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Ocean Thermal Gradient Hydraulic Power Plant

Abstract. *Solar energy stored in the oceans may be used to generate power by exploiting thermal gradients. A proposed open-cycle system uses low-pressure steam to elevate water, which is then run through a hydraulic turbine to generate power. The device is analogous to an air lift pump.*

For the last few years, a voluminous literature on energy-related problems has shown one thing clearly: for the way of life we enjoy to continue phenomenal progress will be needed in power generation methods. Reallocation and minor reductions in the use of oil, coal, and nuclear fission can do little more than give us time for using our ingenuity—if we hurry. Only fusion and solar power promise long-time solutions, and if we are responsible enough to look ahead for the probable life of the earth, only solar power remains. One possible method of utilizing solar energy for power generation is discussed in this report.

In the last century, the French physicist D'Arsonval suggested use of a refrigerant as the working fluid in a machine using a closed Rankine cycle to exploit the thermal differences between the cold currents emanating from the polar regions and the warm currents, such as the Gulf Stream and the Japanese Current, emanating from tropical seas. Another French investigator, Claude, foresaw the extreme difficulties of heat transfer with the small temperature difference available (typically 22°C or less) and attempted to develop an open-cycle machine in the late 1920's (*1*). His efforts resulted in thermodynamic successes but ocean engineering disasters. His main difficulties were mechanical problems with the draft tube used to bring cold ocean water from ocean depths to the condenser at the surface. With 45 years additional ocean engineering experience, we are in a position to do better in this area. The problems of heat transfer with a low temperature difference, while better understood, are no less difficult than in Claude's time.

On the basis of Claude's work and some more recent studies of materials and ocean engineering, it would now be practical to build an open-cycle system using low-pressure steam such as Claude attempted. However, for the kind of power generation needed today it would be necessary to use low-pressure steam turbines perhaps hundreds of feet in diameter—far larger than anything built to date.

Recent work (*2*) supported by the National Science Foundation (and now under the new Energy Research and Development Administration) promises not only feasibility but perhaps reasonable costs in a closed-cycle system such as suggested by D'Arsonval. The projected size of the necessary heat transfer equipment is so large, and its fouling so poorly known, that the overall potential for development is far from proved. A simpler concept, preferably of the open-cycle type but avoiding the very low pressure steam turbine used by Claude, would provide a more reasonable engineering approach to early development. Such a concept is discussed here.

This concept would retain the simplicity and other advantages of the open cycle proposed by Claude and at the same time avoid the requirement for gargantuan turbines. I propose introducing the warm surface water through a restriction in the lower end of a vertical pipe. The resulting cavitation would provide the necessary nucleation for the formation of steam bubbles, which in a two-phase mixture in the vertical pipe would provide the gravity head to elevate the water well above the ocean's free surface. This would be done inside a pressure hull of the power plant, which could be sited on an island, such as Guam, or on an anchored floating platform. Theoretically, the maximum head could be very great—hundreds of feet. I suggest calling this vertical tube assembly the "steam lift water pump," as it is a steam-driven counterpart of the well-known air lift pump.

After the steam-water mixture exited from the upper end of the pump it would be separated, and the steam would be condensed in some variation of a barometric condenser. This simple device was used by Claude and was well known in power generation before the advent of the surface condenser. Loss of the condensate would be of no consequence since it is not recirculated as in a closed-cycle plant. The water would leave the power plant through a conventional hydraulic turbine under gravity flow into the ocean at a depth commensurate with its temperature, which would be reduced from the surface inlet temperature by evaporation and mixing with cold subsurface water.

This system would avoid most of the problems associated with the closed cycle. However, because of the height of the power plant above the ocean's surface, it could become unstable in tropical storms. For this reason, even if it were otherwise practicable, the very large tower would probably not be used on a floating platform, but only in a land-based power plant. For floating power plants there appears to be a more practical approach, involving a lower overall height. The steam lift water pump would be reduced in height, perhaps to a few tens of feet or less. At the upper end of this lift pump the steam-water mixture would be deflected horizontally and the remaining available energy imparted to the water by the steam. The steam would be condensed just ahead of a nozzle delivering to a mixed flow water turbine. To achieve the large power desired in a single power plant, there would probably be many steam lift pumps delivering water to a single turbine runner.

This concept as described is fully covered in a patent application (*3*).

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18 March 1975

Foam Solar Sea Power Plant

Abstract. *In the accompanying report Beck suggests a new type of open-cycle system for obtaining power from the ocean's thermal gradient. A modification of this open-cycle plant which will ensure a high efficiency, and also a low capital cost per unit power output, is described here.*

In response to the national need for new energy sources, the National Science Foundation has initiated a program (now being carried out by the Energy Research and Development Administration) to study the economical feasibility of extracting power from the thermal gradients in the tropical oceans. We call power plants designed for this purpose Solar Sea Power Plants (SSPP's). Work in this country has been focused almost exclusively on closed-cycle SSPP's, where one uses a working medium with a reasonably large vapor pressure at ambient temperatures. The university and industrial groups who have studied such SSPP's believe they have a good chance of becoming economically competitive with standard fossil- and nuclear-fueled power plants.

In the preceding report, Beck (*1*) proposes an open-cycle SSPP which operates on the same principle as an air lift pump, the air being replaced by the vapor of the water itself. In this report we propose a modification of the Beck concept which we believe will greatly increase the efficiency of such an open-cycle plant and may make it less costly than a closed-cycle SSPP.

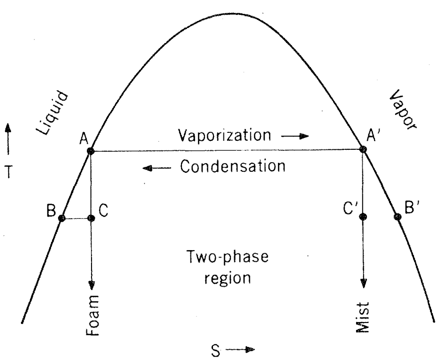

Fig. 1. Typical temperature-entropy (*T-S*) diagram.

Specifically, we propose that the mixed liquid-vapor phase have a foam structure rather than the structure of a continuous vapor phase interspersed with droplets of liquid, or of a continuous liquid phase interspersed with vapor bubbles.

If either the vapor or the liquid forms a dispersed structure of bubbles or of droplets, two problems are encountered:

1) The two phases are mechanically coupled only by frictional forces. An acceleration is therefore associated with a relative velocity between the liquid and gaseous phases, with an accompanying energy loss. In a foam the motion of the vapor within a given cell is mechanically tied to the motion of the fluid in the corners and edges of that cell. Acceleration is therefore not accompanied by frictional losses.

2) The interfacial area between the two phases is relatively small. As a consequence, during rapid changes the equilibrium relation between pressure, density, and temperature (P, ρ, and T) will not be maintained. In contrast, in a foam the interfacial area between liquid and vapor is enormously greater. A foam therefore aids in maintaining equilibrium between P, ρ, and T.

Since the dissolved salt must diffuse away from the surface during evaporation, and since the diffusivity coefficient of all solutes in water is very small, the role of the foam structure in maintaining thermodynamic equilibrium is especially important.

Because we expect a foam to maintain essential thermodynamic equilibrium even during rapid change, we expect that the performance of a foam SSPP will be governed by the thermodynamic properties of the vapor-liquid two-phase region. These properties can be best understood by reference to the standard temperature-entropy (*T-S*) diagram shown in Fig. 1. The heavy curve in Fig. 1 delineates the boundary of a two-phase region. The single-phase fluid bordering the left-hand branch is said to be in the liquid phase, and that bordering the right-hand branch is said to be in the vapor phase.

Isothermal changes are represented in a *T-S* diagram by horizontal shifts. Thus, when a gram of material is taken from A to A' it is said to vaporize, and when it is taken from A' to A it is said to condense. A gram of material can undergo an isothermal change only if it is in thermal contact with other material from which it can absorb heat during evaporation, or to which it can give up heat during condensation.

Adiabatic changes are represented in a *T-S* diagram by vertical shifts. We most commonly effect a vertical lowering by a drop in pressure, a sudden drop in order to avoid heat exchange with the environment. We obtain qualitatively different results depending on whether we cool, through a drop in pressure, below the right-hand or left-hand branch of the *T-S* diagram. A slight cooling from the vapor branch, say from A' to C', results in a small mass fraction of the vapor condensing into droplets. Since the density of these droplets is high

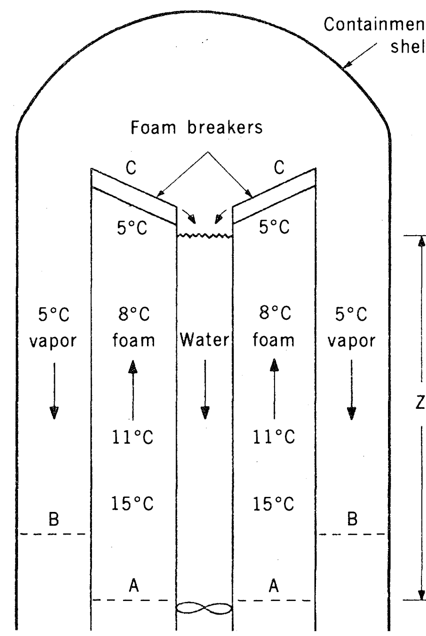

Fig. 2. Schematic diagram of a foam SSPP designed to generate a hydrostatic water head. The transition between the pure liquid and the liquid-vapor mixture (foam) in the warm seawater intake at 25°C takes place at A. This point is at about 30 feet (9 m) above sea level. The foam breaker at C separates the liquid from the vapor in the foam. At B the vapor is condensed by thermal contact with deep ocean water at 5°C. The liquid is channeled down the central pipe through a standard hydraulic turbine at the bottom. The height of the water head above A is represented by Z_f. Points A, B, and C correspond to those similarly labeled in Fig. 1.