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## Projected Capital Costs of a Mist Lift OTEC Power Plant

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### ABSTRACT

A conceptual design of a 4 MW Mist Lift OTEC power plant has been prepared. This design is based on a modest extrapolation of the mist transport data acquired in fresh water experiments in 1980-81 and ocean water experiments in 1983. It was optimized for minimum cold water use with a condenser effectiveness of 0.9 yielding an output of 450 kJ per m<sup>3</sup> of cold water. Allowances for cold water pumping power, mist generator loss, filter loss, hydraulic turbine efficiency, exit loss and non-condensable removal power reduce this yield to a net value of 300 kJ per m<sup>3</sup> of cold water.

The hull is composed of 4600 m<sup>3</sup> of high density reinforced concrete. It has a shape similar to a buoy, with an overall height of 95 meters, of which 80 meters are submerged. A platform at the top, 15 meters above the ocean surface, provides crew quarters and carries auxiliary equipment and the vacuum pump. Preliminary estimates of the cost of a 4 MW plant are in the range of \$2500 to \$3000 per kilowatt of electrical output capacity.

### NOMENCLATURE

a	Mist acceleration
C <sub>p</sub>	Specific heat of sea water
D <sub>c</sub>	Density of concrete
D <sub>w</sub>	Density of sea water
g	Acceleration of gravity
t	Mist acceleration time
T <sub>c</sub>	Condenser temperature
T <sub>f</sub>	Flashdown temperature
T <sub>w</sub>	Warm water supply temperature
V <sub>i</sub>	Mist injection velocity
V <sub>s</sub>	Vapor-liquid slip velocity
V <sub>2</sub>	Accelerated mist velocity
V <sub>a</sub>	Average mist velocity during acceleration

V <sub>c</sub>	Volume of concrete
V <sub>evac</sub>	Evacuated volume of plant below waterline
W <sub>mist</sub>	Work done on unit mass of mist by the vapor
W <sub>air</sub>	Weight of plant components above waterline
W <sub>vapor</sub>	Work extracted from the vapor in accelerating the mist and friction loss due to interphase slip
Z <sub>a</sub>	Height of the acceleration zone

### INTRODUCTION

The tropical oceans of the world are an enormous energy resource. Their surface water is a heat source typically at 25 to 27°C, and the deep water below is available for a heat sink at a temperature of about 5°C. Various attempts have been made to develop low cost heat engines that can exploit this small temperature differential to provide useful mechanical energy.

The efficiency of such heat engines is limited by the laws of thermodynamics to the ratio of the temperature across the cycle (typically 20°C) to the absolute temperature of the heat source (which is about 300°K). This allows a maximum possible efficiency of about 6.7 percent. Practical considerations of equipment efficiencies, temperature drops required to drive the heat transfer, and power to drive the necessary auxiliaries reduce the thermal efficiency obtainable to 3 percent.

One might hope that, since the heat resource is "free", such a low efficiency does not matter. But the necessary consequence of a low thermal efficiency is that a large amount of heat must be processed by the engine for each unit of useful work developed. The Rankine (closed) cycle engines suggested by D'Arsonval (1) using a typical refrigerant as working fluid and equipped with boilers and condensers have very large heat exchanger requirements. Claude (2) avoided the cost of heat exchangers in his open cycle power plants by choosing water vapor evaporated from the warm water as the working fluid. The vapor-liquid interfaces of the warm and cold water flowing through his apparatus

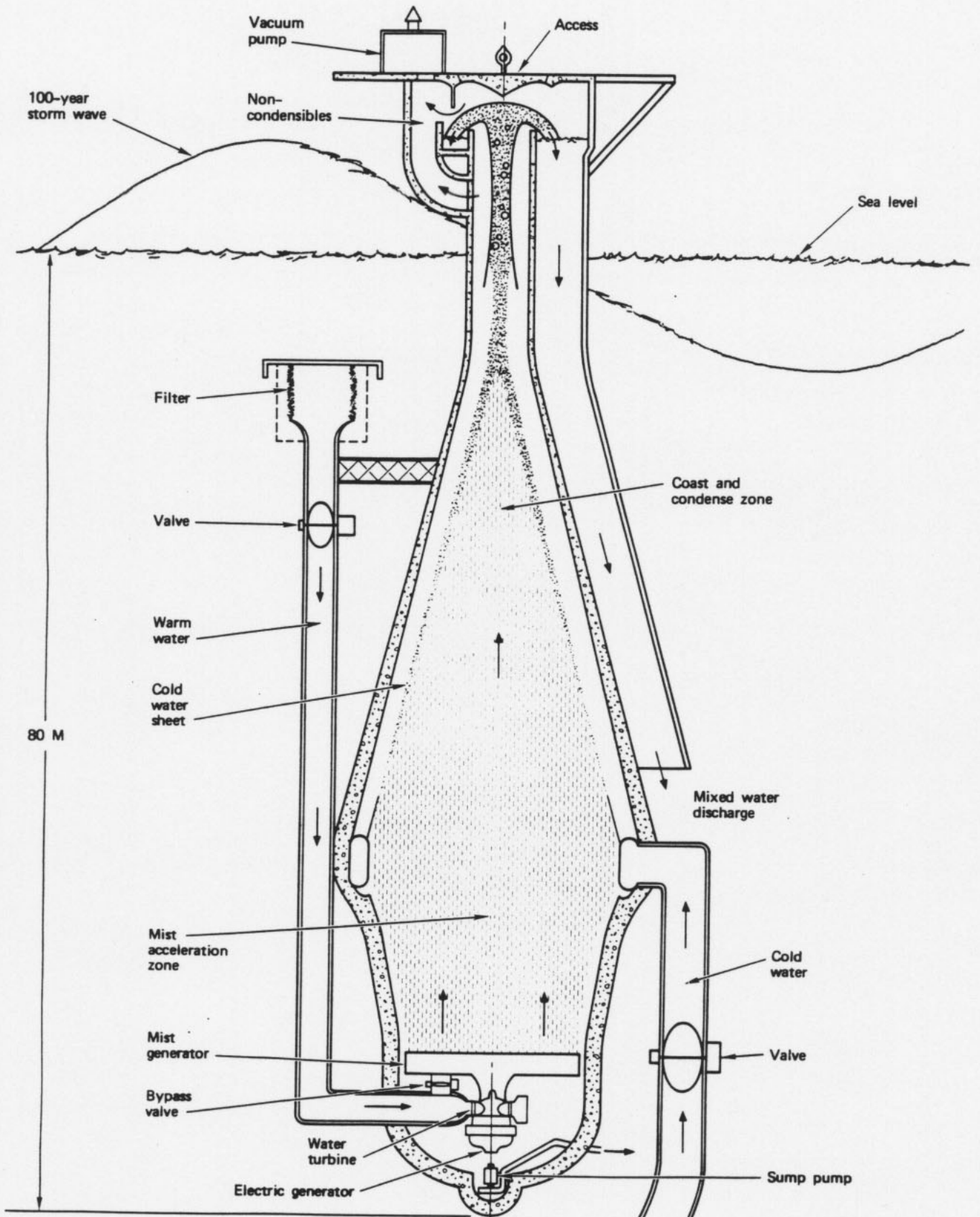


Figure 1. Conceptual Design of a 4-MW Mist Lift OTEC Plant

exchangers, and replaced the large vapor turbine with a hydraulic turbine, were proposed in 1975 by Beck (3), and Zener and Fetkovich (4). The liquid was the continuous phase over much or all of the lift in these concepts. The Mist Lift process, a vapor lift concept in which the vapor is the continuous phase, was introduced by Ridgway (5) to the OTEC community in 1977. In this concept, vapor flashed from a spray of very fine warm water droplets lifts these droplets to substantial heights. The two-phase mist flow regime is established at the beginning of the lift. After the lift is accomplished, the vapor is then condensed in a direct contact condenser. The warm water is passed through a conventional hydraulic turbine to provide the desired power output from the cycle.

The coupling between the vapor and the liquid essential to the process was demonstrated with fresh water and ice in the proof-of-principle experiments accomplished in 1980-81, and reported in Ridgway, et al., (6), and further analyzed in Lee and Ridgway (7). Continuous operation on the actual ocean resource was demonstrated in experiments conducted in the summer of 1983 at the Natural Energy Laboratory of Hawaii (8).

#### OVERVIEW OF THE MIST LIFT OTEC

The general arrangement of a Mist Lift OTEC power plant is shown in Figure 1. The central structure is the large evacuated duct in which the warm water is lifted a distance of about 60 m by the conversion of some of its heat energy into work. The warm ocean surface water enters through the filter at the left of the diagram, and then descends to the water turbine. Most of the gravity head is removed from this water by the turbine to produce the desired output power. The water is then sprayed upward into the bottom of the duct with the remaining head. Sufficient vapor flashes from the warm water at a pressure of about 2400 pascals in the mist formation region to provide a vapor flow a few meters per second faster than the velocity of the injected mist droplets. A valve is provided that can bypass the turbine during start-up, and for power control.

The bottom 20 m of the duct, more or less, comprises the mist acceleration zone, and a pressure of about 1250 pascals is maintained at its top by the condensation of the vapor with the cold water that is introduced in the form of a circumferential spray. A vacuum pump removes noncondensibles. The pressure difference between the bottom and the top of the mist acceleration zone drives the mist to a velocity of nearly 50 m/s. The converging cold water spray merges with the accelerated mist to form a single jet which coasts upward against gravity almost to a stop, and then drains into the ocean. Momentum transfer from the mist to the cold water supplies the kinetic energy needed to carry the cold water to the barometric level, from which it can drain back into the ocean against atmospheric pressure. This arrangement turns out to be a more efficient and less costly way to pump the cold water than a rotating impeller pump driven by the hydraulic turbine. It is appropriate to emphasize here that the mist lift power plant has neither a warm water circulating pump, nor a cold water circulating pump, which is a considerable cost saving.

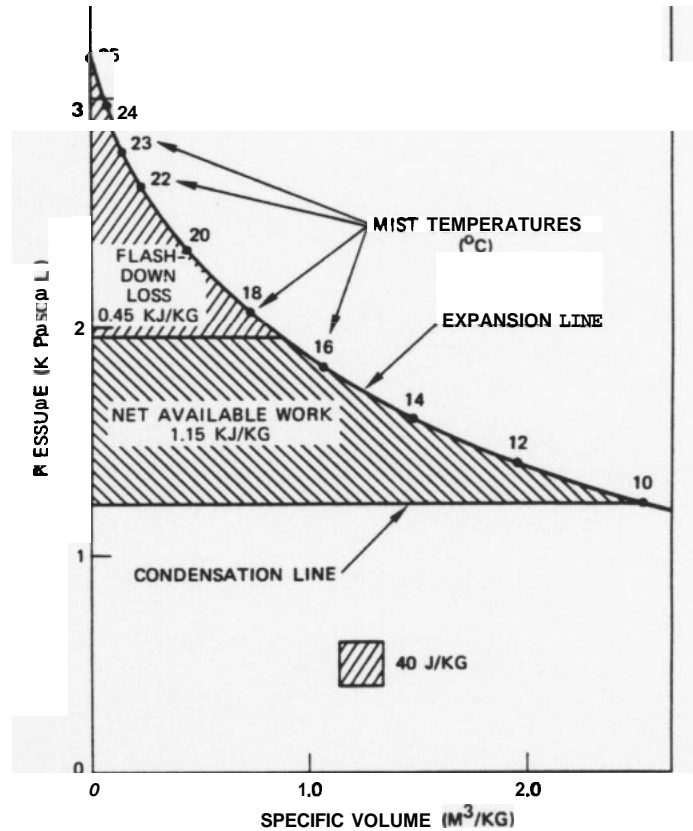


Figure 2. P-V Diagram for Mist Lift Process

a plot of the pressure volume isentrope for the expansion of liquid water from the vapor-liquid saturation line into the two-phase region. The initial state is taken as saturated liquid water at 25°C and a pressure of 3.17 kilopascals. The water becomes a two-phase mixture which expands to do external work. At the end of the expansion, the cold water is introduced to condense the vapor, and the mist volume contracts back to liquid density at constant pressure and absorbs work. The net work theoretically available is represented by the triangular area bounded by the expansion line, the condensation line, and the y axis. This net work per unit quantity of warm water increases as the square of the temperature difference between the warm water supply temperature and the condenser temperature. The cold-to-warm water ratio and the condenser effectiveness determine the condenser temperature. If one varies the cold-to-warm ratio to maximize the theoretical output per unit cold water, the optimum cold/warm ratio is 1.0, and if the output is maximized per unit total water, the optimum ratio is 2.0. The cold/warm ratio for practical designs tends to fall between these values.

In the mist generation region, the ambient pressure is appreciably less than the saturation pressure of the injected water. The vapor coming off the droplets does work against this ambient pressure rather than the

equilibrium pressure. This work difference is a loss we call the flashdown loss, and is shown as the small triangular area in the upper left of Figure 2 for a flashdown in the mist generator to 17°C from 25°C.

Taking this flashdown loss in the mist generation process is central to the mist lift concept. The warm water jets in the mist generator are spaced so that the vapor generated in the flashdown will adequately separate the mist droplets and delay droplet coalescence. Based on analysis of the expected droplet-droplet collision rate in the initial stages of the mist acceleration, we anticipate that a temperature drop of 5-7°C in the initial flashdown will provide a mist with a good coupling to the vapor that will persist through the acceleration process.

#### PLANT OPTIMIZATION

Preliminary cost estimates showed that approximately one-half the cost of a mist lift plant would be in the evacuated upward mist lift duct which also serves as the platform. This hull floats mostly submerged, and therefore its weight is equal to that of an equal volume of seawater. Since cost will be proportional to weight, it is clearly desirable to minimize the volume of this floating duct.

The cold water resource is not easily obtained. The cost of the cold water pipe is uncertain, and likely to be large. Therefore, attention was focused on minimizing the plant volume and the cold water usage by varying the plant parameters that are at the disposal of the designer. Fortunately, it turns out that the cold water usage and the plant volume minimize for nearly identical parameter choices. The major parameters under the control of the plant designer are:

1. Cold/warm water flow ratio.
2. Mist injection velocity.
3. Height of acceleration zone.
4. Divergence of acceleration zone.
5. Warm water injection rate per unit injector area.

In order to proceed with the cost minimization process, one needs a model of the vapor liquid coupling that can be used to predict the behavior of the mist as a function of the available parameters. We appeal to experiment.

In Figure 3 is plotted the mist acceleration as a function of the vapor-liquid slip velocity observed under OTEC temperature conditions in the proof-of-principle experiments that were accomplished in 1980-81 (6). The solid line was selected as giving a conservative estimate of the vapor-liquid coupling that could be achieved with injection pressures in the range from 3 to 4 bars.

For simplification of the analysis, we assume constant relative slip velocity between the mist and the vapor, and constant acceleration of the mist in the lift column. We have also integrated the differential equations governing the flow without these assumptions up a prespecified duct contour with appropriate initial and terminal conditions. The results of this more elaborate calculation verified that the simplified model is accurate enough for the present purpose.

The work done on a volume element of the mist is the force  $(a + g)$  on the element times the distance it travels in the process of being accelerated. For a mist volume element of unit mass:

$$W_{\text{mist}} = t(V_i + at/2)(a + g) \quad (1)$$

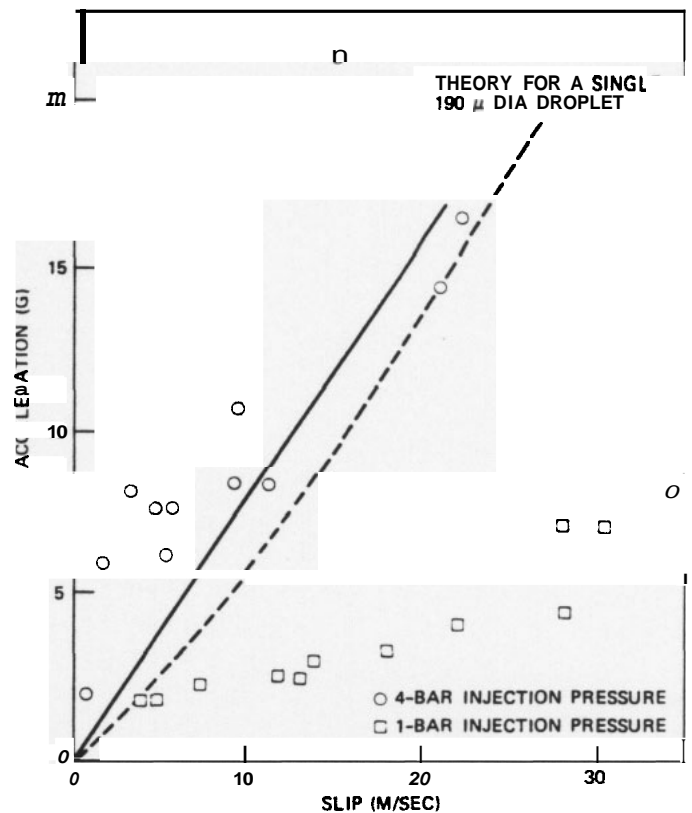


Figure 3. Acceleration Achieved in the 4-Meter Lift Column vs Slip ( $V_{\text{Vapor}} - V_{\text{Droplets}}$ )

The work removed from the vapor is this same force (since action equals reaction) times the distance that the vapor moves in the acceleration, which is greater because of the interphase slip.

$$W_{\text{vapor}} = t(V_i + V_s + at/2)(a + g) \quad (2)$$

The derivation of the work available from the vapor in an isentropic expansion from the liquid state at absolute temperature  $T_w$  to a two-phase mixture at an absolute temperature  $T$  is reproduced in the Appendix from Reference 9, and the result is:

$$w_{\text{vapor}} = C_p(T_w - T)^2 / (T_w + T) \quad (3)$$

The work available in an isentropic expansion to the flashdown temperature  $T_f$  is:

$$C_p(T_w - T_f)^2 / (T_w + T_f) \quad (4)$$

which is lost to the lift process, and must be subtracted from the expression (3) to obtain the net work available from the vapor:

$$W_{\text{vapor}} = C_p \left[ \frac{(T_w - T_c)^2}{(T_w + T_c)} - \frac{(T_w - T_f)^2}{(T_w + T_f)} \right] \quad (5)$$

Then the quadratic equation (2) is solved for the acceleration time  $t$  which is then substituted into (1) to give the work done on the mist. The final velocity is given by:

$$v_2 = v_1 + at \quad (6)$$

The average velocity during acceleration is

$$v_a = v_1 + at/2 \quad (7)$$

The height of the acceleration zone is

$$z_a = v_a t \quad (8)$$

Knowing the velocities and mist specific volumes, the dimensions of the duct and the net power output can then be calculated in a straightforward manner.

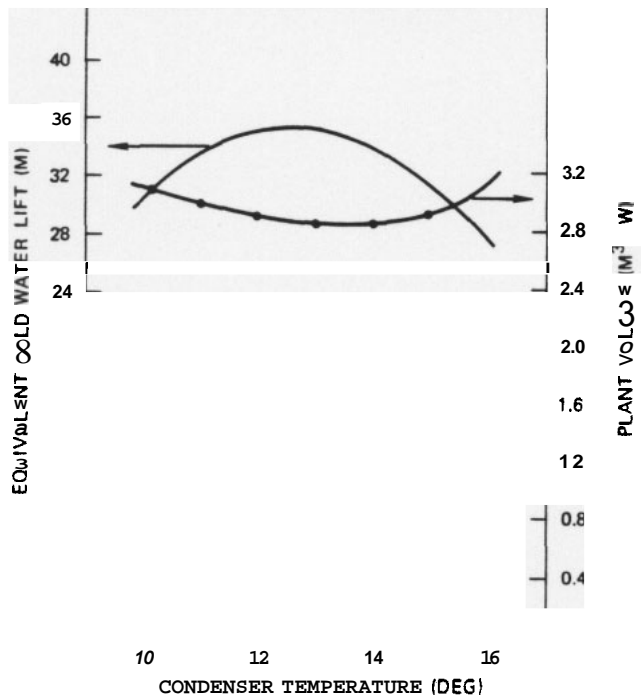


Figure 4. Power Yield and Plant Volume as Function of Condenser Temperature

A flashdown temperature, mist acceleration, and injection velocity were selected. The evacuated volume of the plant and the cold water usage were computed as a function of the condenser temperature. Results are plotted in Figure 4 for a flashdown to 20°C, a mist acceleration of 30 m/s<sup>2</sup>, an injection velocity of 24 m/s and a slip of 4 m/s. The plant volume minimizes at condenser temperature of 13.5°C, and the cold water usage minimizes at a condenser temperature of 12.5°C. Both quantities are near their minima in the range 12.5 to 13.5°C. Any choice of a condenser temperature in this range will minimize the cold water usage and the hull cost.

The position of this minimum was the same for an injection velocity of 28 m/s and slip velocity of 6 m/s. The position of the minimum was lowered by about a degree by setting the flashdown temperature to 18°C. This temperature change increased the volume of the plant by about 20 percent, and the cold water required by about 24 percent; consequently, it is advisable to take no more flashdown than is necessary to ensure that coalescence in droplet-droplet collisions is slow

enough so that the vapor-droplet coupling persists throughout the lift.

#### STRUCTURE COST

The parameters of a Mist Lift power plant to generate 4 MW of net electrical output based on the optimization in the previous section are given in Table 1.

The evacuated volume of the power plant below the waterline determines the height, and, therefore, the structure cost. Let  $W_{air}$  be the weight of structure and equipment above the waterline,  $D_c$  be the density of the submerged concrete (3.68 T/m<sup>3</sup>), and  $D_w$  the density of seawater (1.03 T/m<sup>3</sup>). Then:

$$W_{air} + v_c D_c = D_w (v_{evac} - v_c) \quad (9)$$

$$v_c = (D_w v_{evac} - W_{air}) / (D_c - D_w)$$

The volume of the acceleration region works out to be 3890 cubic meters, and that of the coast region below the waterline is 6740 cubic meters. Below the acceleration region is

TABLE 1

Warm water temperature	25°C
Flashdown temperature	20°C
Condenser temperature	13°C
Cold water temperature	5°C
Cold/warm ratio	1.67
Condenser effectiveness	0.9
Cold water flow	13.0 T/s
Warm water flow	7.8 T/s
Mist injection velocity	24 m/s
Vapor liquid slip velocity	4 m/s
Mist injector area	137 m <sup>2</sup>
Mist acceleration	30 m/s <sup>2</sup>
Injector diameter	13.2 m
Height of acceleration zone	18 m
Maximum cross-sectional duct area	306 m <sup>2</sup>
Maximum duct diameter	19.7 m
Coast distance	64 m
Ideal work of cycle	969 kJ/T
Flashdown loss	166 kJ/T
Net work into mist	683 kJ/T
Noncondensable removal work at 50 percent efficiency from:	
(a) warm water	13 kJ/T
(b) cold water	28 kJ/T
Cold water pumping allowance	71 kJ/T
Turbogenerator efficiency	.90

a hemispherical volume of 600 cubic meters for the turbogenerator, mist generator, and sump pump. This totals to 11,230 cubic meters. We increase this value by 5 percent to provide for clearance in the coast region between the flow and the wall, and recesses in the wall for the spray nozzles that introduce the cold water into the condensing region. The final estimate of the volume below the waterline is 11,790 cubic meters. The structure and equipment above the waterline will have a weight of about 660 T. From (9) is derived a submerged concrete volume of 4333 cubic meters. The structural concrete above the waterline is 265 cubic meters. The structure has been informally quoted by a shipbuilding and offshore engineering firm at \$743 per cubic meter using high-density reinforced concrete. The structure cost estimate is \$3,420,000 which is \$854 per kilowatt.

The amount of concrete required to ballast the structure down in the water exceeds by a factor of three that needed to provide sufficient structural strength to resist the external pressure forces on the hull. Therefore, it is correct to count concrete used in the warm water piping, the cold water plumbing next to the plant, and the discharge line as part of the weight requirement, and so they have already been included in the cost estimate as part of the structure.

We have not had the opportunity to explore the savings that might result from using less concrete and providing a container for inexpensive ballast material. The design is made difficult by the problem of transmitting the ballast load to the buoyant hull without spending more money on steel than is saved in concrete.

#### THE COLD WATER PIPE

In the plant optimization, 3.5 meters of head were allowed for cold water pumping. If the friction factor is a dirty .02, then a 900-m-long pipe needs to be 8 feet in diameter to be able to deliver the needed water within the allowable head loss. If the friction factor is a clean .012, then the pressure drop in a 900-m-long pipe will be 1.8-m gravity head. Thus, 8 feet diameter is sufficient. This is the diameter that was recently built under a NOAA contract as a fiberglass-epoxy syntactic-foam sandwich and tested in a 400-ft length last year. From discussions of the cost of this pipe with NOAA, Ershigs, and TRW, we have chosen \$1,500/foot for the assembled cost of such a pipe at the plant. The Mini-OTEC experiments in 1979 found 6°C water at a depth of 670 meters 2 miles offshore at Keahole Pt. on Hawaii, and had a temperature differential of 20.9°C across the cycle (10). The cold water pipe will attach to the Mist Lift plant about 100 m below the surface; so to duplicate the Mini-OTEC operating conditions, a cold-water-pipe length of 570 meters is needed, which would cost \$2,800,000 or \$700/kw.

TABLE 2 COST SUMMARY

Subsystem	cost	Cost/kw
Structure	\$3,420,000	\$ 854
Cold water pipe	2,800,000	700
Mist generator	300,000	75
Hydraulic turbine	400,000	100
Alternator	200,000	50
Vacuum pump	160,000	40
Cold and warm water valves	100,000	25
Warm water filter	100,000	25
Auxiliary power system	500,000	125
Total of subsystems	\$7,980,000	\$1,995
System integration	2,000,000	500

#### SUMMARY

The cost of a 4MW Mist Lift power plant will be \$10,000,000 or \$2,500/kw.

#### APPENDIX

##### Lift as a Function of Temperature Drop

In the Mist Lift OTEC process, the warm water is introduced into the bottom of the lift tube as a fine spray. Some of this water flashes into vapor, and the expansion of this vapor lifts the water to the condenser.

As the mixture of vapor and water cools, more vapor evaporates from the water and becomes available to expand and do work on the water droplets. Since the temperature and pressure range in OTEC is small, most of the thermal properties of water are sufficiently constant so that a simple analytical formula will give the output work.

Start with unit mass of saturated liquid water at absolute temperature  $T_w$ . Expand this water isentropically to some lower absolute temperature  $T$  doing external work, and forming a large volume of vapor liquid mixture. Condense the vapor at that temperature  $T$ , obtaining unit mass of liquid water at temperature  $T$ . The entropy of the water has been decreased by the amount  $C_p \cdot \ln(T_w/T)$ . This entropy went into the heat sink that condensed the vapor. The heat rejected in the condenser associated with this entropy is  $T\Delta S$  or  $C_p \cdot T \cdot \ln(T_w/T)$ . The difference between the heat removed from the warm water,  $C_p(T_w - T)$ , and the heat rejected to the condenser is the work output of the isentropic expansion.

$$W = C_p [T_w - T - T \cdot \ln(T_w/T)] \quad (11)$$

For  $T_w - T$  less than 20°C, this expression may be approximated to better than a percent by

$$W = C_p (T_w - T)^2 / (T_w + T) \quad (12)$$

The work output is proportional to the square of the temperature drop: For  $T_w = 298^\circ\text{K}$ ,  $T = 283^\circ\text{K}$ ,  $W = 1.6$  joules/gram, which corresponds to a potential lift of 164 meters.

#### Coast and Condense

The operation of the coast and condense process has not yet been experimentally demonstrated, since to do so requires essentially a full-scale apparatus. However, the proposed process depends upon a combination of heat transfer and elementary ballistics that are individually well understood, and it is expected that there will be few surprises when the complete system is put together.

The condensation process is best divided into two phases. In the first, the vapor at 13°C enters the condenser in parallel flow to the cold water spray. Ninety-five percent of the cold water is supplied to this first phase where it accomplishes the bulk of the condensation at an approximately constant vapor temperature. By the end of this phase, 95 percent of the vapor has been condensed and the vapor temperature has fallen 0.4°C as the concentration of noncondensibles rises. This temperature drop is 5 percent of the total possible temperature rise in the cold water. If the individual effectiveness of the cold water droplets is 95 percent, i.e., the average droplet temperature rises to 95 percent of the rise to the local vapor temperature, then the overall effectiveness for this part of the condensation will be 0.90.

The flow of heat from condensing vapor into a droplet of cold water was analyzed in Reference 8 as part of the process of designing a three-effect cross-flow condenser for the Mist Lift experiment at Keahole Pt. in 1983. Turbulent flow and convection currents interior to the drop were neglected in that analysis, and the heat flow ascribed to conduction. The results are thus a lower limit to the heat transfer effectiveness. Figure 2 of that reference shows that 1-mm radius drops with two-second contact time will have the desired effectiveness of .95. The contact time in the present condenser configuration is over three seconds, and 1-mm

radius drops are easy to prepare. If it turns out to be desirable to moderate the rate of initial condensation of the vapor, the cold water converging sprays could be distributed among several galleries at different elevations to give a more precise match to the requirements of the mist flow. Details are given in Reference 11.

A second stage counterflow, or two-effect cross-flow condenser is then provided to strip as much vapor from the vent gases as practicable. This condenser is supplied with the remaining 5 percent of the cold water, and for 2 transfer units occupies a modest volume since the cold water and vapor flow is low. The overall effectiveness of these combined condensers is 0.90, which was the value assumed in the power plant design analysis.

The vapor-air mixture exiting the system from the second condenser is pumped up to atmospheric pressure and exhausted by a vacuum pump. The energy and capital costs of this pump were estimated from the analysis by Westinghouse (12), pages 4-160 to 4-174.

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