5, indicates that a geothermal operation producing its own steam will expend 65 percent of operating cost and 29 percent of investment cost for steam-winning operations. Where steam is purchased, fuel will account for 82 percent of operating cost and 16 percent of investment cost. Inasmuch as there are few other adjustments in cost that can be made to balance the higher fuel costs, the plant that purchases steam has a total cost one-third higher than that for an integrated-operation plant. The costs in Table 5 may not be representative of costs for geothermal energy throughout America because The Geysers is a unique deposit, and the steam it produces is relatively clean and can be tapped at shallow depths.

Using The Geysers as the basis for Table 6, and assuming an integrated operation that involves generating units of varying sizes, analysis of the tabulated data discloses that a 1,500 percent rise in plant capacity could be accompanied by a 50 percent drop in total investment cost per kilowatt-hour and a 69 percent decline in operational cost per kilowatt-hour. The major saving would occur in cost of steam (70 percent decrease in investment cost and 74 percent decrease in operational cost), with more modest declines in generative costs (32 percent decrease in investment cost and 60 percent in operational cost).

Geothermal plants operate at a higher plant-factor than do other types of electric power generating plants, and consequently produce comparatively low-cost electricity. This is shown in Table 7. The choice shown is arbitrary in order to obtain a list of various-capacity plants using various sources of energy, and representing base-load or minimum-demand power plants and also peak-load or maximum-demand plants. As indicated in Table 7, cost of investment at a geothermal installation approximates that at a very large steam plant (e.g., Morro Bay), and is about one-half of that for hydroelectric plants. Cost of power production at a geothermal installation is about one-third of that at a steam plant of comparable capacity (e.g., Humboldt Bay) and seven times the average cost at hydroelectric plants.

Table 8 incorporates principal constructional data for a hot-water power plant at the Otake geothermal field in Japan. Since similar data for other foreign hot-water geothermal power plants are unavailable and American geothermal hot-water power installations are few and rather recent, no extensive comparisons are possible now.

The above requirements may be summarized by considering anticipated total capital cost versus installed power plant capacity, as depicted by Figure 43. Cost per kilowatt of electricity is influenced by the type of geothermal resource, geographic location, and degree of success in developing the resource. Nevertheless, Figure 43 suffices for purposes of planning and estimating; examination of the curves discloses interesting trends, as noted in the following. As planned plant capacity doubles from 5 to 10 mW_e, capital cost per kW_e reduces about 35 percent; from 20 to 40 kW_e, costs reduce about 17 percent; and from 100 to 200 kW_e, costs reduce about 14 percent. As a proven geothermal field is further developed, and costs of exploration and major equipment gradually become paid, subsequent unit costs are less than indicated in Figure 43. For example, the last two 55 mW_e power units at The Geysers cost \$100 per mW_e; conversely, the cost of the 11 mW_e Magmamax power plant at the Salton Sea is about \$550 per kW_e which approximates the unit cost indicated in Figure 43.

The unit costs of electricity generated from various types of energy sources, as shown in Table 9, include amortized investment (installation and operation) calculated for the expected service life of each corresponding type of power plant. Cost of hydroelectric power most nearly approaches that of geothermal power. Although the investment cost of the typical geothermal electric plant is only about one-half of that required for the typical hydroelectric plant, electric power production expenses are roughly six times larger than those for hydroelectric plants (27). The currently limited development of geothermal energy, in conjunction with a general lack of detailed information on related geologic conditions, intensifies the complexity of assessing the available resources and the economics of this potential energy source. Nevertheless, the costs of geothermal power appear favorable, as shown in Table 9. The main problem may be the accessibility of American geothermal resources.

Estimates by the U.S. Geological Survey, according to (27), indicate that the geothermal potential of the Earth's crust beneath the continental United States (to a depth of 10 kilometers or 6.2 miles) is 6 X 10^{24} calories, which is the equivalent of 6.97 X 10^{18} kW_eh or 9 X 10^{14} tons of coal or five times the total coal reserves in America. To further illustrate this geothermal potential, 6.97 X 10^{18} kW_eh or 6.97 X 10^{15} mW_eh is the output of a 1,000 mW_e nuclear power plant operating continuously for 800,000,000 years. If recovery of the geothermal potential is only 1 percent, which is a very conservative approach, America has sufficient geothermal energy to produce about 7 X 10^{13} mW_eh of electricity. This would satisfy the electric power needs in the continental U.S. for many thousands of years.

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Table 1. SOLAR HEATED OPEN-BRAYTON-CYCLE AIR-TURBINE GENERATOR WITH TRACKING REFLECTOR (NO STORAGE OF ELECTRICITY)

1. Dimensions:

Entire Unit

length = 30 ft
width = 30 ft
height = 50 ft (if engine and generator are beneath concentrator)

Horizontal Spacing:
minimum = 75 ft (center to center of adjacent collection systems)

Unobstructed area required:
minimum = 5,625 sq ft

2. Weight:

Collection System

Concentrator	
reflective panels (24)	2,808 lb
circular frame	240
Polar Mounting	
central shaft and concentrator struts	1,050
rotational drive	500
elevational drive	450
Supportive structure	1,500
subtotal	6,548

(continued)

Table 1. Continued

Engine and Generator System		
gas turbine, reduction gear, and engine-mounted accessories		90 lb
generator		170
frame		100
controls and electric components		40
related accessories		80
recuperator and ducting		340
insulation		60
	subtotal	880
	total	7,428
3. System Design Parameters:		
Concentrator		
aperture area		705 sq ft
dish diameter		30 ft
geometric concentration ratio		400
reflectance		85 percent
tracking & surface contour accuracy		0.5° arc
focal length/diameter ratio		0.6
Receiver		
aperture area		1.76 sq ft
cavity diameter		1.5 ft
absorptivity		98 percent
air temperature		
inlet		980°F
outlet		1,310°F
efficiency of collection system		64.5 percent

(continued)

Table 1. Continued

Direct Solar Flux	275 Btu/h/sq ft
System Efficiency	17.6 percent
Operational Temperature	1,300°F

4. Financial Analysis:

Initial Capital Investment	Limited Production	Mass Production*	Hybrid System
concentrator	$28,000	$ 6,000	$ 6,000
engine & generator	12,000	3,000	4,000
controls	2,000	1,000	2,000
receiver & connections	4,000	2,000	2,000
total	46,000	12,000	14,000
Operational Costs			
annual O&M (goals)	3,000	1,500	2,731
annualized capital	5,149	1,143	1,567
fuel ($0.50/gal)	0	0	1,832
total	8,149	2,190	6.130
Unit Electric Cost			
output (solar) = 25,000 kW_eh/yr	326 mills/kW_eh	116 mills/kW_eh	inapplicable
output (hybrid) = 70,000 kW_eh/yr	inapplicable	inapplicable	87.5 mills/kW_eh

*Mass production implies batches of at least 1,000 units.
SOURCE: Data in Sections 1, 2, and 3 are from (2); data in Section 4 are from (8).

Table 2. PHOTOVOLTAIC SYSTEMS

Example 1. Flat panel, consisting of photovoltaic wafers mounted behind Fresnel lenses, mounted on a solar tracking mechanism.

1. Each Silicon Solar Wafer:

diameter = 3.15 in.
area = 7.79 sq in.
thickness = 0.03 in.
weight = 0.02 lb

2. Each Acrylic Resin Fresnel Lens:

length = 11.8 in.
width = 11.8 in.
area = 139.2 sq in.
thickness = 0.14 in.
weight = 1.00 lb

3. Each Solar Panel:

length = 16.4 ft
width = 9.8 ft
area = 160.7 sq ft
weight = 350 lb

4. Design Parameters for Each Solar Panel:

silicon cells = 135 total
Fresnel lenses = 1 per wafer or 135 total
power output = 1.0kW$_e$ (peak)

5. Financial Analysis:

Capital Costs	Limited Production	Mass Production*
entire assembly consisting of tracking mount and solar panel	\$3,500	\$2,000
Operational Costs		
annual maintenance	400**	380**
annualized capital	196**	96**
Total Cost Per Assembly	4,096	2,476
Unit Cost of Electricity per Assembly for annual output of 2,500 kW$_e$h***	1,638 mills/kW$_e$h	990 mills/kW$_e$h

Example 2. Flat panel (consisting of photovoltaic wafers mounted on topside for direct conversion of insolation and on underside for focused insolation) situated above a trough (parabolic cross-section) the concave surface of which supports Fresnel lenses (for concentrating solar energy upward into solar wafers mounted on the underside of the panel). Each assembly of flat panel and parabolic trough is considered a solar assembly; no tracking mount is needed.

1. Each Silicon Solar Wafer:

length = 1.97 in.
width = 1.97 in.
area = 3.88 sq in.
thickness = 0.015 in.
weight = 0.01 lb

2. Each Acrylic Resin Fresnel Lens:

length = 12.7 in.
width = 12.7 in.
area = 161.5 sq in.
thickness = 0.14 in.
weight = 1.15 lb

Table 2. Continued

Example 2. Continued

3. Each Solar Flat Panel:

   length = 16.0 ft
   width = 8.0 ft
   area = 128.0 sq ft
   weight = 2 lb

4. Each Trough of Fresnel Lenses:

   length = 16.0 ft
   width = 8.0 ft
   weight = 500 lb

5. Design Parameters for Each Solar Assembly:

   Fresnel lenses = 100 total
   silicon wafers = (100) (2 sides of panel) = 200 total
   power output = 0.8 kW_e (peak)
   net area occupied = 128 sq ft = 0.0029 acre
   gross area required = 450 sq ft = 0.0103 acre

6. Total area of land required:

   for 288 solar assemblies = 3 acres[a]

7. Financial Analysis:

	Limited Production	Mass Production*
Capital Costs		
each solar assembly	b	$1,000[c]
Operational Costs		
annual maintenance	b	190[c]
annualized capital	b	48[c]
Total Cost Per Solar Assembly	b	1,238
Unit Cost of Electricity per Solar Assembly for total annual output of 2,000 kW_eh***	b	1,615 mills/kW_eh

* Mass production implies batches of at least 1,000 solar assemblies.

** Estimated by L. I. Dimmick.

*** (1kW_e)(8h/day)(312.5 sunny days/yr) = 2,500 kW_eh/yr, and (0.8 kW_e)(8h/day)(312.5 sunny days/yr) = 2,000 kW_eh/yr.

a Actual or net area occupied by 288 solar assemblies is 0.84 acre, but (3.5)(0.84 acre) or 2.94 acres are required to allow access for maintaining each assembly and to preclude shadows cast by adjacent assemblies.

b Data unavailable because equipment is in design stage.

c Estimated by D. Ahearn (9).

SOURCE: Data in Example 1 are derived from (6); data in Example 2, from (8, 9, 10).

Table 3. WIND-TURBINE GENERATORS

Requirement	ELEKTRO Model WVG-50	ERDA Model 0A	ERDA Model 1	DUNLITE Model BP
1. Maximum or rated output:	5kW	200kW	1,500kW	2kW
2. Initial capital investment:				
tower & foundation, $	3,000*	100,000*	274,000*	3,600*
rotor (blades, hub, and other), $	2,000*	255,000*	552,000*	1,100*
power (drive, electrical, controls), $	5,000*	113,000*	567,000*	2,800*
load-matching system, $	700	none	none	700
subtotal, $	10,700	468,000	1,393,000	8,200
installation (10% of subtotal), $	1,070	46,800	139,300	820
total, $	11,770	514,800	1,532,300	9,020
3. Annual cost of maintenance (overhauls, replacement of parts, periodic servicing):				
rotor (10% of initial cost), $	200*	25,500*	55,200*	110*
power (4% of initial cost), $	200*	4,520*	22,680*	114*
tower (1% of initial cost), $	30*	1,000*	2,740*	36*
total, $	430	31,020	80,620	260
4. Useful life:				
rotor system, yr	10	20	20	10
power system, yr	15	30	30	15
tower structure, yr	25	50	50	25
5. Horizontal linear spacing: center to center of adjacent towers, ft	171	2,865	3,718	34

(continued)

Table 3. Continued

Requirement	ELEKTRO Model WVG-50	ERDA Model 0A	ERDA Model 1	DUNLITE Model BP
6. Tower:				
material	steel truss**	steel truss	steel truss	steel truss**
height to rotor centerline, ft	47	100	124	60
number of legs	4	4	4	3
7. Dead weight:				
rotor and power systems, lb	650	34,000	106,190	680
tower, lb	1,160	56,000	128,140	800
total, lb	1,810	90,000	234,330	1,480
8. Foundation (concrete):				
structural plan	10-ft-sq slab 4 ft thick	Figures 21 and 22	Figure 23	Figure 24
9. Area of land required:				
unobstructed, sq ft	300	15,700	32,400	200
10. Wind speeds:				
for rated output, mph	23	23	26	27
for cut-in, mph	8	8	12	10
for cut-out, mph	45	40	45	***
maximum withstandable, mph	120	unknown	unknown	80
11. Rotor:				
rotational axis	horizontal	horizontal	horizontal	horizontal
speed at rated output, rpm	180	40	34	170
number of blades	3	2	2	3
diameter of blades, ft	16.5	125	180	12.5
circular swept area, sq ft	212	11,910	25,165	123
location relative to tower	upwind	downwind	downwind	upwind

(continued)

Table 3. (continued)

Requirement	ELEKTRO Model WVG-50	ERDA Model 0A	ERDA Model 1	DUNLITE Model BP
12. Generator:				
frequency at rated output, Hz	110	60	60	60
voltage at rated output, v	190	480	4,160	210
number of phases	3	3	3	3
13. Output vs. wind velocity:	Figure 20	Figure 25	Figure 26	Figure 27
14. Energy storage system:	none	none	none	none
15. References:	(15, 16, 17, 18)	(12, 19, 20)	(21)	(13, 22)

* Indicated costs are for prototype models; reduce such costs by 50 percent if models are mass-produced in batches of at least 1,000 units. For ERDA models, all dollars are based on monetary values in CY 1975; for Dunlite and Elektro models, CY 1977.

** Equipped with steel guy cables.

*** Does not cut out, but automatic feathering of blades protects unit from overspeeding in winds less than 80 mph.

Table 4. CONSTRUCTIONAL COST ANALYSIS OF GEOTHERMAL POWER PLANT

Main Components	Estimated Percent of Total Constructional Cost
Turbine	17.7
Condenser	13.2
Control Room	10.2
Generator	4.1
Instrumentation	3.0
Transformer	2.0
Pipe System for Machinery	1.5
Supplies	5.3
Structural Steel Supports for Machinery	1.2
Other (minor) Equipment	2.2
Pipe System for Wells	12.2
Buildings	8.0
Land	4.1
Overhead	15.3
	100.0

NOTE: Estimated percentages are based on plant capacities ranging from 10 to 70 mW_e inclusively.

SOURCE: Figures 1 through 5 and Tables 1 through 6 in (34).

Table 5. COST OF GENERATING GEOTHERMAL POWER

Itemized Costs		Owned Steam	Purchased Steam
1. Investment Cost:			
a. Steam-winning			
Preoperating and Land, $		351,000	none
Exploration and Development, $		3,448,000	none
	subtotal $	3,799,000	none
b. Generating Plant	$	9,500,000	9,500,000
	total $	13,299,000	9,500,000
c. Plant Capacity, kW_e		83,000	83,000
d. Investment Cost, $ per kW_e		160	114
2. Operating Cost:			
a. Steam-winning			
Operating and Maintenance, $		495,000	none
Royalties, $		96,000	none
	subtotal $	591,000	none
b. Generating			
Operation and Maintenance, $		325,000	325,000
Fuel, $		none	1,495,000
	subtotal $	325.000	1,820,000
	total $	916,000	1,820,000
c. Estimated output, kW_eh		654,372,000*	654,372,000*
d. Operating cost per kW_eh, mills		1.4	2.8
3. Total cost per kW_eh, mills		3.0**	4.0

SOURCE: Estimated from data in (27).
*Assuming a 90 percent load factor for a 365-day (24 hours per day) operation of an 83,000 kW_e plant (The Geysers).
**Assuming 20 years for well life and other steam-winning facilities, 30 years for the generating plant, and 7 percent interest on the loan.

Table 6. GEOTHERMAL POWER COSTS ACCORDING TO PLANT CAPACITY

Power Plant Capacity, mW_e	Investment Cost, $\$/kW_e$			Operational Cost, $mills/kW_eh$**		
	Steam*	Power Generation	Total	Steam*	Power Generation	Total
12.5	113	153	266	1.9	1.0	2.9
28.0	71	143	214	1.6	0.8	2.4
54.5	59	129	188	1.2	0.6	1.8
83.0	46	114	160	0.9	0.5	1.4
137.0	37	109	141	0.6	0.4	1.0
192.0	34	104	138	0.5	0.4	0.9

SOURCE: Estimated from data in (27).
*Assuming that steam source is owned by power producer.
**Excludes capital cost.

Table 7. COMPARISON OF SELECT PACIFIC GAS & ELECTRIC COMPANY'S POWER PLANTS

Power Plant	Type of Energy Converted into Electricity	Capacity, mW_e	Plant Factor, percent	Investment Cost, $\$/kW_e$	Production Expense, $mills/kW_eh$*
Humboldt Bay	steam	102	21	181	7.56
Hunters Point	steam	408	54	122	4.12
Morro Bay	steam	1,056	41	101	3.72
Humboldt Bay	nuclear	60	62	375	5.23
Fall River Mills	hydro	56	62	200	0.53
Pit No. 5	hydro	128	92	250	0.28
The Geysers	geothermal	83**	90**	114**	2.80**

SOURCE: (27).
*Excludes capital charges.
**Estimates by C.L. Crader.

Table 8. *OTAKE (JAPAN) GEOTHERMAL POWER PLANT CONSTRUCTIONAL DATA*

1. Geothermal Well:			
depth, ft	1,640	3,281	4,921
2. Prospecting:			
geological, sq miles	-----	19.3	-----
resistivity sounding, acres	-----	247	-----
seismic exploration, ft	-----	3,280	-----
gravity exploration, sq miles	-----	19.3	-----
magnetic exploration, acres	-----	247	-----
3. Exploratory Drilling:			
casing diam, in.	6 4	6 4	-----
cased depth, ft	164 820	328 1,312	-----
4. Production:			
drilled diam, in.	19	19	19
drilled depth, ft	33	66	66
casing diam, in.	16	16	16
cased depth, ft	33	66	66
drilled diam, in.	14.8	14.8	14.8
drilled depth, ft	328	492	656
casing diam, in.	11.8	11.8	11.8
cased depth, ft	328	492	656
drilled diam, in.	10.6	10.6	10.6
drilled depth, ft	820	1,476	1,969
casing diam, in.	8.6	8.6	8.6
cased depth, ft	820	1,476	1,969
drilled diam, in.	7.6	7.6	7.6
drilled depth, ft	1,640	3,281	3,937
casing diam, in.	-----	-----	-----
cased depth, ft	-----	-----	-----
drilled diam, in.	-----	-----	5.6
drilled depth, ft	-----	-----	4,921
casing diam, in.	-----	-----	-----
cased depth, ft	-----	-----	-----
5. Costs (American $):			
prospecting	117,500	117,500	117,500
exploratory drilling	30,000	60,000	-----
preparation	14,000	17,000	20,000
drilling	53,000	98,000	135,000
casing	5,000	8,000	11,000
finishing	3,000	6,000	7,000
settlement	3,000	6,000	7,000

NOTE: Data pertain to one hot-water power plant at the Otake geothermal field and are based on a study by the Research Division of Kyushu Electric Company (Fukuoka, Japan).

SOURCE: (34).

Table 9. UNIT COSTS OF ELECTRIC POWER DERIVED FROM VARIOUS SOURCES OF ENERGY

Source of Energy Converted into Electricity	Average Unit Cost of Electric Output, mills/kW_eh
nuclear	5.49
coal	5.22
oil	4.87
natural gas	4.82
hydropower	3.45
geothermal heat	2.96

NOTE: Assumed capacity of typical power plant, needed to convert indicated source of energy, is 1,500 mW_e. Assumed load factor throughout service life of such power plant is 90 percent. Amortized costs of installation and operation of such power plant are included in the unit cost corresponding to the indicated source of energy.

SOURCE: Unnumbered Tables, pp. 971 and 972 in (27).

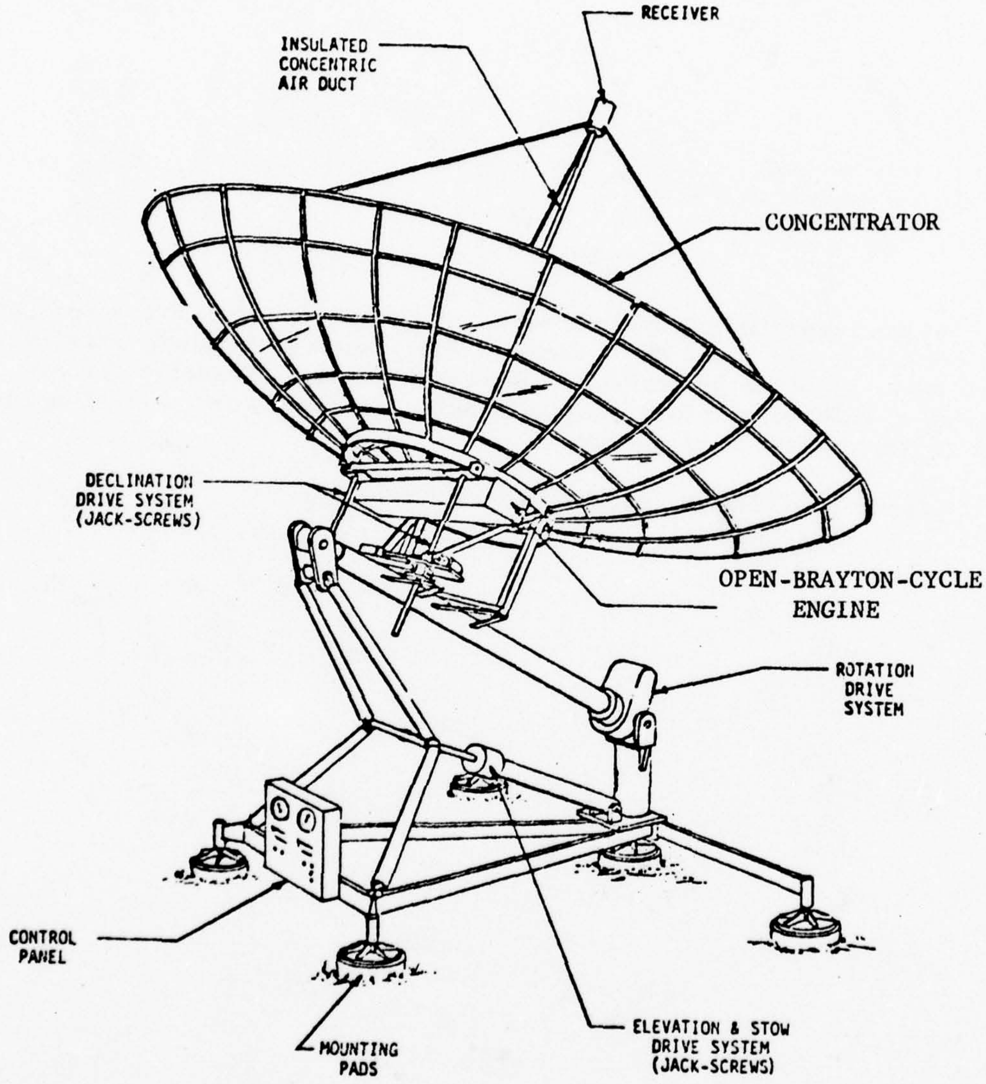


Figure 1. CONCEPTUAL DESIGN FOR 10 kW_e SOLAR COLLECTION SYSTEM. (Amended version of Figure 4.7 in Reference 2).

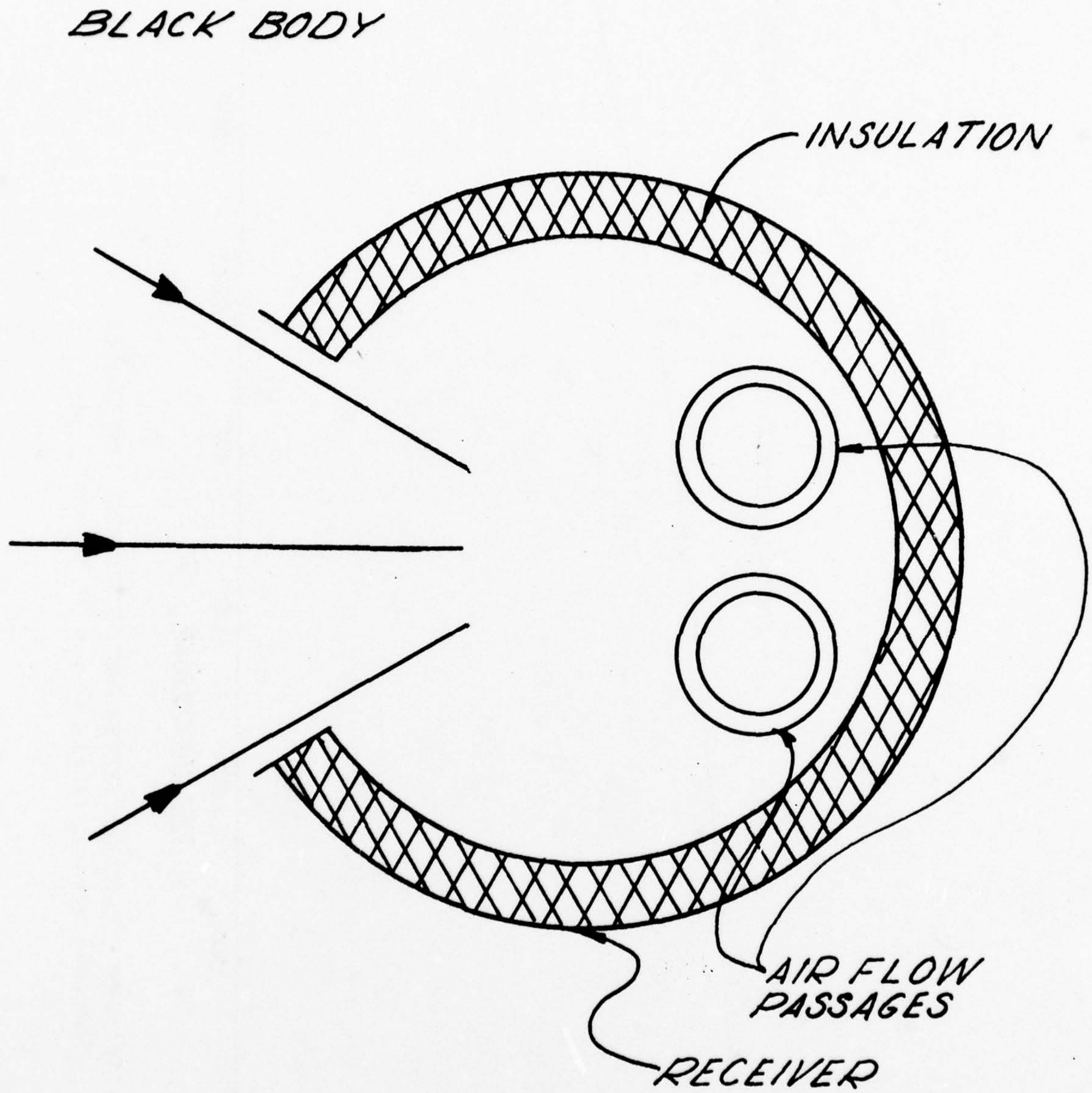


Figure 2. RECEIVER DESIGN. (Source: Figure 2.1 in Reference 2).

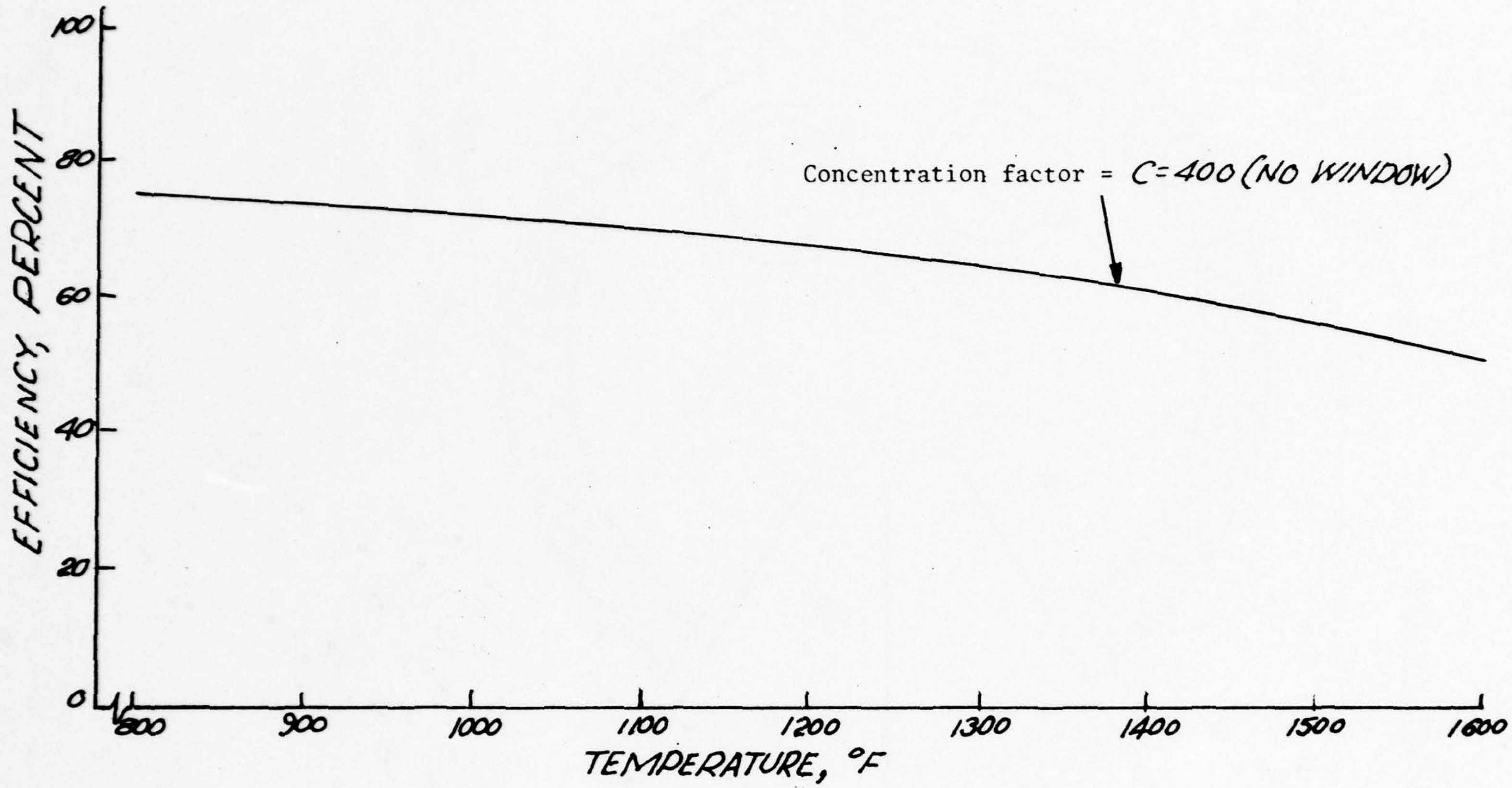


Figure 3. VARIATION OF COLLECTION SYSTEM EFFICIENCY WITH TEMPERATURE. (Amended version of Figure 2.2 in Reference 2).

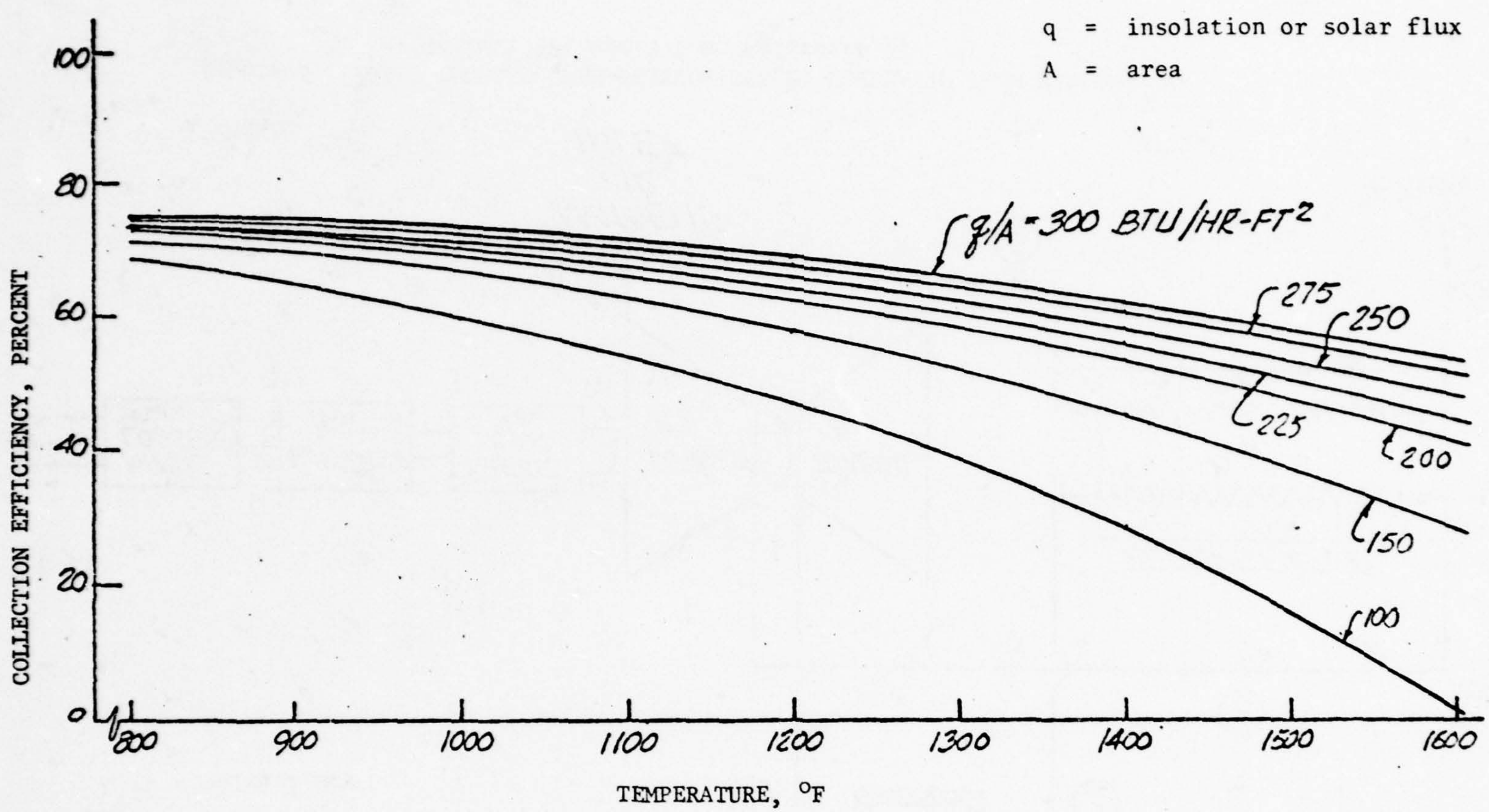


Figure 4. VARIATION OF COLLECTION SYSTEM EFFICIENCY WITH SOLAR RADIATION LEVEL. (Source: Figure 3.1 in Reference 2).

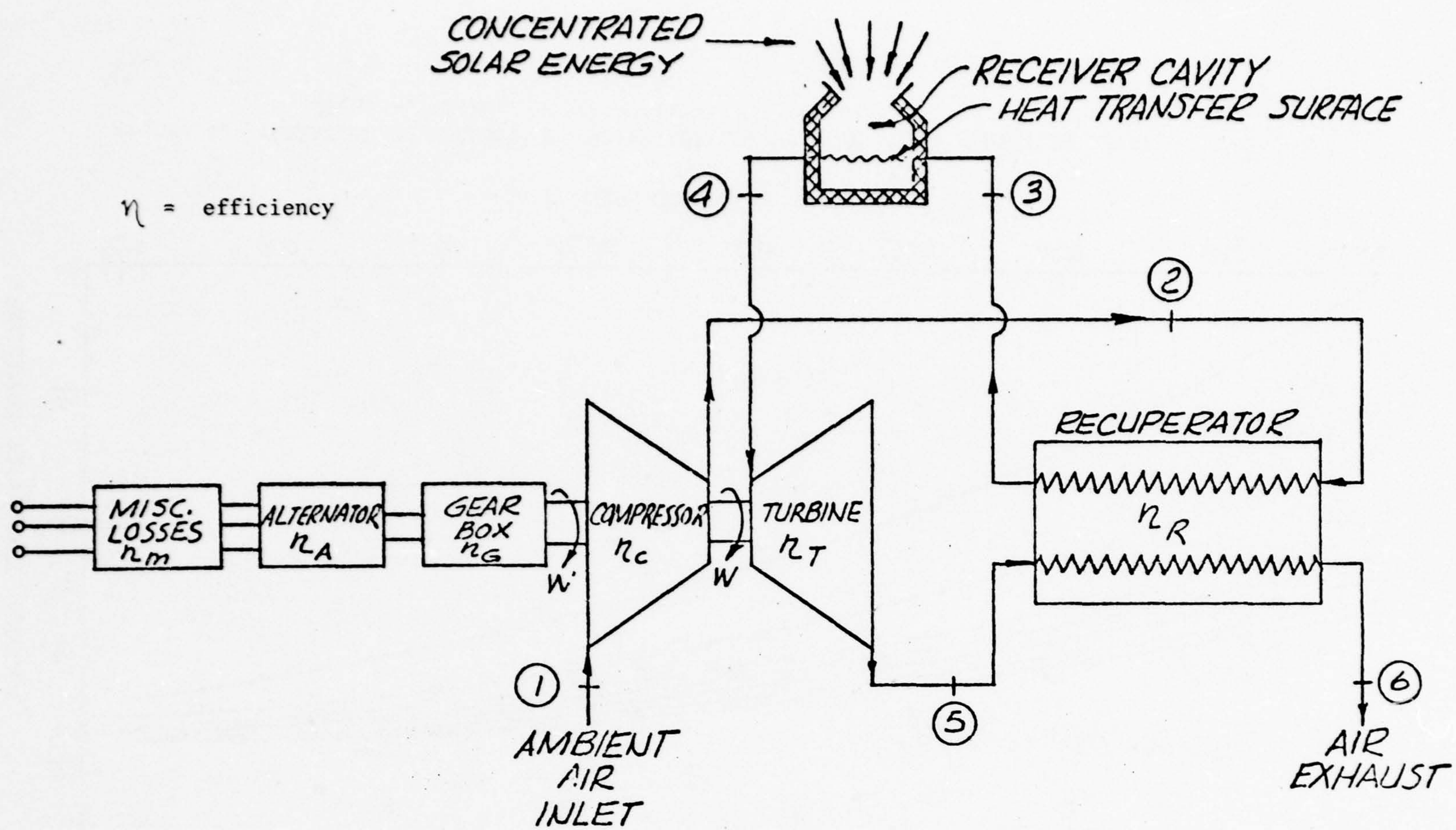


Figure 5. SOLAR POWERED OPEN-BRAYTON-CYCLE; SCHEMATIC FLOW DIAGRAM. (Source: Figure 3.2 in Reference 2).

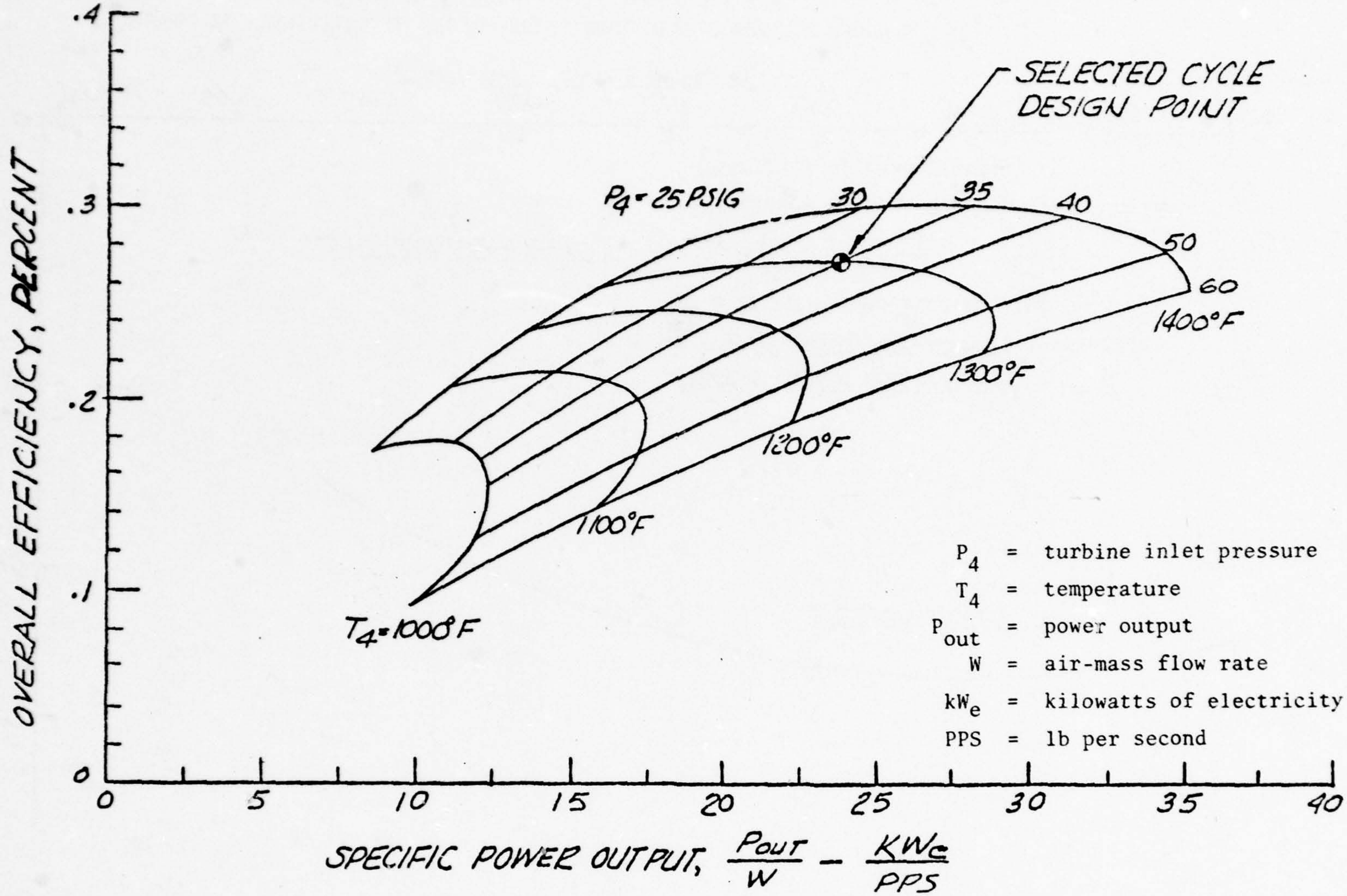


Figure 6. ENGINE CHARACTERISTICS FOR VARIOUS TURBINE INLET CONDITIONS. (Source: Figure 3.3 in Reference 2).

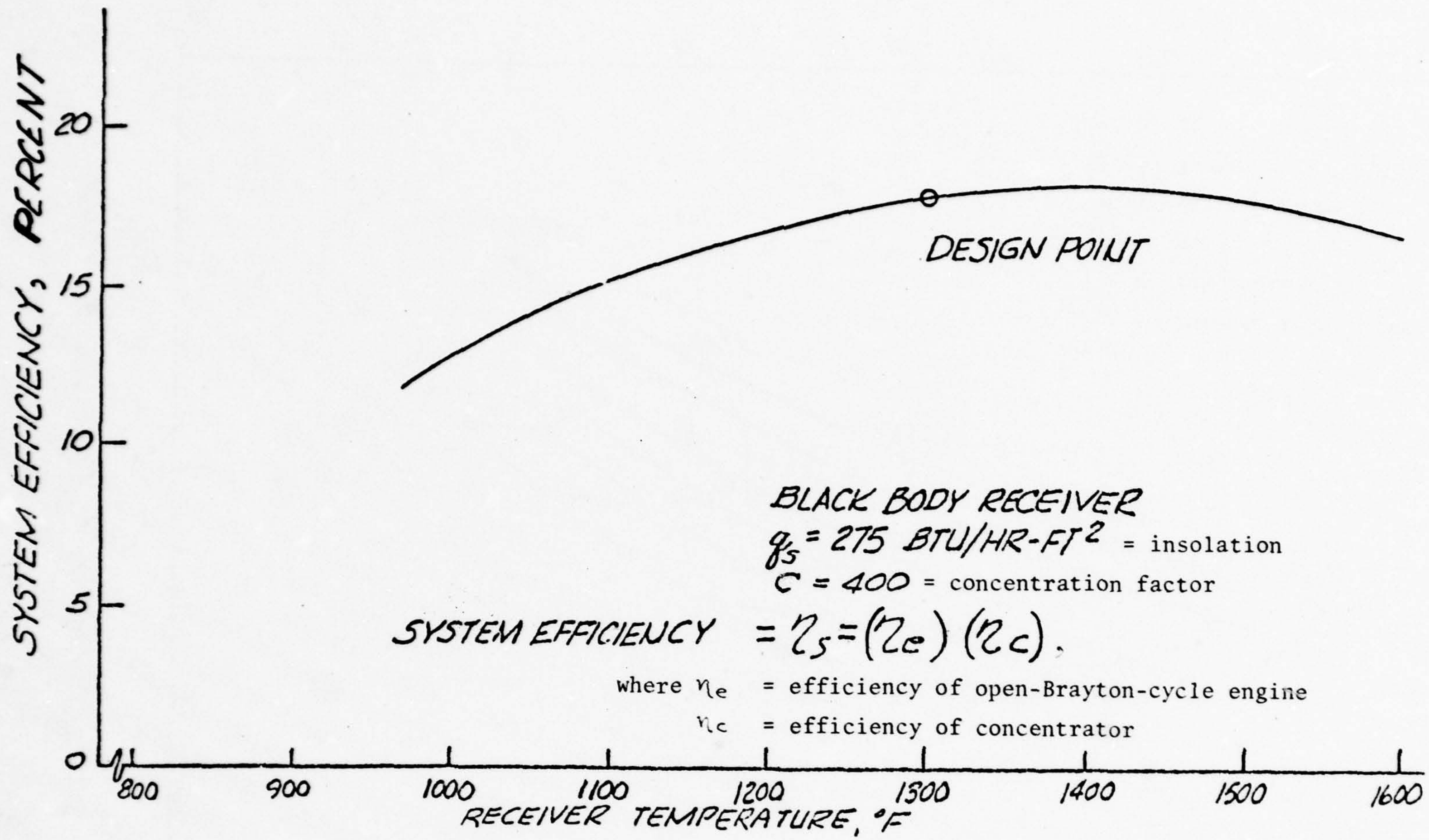


Figure 7. VARIATION IN SYSTEM EFFICIENCY WITH OPERATING TEMPERATURE. (Source: Figure 3.4 in Reference 2).

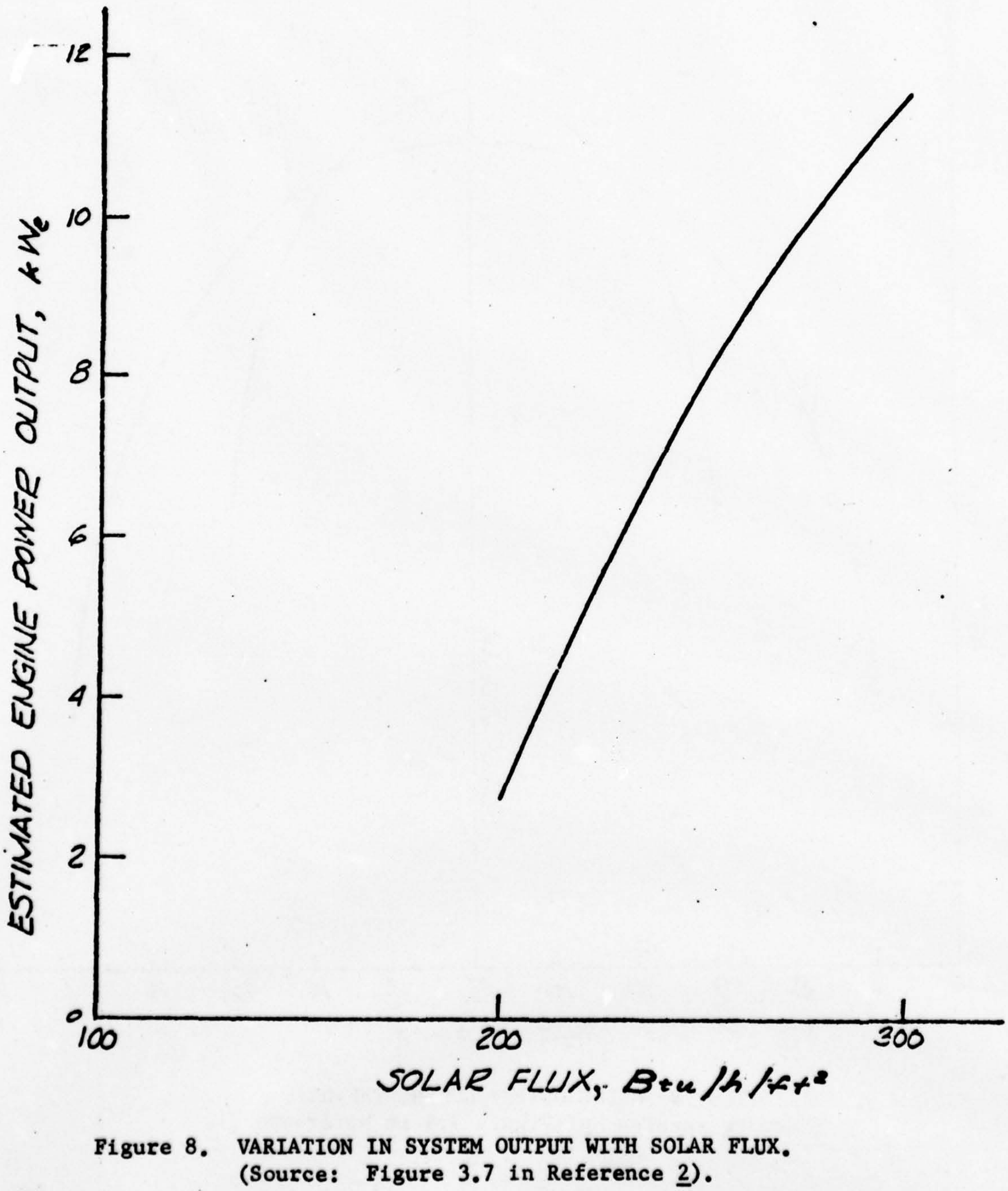


Figure 8. VARIATION IN SYSTEM OUTPUT WITH SOLAR FLUX. (Source: Figure 3.7 in Reference 2).

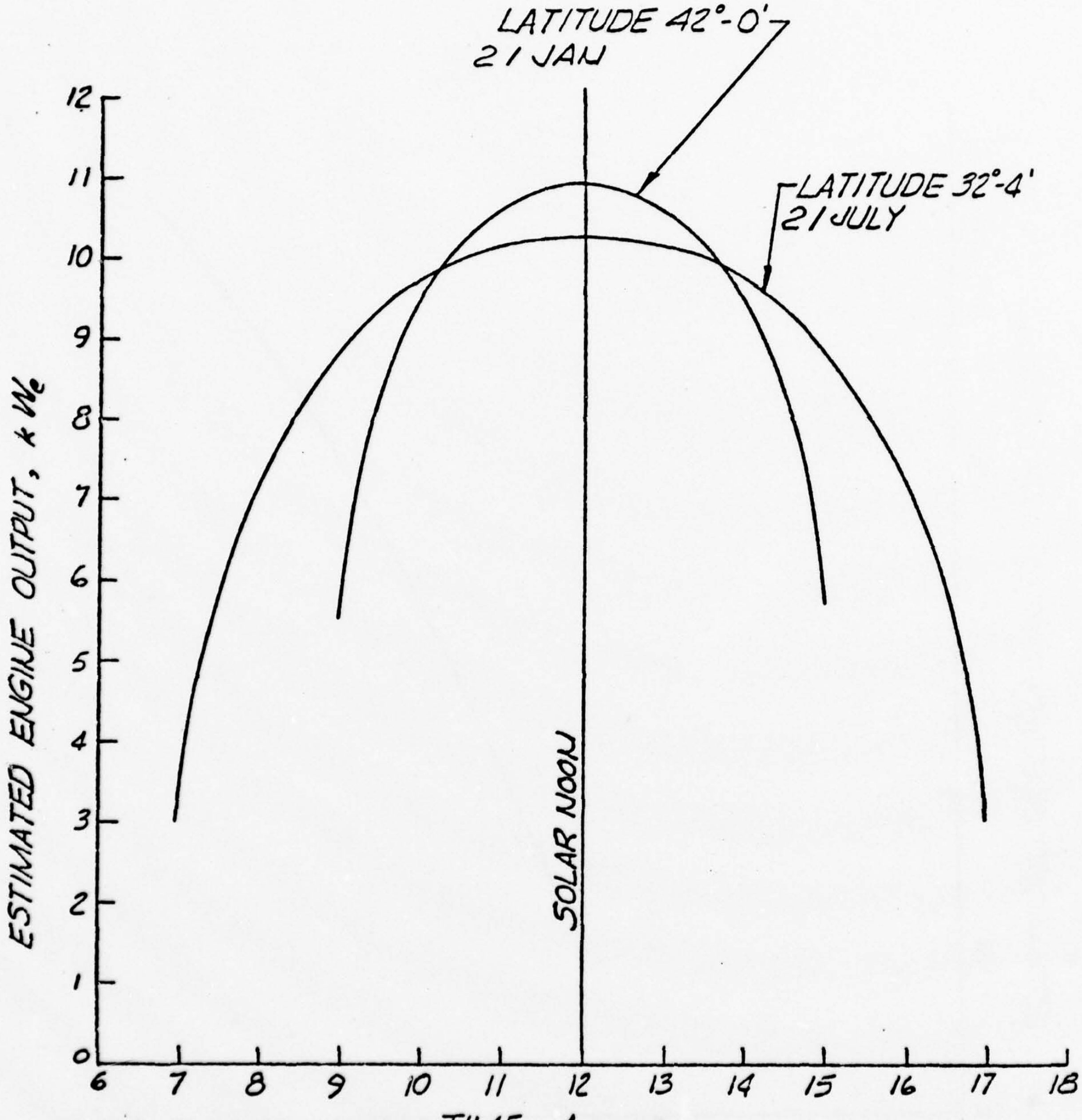


Figure 9. VARIATION IN ENGINE OUTPUT DURING THE DAY. (Amended version of Figure 3.9 in Reference 2).

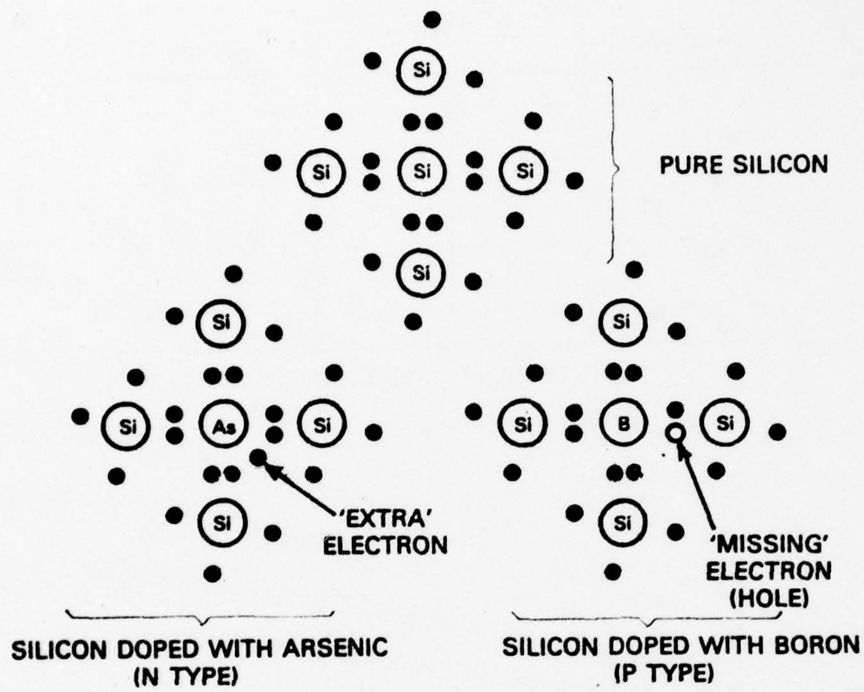


Figure 10. REPRESENTATION OF ELECTRON STRUCTURE IN DOPED SILICON. (Source: Amended version of Figure II-1 in Reference 5).

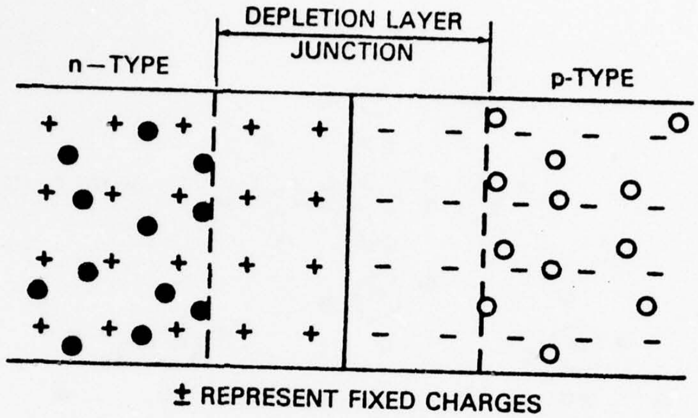


Figure 11. MAJORITY CARRIERS IN VICINITY OF p-n JUNCTION. (Source: Figure II-2 in Reference 5).

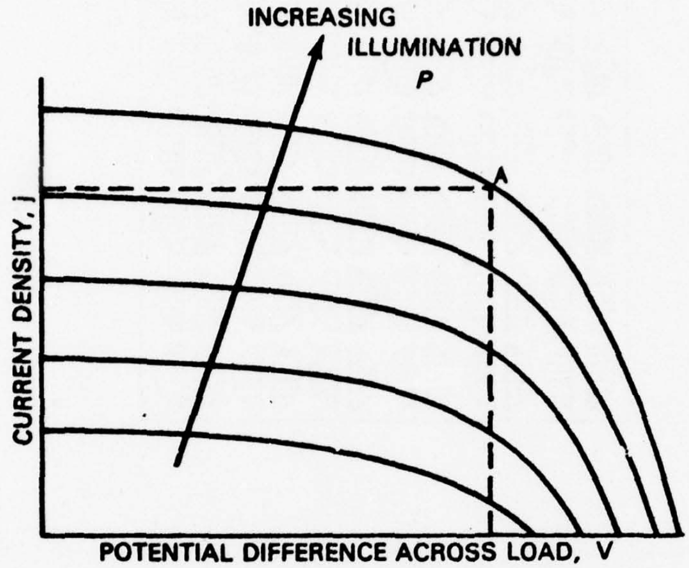


Figure 12. TYPICAL CHARACTERISTIC CURVES FOR PHOTOELECTRIC GENERATOR. (Source: Figure II-3 in Reference 5).

Figure 13 A.
SOLAR PANEL.

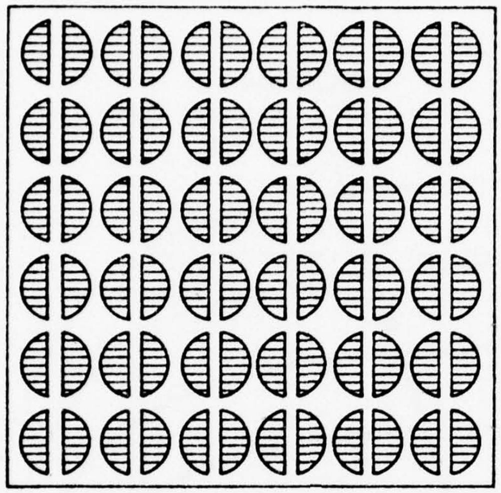


Figure 13 B.
18-WATT ARRAY OF SOLAR PANELS.

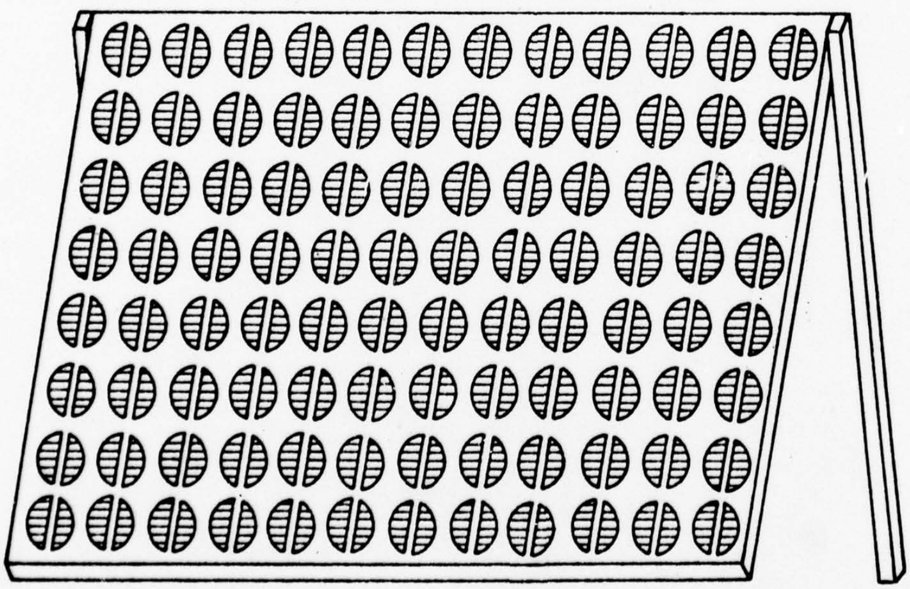


Figure 13. CONFIGURATIONS OF SILICON WAFERS, PANELS, AND FREE STANDING ARRAYS.
(Source: Figures III-1-a and III-1-b in Reference 5).

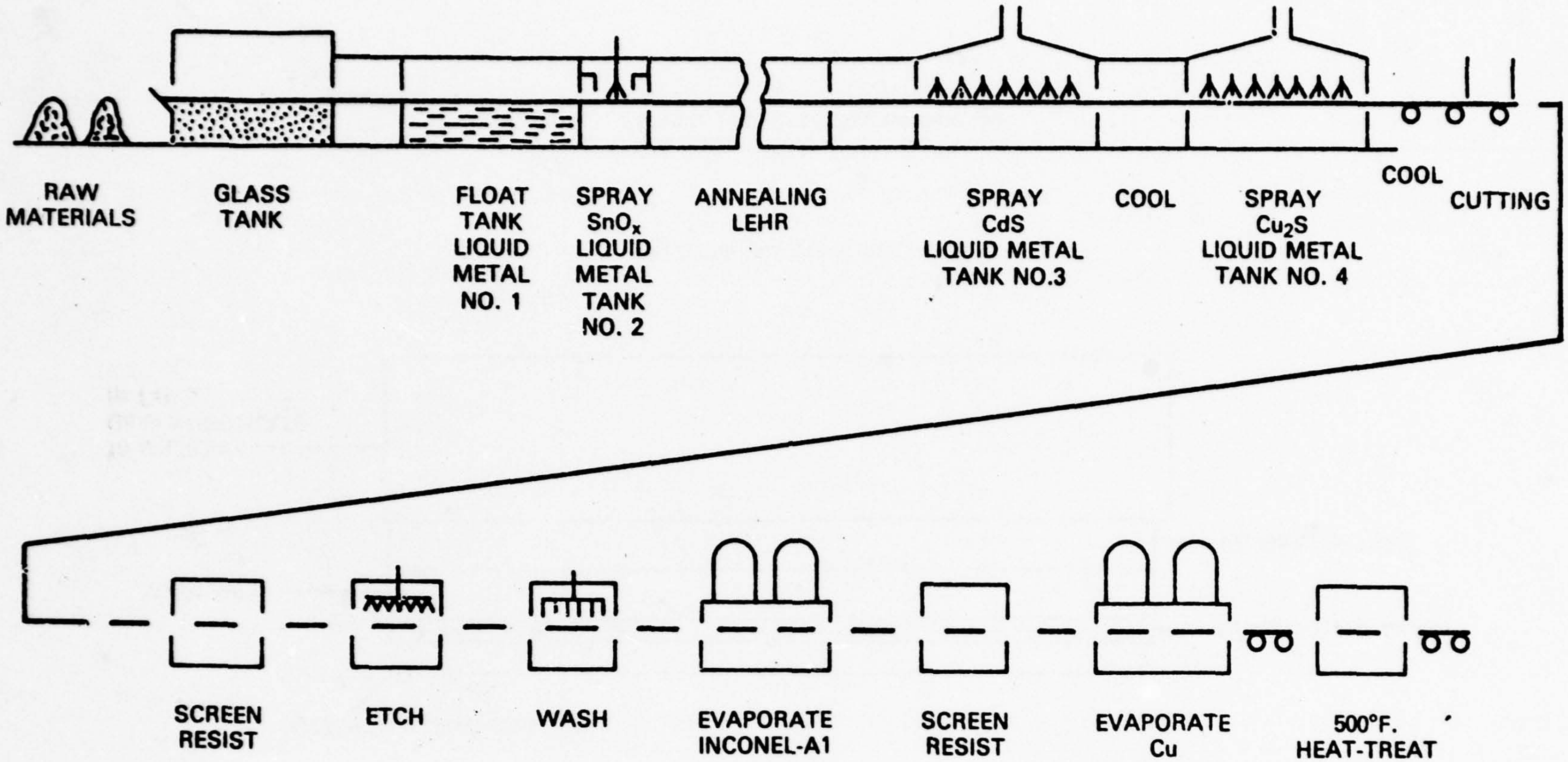
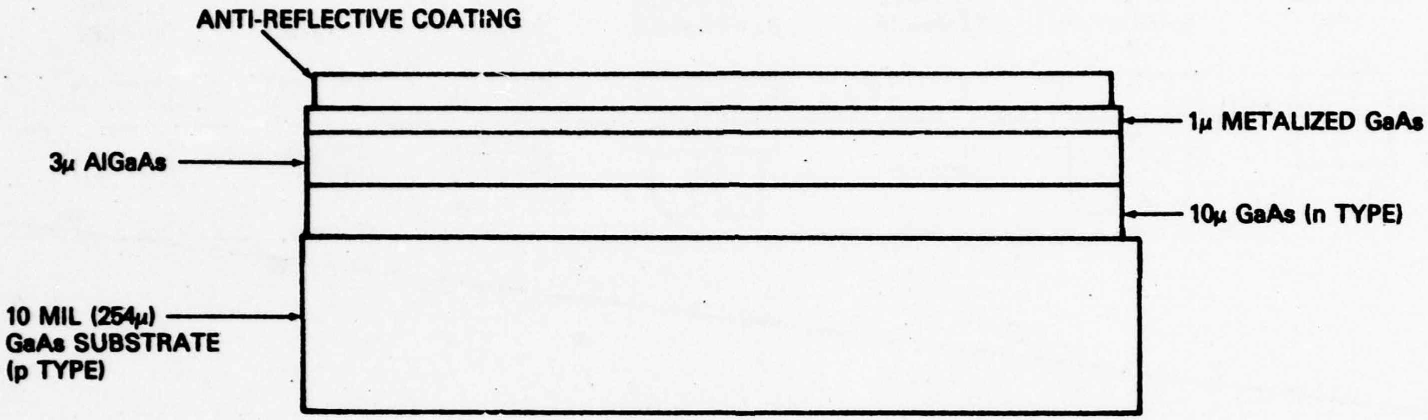


Figure 14. SCHEMATIC OF A FLOAT-GLASS SOLAR-CELL PLANT.
(Source: Figure III-2 in Reference 5).

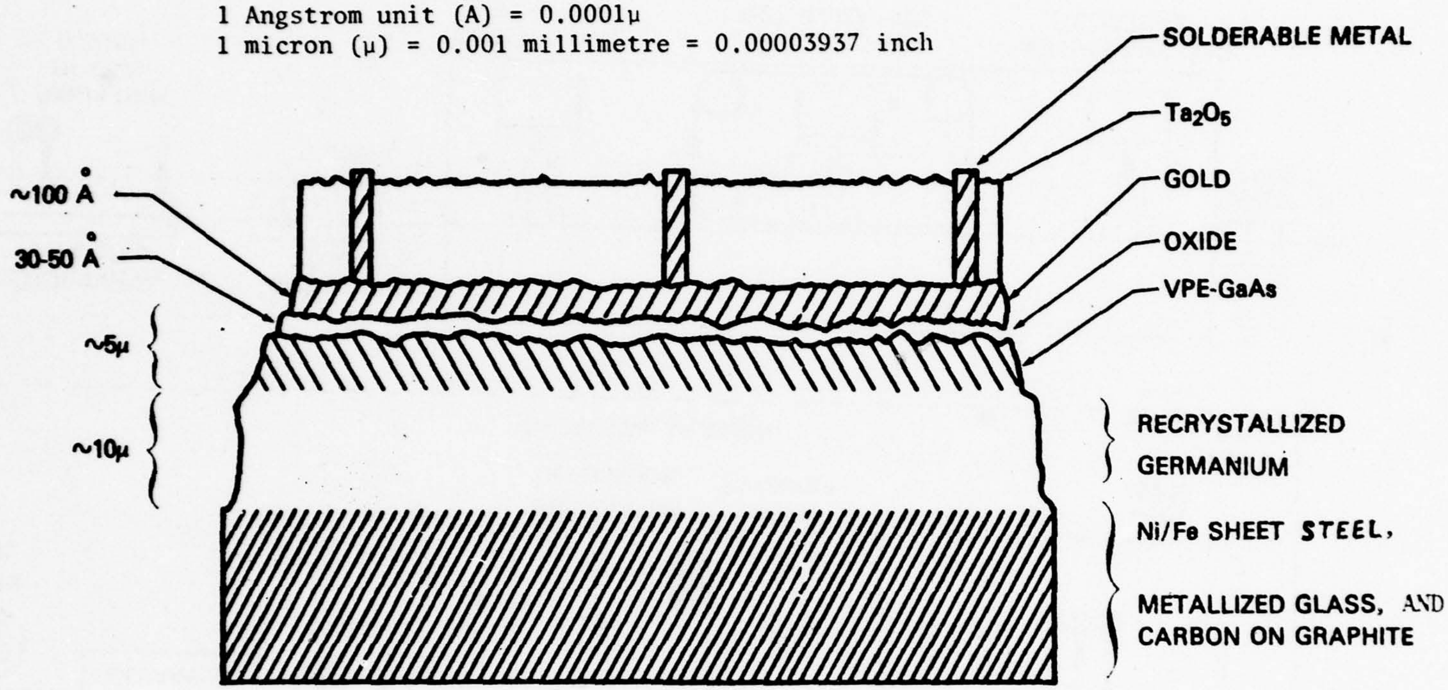
1 micron (μ) = 0.001 millimetre = 0.00003937 inch



(NOT DRAWN TO SCALE)

Figure 15. SINGLE CRYSTAL GaAs CELL FORMATION.
(Source: Figure III-3 in Reference 5).

1 Angstrom unit ($\mathring{A}$) = 0.0001μ
1 micron (μ) = 0.001 millimetre = 0.00003937 inch



(NOT DRAWN TO SCALE)

Figure 16. THIN FILM AMOS SOLAR CELL:FIRST GENERATION. (Source: Figure III-4 in Reference 5).

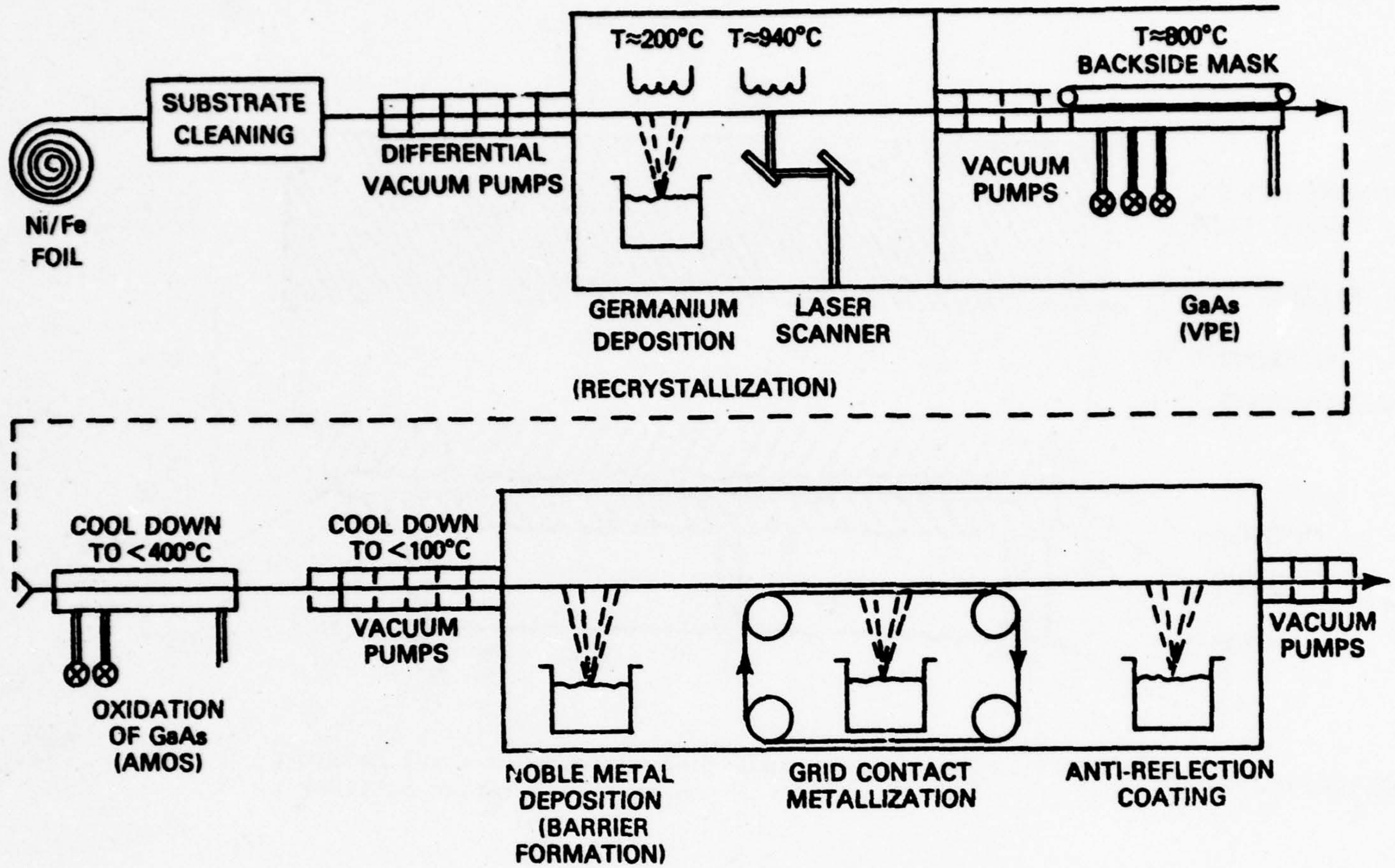


Figure 17. CONCEPTUAL DIAGRAM OF A POSSIBLE THIN FILM AMOS PRODUCTION LINE. (Source: Figure III-5 in Reference 5).

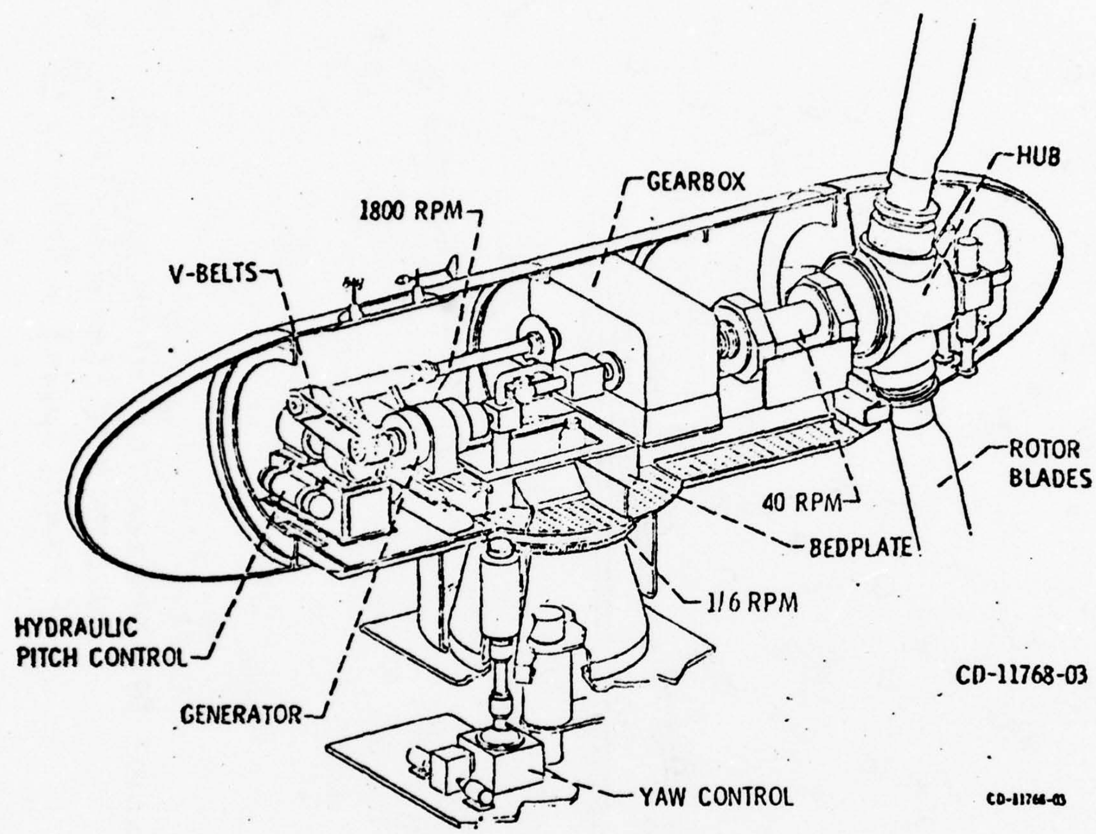


FIGURE 18. TYPICAL WIND-TURBINE GENERATOR. (Amended version of Figure 12 in Reference 12).

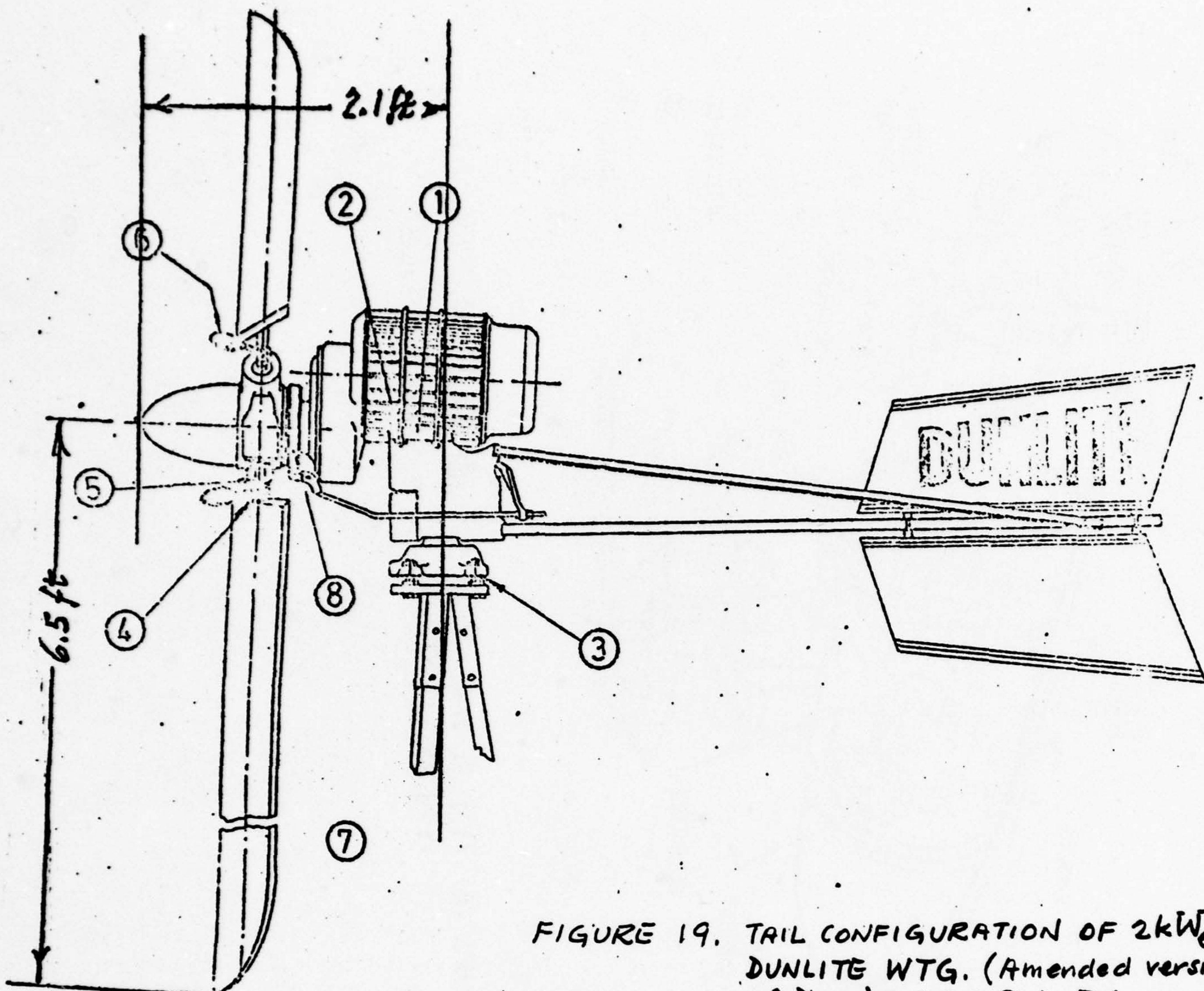


FIGURE 19. TAIL CONFIGURATION OF 2kW$_e$ DUNLITE WTG. (Amended version of Drawing 2507-B in Reference 13).

FIGURE 20. SPO OF 5kW$_e$ ELEKTRO WTG. (Amended version of Figure 2 in Reference 14).

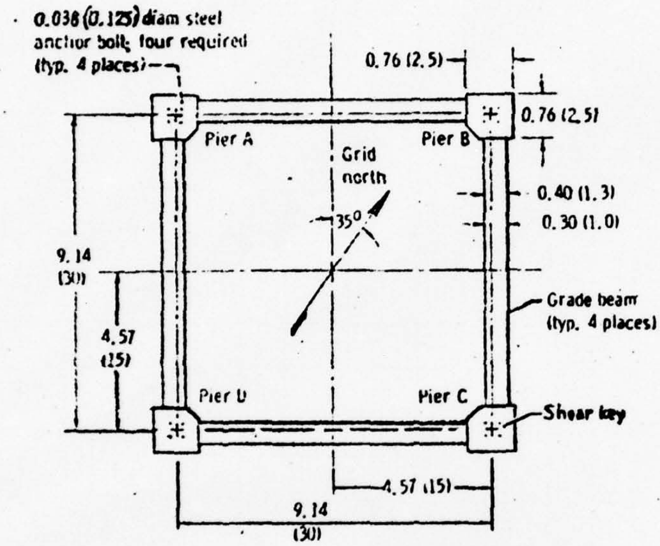


FIGURE 21. FOUNDATION FOR 200kW$_e$ ERDA WTG.
(Amended version of Figure 3 in Reference 19).
(Dimensions in metres; parenthetical, in feet).

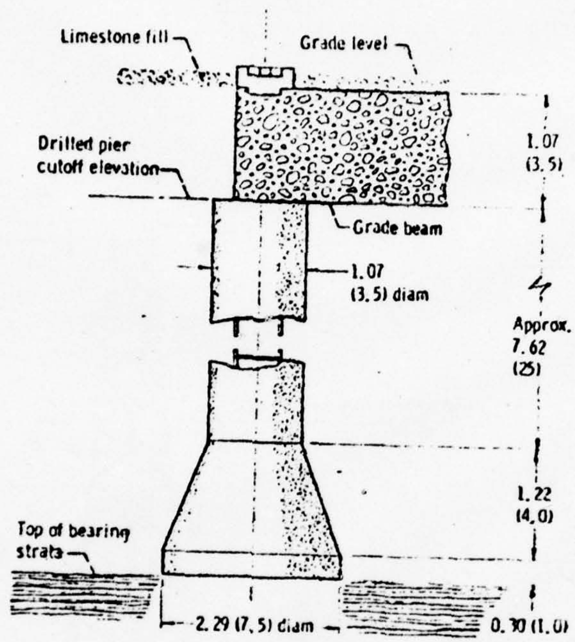


FIGURE 22. ELEVATION OF TYPICAL PIER AND GRADE BEAM IN FOUNDATION OF 200 kW$_e$ ERDA WTG. (Amended version of Figure 4 in Reference 19). (Dimensions in metres; parenthetical, in feet).

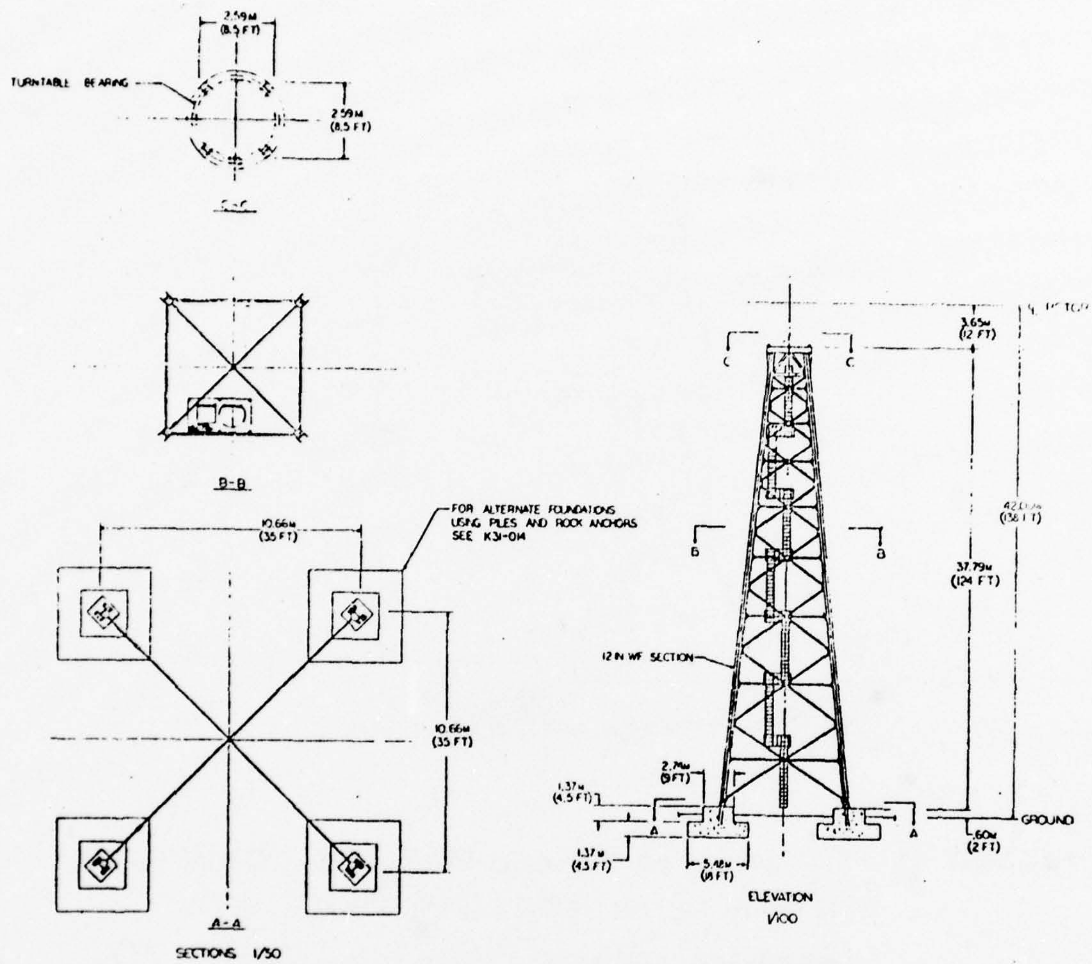


FIGURE 23. FOUNDATION AND TOWER FOR 1,500 kW_e ERDA WTG.
(Source: Figure 6-4 in Reference 21).

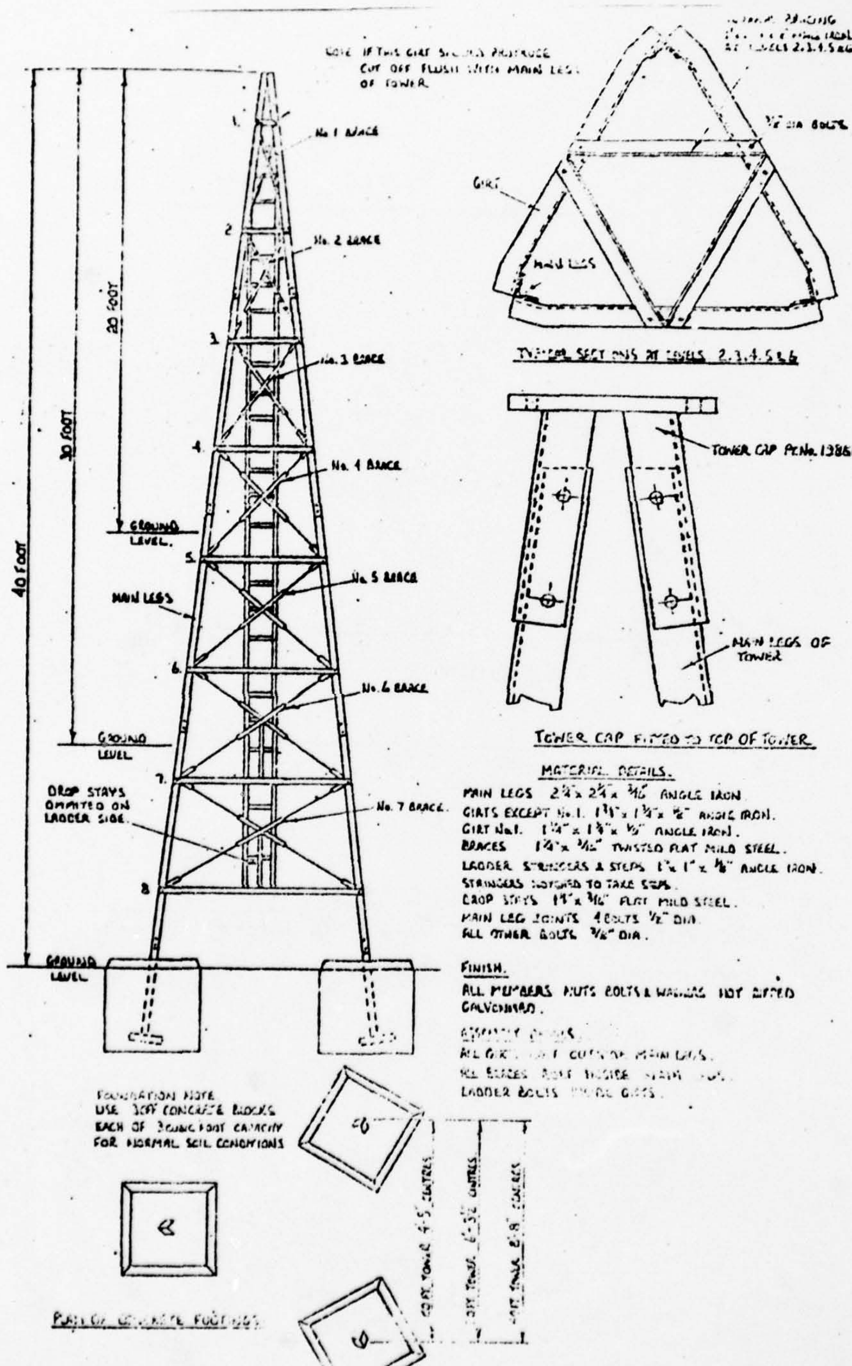


FIGURE 24. FOUNDATION AND TOWER FOR 2kW$_e$ DUNLITE WTG.
(Source: Drawing 1114 in Reference 13).

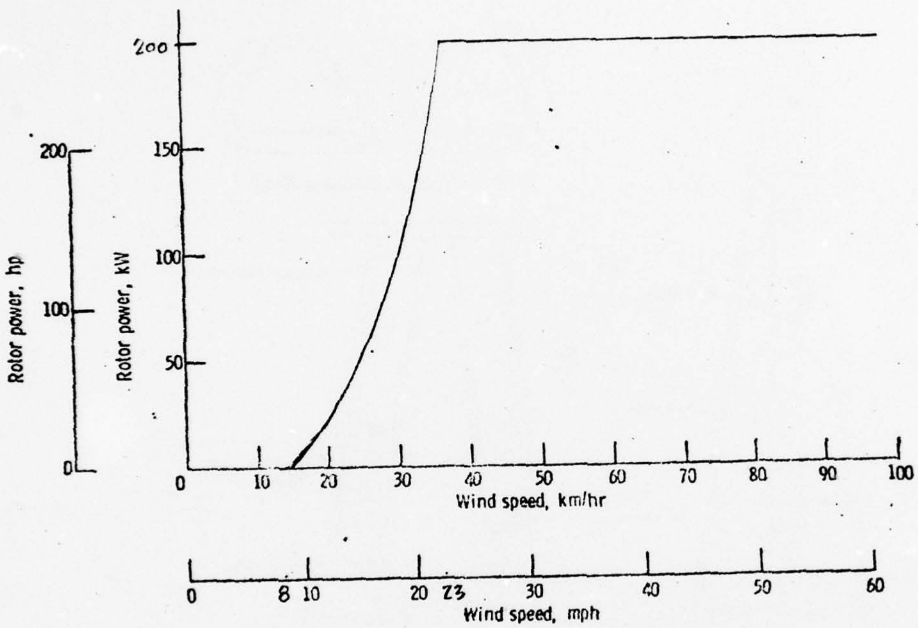


FIGURE 25. POWER OUTPUT OF 200kW$_e$ ERDA WTG.
(Amended version of Figure 6 in Reference 20).

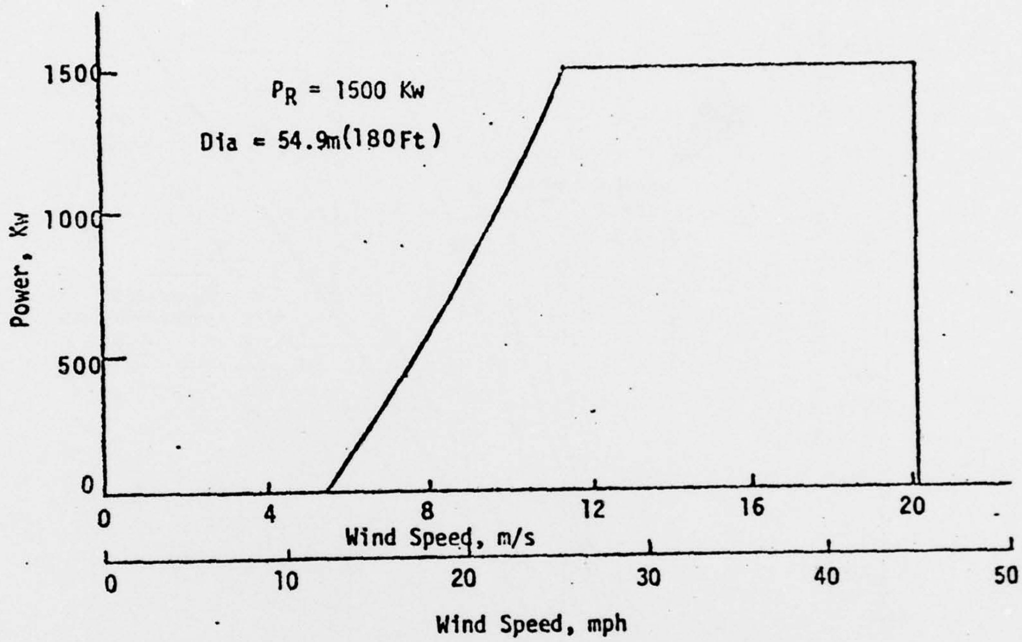


FIGURE 26. POWER OUTPUT OF 1,500 kW_e ERDA WTG.
(Source: Figure 3-45 in Reference 21).

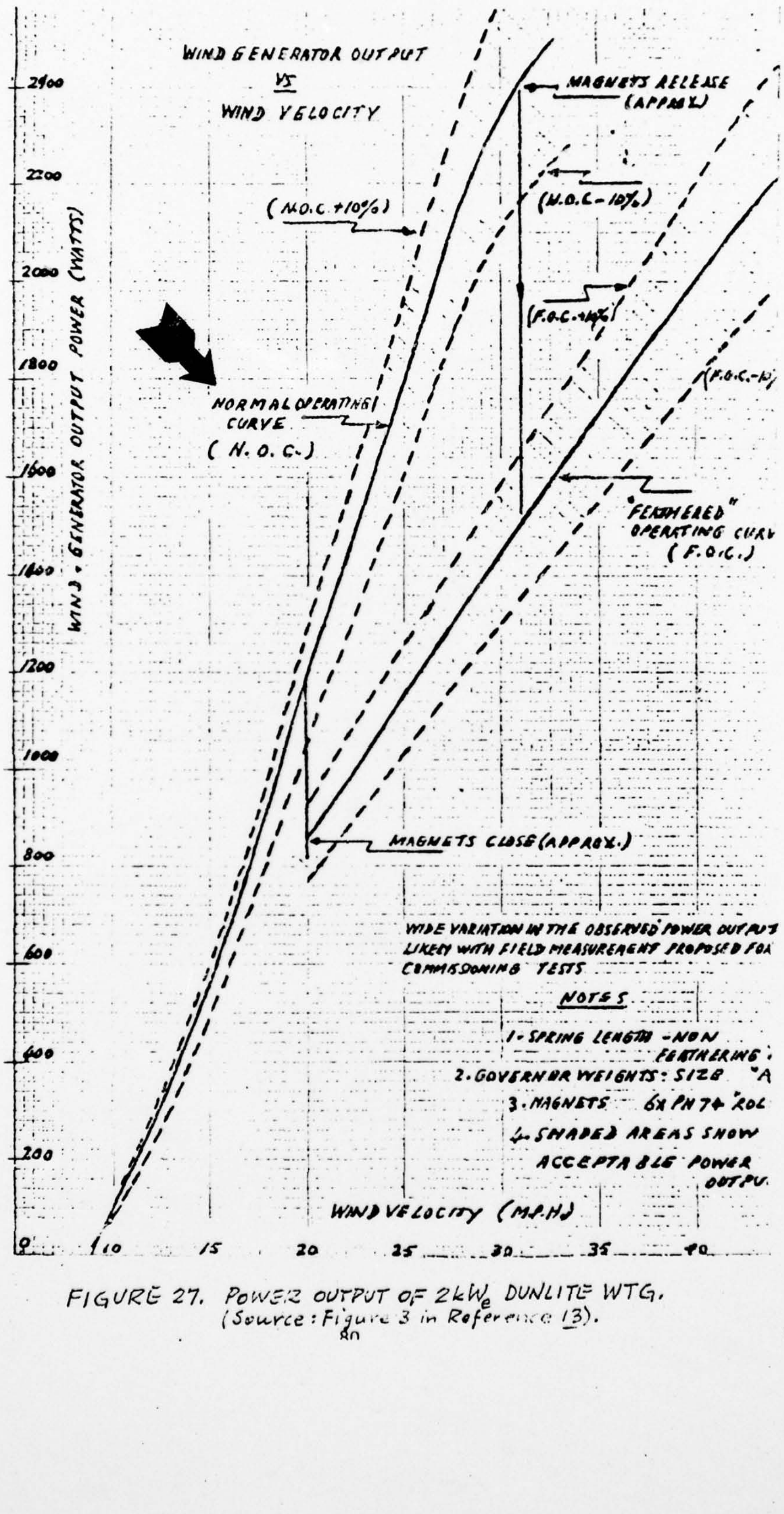


FIGURE 27. POWER OUTPUT OF 2kW$_e$ DUNLITE WTG.
(Source: Figure 3 in Reference 13).

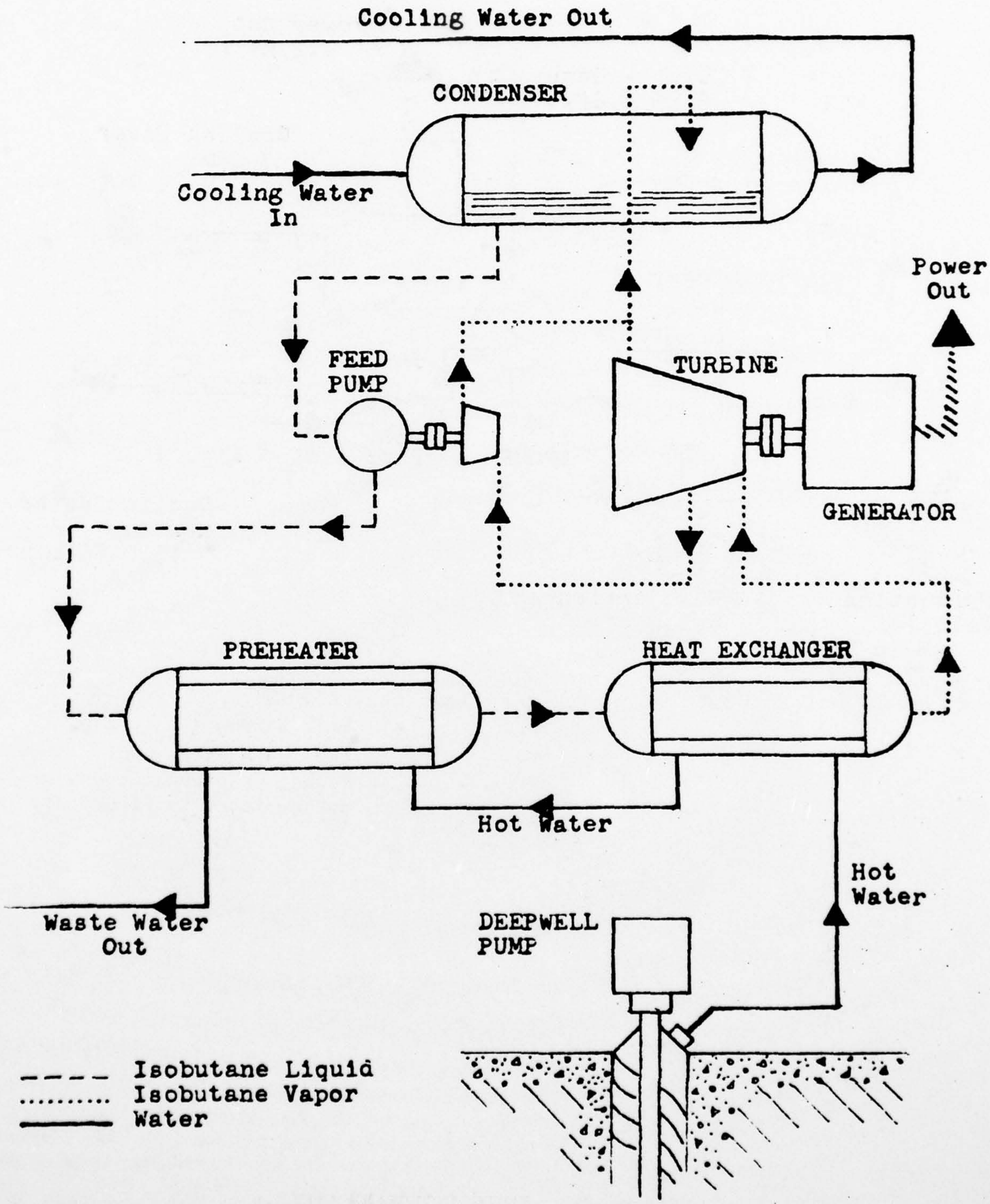
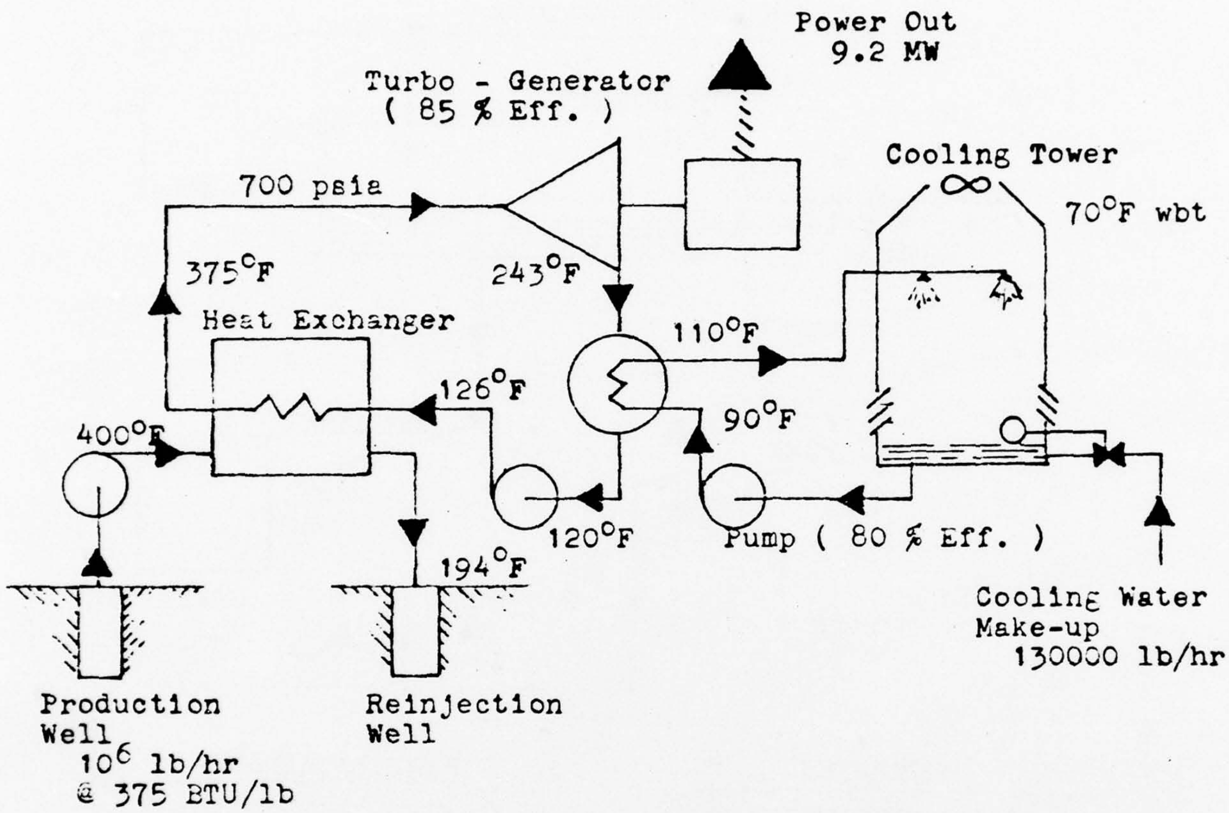


Figure 28. MAGMAMAX POWER CYCLE. USED AT SALTON SEA R&D PROJECT IN CONJUNCTION WITH SAN DIEGO GAS & ELECTRIC COMPANY. (Source: Figure 1 in Reference 30).



NOTE: This schematic excludes the waste water and isobutane preheater which are depicted in Figure 28.

Figure 29. BASIC ISOBUTANE CYCLE.
(Amended version of Figure 1 in Reference 32).

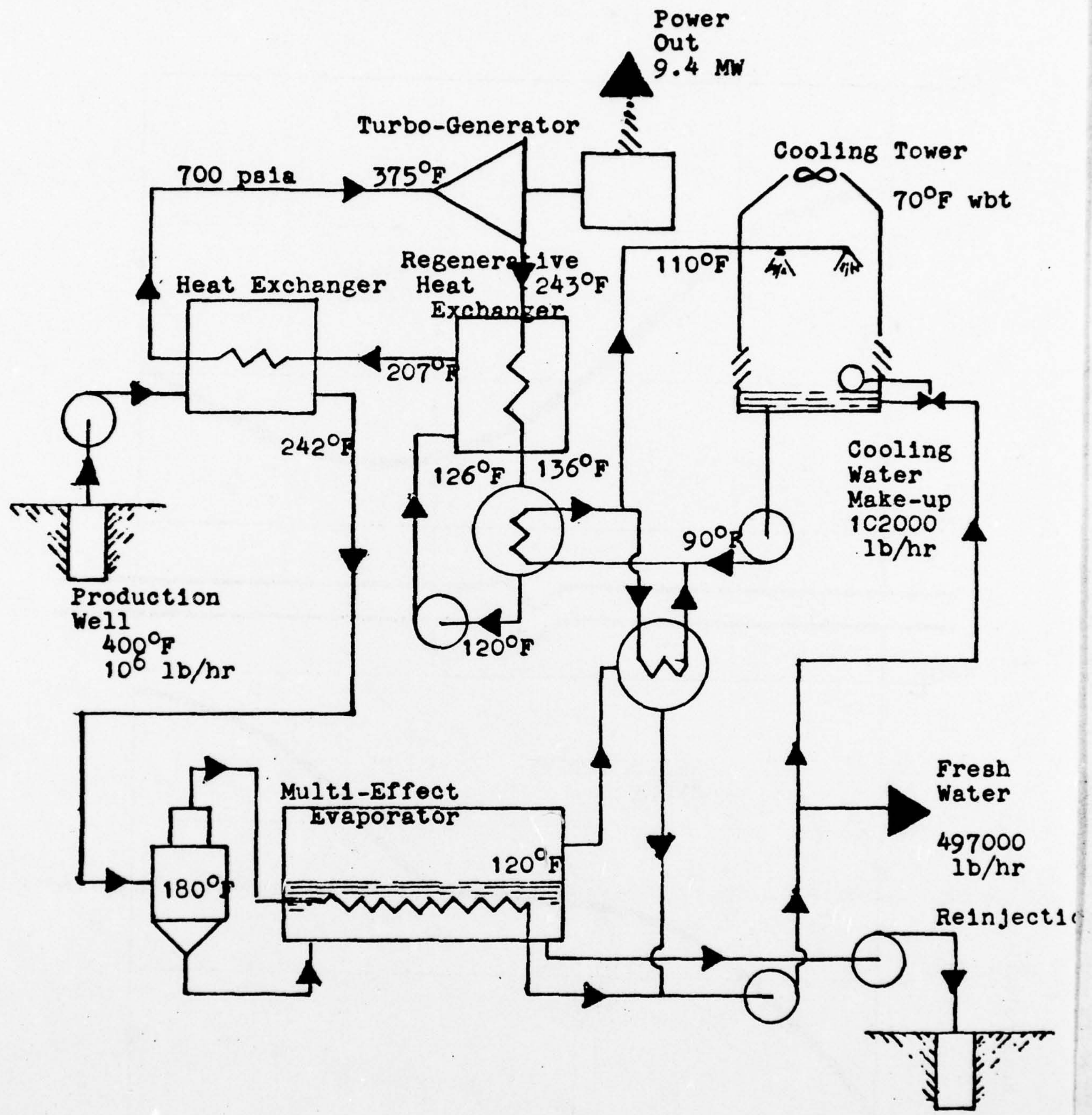


Figure 30. REGENERATIVE ISOBUTANE CYCLE AND MULTI-EFFECT EVAPORATOR. (Amended version of Figure 2 in Reference 32).

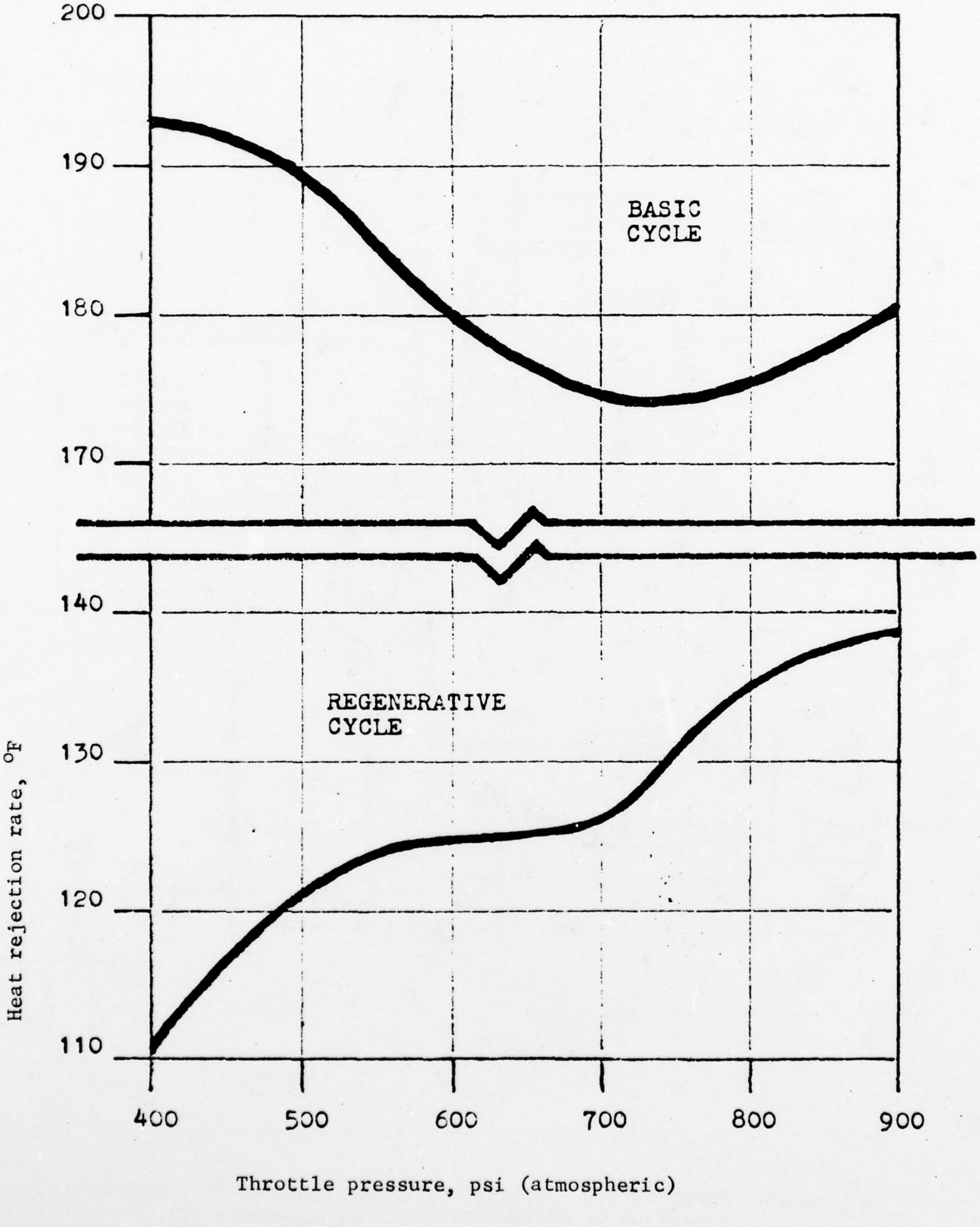


Figure 31. HEAT-REJECTION RATE USING 400°F SATURATED WATER (120°F CONDENSING TEMPERATURE).

(Source: Figure 5 in Reference 32).

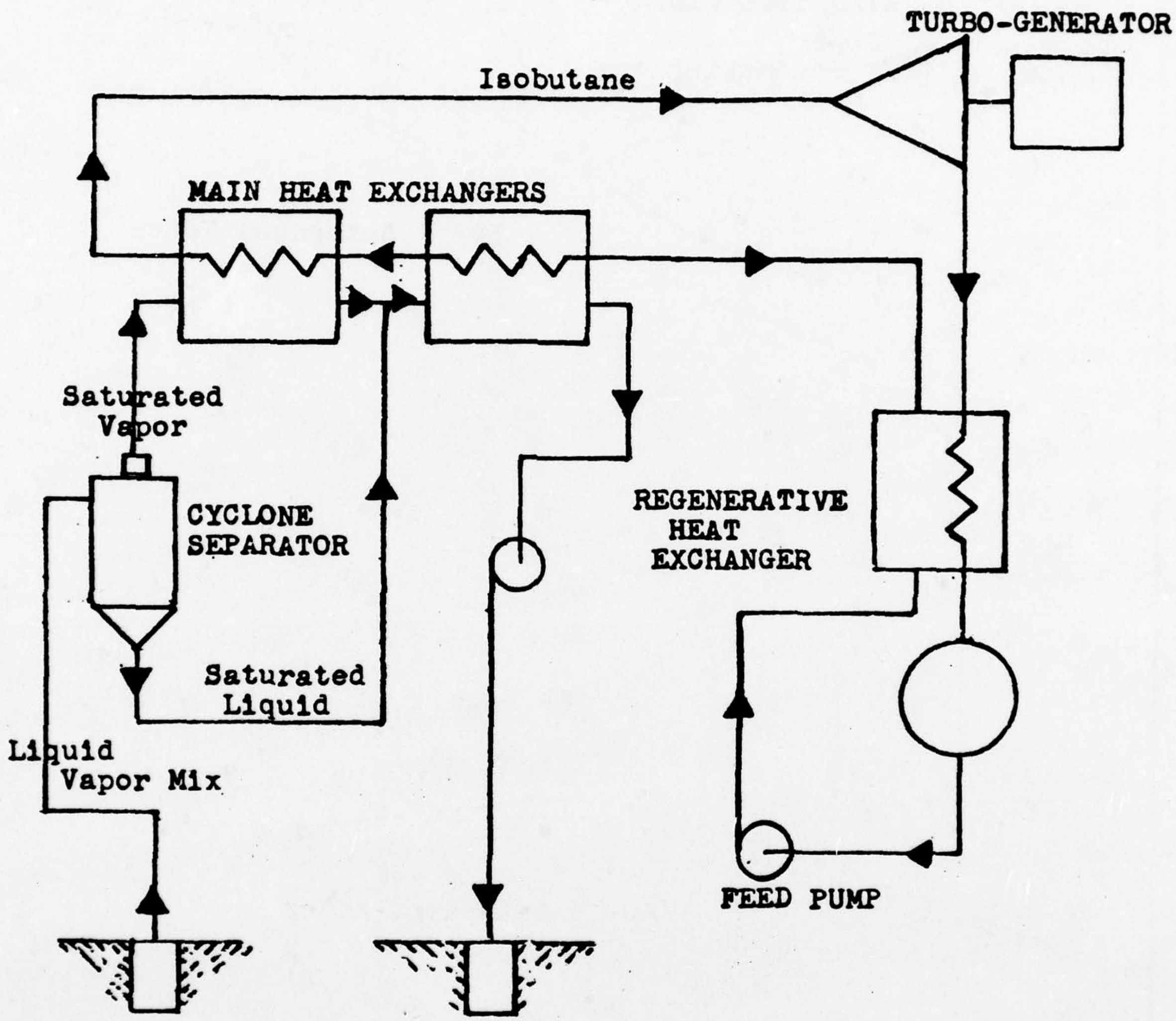


Figure 32. REGENERATIVE CYCLE WITH TWO-STAGE HEATING.
(Source: Figure 6 in Reference 32).

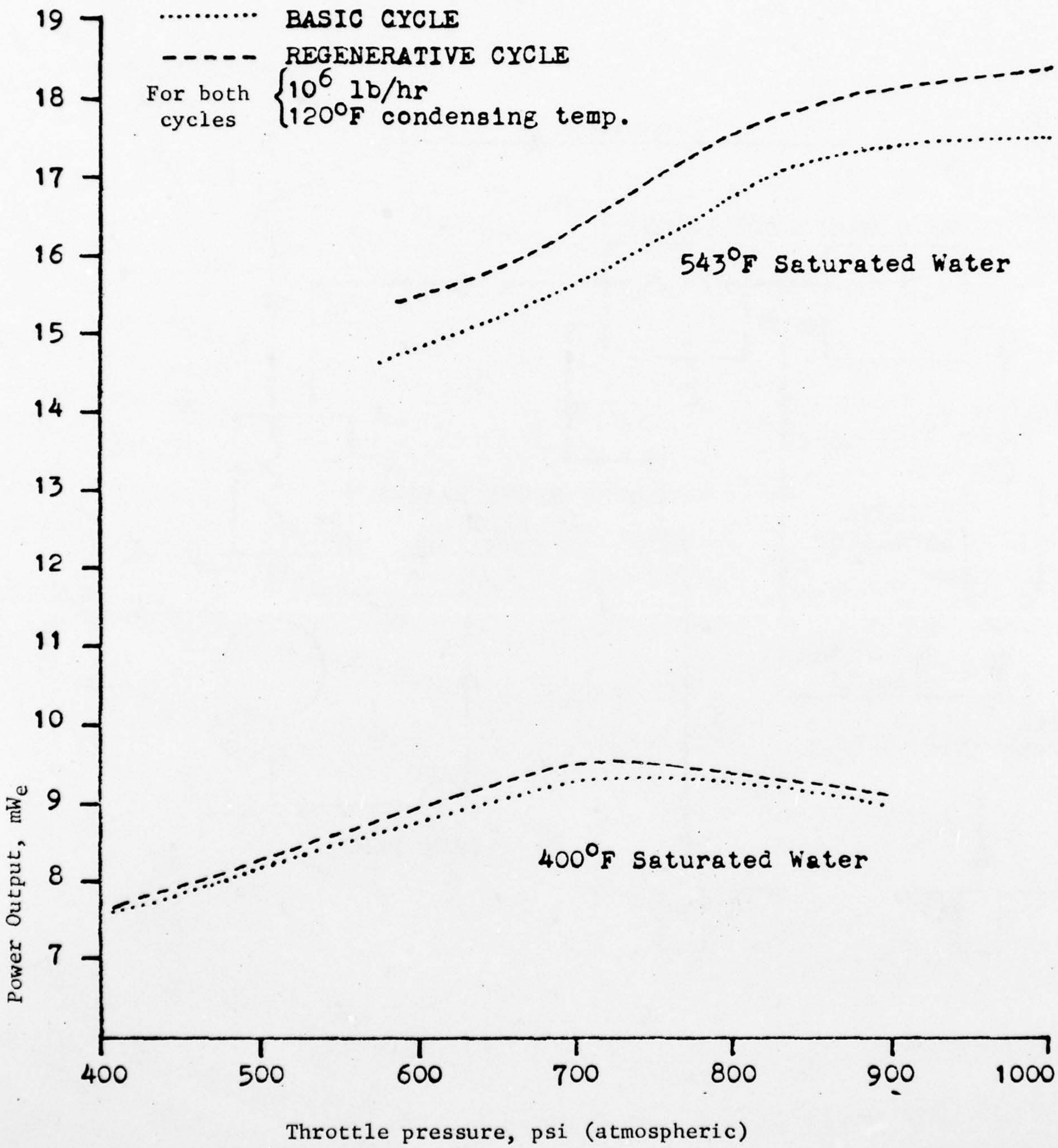


Figure 33. POWER OUTPUT VERSUS THROTTLE PRESSURE
(Amended version of Figures 4 and 9 in Reference 32).

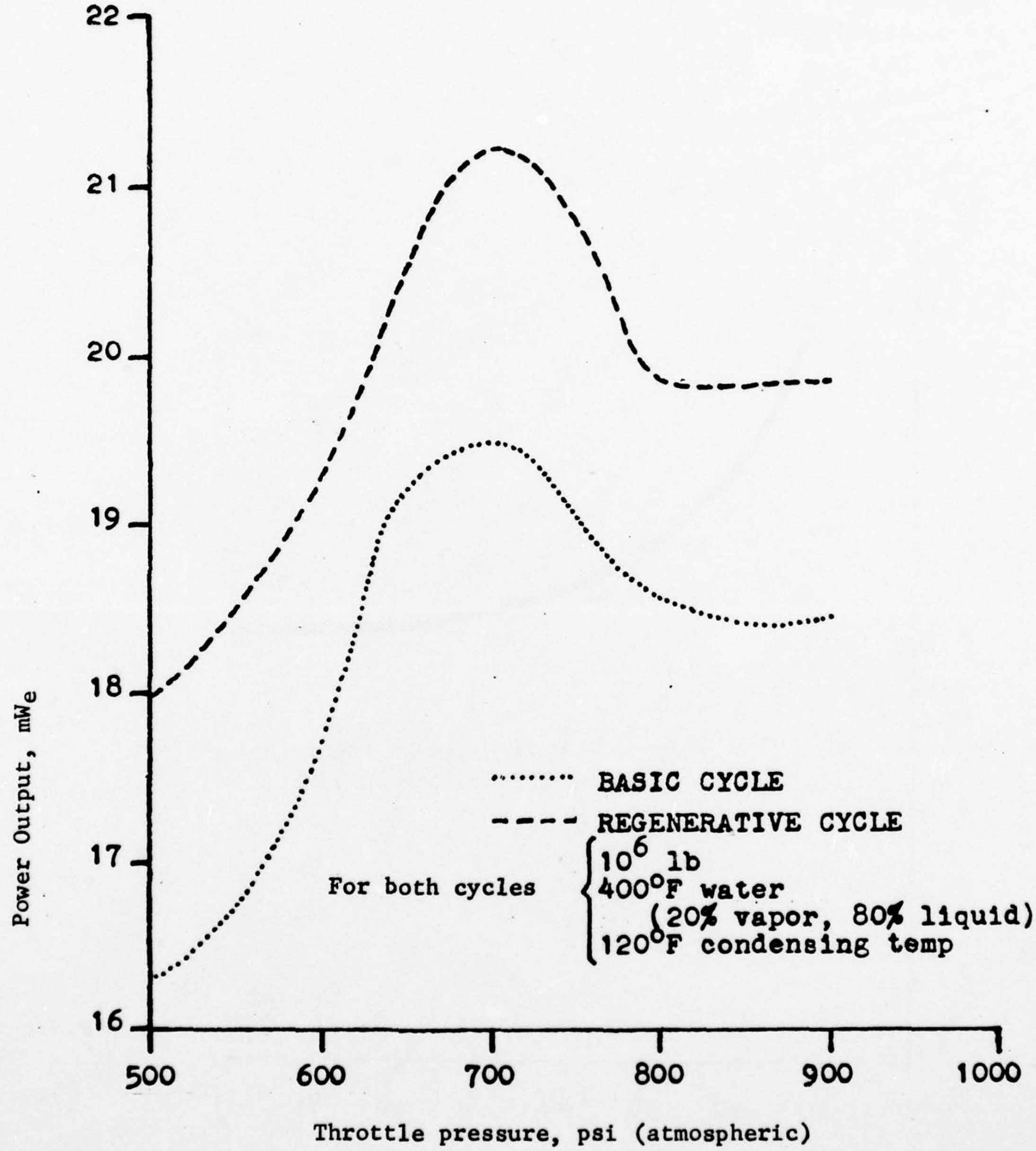


Figure 34. POWER OUTPUT VS. THROTTLE PRESSURE (20% VAPOR, 80% LIQUID) (Source: Figure 8 in Reference 32).

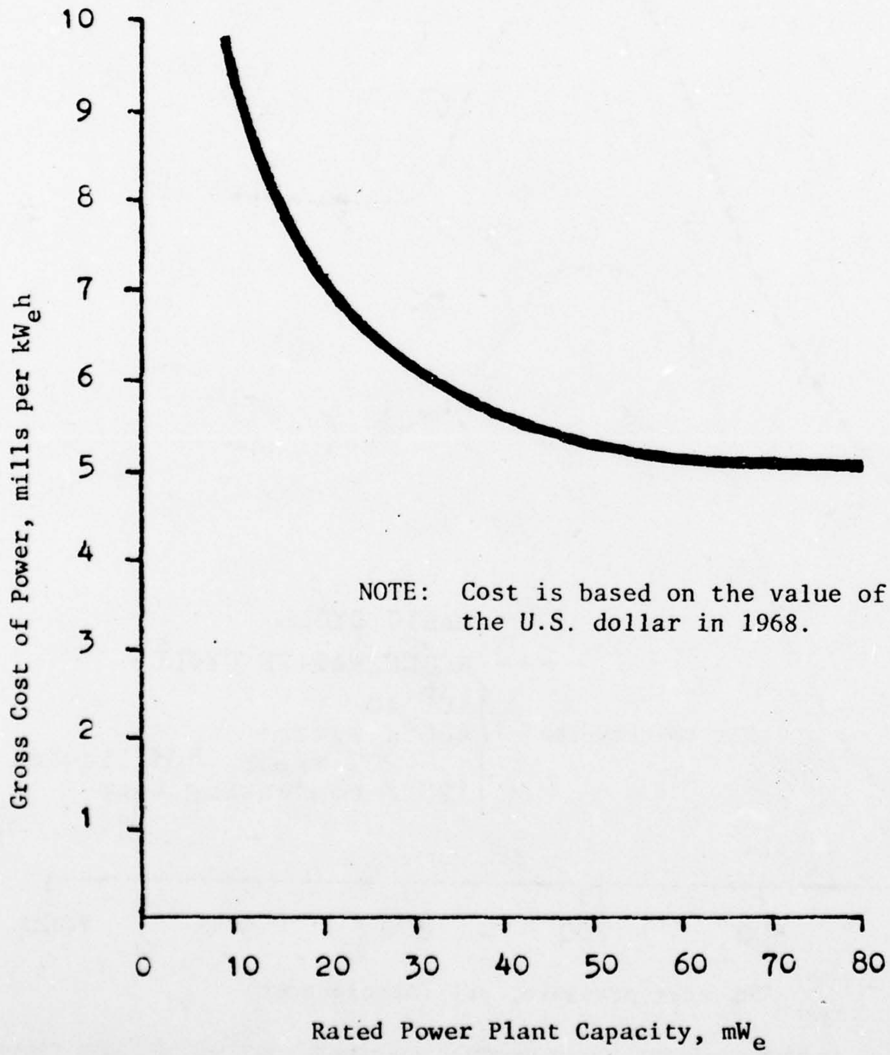


Figure 35. GROSS COST OF POWER VERSUS RATED CAPACITY. (Source: Reference 34).

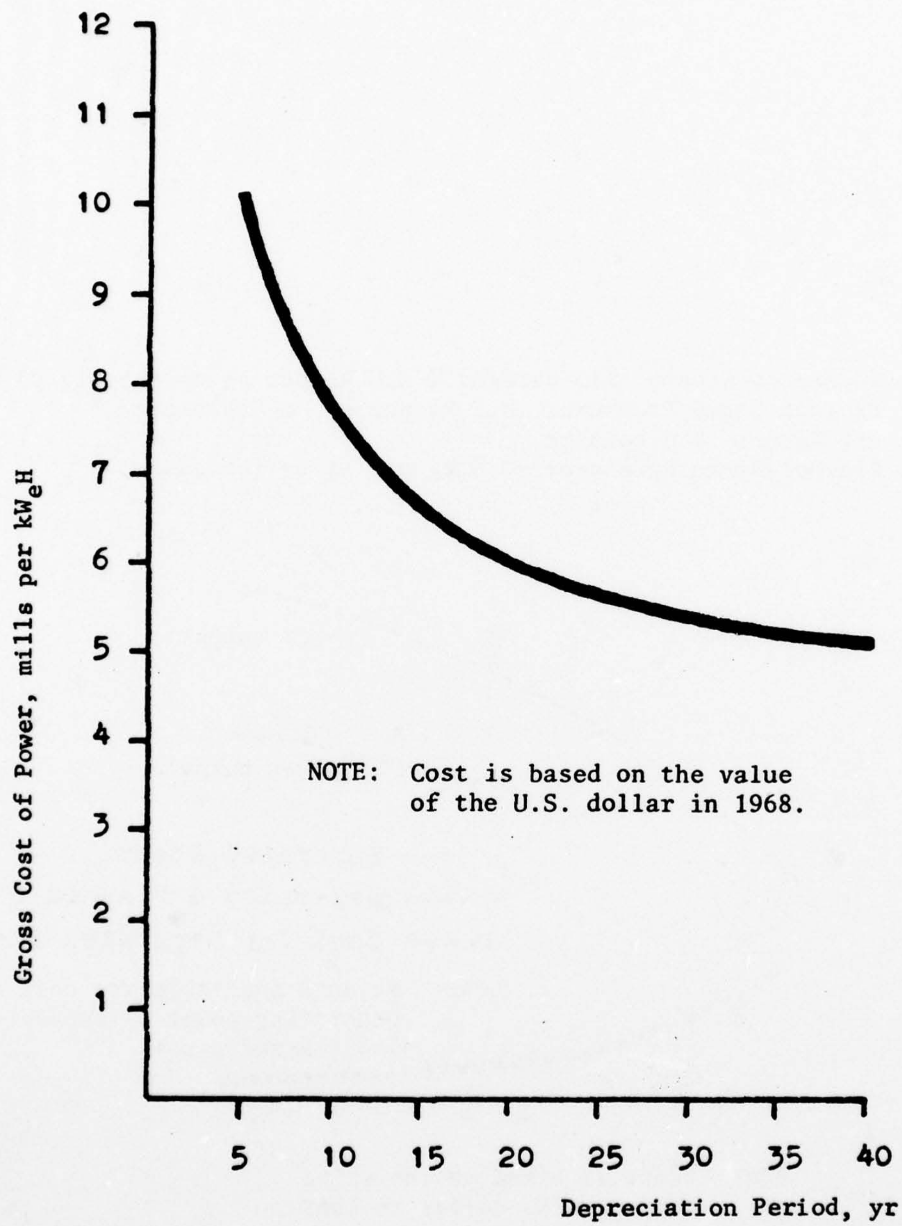


Figure 36. GROSS COST OF POWER VERSUS AVERAGE PERIOD OF DEPRECIATION. (FOR RATED POWER PLANT CAPACITY OF 30 kW_e).

(Source: Amended version of Figure 2 in Reference 34).

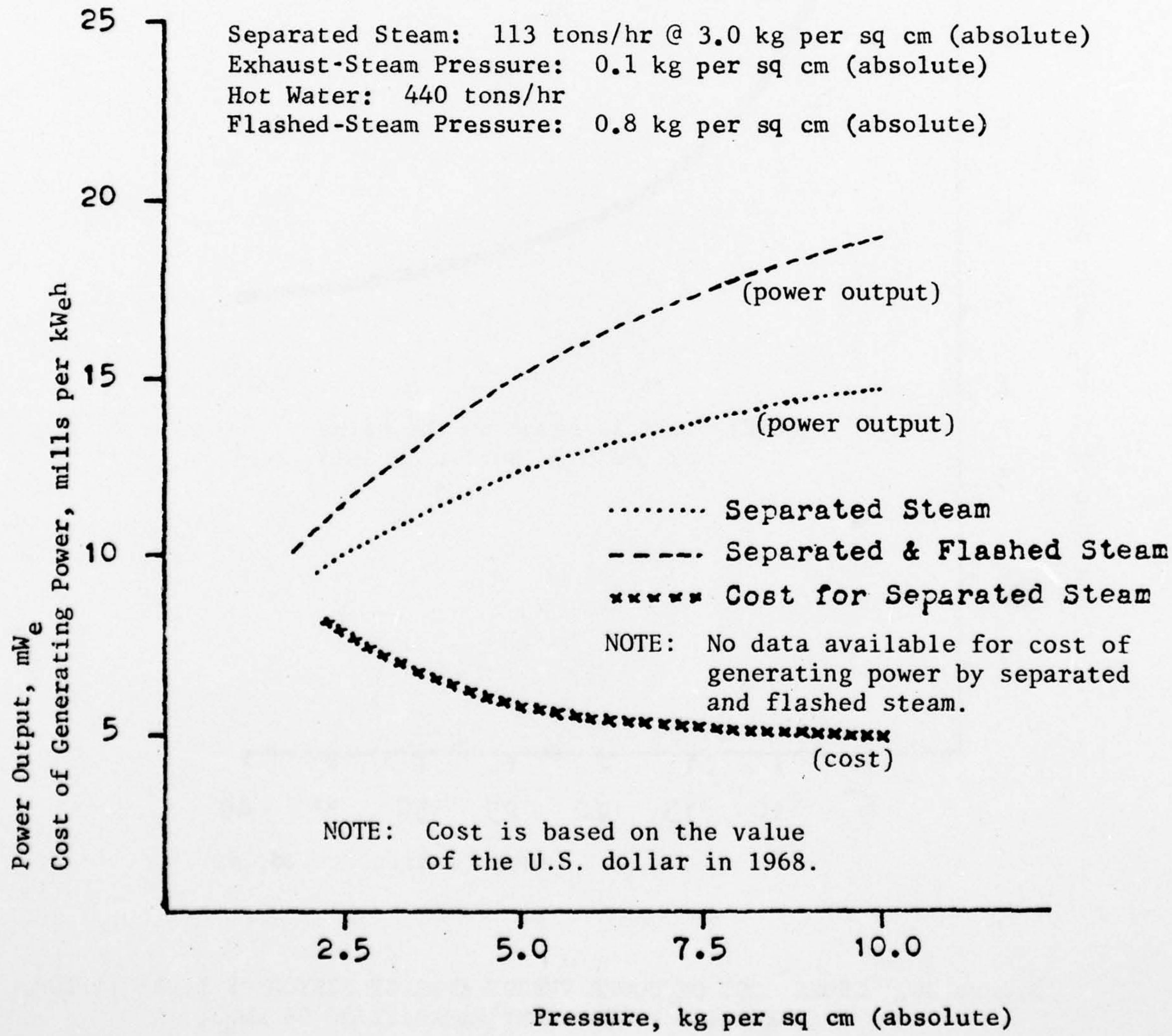


Figure 37. POWER OUTPUT AND ASSOCIATED GENERATING COST VERSUS TURBINE INLET-PRESSURE.

(Source: Reference 34).

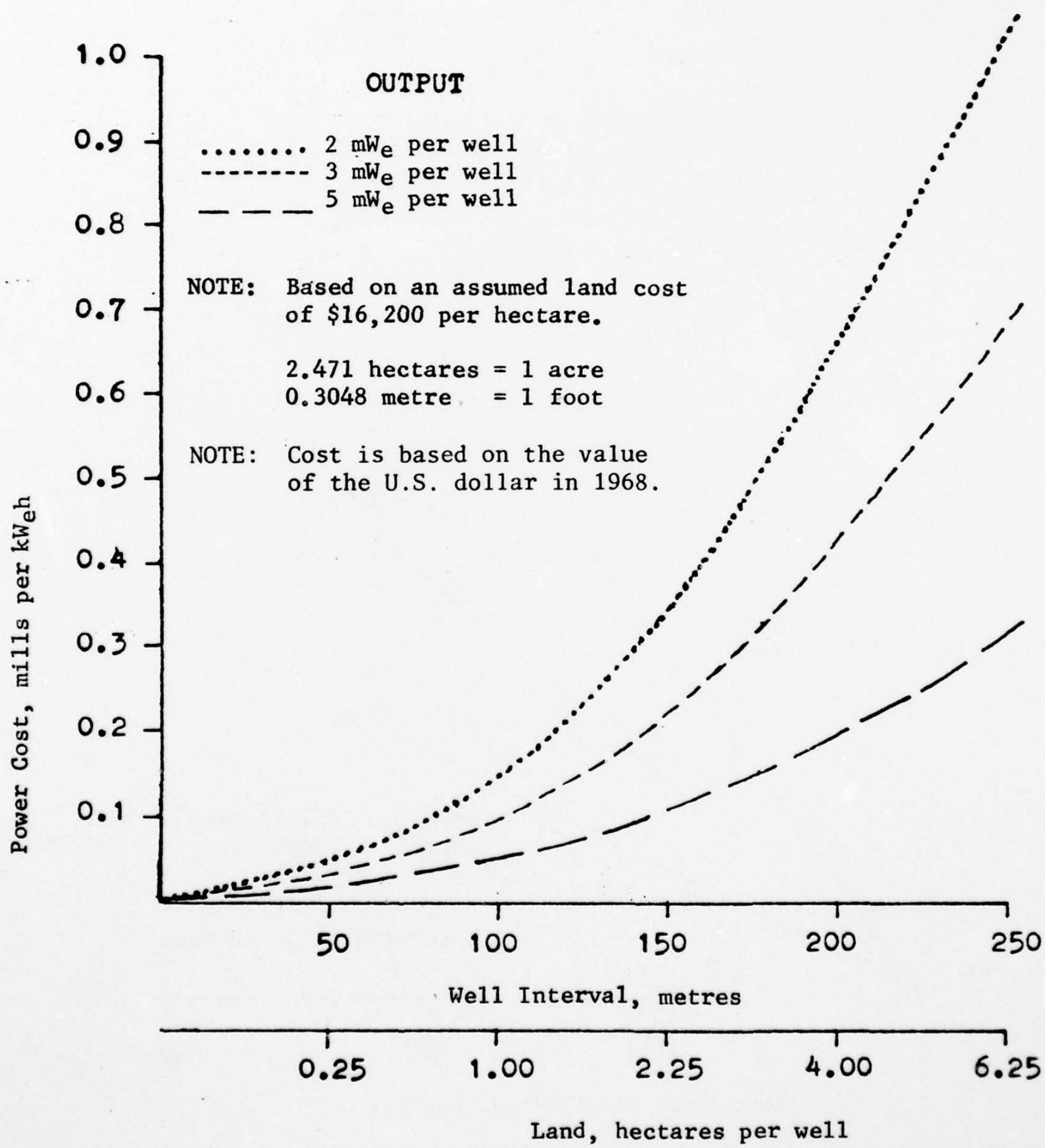


Figure 38. COST OF POWER VERSUS WELL INTERVAL (Source: Figure 4a in Reference 34).

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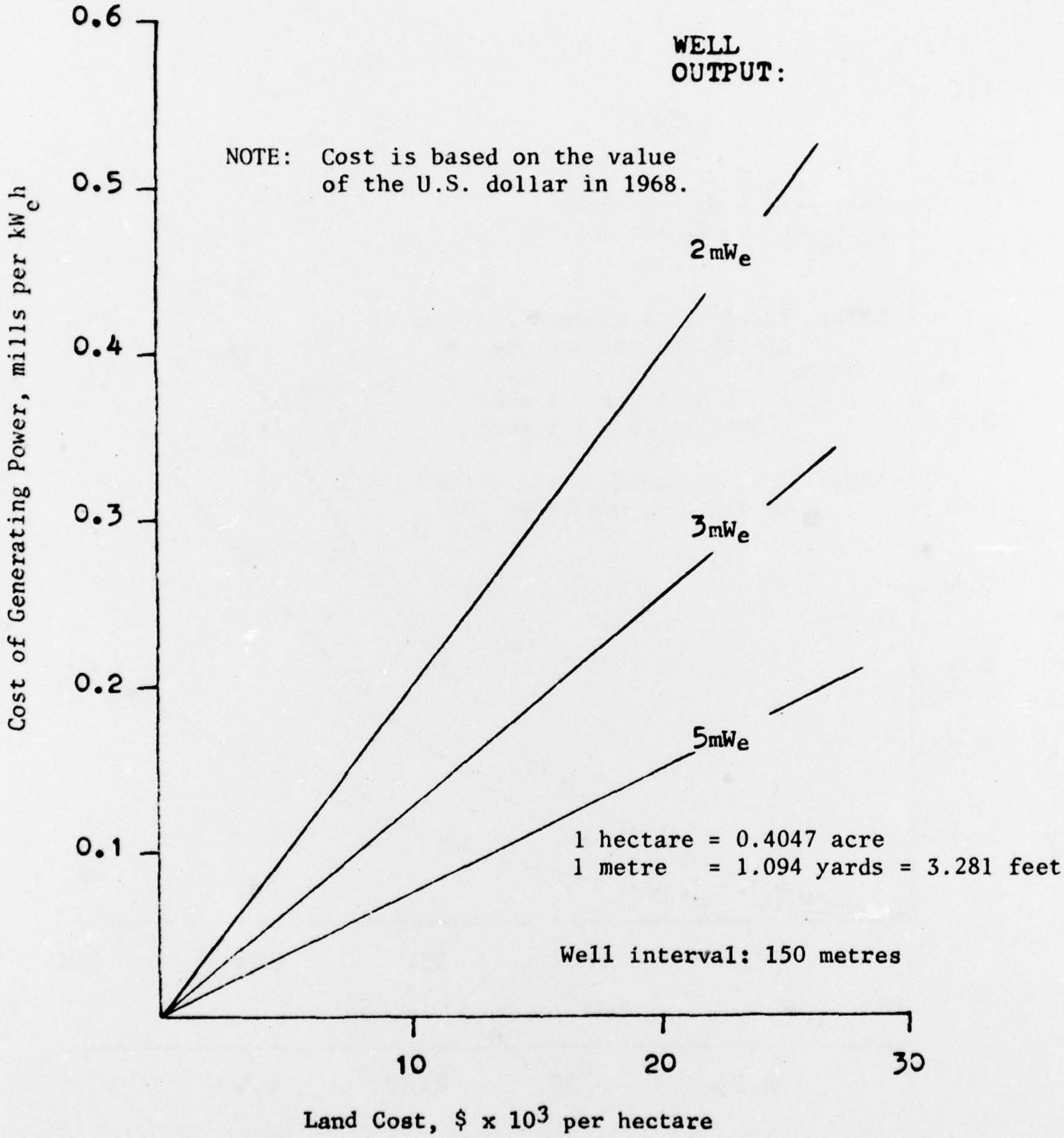

Figure 39. GENERATING COST VERSUS LAND COST. (Source: Figure 4b in Reference 34).

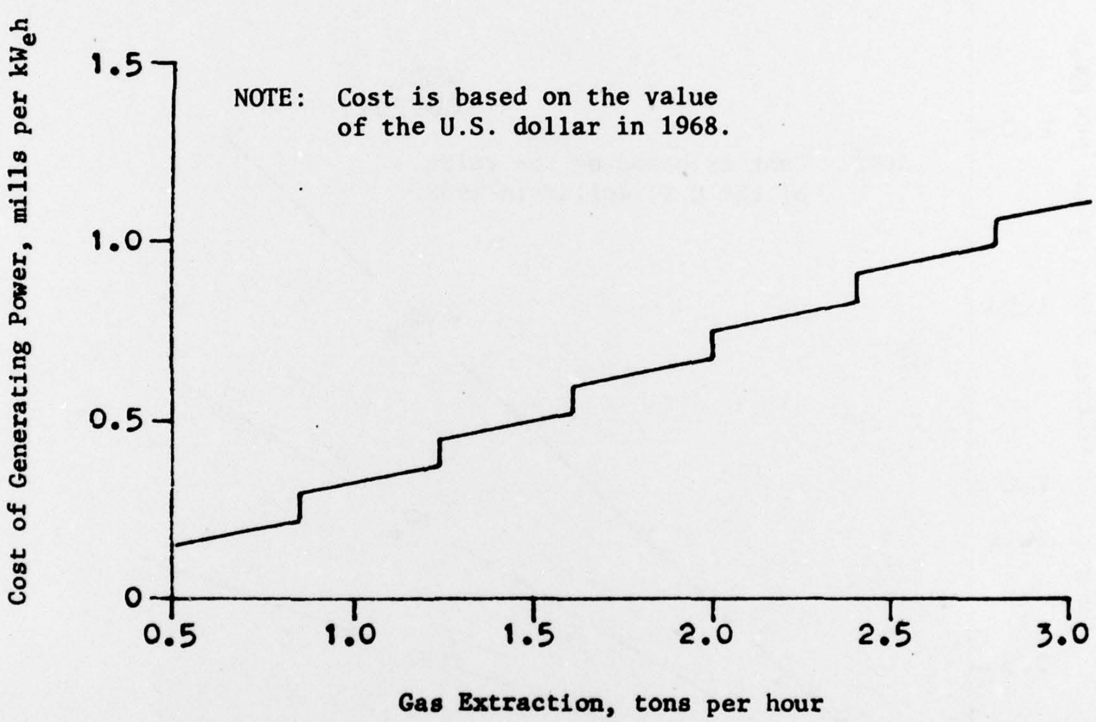

Figure 40. GENERATING COST VERSUS GAS CONTENT. (Source: Figure 6a in Reference 34).

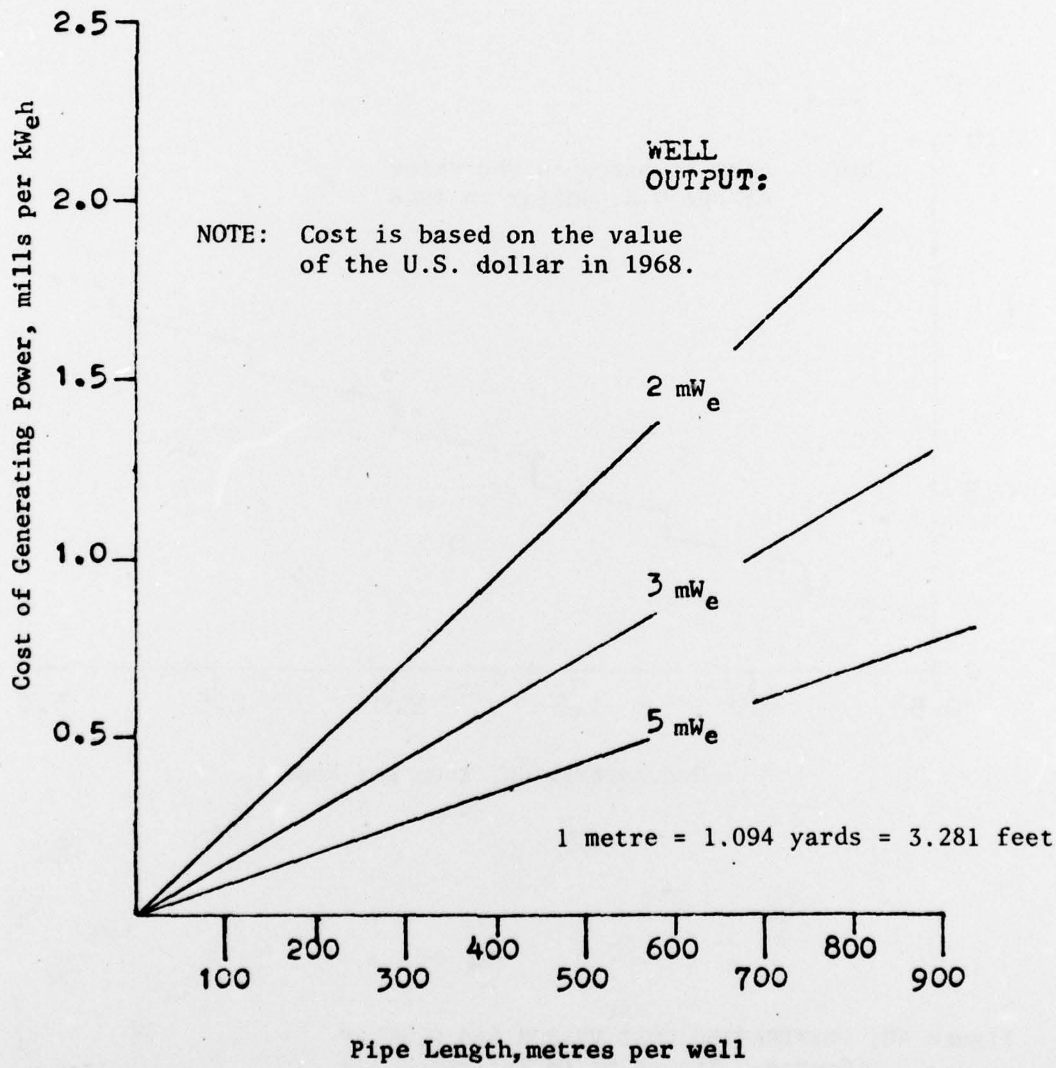

Figure 41. GENERATING COST VERSUS STEAM PIPELINE-LENGTH. (Source: Figure 5 in Reference 34).

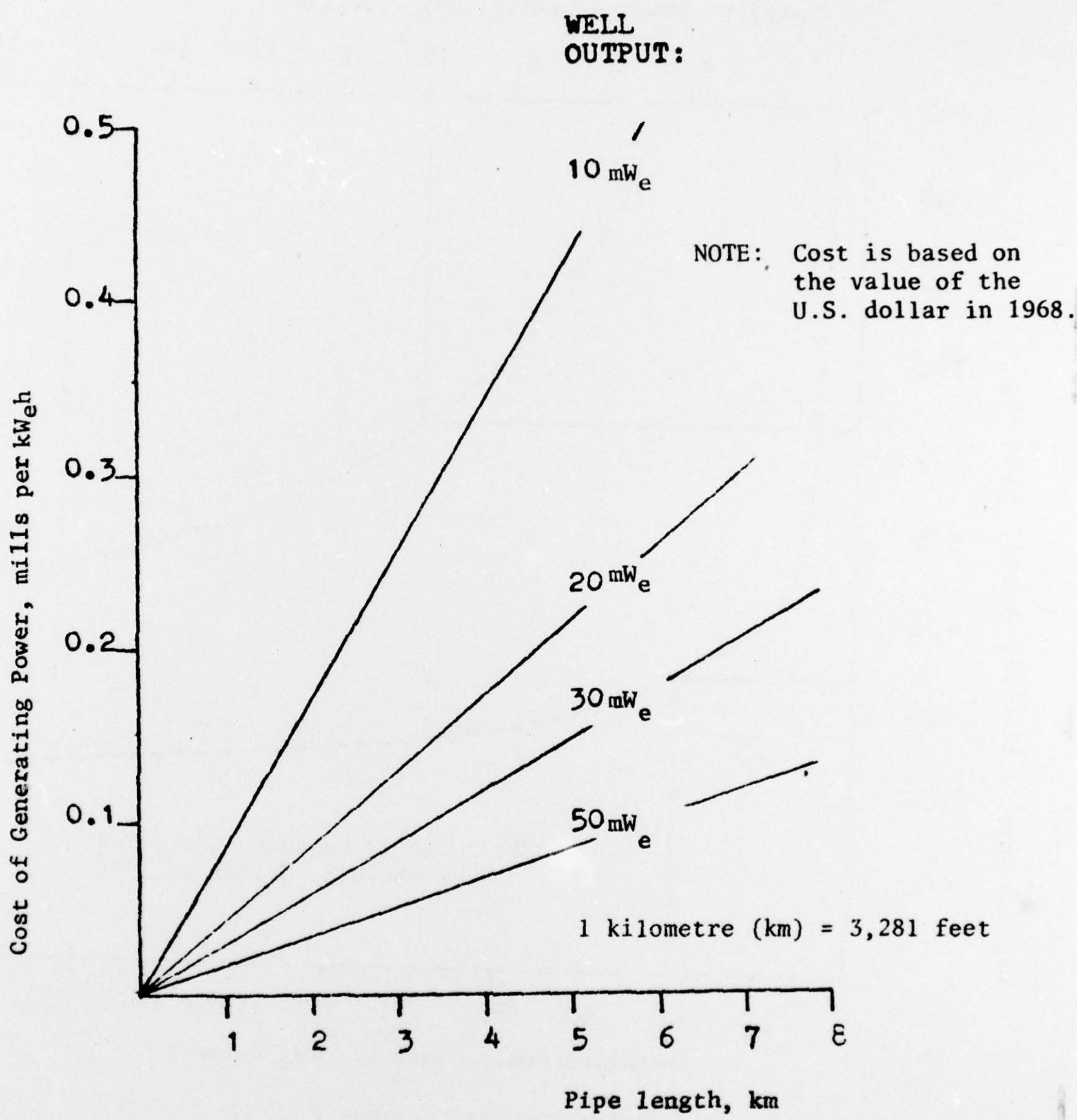

Figure 42. ADDITIONAL COST OF USING A HOT WATER WASTE PIPELINE. (Source: Figure 7 in Reference 34).

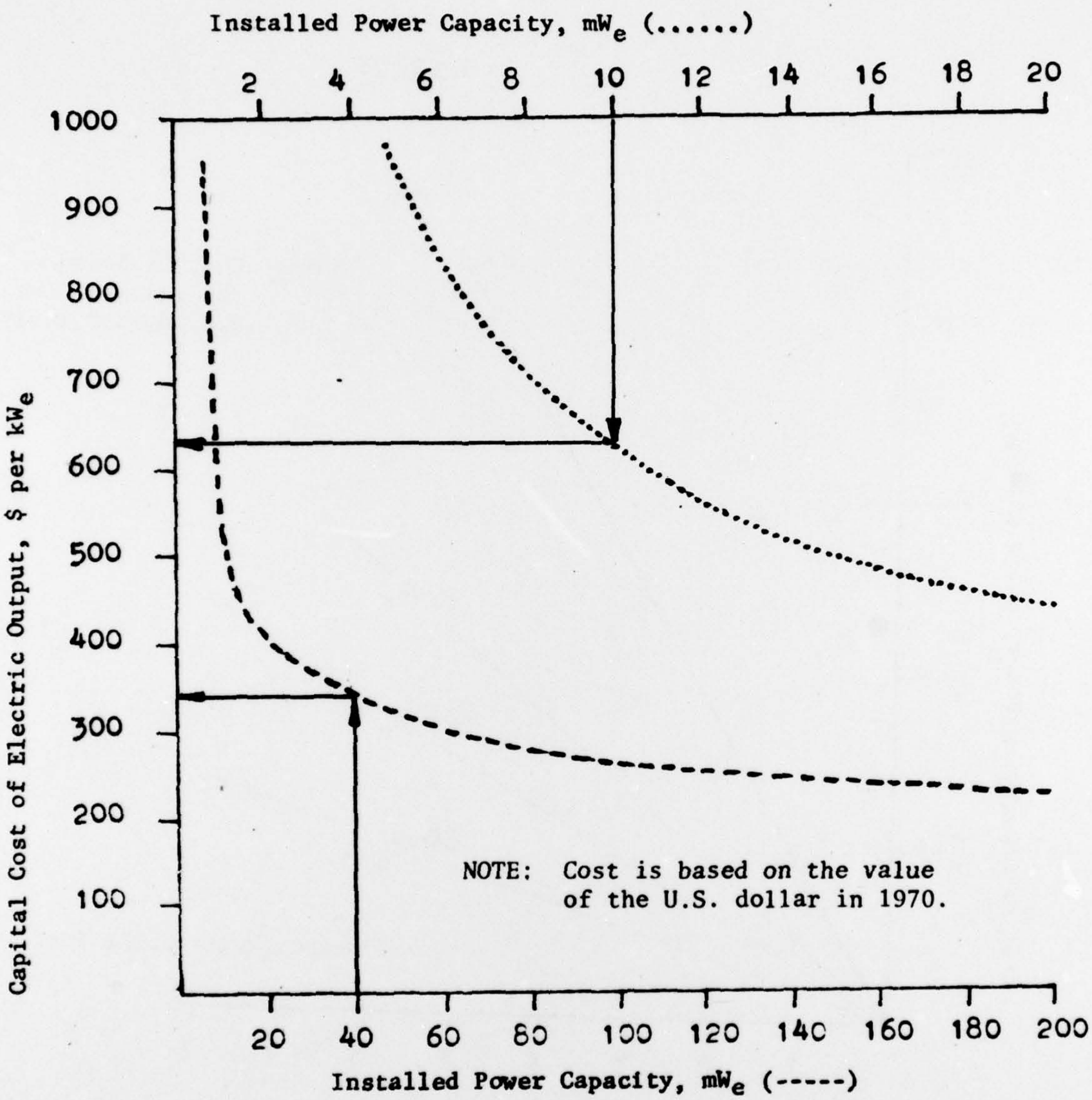

Figure 43. ESTIMATED TOTAL CAPITAL COST OF A GEOTHERMAL POWER PLANT.
(Source: Figure 2 in Reference 35).

NOTE: Capital costs are those associated with exploration, drilling, power plant, and pipelines.

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