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ALTERNATE CYCLES APPLIED TO OCEAN THERMAL ENERGY CONVERSION

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ABSTRACT

The national program to meet its energy needs has addressed the potential of the thermal gradient in tropical oceans to meet part of that need. Research and development into closed cycle, ocean thermal energy conversion (OTEC) systems has resulted in system concepts and component hardware which show great promise for capability to deliver cost-effective power to consumers. As these systems are brought to the ocean experiment stage the program research emphasis is beginning to shift in the direction of alternative cycles which address the primary OTEC technical issue, namely the cost and performance (including lifetime degradation effects) of sea water heat exchanger structures.

An especially attractive alternative is the open cycle approach to utilize the ocean thermal gradient for power generation. In this approach the sea water itself is used as the working fluid in a thermodynamic cycle and the thermal resistance of a metal heat exchanger between the heat source or sink (sea water) and the thermodynamic working fluid is elimated. This advantage is not achieved without the substitution of other important technical problems. These include:

- Direct contact heat transfer to sea water at low pressure.
- Thermodynamic performance and cost-effective producibility of large, low-pressure turbomachinery.
- Deaeration of large quantities of sea water.

In this paper four open cycle OTEC concepts are described. These are:

- Single, vertical-axis turbine
- Multiple, horizontal-axis turbines
- Foam lift/hydraulic turbine
- Mist lift/hydraulic turbine

A preliminary assessment of achievable performance is made in addition to a description of the subsystem performance objectives which would support the achievement of the full potential inherent in these concepts.

The results and conclusions of the paper are a description of the research objectives, achievement of which make open cycle OTEC a viable alternative as a national energy source.

INTRODUCTION

The ocean contains within it the potential to supply more than all of the projected energy needs that our society might demand. This energy potential is in kinetic, chemical, and thermal forms. Waves, tides, and ocean currents are forms of kinetic energy which can readily be converted to more usable forms through the use of innovative conversion equipment. The salinity gradient between seawater and inflowing fresh water rivers can also be converted to mechanical or electrical energy using various membrane processes. However, the resource which has been tapped as a first priority is the thermal energy contained in the temperature difference between warm surface waters and the colder deep waters of tropic or semitropic seas.

The baseline program being pursued by the U.S. Department of Energy for exploitation of this thermal resource is based on the development of a closed Rankine cycle heat engine which converts this thermal resource into mechanical energy. This energy, in turn, can drive electrical generation machinery. The key thermodynamic elements in this process are heat exchanges which couple the hot and cold seawater into the cycle working fluid which currently is ammonia. Because the thermal resource is small (typically less than 20°K) the performance of these heat exchangers must be high and their size large in order to make practical use of the energy. In addition, because the resource exists in a hostile environment in terms of corrosion and biological activity, the materials and maintenance of the heat exchangers must be carefully prescribed. This combination of conditions results in a subsystem which is the most costly and uncertain element in the Ocean Thermal Energy Conversion (OTEC) plant. The Department of Energy program is currently involved in extensive development and testing of large heat exchanger systems ($40\ MW_t$). The testing will be

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Tables and Figures at the end of the paper extended to the sea environment and represents a critical step toward the scaled full system experiment which must precede any commercialization activity.

Because the heat exchangers are such a key and vulnerable part of the OTEC program, the research and development activities are structured to provide supporting data for heat exchanger development as well as alternatives which can provide a backup or second generation approach to the baseline effort. These alternatives are in the form of two open cycle implementations of the basic thermodynamic processes.

DESCRIPTION OF CONCEPTS

The open cycle concept, first demonstrated by Claude [1] in 1930, uses sea water directly as the working fluid. The sea water can be utilized in one of two ways. One approach is to flash the sea water to steam and extract energy via a low-pressure turbine. The other approach is to lift the sea water to a sufficient height to drive a hydraulic turbine. Each of these methods are being explored as alternatives in the National OTEC Program. The low pressure approach can accomplish the elimination of surface exchangers from the system. This eliminates their cost and minimizes concern over corrosion and biofouling. Pursuit of this approach, however, introduces uncertainty with regard to the necessary heat and mass transport processes and a unique turbine development problem. The hydraulic turbine approach further eliminates the need for a vapor turbine but introduces additional uncertainty with respect to certain critical, two-phase-flow problem. This approach must still be considered as an interesting but unproven concept.

Figure 1 shows a schematic representation of the open-cycle, steam-turbine concept. Warm sea water (typically at 25°C) enters an evacuated chamber whose pressure is below the vapor pressure of the warm sea water. The vapor pressure of fresh water at 25°C is approximately $3.4 \times 10^3 N/m^2$ (0.5 psi). With the evaporator maintained at this low pressure, the water in the inlet ducts will rise to approximately 10 m. In order to avoid large penalties in pumping requirements, the evaporator and condenser should, in principal, be located at this 'barometric' level. About 0.5% of the warm sea water flow is evaporated to steam. Because of the high specific volume of steam at low temperature and pressure, the turbine must be relatively large. After energy is extracted by the turbine, the exhausted steam is condensed using a sea water stream drawn from the ocean depths. The condensation can take place in a surface type condenser where the fresh water condensate is a by-product. A direct-contact condenser could be employed in which case the need for an expensive heat exchanger can be eliminated. Since there is some air dissolved in sea water, there will be a need to deaerate the warm and possibly the cold sea water streams. This would be done to minimize the degrading effect of non-condensibles on condenser performance. An air removal capability in the condenser is also required to prevent the build-up of air and to remove the remaining uncondensed vapor.

Several feasibility studies have been completed by Hydronautics, Inc. [2], the University of Massachusetts [3], and Colorado School of Mines [4]. The general conclusion reached is that the open cycle concept can be technically achieved and may be cost competitive with the closed cycle. An additional study for an open cycle preliminary engineering design has just been completed by Westinghouse [5]. A comparison of the performance and component characteristics from those studies is shown in Table 1

Two basic system configurations have been proposed for the steam-turbine concept. The first is a multiple, horizontal-axis turbine configuration, proposed by the Colorado School of Mines, and the second is a single, vertical-axis turbine, proposed by Westinghouse. Both conceptual designs result in compact configurations with minimum losses between components and adherence to the barometric principal where necessary.

The horizontal-axis configuration, shown in Figure 2, utilizes multiple turbines to maintain the turbine diameter to practical sizes and maintain the barometric height in the evaporator and condenser. The condenser, as proposed by the Colorado School of Mines, would be a direct-contact spray or cascade type. In order to utilize a single, large-diameter turbine, Westinghouse proposed the vertical configuration with surface condenser shown in Figure 3. This design is unique in that some of the components are integral with the platform structure, namely the flash evaporator, sea water and vapor flow passages and diffuser. For the option with a direct-contact condenser, the vertical-axis turbine must be located above the barometric level, resulting in the configuration shown in Figure 4. The flash evaporator in both of these cases is a toroidal, open-channel type with the turbine axis and condenser located on the center line of the structure.

The open-cycle, hydraulic-turbine concept has the advantage of using state-of-the-art hydroelectric technology. However, the sea water lift mechanism is still in a research phase and requires further work in order to make an adequate comparison with either the closed cycle or other open cycle technologies. A schematic of the process is shown in Figure 5. The hydraulic head can be created by either lifting the warm sea water via a mist downstream of the turbine or by lifting the sea water in a foam structure upstream of the turbine. The mist system concept was proposed and is being researched by Ridgway [6] and the foam system concept by Zener [7].

In the mist system, a fine spray of droplets (~200μm diameter) is injected into a low pressure region at the bottom of the lift tube. A small fraction of the warm sea water evaporates and the vapor flowing upward carries the droplets with it. At the top of the tube, cold sea water is used to condense the vapor to complete the cycle. The major question here is whether an adequate mist can be generated with minimum loss through the injector and whether stability in the mist flow can be achieved. A conceptual design for a mist flow plant is presented in Figure 6.

In the foam system, the liquid phase of a liquid/vapor mixture is stabilized within a foam structure generated by adding a surfactant to the warm sea water. The liquid in the foam structure rises between top and bottom of the lift tube so that the thermal difference between the warm and cold water is converted to potential head at the top of the tube. The liquid head created can then be converted to mechanical energy in hydraulic turbine.

The steam-turbine concept is the most advanced of the open cycle ocean thermal concepts. Technical feasibility has been established both theoretically and experimentally and a preliminary engineering design study has been completed (Westinghouse). There are several technical issues which need further research in order to reduce the uncertainty in subsystem and system performance. These uncertainties relate to component performance and directly effect the overall system cost effectiveness. The foam and mist lift concepts still need additional basic research before they can be considered as viable alternatives to the closed cycle and the other open cycle ocean thermal concepts.

Basic technical data and major subsystem hardware needs to be developed in several areas before a definitive assessment of open cycle, ocean thermal system potential can be made. These areas include:

- Sea water deaeration
- Direct contact heat and mass transport with sea water at low pressure
- Low pressure turbomachinery
- Efficiency and stability of sea water lift in two phase flow
- Special requirements on the marine systems imposed by the cycle

There is no question that air in the vapor stream has a degrading effect on condenser performance. The question is how much can be tolerated and how can the effects be minimized. In order to minimize the amount of air entering the system, the sea water streams can be pre-deaerated. Deaeration issues include:

- How much air will be released from the warm and cold sea water streams?
- How should the air be removed?
- How much vapor is removed with the air?
- What kind of equipment can be used for air removal and how can the power to operate this equipment be minimized?

Ongoing and future research will provide the data base necessary to make the trade-off between heat transfer performance and auxiliary power losses related to dissolved and entrained gases. This will permit the selection of preferred designs and lead ultimately to an accurate assessment of cycle potential.

Flash evaporators for use in desalination have been studied extensively. However, the operation of these units have been at temperatures and pressures higher than those encountered in an open cycle OTEC plant. Empirical correlations for flash evaporator performance, characterized by thermal non-equilibrium, have been developed but require unacceptable extrapolation to the dimensions and operating conditions of the application considered here. It appears that an open channel geometry for the flash evaporator design is the most attractive. This geometry is one which minimizes head losses and may provide an acceptably small value of non-equilibrium temperature difference with a reasonably sized unit. There is a need for laboratory scale experimental verification of analytical work and for development of scaling laws which would provide information about full-scale operation of a low temperature sea water evaporator.

The unique requirement for open cycle turbomachinery is in the sizes required for a cost effective system. Because of the low pressures and temperatures involved, a credible extension of aerodynamic state-of-the-art technology would be adequate. Turbine blades similar in design to helicopter blades have been proposed for this application. The main question is whether the turbine can be cost effectively produced. Another major issue is the thermodynamic and structural performance of the turbine, especially in the presence of air.

If a surface condenser is used, many of the same problem areas associated with closed cycle heat exchangers exist, namely biofouling, corrosion, enhancement and their cost-effectiveness trade-offs. In addition, the presence of air requires design considerations to minimize its degrading effect and to provide for an air removal system. The solution of these problems is not beyond present heat exchanger design capabilities.

Direct contact condenser analysis presents a more difficult problem. There exists very little data or practical experience with this type of equipment due to the widespread application of surface condensers. The potential for high heat transfer rates and simplified design make this alternative very attractive. Recent information from Hungary [8] on jet-type, spray condensers indicates that the promising expectations are being realized in practice. If heat transfer in the condenser can be maintained with reasonable auxiliary power requirements, then the direct contact condenser may be more cost effective than the surface condenser.

For the mist and foam lift concepts, the major technical questions are the generation and the stability of the mist or foam. The range of operation, lift efficiency and conditions which promote mist or foam instabilities are being researched at the laboratory scale in order to determine potential viability of this concept. If the lifting processes prove feasible, then the power required in the generation process becomes important from a cost-effectiveness standpoint. The injector assemblies envisioned require small diameter orifices that may easily clog with the particulates in sea water. Filtration to the degree necessary could possibly use a large fraction of the gross output of the plant.

Since the open cycle operates at reduced pressures, vacuum integrity of the platform structure is a common requirement among the various concepts. A platform design is needed that minimizes leakage rate, provides structural stability and can maintain the barometric height within acceptable tolerances over a range of sea states.

In general, the technical feasibility of the open-cycle, steam-turbine concepts has been established. There are no 'show stopper' technical issues. However, the overall performance of these plants is sensitive to the amount of auxiliary power requirements in the subsystems. These requirements can be a significant percentage of the net power output, therefore, the ultimate cost-effectiveness of the concept will depend in an important way on the careful design to optimize the subsystem components.

A system model has been generated by SERI to assess the sensitivity of the overall performance to the important parameters of the open-cycle, steam-turbine system. The model is based on the single-turbine, vertical-axis concept. The system model includes deaeration in both warm (25°C) and cold (5°C) sea water loops, flash evaporation at the barometric level, a vertical-axis turbine/generator, and a direct-contact condenser, also at the barometric level.

The deaeration model includes a series of compression stages from which the air is removed. Each stage has an intercooler/condenser to condense out the water vapor which is released by the sea water along with the air. Power requirements associated with the hydraulic head and gas compression are calculated. The parameters which are independently varied are the fraction of gas released by the sea water and the fraction of non-condensibles removed.

The flash evaporator is a toroidal-design, open-channel-flow type. The fluid depth is calculated as a function of mass flow rate and the length of the channel is calculated to achieve a specified value of the thermal non-equilibrium parameter. Pumping power is calculated as a function of free fall height in the evaporator necessary to maintain the flow.

The turbine is on a vertical axis with a diameter of 46m for a 100MW gross output. The steam flow is calculated knowing the available enthalpy drop and the overall turbine/generator efficiency. The enthalpy drop is calculated for a given partition of the available temperature difference (20°C) between components. Turbine/generator efficiency is a variable parameter.

An overall, volumetric heat transfer coefficient is used to size the direct-contact condenser. A range of values for this coefficient is established from previous work. The cross-sectional area is fixed by the turbine diameter and the cold water pipe diameter (10m). The cold water pipe is located along the same vertical axis as the turbine. The approach temperature in the condenser is varied to look for that value which maximizes output power. Pumping power in the cold water loop includes, besides height of the condenser, the frictional losses in the cold water pipe, density differences, and cold water distribution losses.

A computer code was written and executed with a baseline set of valves for the subsystem parameters. Additional runs were made with perturbations of an individual parameter from the baseline case. In this way, the sensitivity of the system model to each subsystem parameter was analyzed.

RESULTS AND CONCLUSIONS

Results of the baseline run for the open cycle model show that about half of the 100MW gross power is used to supply auxiliary power necessary to run the system. These results are summarized in Table 2. It is obvious, in this model, that the condenser pumps use a large fraction of the gross power output. This is because of the conservative value used for the volumetric heat transfer coefficient. Sensitivity runs showed that the net output could be improved to 72MW if the heat transfer coefficient were at the upper limit of its expected range of uncertainty.

Improved algorithms relating heat transfer rate to hydraulic pumping power are being developed. In addition, more detailed head loss calculations within the system are being incorporated in order to improve the quality of the output results.

Estimates of cost for the open cycle are now being developed for the first time. Costs for a 100MW net power module, open-cycle plant with a surface condenser have been generated by Westinghouse. These costs are summarized in Table 3. The platform cost includes components which are integral such as flash evaporator, turbine and condenser shells, hotwell, etc. Total cost does not include cold water pipe, mooring or electrical cable. If a direct-contact condenser is employed, Westinghouse estimates that a savings of $200/KW could be realized.

These costs indicate, that the open cycle will be competitive with closed-cycle technology. Certainly they indicate that further study into alternate OTEC power systems should be pursued. A continuing research and development program is being pursued in order to narrow the range of uncertainty in the open-cycle performance and cost estimates. The promise of lower cost and higher reliability possible because of the elimination of the heat exchangers is the objective of the open-cycle, thermal-systems program.

Based on the results of the conceptual design studies mentioned earlier and on the results of the sensitivity study discussed, the research program includes studies in the following areas:

- Direct-Contact Heat Transfer
  - Flash evaporation (thermal non-equilibrium)
  - Contact condensation
- Turbine/Generator
  - Blade design/producibility
- Deaeration
  - Pre-deaeration
  - Air removal
- Mist/Foam Lift
  - Stability
  - Generation

Overall, the open-cycle, steam-turbine concept appears to be technically feasible. Additional research efforts are underway to reduce performance uncertainties. This should lead to refined cost estimates and a more meaningful comparison with closed cycle technology. The open-cycle, hydraulic-turbine concept needs more basic research in order to establish its viability in the OTEC arena.

ACKNOWLEDGMENTS

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	Westinghouse	CSM	U Mass	Hydronautics
System Performance (MW_e)				
Gross Output	148	100	100	130
Net Output	100	55	59	100
Turbine Characteristics				
Number of Turbines	1	8	1	6
Outer Diameter (m)	46	20	72	24
Efficiency	0.82	0.85	0.93	0.84
Blade material	Composite	HS Steel	Mild Steel	Composite
Flash Evaporator Characteristics				
Type	Open Channel	Bubbler Tube	Falling Film	Falling Film
Steam Rate (kg/s)	1.3×10^3	1.7×10^3	1.1×10^3	2.0×10^3
Sea Water Rate (kg/s)	3.4×10^5	2.5×10^5	1.2×10^5	3.9×10^5
Parasitic Power (MW)	13.0	14.5	27.6	*
Deaerator Characteristics				
Gas Removed (%)	90	80	99.9	10
Parasitic Power (MW)	15.0	6.0	0.6	0
Condenser Characteristics				
Type	Surface	Direct Contact	Surface	Direct Contact
Sea Water Rate (kg/s)	4.2×10^5	1.9×10^5	2.4×10^5	3.9×10^5
Parasitic Power (MW)	20.0	19.4	12.6	*

*data not given

TABLE 1. Comparative Analysis of Open Cycle OTEC Conceptual Designs

Mass Flow (kg/s)	
Warm water	$3.5\text{x}10^5$
Steam	$1.5\text{x}10^3$
Cold Water	$1.4\text{x}10^5$
Gross Output	100 MW
Warm Loop Losses	14.6
Deaeration Losses	1.8
Cold Loop Losses	31.3
Net Power	52.3 MW

Table 2. Baseline output for open cycle model.

	1977$/KW
Turbine/Generator	263
Condenser (Surface)	356
Pumps (Sea Water & Condensate)	119
Air Removal System	193
Cleaning System	15
Auxiliaries, Conditioning & Control	30
Platform	500
Total Cost	$1,476/KW

Table 3. Costs for a 100 MW_e Open Cycle Power Module (Westinghouse)

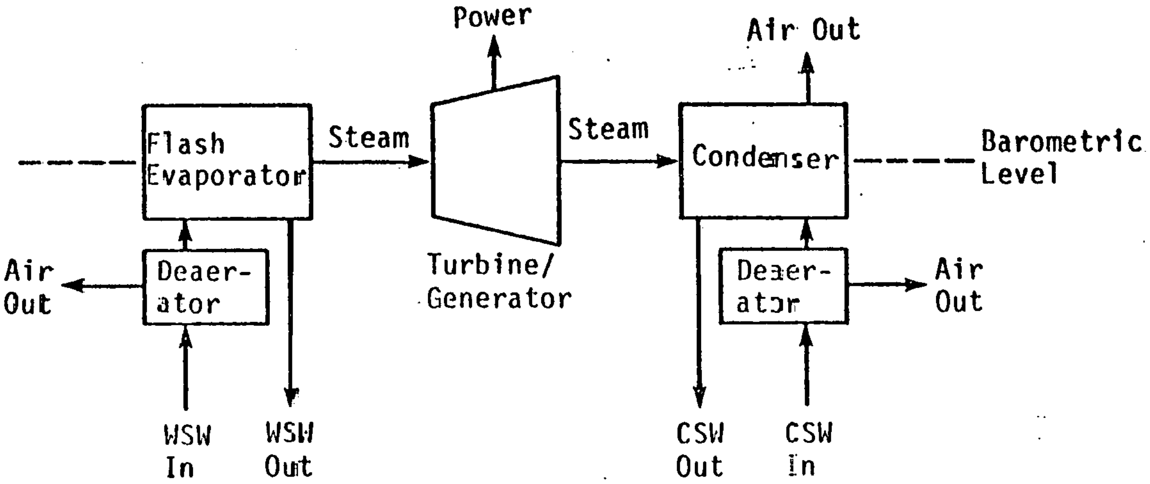

Figure 1. OPEN-CYCLE, STEAM-TURBINE SCHEMATIC

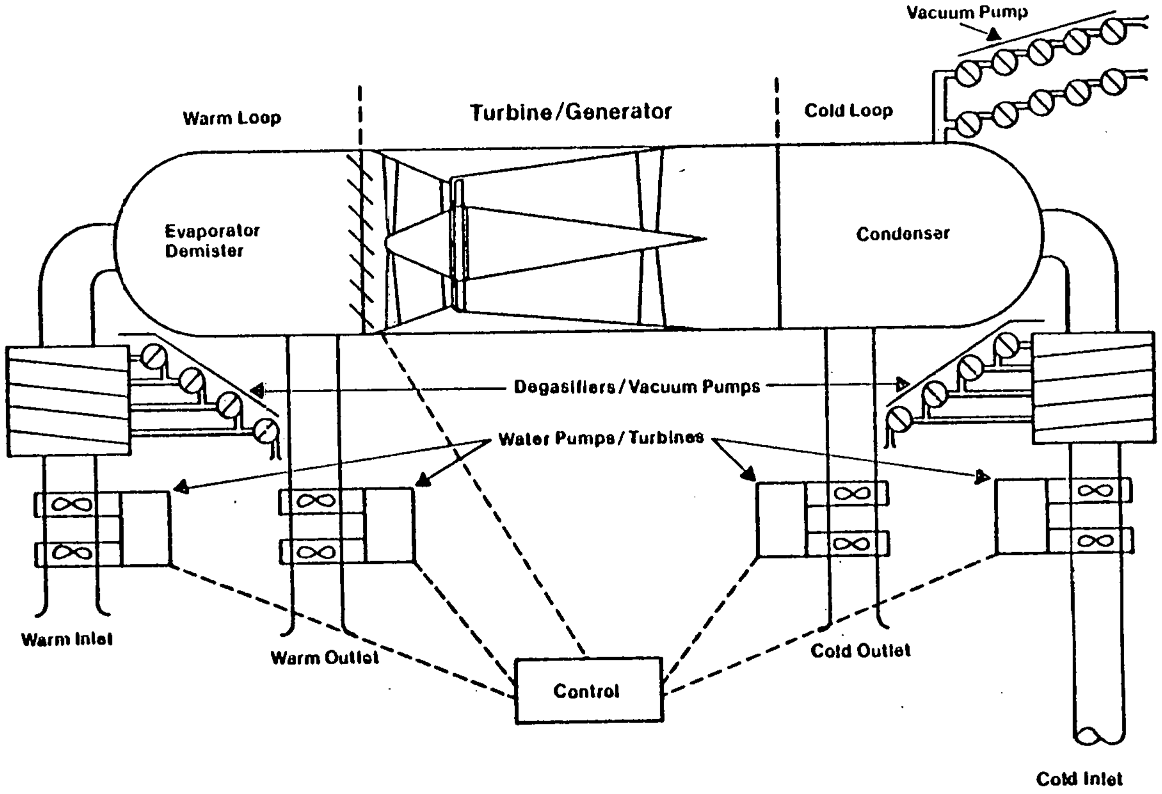

Figure 2. HORIZONTAL-AXIS CONFIGURATION (COLORADO SCHOOL OF MINES)

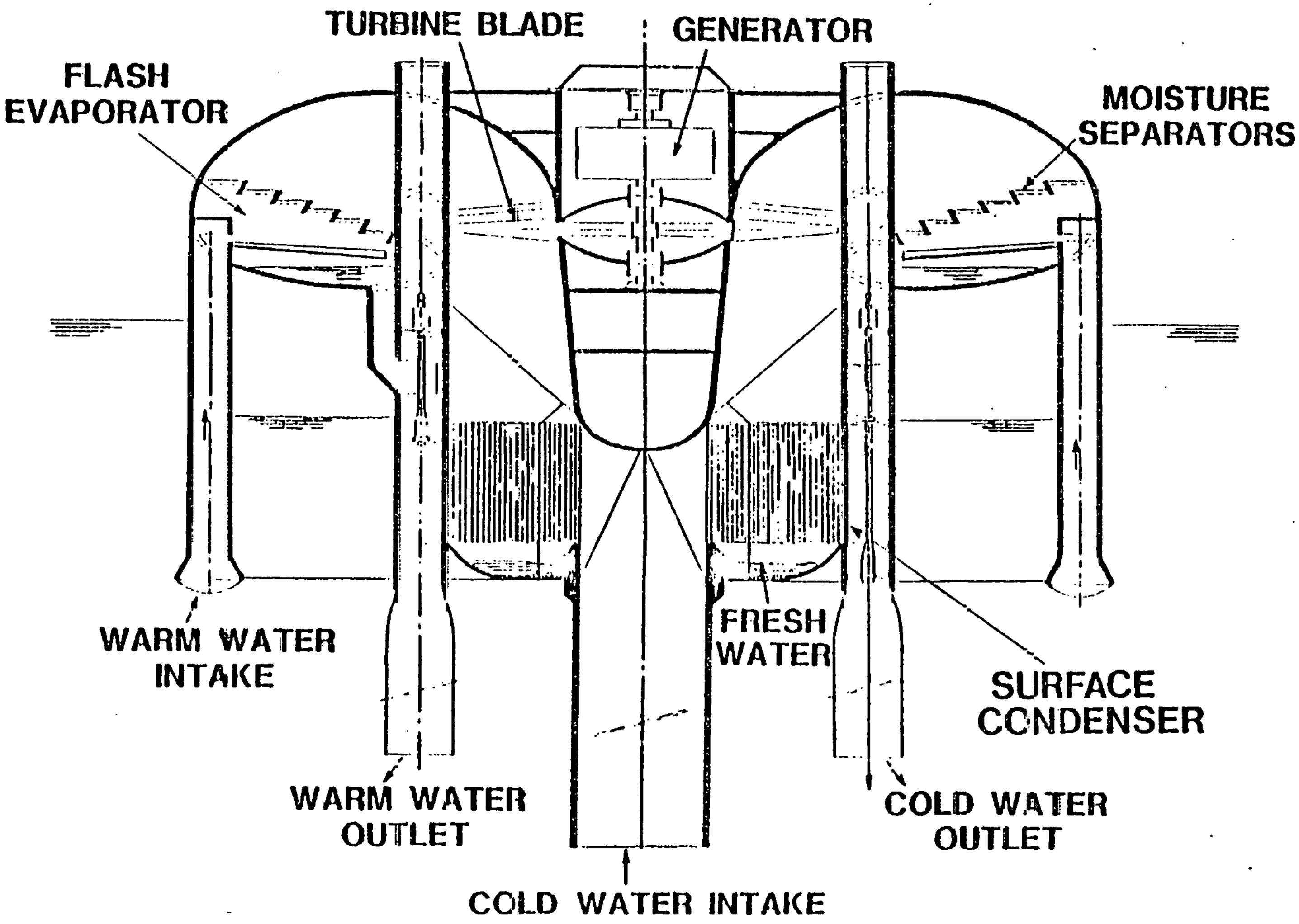

Figure 3. VERTICAL-AXIS, SURFACE-CONDENSER CONFIGURATION (WESTINGHOUSE)

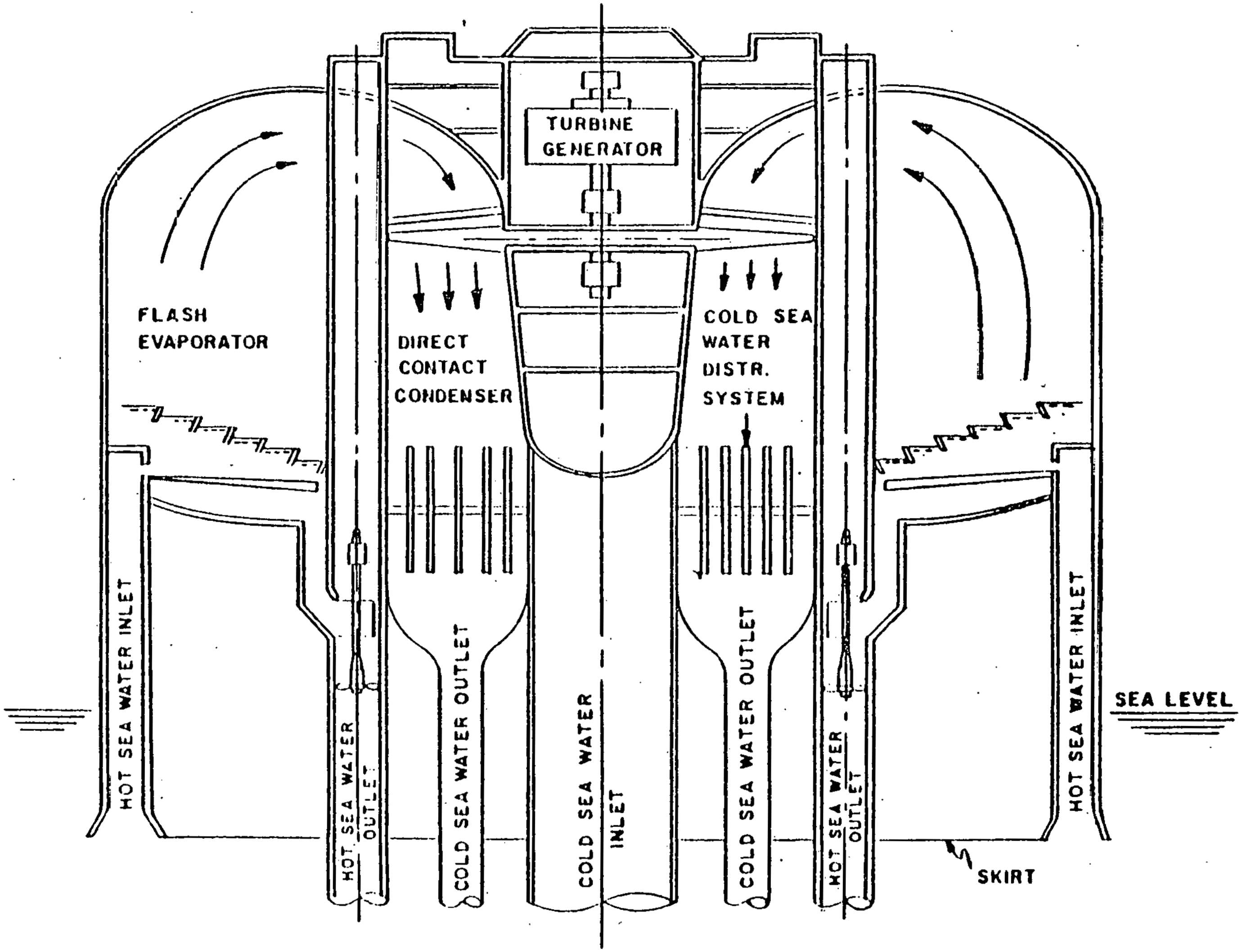

Figure 4. VERTICAL-AXIS, DIRECT-CONTACT-CONDENSER CONFIGURATION (WESTINGHOUSE)

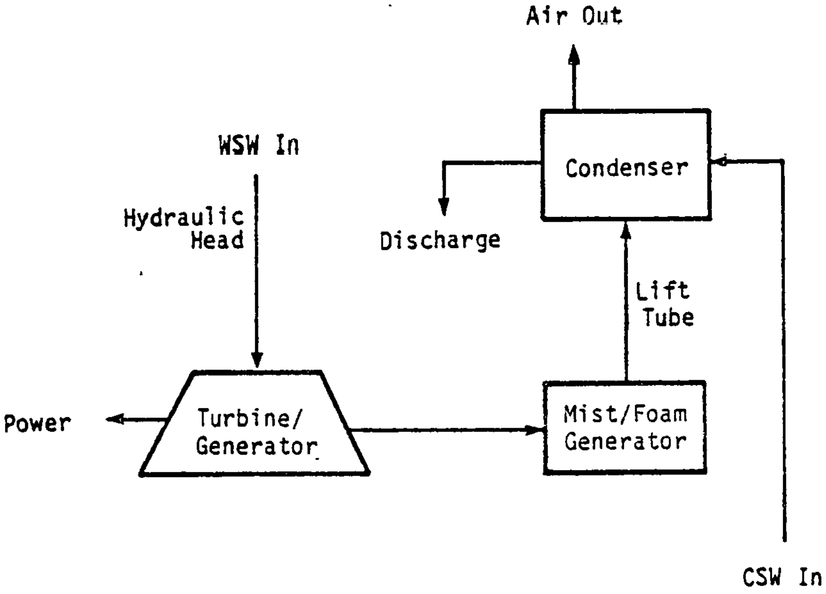

Figure 5. OPEN-CYCLE, HYDRAULIC-TURBINE SCHEMATIC

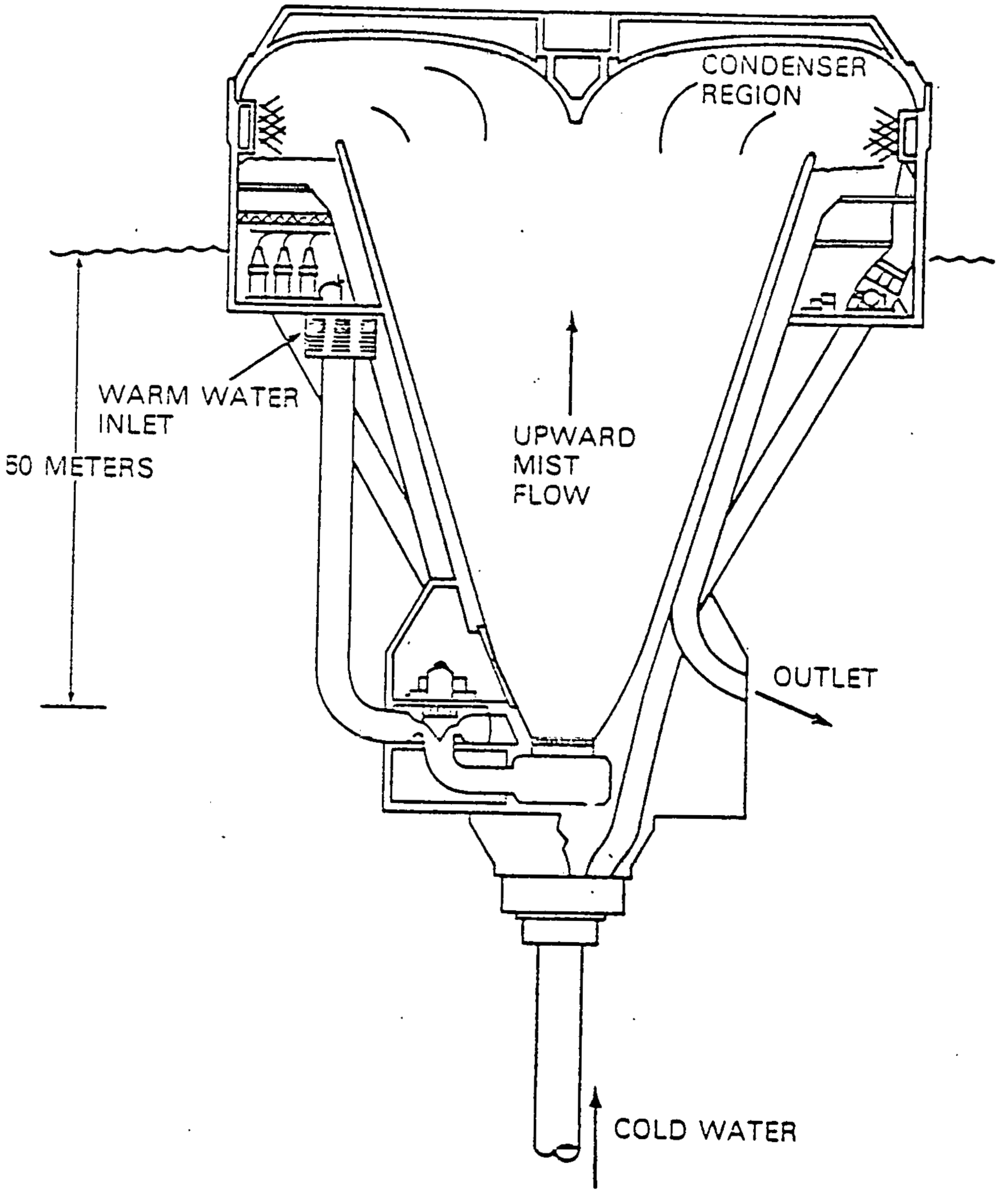

Figure 6. 10MW$_e$ MIST FLOW PLANT (RIDGEWAY)