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# An Investigation of Thermal Energy Potential in Florida Lakes as a Power Source to Arrest Conditions of Oxygen Deficiency

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# AN INVESTIGATION OF THERMAL ENERGY POTENTIAL IN FLORIDA LAKES AS A POWER SOURCE TO ARREST CONDITIONS OF OXYGEN DEFICIENCY

BY

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A Research Report Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science in Environmental Systems Management

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# PREFACE

This report is based on the results of an investigation into the feasibility of using the temperature differential in Florida lakes as a source of energy to arrest oxygen deficiency by aeration of the water. The system that is presented is based on the theories of Professor Jacques D'Arsonval, first published in 1881, and on the experience gained from the qualified successes of several inventors and engineers in developing working systems.

The author of this study acknowledges the constructive criticisms of Dr. Robert D. Doering, the Committee Chairman, and committee members Dr. Martin P. Wanielista and Dr. Donald B. Wall. Valuable technical guidance was provided by Dr. Ronald D. Evans, Chairman of the Department of Mechanical Engineering and Aerospace Sciences and Professor of Engineering. The author would also like to express appreciation to his wife for her excellent typing and moral support.

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# INTRODUCTION

## Need For The Study

The need to arrest oxygen deficiency in Florida's lakes has become apparent to engineers and laymen alike in past years. The publicity surrounding the pollution of Lake Apopka and Lake Eola in Central Florida has dramatized the need for the prevention of lake pollution wherever possible, and for the correction of polluted conditions where they exist. Many of Florida's lakes are remote from the urban environment; yet they are polluted by it. For such lakes, a self-contained source of power could be used to drive air compressors that would provide reaeration of the water. The power source would have to be economical, and it should be simple. This report is an investigation into the feasibility of using the vertical temperature differential of the lake water as an energy source.

## Objective

The objective of this study is to investigate the feasibility of extracting usable power from the thermal energy potential of a lake as a reliable energy source to power a reaeration system. Such a power source could be used to reaerate those lakes which are polluted and rapidly becoming eutrophic. The study is general enough to be applied to other waters.

## CONCLUSIONS AND RECOMMENDATIONS

A thermally stratified lake in Central Florida where the bottom water temperature is 72°F and the surface water temperature is 82°F is theoretically capable of producing power to reduce oxygen deficiency. The same potential is available in shallow lakes where springs of sufficient size produce water as cool as 72°F for use as a heat sink for the condenser of the power generating system.

In some remote areas, a power source based on a lake's thermal differential might be useful for purposes other than driving an air compressor. Such a system could be used to provide electrical power for campsites or for automatic monitoring stations.

The maximum theoretical efficiency of a thermal differential power system in Central Florida lakes is only about 1.8 percent, and the actual efficiency would be much lower--probably less than 1.0 percent. Much higher efficiency, and thus greater economic feasibility, would be attained if the lake water thermal differential power system were augmented by a flat-plate solar energy absorber.

It is recommended that a thermal differential power generating system, augmented by a flat-plate solar energy absorber, be built and used in appropriate lakes.

It is also recommended that an "air lift" device be included in the system to increase the rate of oxygen uptake and reduce thermal stratification.

Finally, it is recommended that the entire system be very carefully designed in order to preclude or minimize those problems that have, in times past, turned feasible engineering projects into grand failures.

Initial efforts would include building an integrated pilot model to prove the system's effectiveness in a real life environment.

## STATEMENT OF THE PROBLEM

### General

Bodies of water become eutrophic when the pollution applied to them becomes greater than their natural capacity for self-purification. The direct introduction of air can restore many of these bodies of water to a condition where they can conform to federal and state pollution regulations, support aquatic life, be used for recreation, present an aesthetically-pleasing appearance, and avoid the malodorous emissions of polluted waters.

Aeration can be accomplished by both mechanical and pneumatic means. Both methods require a source of power to agitate the water or pump the air into the water. This report describes a means of providing a supply of power to be used for direct air injection into Florida lakes.

At many locations, the necessary power can be obtained at very low cost from a nearby electric utility power line. In more remote areas, however, the body of water may be far removed from the nearest power line. (Pollution in remote areas is often the result of urban pollutants being carried great distances by natural streams.) This suggests the need for a power source that is independent of the surroundings. Two power systems will be discussed in this report, one using lake water thermal energy; the other using solar energy.

One common indicator of badly polluted water is the absence of a fish population that would be present in unpolluted waters. Most fish will survive in water that has at least four milligrams of dissolved oxygen (D.O.) per liter of water, but they will die if the D.O. level is lower for prolonged periods of time (one or two days). Due to natural aquatic plant and surface aeration, most waters will have a sufficient D.O. content (greater than four mg/l) near the surface.

The depth of water that is benefited by surface aeration depends largely upon the shore contour, wind velocity, depth of the lake, and water temperature. A lake may be divided into three zones: circulation, transition, and stagnation. These three zones are also called the epilimnion, thermocline or mesolimnion, and hypolimnion, respectively. The circulation zone is so named because the water within it, being of substantially uniform temperature and density, is easily moved along horizontally by the wind and vertically by convective currents. This uppermost zone is separated from the lowermost stagnation zone by the transition zone, a relatively thin stratum in which the temperature changes rapidly. The transition zone is generally defined as comprising a layer in which water temperatures decrease by $0.5^{o}F$ or more in each vertical foot. Horizontal movements are very slight in the stagnation zone, and vertical movements are almost absent (6).

In most of Florida's shallow lakes, the temperature is nearly constant all the way to the bottom so that the whole lake may be considered the circulation zone. This causes the entire volume of the lake to be approximately constant in its D.O. concentration.

Some of Florida's lakes are deep enough to become stratified along more or less conventional lines during the summer. Lake Porter in Orange county shows evidence of a transition zone near the 20-foot level. Both the temperature and D.O. levels are somewhat lower at 20 feet than at ten feet or at the surface, but at 30 feet the D.O. is almost totally depleted and the mean temperature is about $10^{\circ}$F lower than the surface temperature. (Data are included in Appendix A.) If a lake is deep enough to permit stratification, the volume of water in each zone can be estimated. (See Figure 1).

For any body of water, raising the D.O. concentration from zero mg/l to four mg/l (PPM) will require dissolving 10.85 pounds of oxygen per acre-foot of water (6). In a ten-acre lake with 25 feet of oxygen-depleted water, the amount of dissolved oxygen required is 2715 pounds. Appendix B contains calculations for reference.

A well-known treatment process equipment manufacturer reports oxygen uptake efficiencies of 12 to 14 percent in tap water and 6.5 percent in strong industrial wastes, which have a lower overall rate of oxygen mass transfer (lower alpha factor), when the air is injected at the 12-foot level in tanks with 24 to 30 feet of water depth (29). Another publication (6) states that the oxygen transfer efficiency for bubble aeration normally lies between five and 15 percent. Since the actual efficiency can only be determined by on-site tests of the water under investigation, it is necessary to make a reasonable assumption based on what is known.

The polluted lake water should have an oxygen uptake or mass transfer capability somewhere between that of a strong industrial wastewater and that of ordinary tap water, probably closer to that of

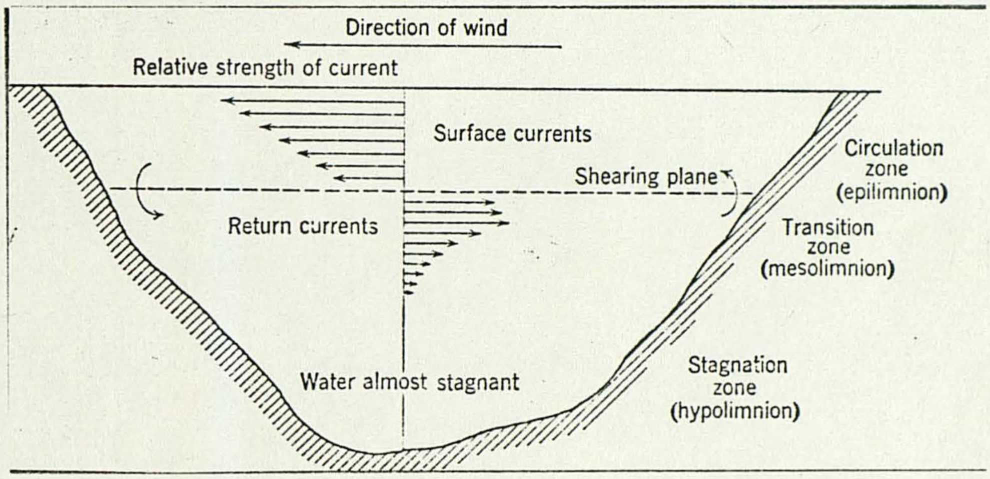


Fig. 1.--Direction and relative horizontal velocity of wind-induced currents in a lake or reservoir (idealized). (After G. C. Whipple, G. M. Fair, and M. C. Whipple, Microscopy of Drinking Water, 4th ed., Wiley, New York, 1948.)

the tap water. For a conservative solution, a value of nine percent seems reasonable.

Since there is about 0.017 pound of oxygen in each cubic foot of air at standard conditions (6), the amount of air required to dissolve one pound of oxygen at nine percent transfer efficiency is 655 std. cu. ft. The output of a small centrifugal compressor is about 1500 std. cu. ft./horsepower-hour, which will result in 2.3 pounds of oxygen being dissolved per horsepower-hour. This calculated value is in general agreement with actual values reportedly attained recently in the River Thames in England. If the equipment operates eight hours per day, the D.O. level could be raised from zero to four mg/l in 1.7 acre-feet of water each day. (See Appendix B for calculations.)

In the River Thames, a large surface aeration unit is being used to furnish dissolved oxygen for the bacteria that are feeding upon the high concentration of organic pollutants in the river. According to a report of the Department of the Environment's Water Pollution Research Laboratory (23), the surface aeration devices can operate in the Thames with an "efficiency" of 1.7 pounds of dissolved oxygen per kilowatt-hour. A more recent report says that the Simplex Core Aerator, a 200-horsepower unit, has shown an efficiency of 2.5 lb. of oxygen per kilowatt-hour (23). In more familiar terms, these efficiencies are 1.27 to 1.86 pounds per horsepower-hour. (See Figure 2).

The operational results of 1.27 to 1.86 pounds of oxygen being dissolved in the Thames River for each horsepower-hour expended indicate that the 2.3 pounds per horsepower-hour calculated for polluted lakes is not unreasonable. The oxygen requirements having been

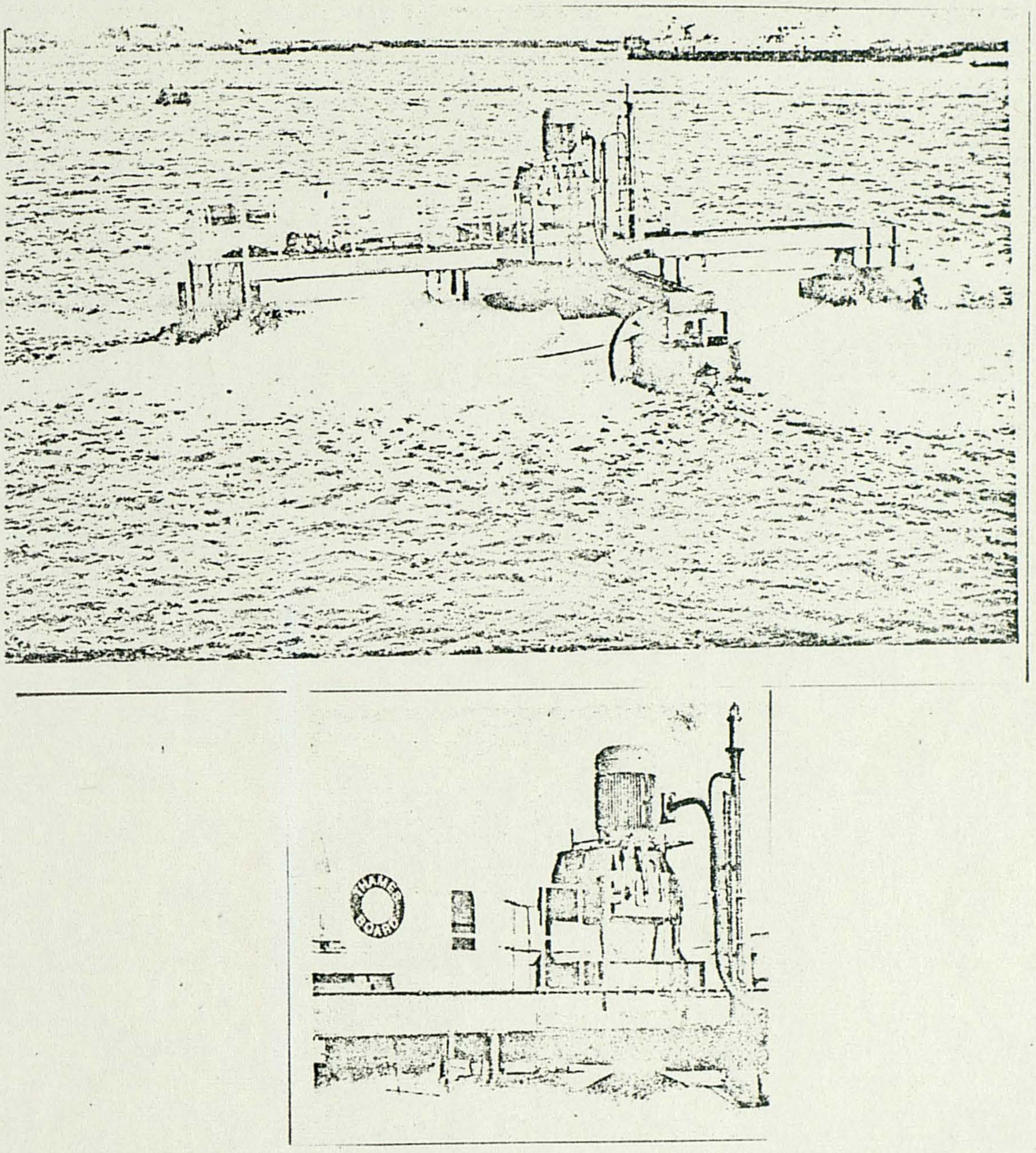


Fig. 2.--Equipment used for reaeration of the River Thames.

Pictures from Reference 23.

defined, and the power necessary to deliver oxygen having been determined, the energy required to aerate a given volume of water can be readily calculated. To raise the D.O. level from zero to four mg/l in one acre-foot of water requires 4.7 horsepower-hours. (See Appendix B for calculations.)

## STATEMENT OF THE PROBLEM

### Thermodynamics

The Carnot cycle is impractical; however, it may be used as a criterion of perfection since its efficiency is the maximum theoretically possible (20). The cycle efficiency expressed in terms of temperature is $(T_2 - T_1) / T_2$ where $T_1$ is the condenser (sink) temperature and $T_2$ is the boiler (source) temperature.

The Rankine cycle, a more practical measure of the perfection of steam or vapor cycles, is made up of the following reversible steady-flow processes (see Figure 3) (20):

(a) isentropic compression (frictionless with no heat flow) in the pump, of the saturated liquid leaving the condenser,

(b) constant-pressure heating and evaporation of the fluid in the boiler,

(c) isentropic expansion of the steam or vapor in the engine or prime mover, and

(d) constant-pressure condensation in the condenser.

Ignoring kinetic energy terms and the minor losses caused by the pump, the thermal efficiency of the Rankine cycle using saturated steam or vapor can be expressed in enthalpies as $E = (h_3 - h_4) / (h_3 - h_2)$.

Reciprocating steam engines are frequently preferred over turbines as prime movers where the required speed of rotation is low. These engines have good efficiencies, and they are extremely reliable (20). Vapor engines are the same as steam engines except that

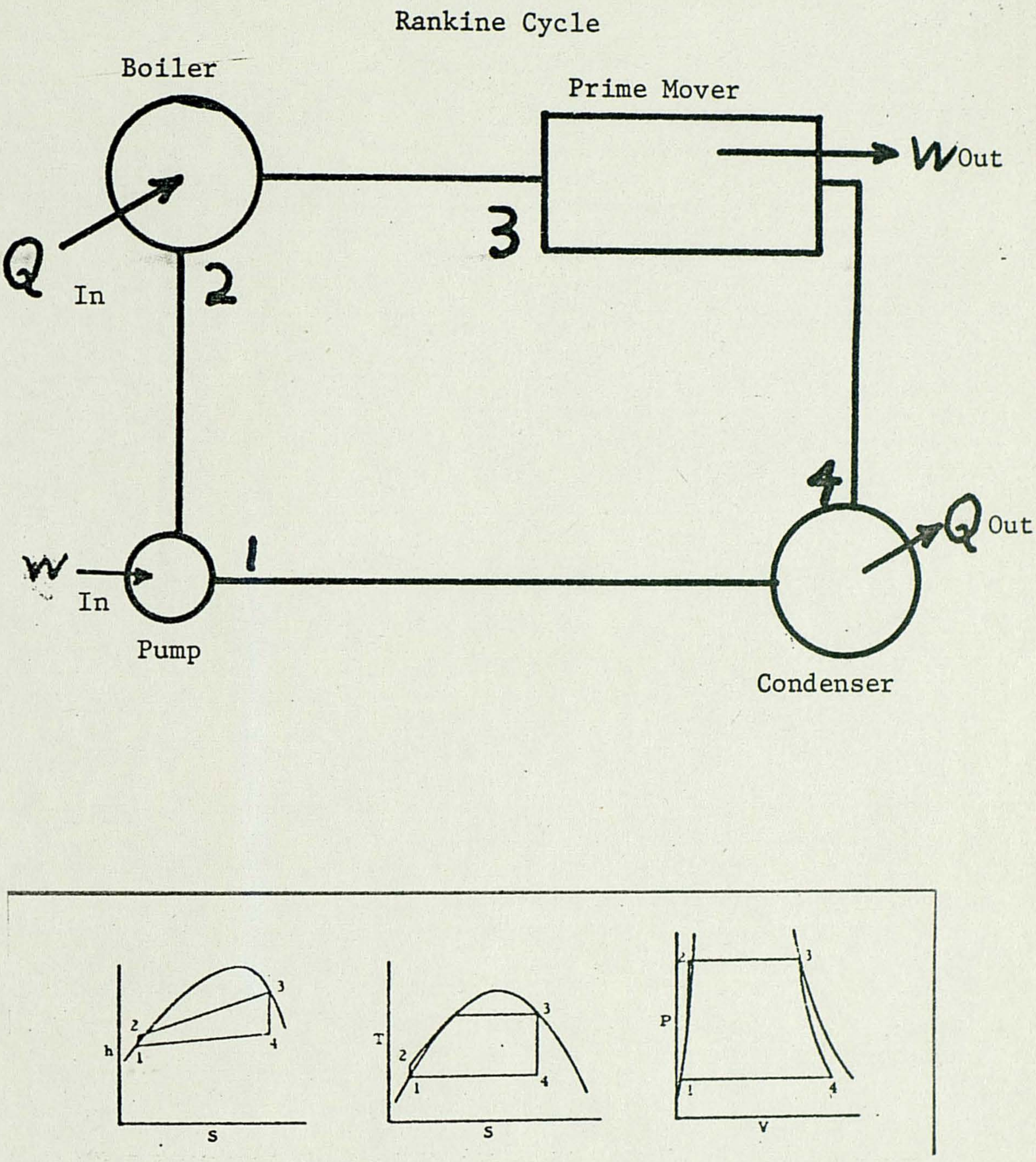


Fig. 3.--Rankine vapor cycle using saturated vapor, shown schematically and by three conventional thermodynamic process diagrams.

they use some fluid other than water as a working fluid. Since this report is based upon the use of Freon-12 as a working fluid (because tables of its thermodynamic properties are readily available), the term "vapor engine" will be used.

The vapor engine can be analyzed as an intermittent-flow device by using the indicator card method, or as a steady-flow device, using enthalpies designated $h_1$, $h_2$, $h_3$, and $h_4$. In a case such as the one being investigated, where the thermal boundaries are known, the steady-flow method is the most desirable. The work output of an engine is expressed as: $W = h_3 - h_4$. For a graphical representation of the complete saturated Rankine cycle, see Figure 4.

The surface water of the lake is assumed to be at an average temperature of 82°F and the bottom water is assumed at 72°F since these are approximately correct figures for summertime daylight conditions in the lake surveyed. Using these values, the work output-potential of the fluid circulating through the system is 0.734 BTU/lb and this will require a mass flow rate of 3490 lb/hp-hr. See Appendix C.

A practical method for actually producing this power is described in the following sections.

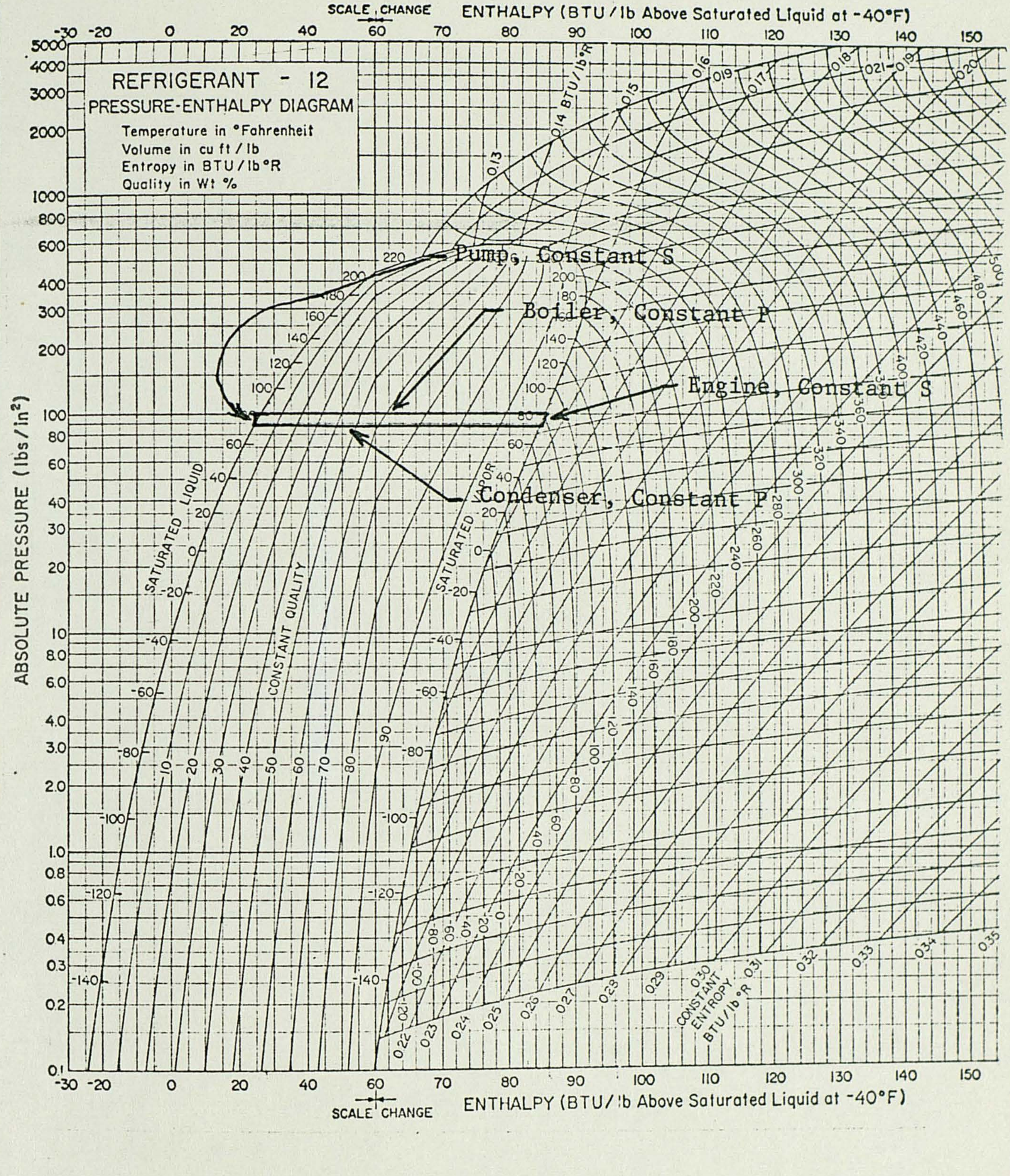


Fig. 4.--Pressure-Enthalpy diagram for refrigerant 12.

Diagram from Reference 8.

# HISTORICAL DEVELOPMENT

## D'Arsonval's Theory

In the September 17, 1881, issue of the scientific magazine, Revue Scientifique, Professor Jacques D'Arsonval made the first recorded suggestion of the possibility of extracting energy from bodies of water with small temperature-level differences. Referring to the warm waters of the Srping of Grenelle, he suggested construction of a low temperature vapor power system. It would be similar to an ordinary steam power system except that liquid sulfur dioxide would be used in place of water as the working fluid in the closed-loop system.

As the boiler of this system was being heated by the $86^{0}$F spring water, the sulfur dioxide would be vaporized and the pressure would increase to 66 psia. If this vapor were conducted to the condenser which was cooled by the $60^{0}$F water of a nearby stream, the pressure would be reduced to 41 psia and condensation would occur. Professor D'Arsonval wrote that this difference in pressure would be enough to drive an engine of some kind without any expense other than the initial cost and maintenance. D'Arsonval suggested that ideally the boiler would be in the ocean at the equator and the condenser in the ice of Greenland's interior (10). Most people who read D'Arsonval's article considered this an amusing as well as novel idea, correct in theory but of no practical value.

In tropical ocean areas, the surface water is heated to about 82°F by the sun, while in many very deep areas the water temperature remains at about 40°F as a result of having been previously circulated through the polar seas. D'Arsonval's suggestion was that this practically limitless source of energy could be tapped, taking advantage of the natural phenomenon.

After the Geological Congress of 1913 reported on the probable supplies of fossil fuels remaining, several men around the world, some of whom were familiar with D'Arsonval's works, started to investigate the phenomenon (10). Some of them were much more thorough in their analyses than D'Arsonval, but nothing much happened until 1926 when the French Academy of Sciences received a report from Georges Claude and Paul Boucherot.

## Warm Ocean Power Plant

Two Frenchmen, Messrs. Claude and Boucherot, worked together for many years to develop a warm ocean steam power plant. M. Boucherot was the engineer of the team; Georges Claude was a rich and enthusiastic inventor.

In 1926, Claude and Boucherot wrote of their success in building a scale model in which one glass bottle was partially filled with water at 82°F and another contained some crushed ice. A small turbine was mounted in such a way that any vapor flowing from the water at 82°F to the ice at 32°F would cause the turbine to turn a small electric dynamo. A vacuum pump was connected to the two interconnected bottles, and the internal air was pumped out until the pressure was only about three percent of ambient pressure. At this pressure, the water started boiling and the vapors passed through the turbine and were condensed to liquid around the crushed ice. The dynamo produced current which operated three small electric light bulbs.

Encouraged by this success, Claude and Boucherot built a large plant which was first assembled in Belgium in 1928. They used the cooling water from blast furnaces as a heat source for the boiler and the waters of a nearby river as a heat sink to remove heat from the condenser. With a constant temperature differential of $36^{O}F$, the plant operated well enough that Claude decided to invest more of his own money and transport the plant to the shore of the Caribbean.

Since the gross power output of any steam or vapor plant depends upon the type and size of equipment and its thermal efficiency, it is obvious that the efficiency should be optimized. The maximum theoretical efficiency is limited by $(T_2-T_1)$ where $T_2$ is the source temperature in absolute degrees and $T_1$ is the sink temperature in absolute degrees. With a source temperature of $82^{O}F$ ($542^{O}R$) and a sink temperature of $40^{O}F$ ($500^{O}R$), the theoretical efficiency will not exceed the maximum 7.8 percent.

Claude knew that the surface water temperature near the Bay of Matanzas, Cuba, was about 82 or $83^{O}F$ and the water at the bottom in the same spot was between 39 and $41^{O}F$. He believed that the colder bottom water could be easily pumped to a shore-based power plant through an insultated pipe. (See Figure 5.)

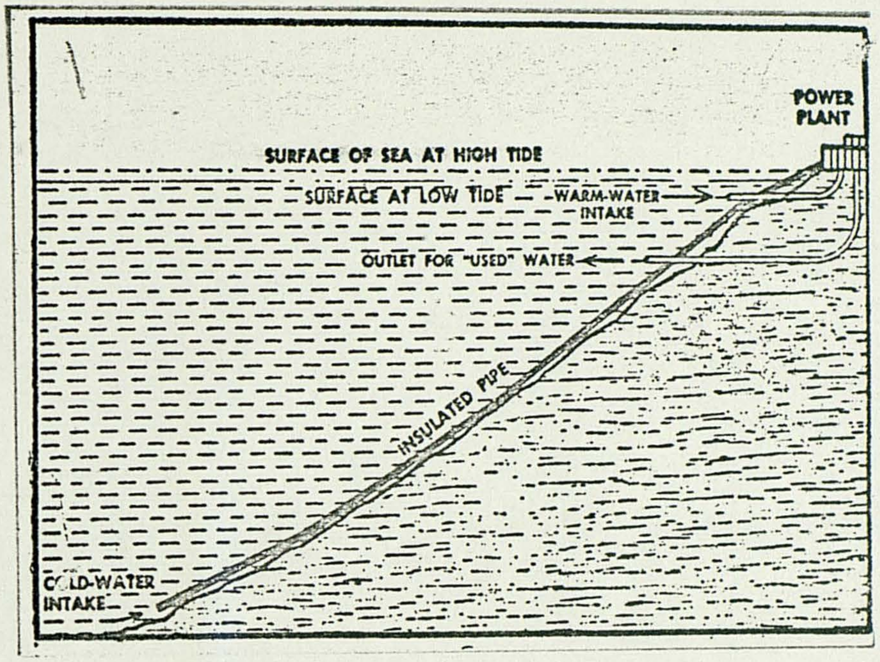


Fig. 5.--A Claude power plant, shore-based as in the Bay of Matanzas.

Picture from Reference 10.

This could provide a temperature differential of about 42°F if there were no losses, and this should make the plant more efficient than it had been in Belgium.

The shore line in the area selected for the plant did not slope down as steeply as desired, and the cold-water pipe had to be 1.2 miles long.

A series of installation accidents in which one pipe was lost when the supporting ropes broke, and another pipe was badly kinked and split open, caused the remaining pipes to reach only 2000 feet below the surface. At this depth, the water temperature was 58°F.

On October 1, 1930, the machine ran for the first time, but the temperature differential was only 24°F. What had reportedly been a 500-kilowatt unit in Belgium was only a 22-kilowatt unit in Cuba (10). Claude's cold-water pump was much larger than would have been required for such a small plant. Since the oversize pump consumed more power than the plant produced, Claude had to buy commercial electric power from the local Cuban utility to keep the pump operating.

The same type of system was used by a French corporation (Energie Electrique de la Cote d'Ivoire) at Abidjan, on the west coast of Africa, in the 1950's. A temperature difference of 36°F was to provide 7000 kilowatts of electric power. A pipeline of eight-foot diameter extended to a three-mile depth at about three miles from shore. The plant used only about 25 percent of the generated power for its accessories, but full production was never realized because of difficulties in maintaining the pipeline (28).

Claude and Boucherot both saw that the demonstration at the Bay of Matanzas was not an impressive success, but they both felt satisfied that an important point had been proved when the machine had run on ocean water.

Claude's next venture was to build a larger unit on a 10,000-ton steamer named Tunisie. (See Figure 6.) The all-important cold-water pipe was redesigned. However, Claude's critics said that he had failed to correct a very important error. Dr. E. Brauer, whose own very thorough calculations had been announced in 1925, contended that it was a mistake to use sea water as the working fluid (10). He was concerned with the need to continuously remove the dissolved gases as well as the problem of maintaining the system to eliminate vacuum leaks and corrosion. Dr. Brauer suggested that Claude should adopt D'Arsonval's proposal for a separate working fluid and use either sulfur dioxide or ammonia.

The Tunisie was equipped with a large refrigeration unit for utilizing the current generated by the power generating system. The unit eventually operated, but poorly. Claude gave up in disgust and sank the ship in a very deep part of the ocean.

Thermal losses and mechanical problems with the long insulated pipe required to convey the cold water to the surface were largely responsible for Claude's failure to produce usable power above that which was required to operate the plant equipment.

If Claude had followed suggestions made after the Cuban tests and adopted a system which uses a separate working fluid, the problems

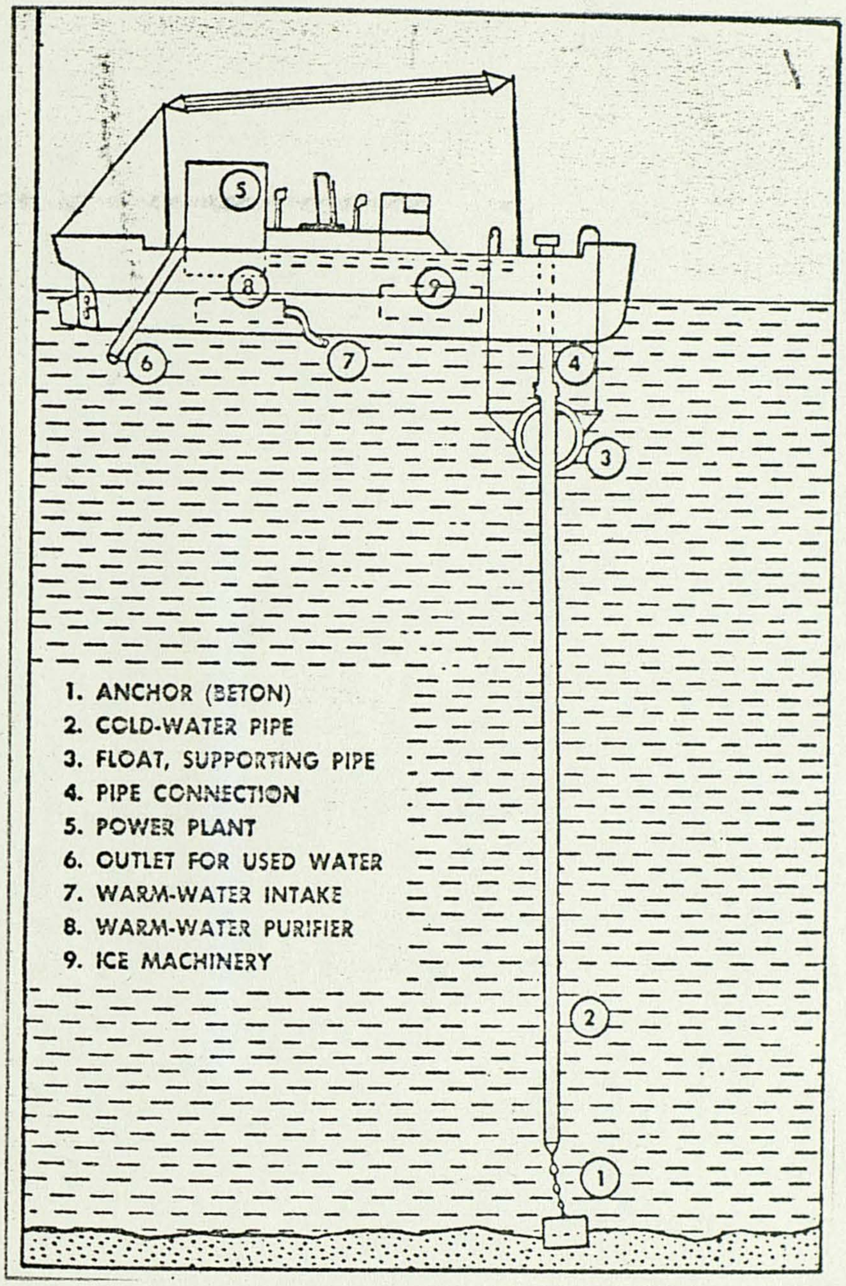


Fig. 6.--Claude's seaborne power plant, the steamer Tunisie.

Picture from Reference 10.

caused by dissolved gases, dissolved solids, vacuum leaks and corrosion inside the apparatus would have been eliminated. A new problem of thermodynamic losses in the heat exchangers would have been created. (See Figure 7.)

The following section serves as an introduction to solar energy, a valuable source of supplemental energy.

## Solar Energy

The first description of an actually working "solar motor" can be found in a book published in 1615, Les Raisons des forces Movantes by Salomon de Caus (See Figure 8.)

The next known use of solar powered devices was between 1864 and 1878 when Professor Augustin Bernard Mouchot built a number of solar power plants which actually performed useful work (10). People praised Professor Mouchot for his ingenuity, but nobody bought his engines for the simple reason that a normal boiler with a firebox was much cheaper, and coal did not cost much.

From 1870 to 1880, Swedish-American engineer John Ericsson, the inventor of the ship's propeller and architect of the warship "Monitor", worked on solar power plants but gave up because nobody seemed interested.

In the following years a series of inventors built solar power plants with varying degrees of success. A. G. Eneas built a plant which ran a 15-horsepower steam engine on an ostrich farm at South Pasadena, California. (See Figure 9.) A few years later Frank Shuman of Philadelphia built a model at Tacony, Pennsylvania, which was good

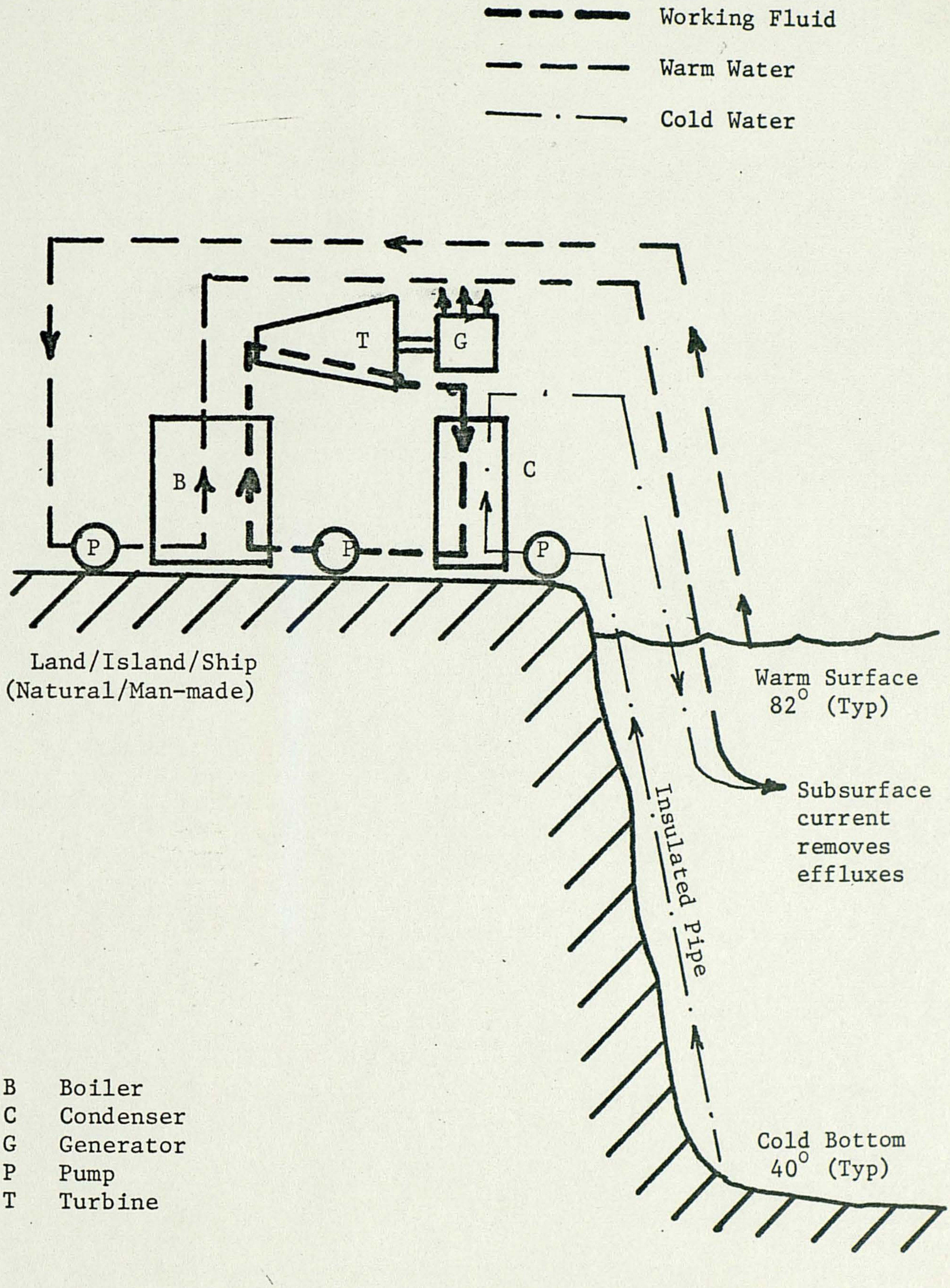


Fig. 7.--Warm-water power generation system.

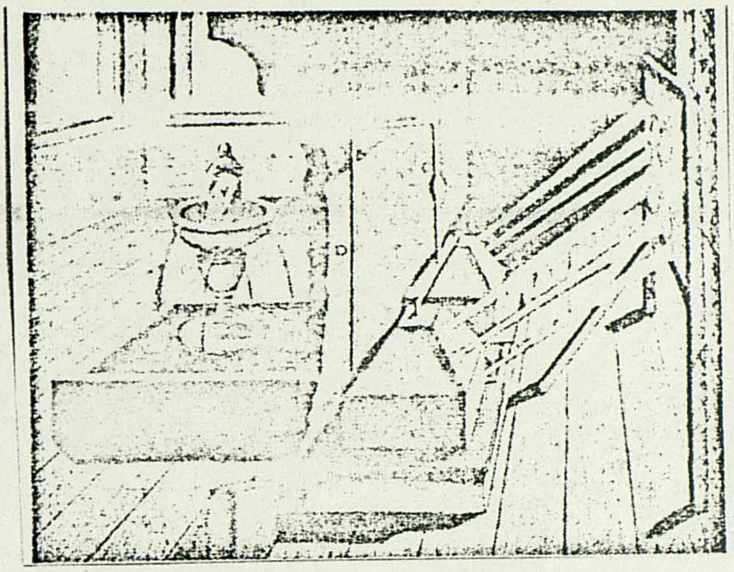


Fig. 8.--The solar motor illustrating Salomon de Caus' Les Raisons des forces Movantes in 1615.

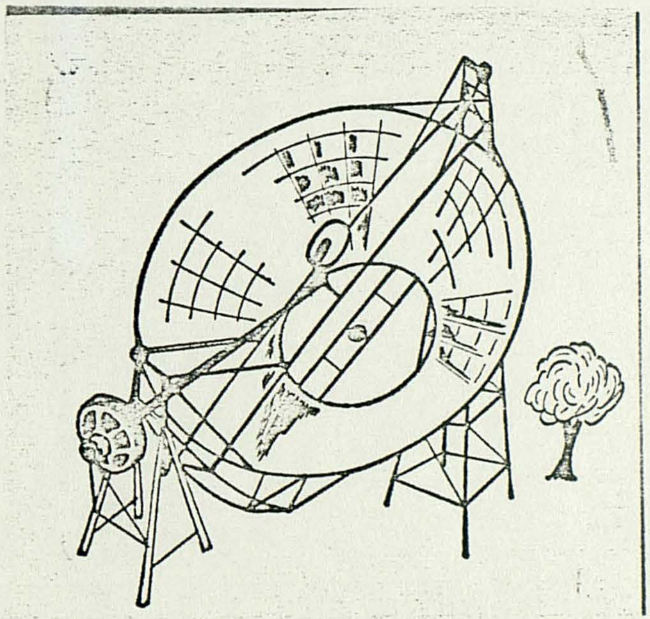


Fig. 9.--Solar steam engine, Pasadena, 1901.

Pictures from Reference 10.

enough to attract capital. He formed Eastern Sun Power, Ltd., and the company later built a solar power plant at Meadi, Egypt, which ran a 100-horsepower low-pressure piston steam engine coupled to irrigation pumps. (See Figure 10.) More than 500 acres of cotton land were irrigated by this system. The overall efficiency of the machinery was about five percent, which means that enough sunlight struck the mirrors to pump 20 times as much water as was actually pumped. The plant worked to the satisfaction of everybody concerned from 1913 until it was allowed to fall into disuse at the end of World War I.

During the next several decades, Dr. C. G. Abbot of the Smithsonian Institute experimented with several types of solar power plants, his purpose being to see which type would work best under a given set of conditions (10).

In 1933 the Russians built a small experimental plant at Tashkent, but the larger unit which they announced would be built, did not materialize.

A solar power plant in the French Pyrenees, built under the direction of Felix Trombe, is the largest in the world (10). Its flat mirror, made up of 516 small mirrors, automatically follows the course of the sun so as to reflect the rays to a concave mirror consisting of 3500 reflectors. This device produces temperatures of up to $5400^{\circ}$F. (See Figure 11.)

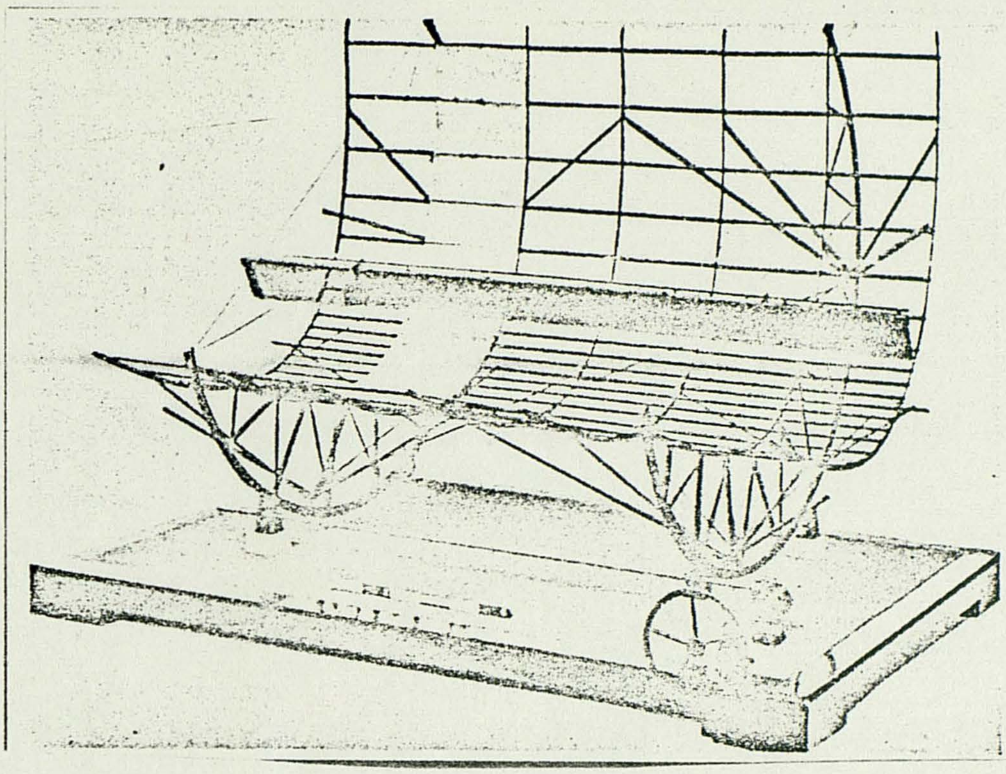


Fig. 10.--A model of part of the solar power plant built at Meadi, Egypt, in 1913.

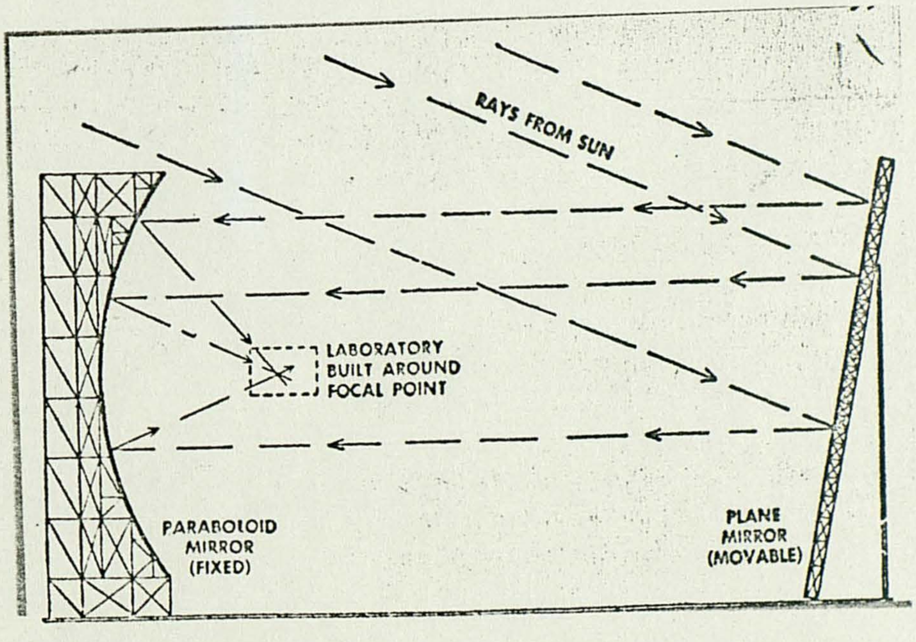


Fig. 11.--Principle of the French solar laboratory in the Pyrenees.

Pictures from Reference 10.

## ENGINEERING CONSIDERATIONS

### System Description-Lake Water Thermal Power Source

A steam or vapor power plant can be made to operate and produce power over any practical temperature span. It is not the magnitude of the lowest or highest temperature that matters, but rather the difference between those temperatures. This temperature differential limits the maximum possible efficiency of the thermodynamic cycle. For any given set of highest available temperature (heat source) and lowest available temperature (heat sink), the differential between source and sink must be sufficiently large to provide enough power to overcome system losses. Another temperature consideration is that the boiler (heat source) temperature must not be high enough to cause physical determioration of either the apparatus or the working fluid. The choice of working fluid will be determined by many factors (cost, availability, ease of handling, corrosiveness, etc.) but its freezing point must be lower than the condenser temperature, and its boiling point must be lower than the boiler temperature. For the range of temperatures in Central Florida lakes (72-82°F), Freon-12 is an appropriate working fluid.

A vapor power plant constructed along the lines of the apparatus suggested by D'Arsonval could be attached to a floating platform. Ideally, the platform would be anchored in the area that had the optimum set of high and low water temperatures.

The main components of such a system are a condenser, boiler feed pump, boiler, and prime mover (engine or turbine), as shown in Figure 12. Power is produced by the prime mover, (engine in this case), when the saturated vapor, produced by boiling the liquid inside the boiler, is allowed to exert its pressure against the head of the piston in the engine and force it downward. The piston is attached to the crankshaft throw by a connection rod and this forces the crankshaft to turn. The rotating crankshaft turns the air compressor and generator. Near the end of the power stroke the engine exhaust valve opens and the expanded vapor, which has undergone a reduction in enthalpy is allowed to flow into the condenser. During its passage through the condenser, the fluid loses additional heat to the cooling water and returns to the liquid state. The liquid next goes into the boiler feed pump, where it is adiabatically compressed and forced into the boiler. The boiler causes the temperature of the fluid to increase until the saturation temperature is reached and vaporization is completed. The vapor is ready to be expanded in the engine again and the closed loop has been completed.

The condenser is a standard heat exchanger in which the vapor which has expanded (and done work) in the engine loses more heat due to the low temperature of the surrounding water at the lake bottom. This loss of heat to the water liquifies the working fluid. In some of Florida's deeper lakes (which have at least a 30-foot depth), the temperature is about 72°F during the summer months at the 30-foot level. Lakes which are located at more northerly latitudes may have a constant bottom temperature of 39.2°F, which is the temperature of water at its maximum density (21).

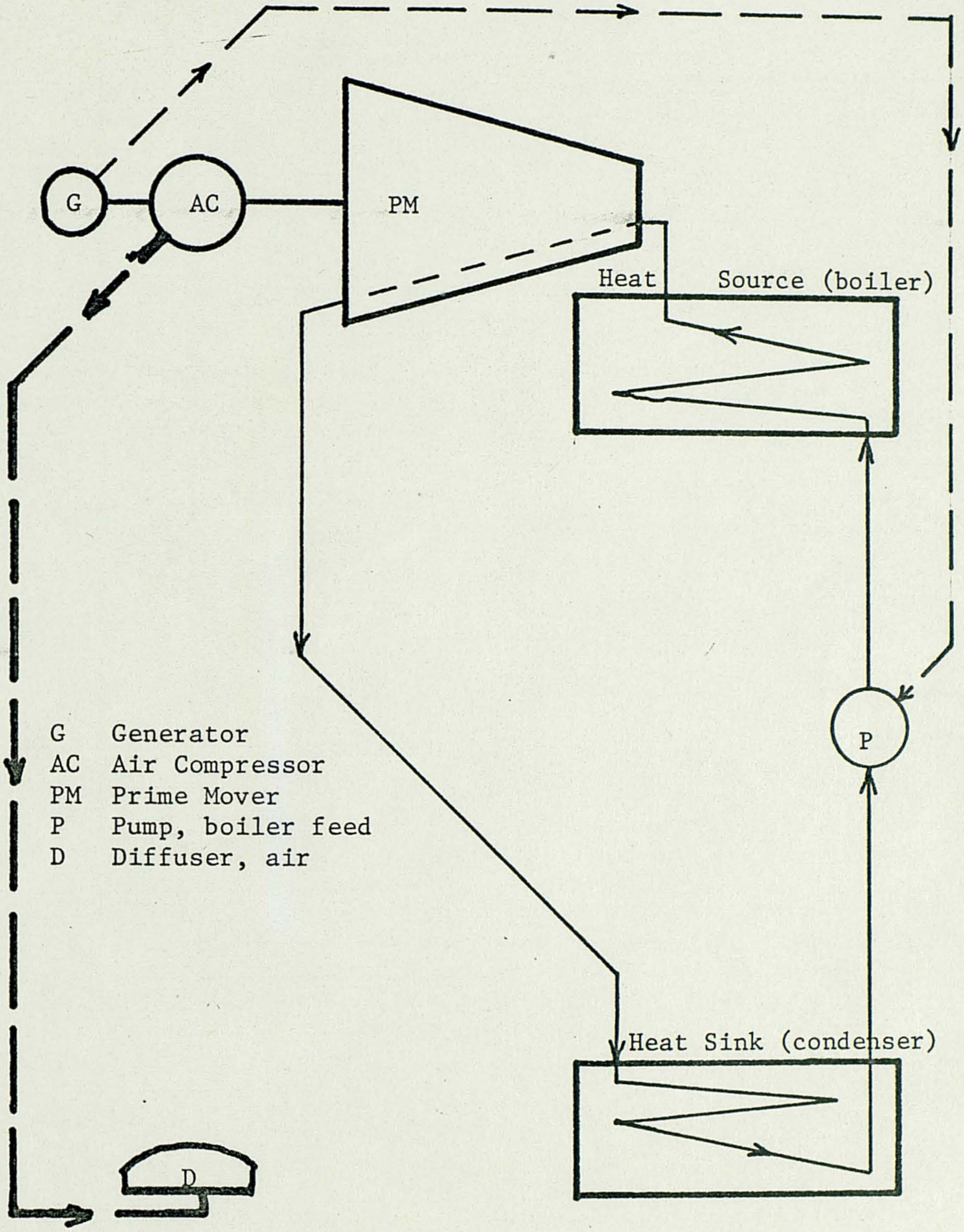


Fig. 12.--Consists of a schematic illustration of the basic saturated vapor system, with air compressor and diffuser.

The boiler feed pump is a simple positive-displacement reciprocating piston pump, powered by an electric motor. It drives the working fluid from the condenser to the boiler.

The boiler is another conventional heat exchanger in which the working fluid is heated and vaporized by absorbing energy from the high-temperature water surrounding the boiler at the lake's surface. Orlando's Lake Porter has an average surface water temperature of about 82°F during the summertime for eight or more hours per day. (See Appendix A.)

The prime mover could be a turbine, but they are generally considered inefficient for small installations. An ordinary reciprocating piston steam engine which operates on the Rankine cycle would be more practical.

Since the primary function of the system is to provide compressed air at relatively low pressure, a rotary blower or centrifugal compressor would be more efficient than a piston type compressor which has more friction losses.

A generator is required to furnish electrical power to the boiler feed pump, and other miscellaneous equipment such as navigation lights.

Overall, the lake water thermal power generating system is relatively simple and can be assembled from off-the-shelf components, provided the major power producing units, the auxiliary equipment, and the working fluid are carefully selected to conform to good engineering design.

As mentioned previously, problems such as dissolved gases which will not condense and thus reduce efficiency, dissolved and suspended solids which could deposit in critical areas, and extremely large specific volumes, can be minimized by using something other than the lake water for the working fluid (thermodynamic medium).

The low boiler temperature limits the system to relatively low pressures and results in a high specific volume for the vapor. The low volatility of water makes it worse in this respect than any of the common refrigerants. Since the rate at which any vapor power system produces power depends upon the mass flow rate through the prime mover, large expensive machinery is required to handle the low-density vapor.

The matter of obtaining the largest possible temperature differential is of utmost importance. This was clearly demonstrated at Matanzas Bay, Cuba in 1930 when Claude, expecting a differential of about 42°F, tried to use the 24°F differential that was available to him.

Claude's work in Cuba demonstrated that "minor" losses due to heat leak, vacuum leaks, dissolved gases, pipe friction, and reduced temperature differential are not minor in a system whose maximum theoretical efficiency is less than ten percent. The efficiency in the example lake is less than two percent, but the above mentioned losses can be eliminated by proper design. Also, there is no need for a pump to lift the cold water to the surface.

Any marine organisms which collect on the heat exchangers can easily be wiped off during routine maintenance operations.

All of these items require serious consideration, especially during the design phase of the project. Anything that in any way affects the system efficiency must be carefully designed. Superior workmanship and good quality hardware will not make up for design deficiency. Minimizing any deviations from the ideal, which tend to reduce the efficiency, must be a prime consideration in every part of the system development, from preliminary design, through feasibility testing, and even in location and operation.

## Heat Exchangers

Since there is no fuel cost, it might seem that the low thermal efficiency is of no concern. However, it is necessary to compensate for the low efficiency by increasing the size of the equipment, resulting in high capital costs. When a separate working fluid is used, an important cost factor is introduced by the large heat exchange surfaces required. Tubular exchangers are expensive and the lighter, less-expensive thin-wall flat plate exchangers are not capable of withstanding the pressure differential required to increase the power output.

In a patent-applied-for design by consulting engineer J. Hilbert Anderson and his son, Lt. James H. Anderson, Jr., U.S. Navy, a floating sea thermal power installation uses liquid propane as a working fluid (25). The Andersons have attempted to minimize the heat exchanger problems by submerging the flat plate boiler and condenser each to a depth at which external water pressure is slightly greater than the heat exchanger's internal pressure. Depths of 150 and 290 feet would be required for the condenser and boiler, respectively (28).

Although construction of a plant using the Andersons' idea has not been attempted, the principle seems to offer a greater potential for economic and technical success than any of the previous designs. However, the idea cannot be utilized for Central Florida's lakes. The depth required to surpass the internal pressures of a propane system such as the Anderson design is not available in the lakes of Central Florida.

Since the saturation pressure in a Freon system is not substantially lower than that in a propane system, a tubular heat exchanger is required for operation in shallow water.

### Air Lift

The aeration effectiveness of the proposed system can be further increased by taking advantage of the bouyancy of the air bubbles to reduce thermal stratification. This can be accomplished through creation of an "air lift" by placing a pipe of appropriate length and diameter in a vertical position surrounding the stream of bubbles created by the injected air.

As the bubbles expand and rise toward the surface, they cause an upward flow of the cooler, more dense, bottom water through the pipe until the surface is approached. The upper end of the pipe should be terminated a few inches below the water surface, and a large, flat, black platform should surround the pipe termination in such a way that the water is forced to flow laterally for a relatively long distance. This direct exposure to solar radiation will cause a temperature rise, thus reducing the density of the water and its tendency to sink to the bottom again. At the same time, the exposure to natural surface aeration will increase oxygen absorption. (See Figure 13).

Underwater treasure hunters use the air lift method to "vacuum clean" sand off of sunken treasures. With this in mind, the author conceived the idea of incorporating an air lift as a part of the reaeration system and thus obtain additional aeration plus a reduction of thermal stratification, with very little additional cost for the pipe and platform. Subsequently, it was discovered that an equipment company uses what they refer to as an "educator tube" to increase the efficiency of aeration in wastewater treatment plants (30). The educator tube is very similar to an air lift except it is terminated six feet from the surface of the water at the upper end and six feet from the bottom of the tank on the lower end in order to create more violent agitation.

For the system described in this study, it is proposed that the air lift pipe be terminated only a few inches below the water surface and it should reach down almost to the bottom, in order to maximize the reduction of thermal stratification.

## System Description-Solar Power Source

The total solar radiation incident on a horizontal surface in Central Florida averages 483 Langleys or 1781 BTU/per square foot per day during the summer months from March through September. If the winter months are included, the average for the entire year is reduced to 1610 BTU per square foot per day (19).

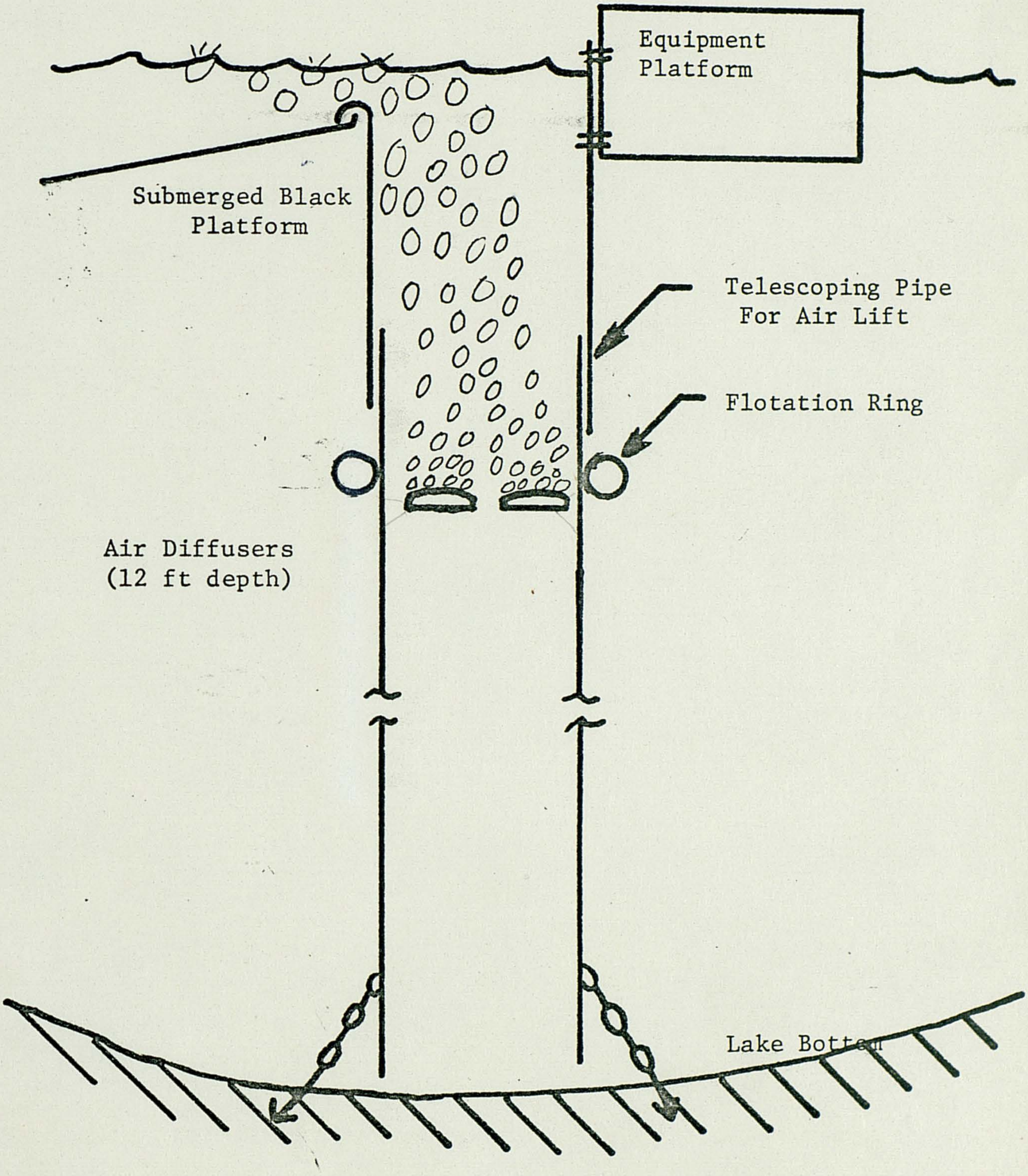


Fig. 13.--Air lift pipe, with diffusers shown.

Most solar water heaters use a so-called flat plate collector in which a copper pipe is soldered in a zigzag pattern on a copper sheet to form a continuous heat absorbing surface. The absorbing surfaces have traditionally been painted black to increase the rate of heat absorption.

Thermal energy losses are caused by conduction, convection and radiation. Losses from the solar energy absorber can be reduced by enclosing it in a well-insulated box with a glass cover. (See Figure 14.) The insulation will prevent losses by conduction. Losses by convection will be reduced if the entire unit is well sealed to prevent the escape of warm air currents. The glass cover transmits the short-wave-length solar radiation with an efficiency of about 80 percent but blocks the escape of the longer wave-length infrared radiation emanating from the heated surface of the absorber (15).

Since the losses due to infrared radiation are proportional to the fourth power of the absolute temperature it is advantageous to keep the surface temperature of the absorber low (15). Domestic water heaters are commonly sized to produce water temperatures of 120 to $150^{\circ}$F.

A more modern method of forming the actual absorber surface is to use the tube-in-strip type which is widely used in the cold walls and shelves of current production types of home freezer units.

The efficiency of a solar energy absorber will be reduced about 20 percent (15) by the absorption and reflection of the glass cover. The selective black coating will reduce absorption efficiency by about

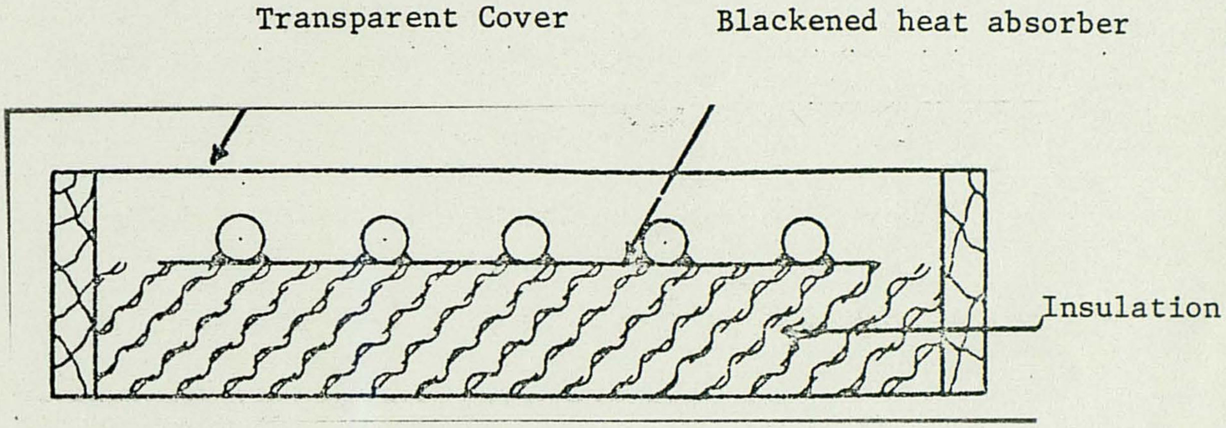


Fig. 14.--Components of a typical solar heat collector.

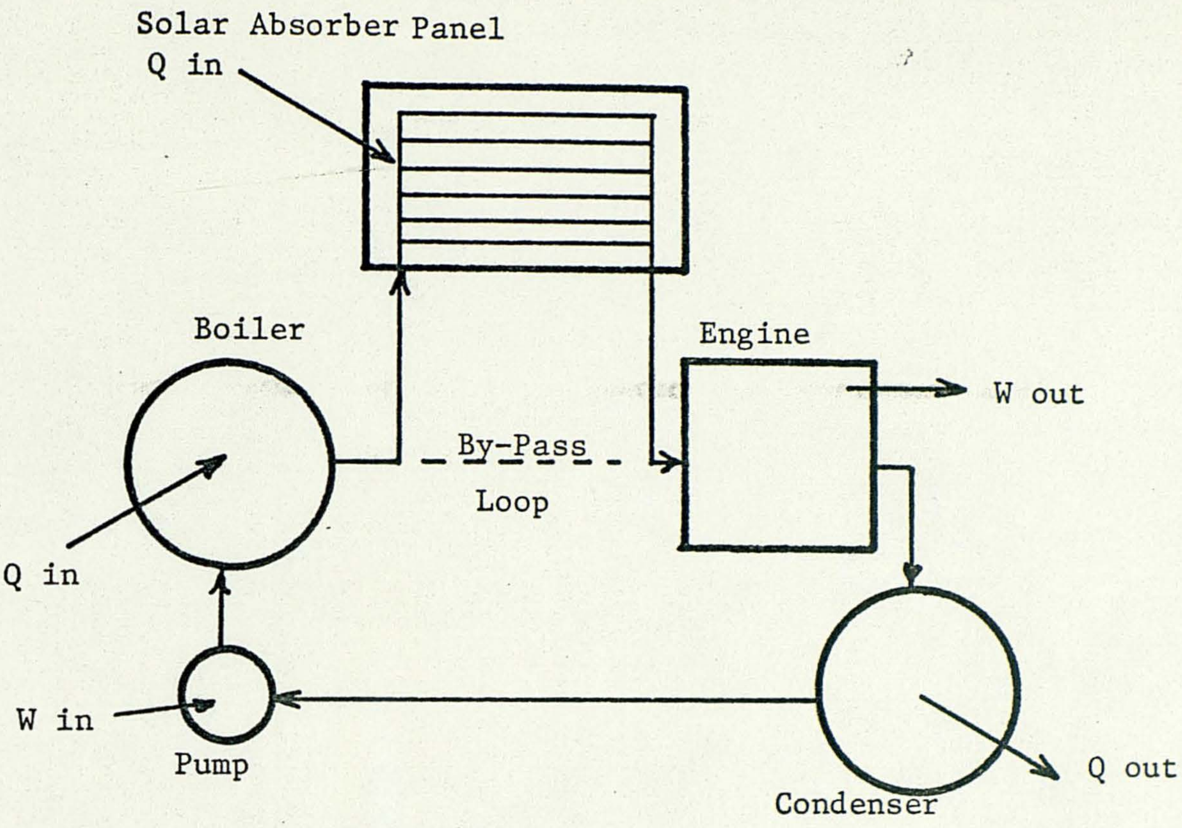
Picture from Reference 14.

ten percent of the incident energy while reducing the re-radiation losses to about ten percent (3). The combination of all these losses yields an overall efficiency of about 65 percent.

The energy which can be absorbed and made available for conversion to useful work by this type of solar energy absorber with 65 percent efficiency is equal to 1160 BTU/ sq ft/day during the summertime or 1047 BTU/sq ft/day on a year-round basis.

Although the flat plate type solar energy absorber is most commonly used to heat water, it could be equally useful as a means of superheating the vapors of a saturated vapor power generating system. The super-heater is connected between the outlet of the boiler and the inlet to the engine.

There are two major advantages to using the superheated vapor concept. As long as a saturated system is used--that is, vapor in contact with its boiling liquid at thermal equilibrium--there is a fixed relationship between temperature and pressure. If the higher efficiency of a higher boiler temperature is desired, it will necessitate the use of increasingly heavier pipes and other fluid system components. In the superheated system, the vapors are heated to a higher energy level without increasing the system working pressure, thus saving weight and expense while operating at a higher temperature differential and a correspondingly higher efficiency. The superheated vapors also allow a greater amount of expansion to take place inside the engine before liquid is formed. (See Figure 15.)



C´ is the state of the steam after expansion from dry saturated conditions.

C is the drier state after expansion when the steam is initially superheated.

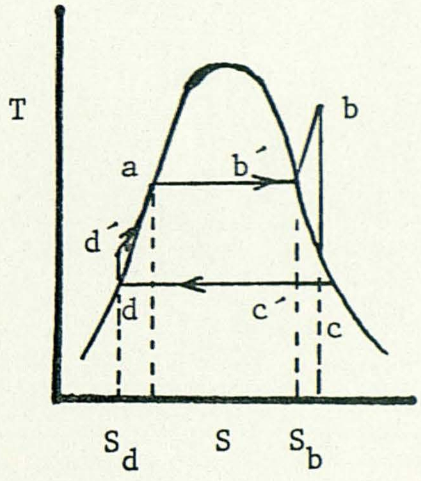


Fig. 15.--Rankine cycle using superheated steam.

If it is desirable to operate the saturated system during the night, a bypass loop can be designed to isolate the solar energy absorber and thus prevent losses through radiation to the open sky. Thermally operated valves can make this an automatic function.

The increase in power production of the combined (saturated plus superheated) system is significant. The operating temperature of solar water heaters may be as high as 200°F, but most of them are operated around 140°F and this is a reasonable temperature for superheated Freon-12 vapor. When the saturated vapor at 100 psia is superheated at constant pressure to 140°F the enthalpy increases to 95.507 BTU/lb. Maintaining the mass flow rate at that which is required to produce one horsepower with only the saturated vapor (3490 lb/hr), the system produces 14.9 horsepower. This means the power output rate is made 14.9 times larger by the addition of the solar energy absorber. No other changes are required.

The solar absorption area required to produce the necessary energy for this system is 244 sq. ft., assuming the total energy received on an average summertime day is evenly distributed over eight sunlit hours. (See calculations in Appendix D.)

## INTEGRATED SYSTEM DESCRIPTION

Maximum economic feasibility of a fuel-free reaeration system depends upon the use of the air-lift and the solar energy absorber because the work output of the integrated system is several times as much as that of the basic lake water thermal energy system, whereas the capital cost is not greatly increased.

The equipment should be assembled as shown. (See Figure 16.)

Mounting the condenser inside the air-lift pipe will cause the counter-current flow of cool bottom water over the vertical surfaces of this heat exchanger to produced more effective heat transfer than if the water were in a static condition.

Since the warmest water in the lake is near the surface, it is important that the boiler not be submerged any deeper than necessary to assure total wetting.

The air-lift pipe must have telescoping capability because of seasonal variations in water level.

The submerged, flat, black platform must be built in the form of a relatively long, inclined, open-ended trough to maximize surface aeration and solar heating. This will also prevent cooling the surface water in the immediate area around the boiler.

Since all published solar energy data are for a flat horizontal surface, the calculations were made with the assumption that the absorber would be horizontal. The absorber would be even more effective if it

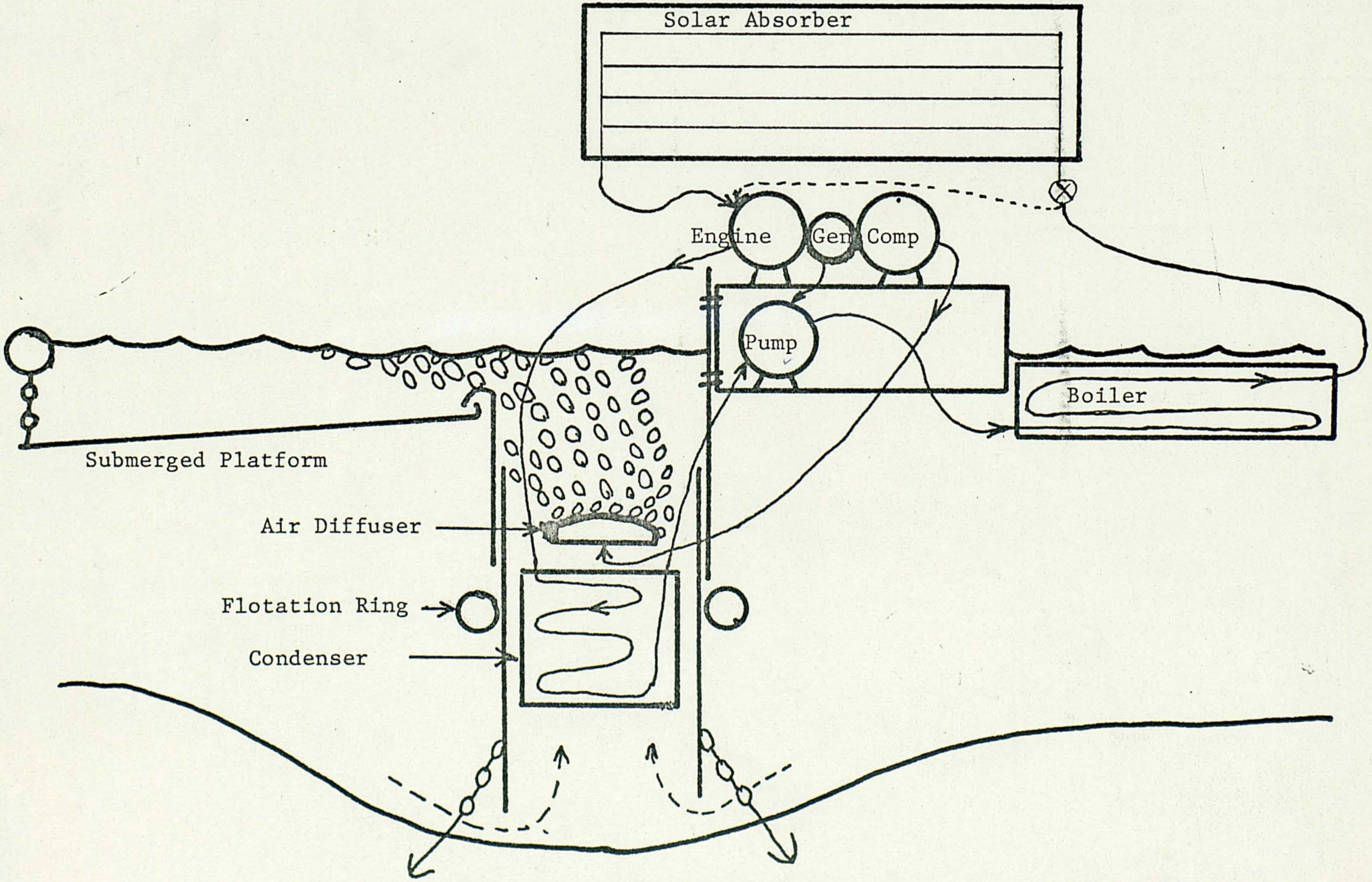


Fig. 16.--Shows Integrated System With Solar Augmentation

were tilted about $30^{\circ}$ and pointed to the south so that its surface is more nearly perpendicular to the averagesolar ray.

## APPENDIX A

PHYSICAL DATA, LAKE PORTER WATER

| DATE | TIME | DEPTH | D.O. mg/l | TEMP $^{o}C$ | THERMAL DIFFERENTIAL | |
|---|---|---|---|---|---|---|
| | | | | | $^{o}C$ | $^{o}F$ |
| 4/14/67 | 8:00 AM | Surf | 9.1 | 23.0 | | |
| | | 10 ft | 9.2 | 23.0 | | |
| | | 20 ft | 9.1 | 21.0 | | |
| | | 30 ft | 1.7 | 18.5 | 4.5 | 8.1 |
| 4/21/67 | 8:30 AM | Surf | 9.7 | 25.0 | | |
| | | 10 ft | 9.5 | 24.5 | | |
| | | 20 ft | 8.6 | 21.5 | | |
| | | 30 ft | 2.4 | 20.0 | 5 | 9.0 |
| 5/5/67 | 2:10 PM | Surf | 10.1 | 26.5 | | |
| | | 30 ft | 0.0 | 20.0 | 6.5 | 11.7 |
| 5/20/67 | 7:00 PM | Surf | 10.0 | 26.0 | | |
| | | 10 ft | 11.3 | 26.0 | | |
| | | 20 ft | 7.8 | 24.0 | | |
| | | 30 ft | 2.6 | 20.0 | 6.0 | 10.8 |
| 6/2/67 | 7:15 AM | Surf | 9.2 | 26.5 | | |
| | | 10 ft | 9.8 | 26.5 | | |
| | | 20 ft | 5.4 | 24.0 | | |
| | | 30 ft | 0.0 | 19.0 | 7.5 | 13.5 |
| 6/4/67 | 7:15 PM | Surf | 9.2 | 29.4 | | |
| | | 10 ft | 10.8 | 28.9 | | |
| | | 20 ft | 5.1 | 25.6 | | |
| | | 30 ft | 0.0 | 19.4 | 10.0 | 18.0 |

APPENDIX A--Continued

PHYSICAL DATA, LAKE PORTER WATER

| DATE | TIME | DEPTH | D.O. mg/1 | TEMP °C | THERMAL DIFFERENTIAL °C | THERMAL DIFFERENTIAL °F |
|---|---|---|---|---|---|---|
| 6/11/67 | 8:15 PM | Surf | 8.6 | 29.4 | | |
| | | 10 ft | 9.5 | 29.4 | | |
| | | 20 ft | 7.1 | 26.0 | | |
| | | 30 ft | 0.0 | 20.0 | 9.4 | 16.9 |
| 6/14/67 | 7:45 AM | Surf | 9.3 | 28.5 | | |
| | | 10 ft | 9.4 | 29.0 | | |
| | | 20 ft | 3.4 | 27.0 | | |
| | | 30 ft | 0.0 | 20.0 | 8.4 | 15.3 |
| 7/17/67 | 3:00 PM | Surf | 9.0 | 32.0 | | |
| | | 4 ft | | 32.0 | | |
| | | 8 ft | | 30.8 | | |
| | | 10 ft | | 30.3 | | |
| | | 15 ft | | 29.4 | | |
| | | 20 ft | 6.9 | 26.0 | | |
| | | 21 ft | | 25.0 | | |
| | | 22 ft | | 24.0 | | |
| | | 23 ft | | 23.0 | | |
| | | 24 ft | | 20.0 | | |
| | | 25 ft | | 20.0 | | |
| | | 26 ft | | 19.5 | | |
| | | 27 ft | | 19.5 | | |
| | | 30 ft | 0.0 | 19.5 | 12.5 | 22.5 |
| 7/29/67 | 9:00 AM | Surf | 8.0 | 26.5 | | |
| | | 10 ft | 8.0 | 26.5 | | |
| | | 20 ft | 4.8 | 26.0 | | |
| | | 30 ft | 0.0 | 21.0 | 5.5 | 9.9 |

## APPENDIX A--Continued

PHYSICAL DATA, LAKE PORTER WATER

| DATE | TIME | DEPTH | D.O. mg/1 | Temp °C | THERMAL DIFFERENTIAL | |
|---|---|---|---|---|---|---|
| | | | | | °C | °F |
| 8/12/67 | 8:30 AM | Surf | 8.9 | 26.5 | | |
| | | 10 ft | 9.1 | 26.0 | | |
| | | 20 ft | 5.5 | 25.5 | | |
| | | 30 ft | 0.0 | 21.0 | 5.5 | 9.9 |
| 8/17/67 | 7:30 AM | Surf | 8.6 | 28.5 | | |
| | | 10 ft | 8.4 | 28.0 | | |
| | | 20 ft | 5.6 | 27.5 | | |
| | | 30 ft | 0.0 | 22.5 | 6.0 | 10.8 |
| 8/23/67 | 7:45 AM | Surf | 8.9 | 26.5 | | |
| | | 10 ft | 6.6 | 26.0 | | |
| | | 20 ft | 0.6 | 25.0 | | |
| | | 30 ft | 0.0 | 22.5 | 4.0 | 7.2 |
| 8/27/67 | 7:45 AM | Surf | 11.3 | 29.5 | | |
| | | 10 ft | 11.0 | 28.0 | | |
| | | 20 ft | 3.2 | 26.0 | | |
| | | 30 ft | 0.0 | 23.5 | 6.0 | 10.8 |
| 9/4/67 | 7:00 PM | Surf | 9.6 | 28.0 | | |
| | | 10 ft | 9.1 | 27.0 | | |
| | | 20 ft | 3.5 | 26.0 | | |
| | | 30 ft | 0.0 | 24.0 | 4.0 | 7.2 |
| 9/7/67 | 7:15 AM | Surf | 7.2 | 25.5 | | |
| | | 10 ft | 7.3 | 26.0 | | |
| | | 20 ft | 3.0 | 25.5 | | |
| | | 30 ft | 0.0 | 22.0 | 3.5 | 6.3 |

## APPENDIX A--Continued

PHYSICAL DATA, LAKE PORTER WATER

| DATE | TIME | DEPTH | D.O. mg/l | TEMP °C | THERMAL DIFFERENTIAL °C | THERMAL DIFFERENTIAL °F |
|---|---|---|---|---|---|---|
| 9/10/67 | 8:30 AM | Surf | 7.8 | 26.0 | | |
| | | 10 ft | 7.4 | 26.0 | | |
| | | 20 ft | 6.2 | 26.0 | | |
| | | 30 ft | 0.0 | 23.0 | 3.0 | 5.4 |
| 9/16/67 | 9:30 AM | Surf | | 27.0 | | |
| | | 10 ft | | 27.0 | | |
| | | 20 ft | | 26.5 | | |
| | | 30 ft | | 22.0 | 5.0 | 9.0 |
| 9/17/67 | 2:00 PM | Surf | 8.0 | 30.0 | | |
| | | 10 ft | 8.4 | 28.5 | | |
| | | 20 ft | 6.0 | 27.5 | | |
| | | 30 ft | 0.0 | 22.5 | 7.5 | 13.5 |
| 9/24/67 | 7:30 PM | Surf | 9.6 | 27.5 | | |
| | | 10 ft | 8.2 | 27.5 | | |
| | | 20 ft | 2.3 | 27.0 | | |
| | | 21 ft | 0.1 | 26.0 | | |
| | | 29 ft | 0.1 | 22.0 | | |
| | | 30 ft | 0.1 | 22.0 | 5.5 | 9.9 |
| | | 34 ft | 0.1 | 21.0 | | |
| 9/25/67 | 3:00 PM | Surf | 8.9 | 29.5 | | |
| | | 10 ft | 8.4 | 27.8 | | |
| | | 15 ft | 7.6 | | | |
| | | 19 ft | 2.0 | 27.1 | | |
| | | 20 ft | 0.8 | 27.0 | | |
| | | 21 ft | 0.2 | 27.0 | | |
| | | 25 ft | 0.2 | 24.5 | | |

## APPENDIX A--Continued

PHYSICAL DATA, LAKE PORTER WATER

| DATE | TIME | DEPTH | D.O. mg/l | TEMP °C | THERMAL DIFFERENTIAL °C | THERMAL DIFFERENTIAL °F |
|---|---|---|---|---|---|---|
| 9/25/67 | 3:00 PM | 29 ft | 0.2 | 22.0 | | |
| | | 30 ft | 0.2 | 21.0 | 7.7 | 13.9 |
| | | 34 ft | 0.2 | 27.5 | | |
| 4/13/68 | 8:30 AM | Surf | 13.60 | 25.5 | | |
| | | 10 ft | 13.75 | 25.0 | | |
| | | 20 ft | 15.70 | 23.5 | | |
| | | 30 ft | 4.70 | 19.0 | 6.6 | 11.7 |
| 4/17/68 | 8:00 AM | Surf | 11.10 | 24.5 | | |
| | | 10 ft | 11.37 | 24.5 | | |
| | | 20 ft | 9.89 | 22.0 | | |
| | | 30 ft | 2.60 | 19.0 | 5.5 | 9.9 |
| 4/23/68 | 8:00 AM | Surf | 10.93 | 24.5 | | |
| | | 10 ft | 13.90 | 24.5 | | |
| | | 20 ft | 1.95 | 21.0 | | |
| | | 30 ft | 1.49 | 20.5 | 4.0 | 7.2 |

## APPENDIX B

### Oxygen Required:

1 acre-foot contains 43,560 x 1 = 43,560 cubic feet.

Since 4 mg/l equals 4 PPM, the oxygen required to increase the D.O. to 4 mg/l in one acre foot of water is equal to 4 PPM x .043560 million cubic feet x 7.481 gallons/cubic foot x 8.34 pounds/cubic foot = 10.85 pounds

10 acres x 25 feet deep x 10.85 pounds = 2715 BTU.

### Air Required:

.273 grams $O_2$/liter of air x 28.32 liters/cu ft = 7.73 g/cu ft. 7.73/454 = .017 pounds $O_2$ per cubic foot of air

One pound of Oxygen is contained in 1/.017 = 58.9 cubic feet of free air.

Since the oxygen transfer efficiency is estimated to be 9 percent, the quantity of air actually required to dissolve one pound of oxygen is 58.9/.09 = 655 cubic feet.

### Power Required:

A small centrifugal compressor is rated at 25 CFM/BHP or 1500 cu ft/horsepower-hour.

1500/655 = 2.3 pounds $O_2$/horsepower-hour.

One horsepower working 8 hours per day will dissolve 1 x 8 x 2.3 = 18.4 pounds of oxygen.

Since one acre foot requires 10.85 pounds $O_2$ to raise the D.O. by 4 mg/l, a one horsepower system will reaerate 18.4/10.85 = 1.7 acre-feet per 8 hour day.

To convert the River Thames data to familiar units -
1.7 lb/KWH = 1.7 lb/1.341 HP-HR = 1.27 lb/HP-HR.
2.5 lb/KWH = 2.5 lb/1.341 HP-HR = 1.86 lb/HP-HR.

Time required to reaerate 1 acre-foot of water is equal to 8/1.7 = 4.7 hours.

## APPENDIX C

### Mass Flow Rate

Since the condenser coolant water temperature is 72°F it is reasonable to assume exhausted vapor from the engine will be cooled to 73°F, where the saturation pressure is 89 psia and the enthalpy is 84.639 BTU/lb.

Additional energy is dissipated by the condenser and the vapors are condensed to liquid at constant pressure.

The boiler feed pump compresses the liquid to 100 psia and forces it into the boiler (heat source) where sufficient energy is absorbed to raise the temperature to 81°F, and to change the liquid into a saturated vapor with enthalpy of 85.372 BTU/lb.

In a Rankine cycle vapor power system, the power output of the prime mover is equal to the change in enthalpy of the vapor flowing through it. This system will produce 85.372-84.639 = 0.734 BTU/lb.

One horsepower is equivalent to 2544 BTU and each horsepower-hour of energy produced will require 2544/.734 = 3490 lb/hr of the saturated vapors.

# APPENDIX D

## Solar Energy Absorption

Increase of enthalpy in super-heater is 95.507-85.372 = 10.135 BTU/lb.

Total energy absorbed by 3490 lb/hr = 3490 x 10.135 = 35,400 BTU/hr.

1160 BTU/sq ft/day equals 1160/8 or 145 BTU/sq ft/hour, assuming 8 sunlit hours/day.

35,400/145 = 244 sq ft of absorber area required.

Combined system power output is limited to (95,507 - 84.639) x 3490/2544 = 14.9 hp.

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