

ering 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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3. "Patent application of E. J. Beck for ocean thermal gradient hydraulic power plant," Navy Case 58,611 (15 May 1975).

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.

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

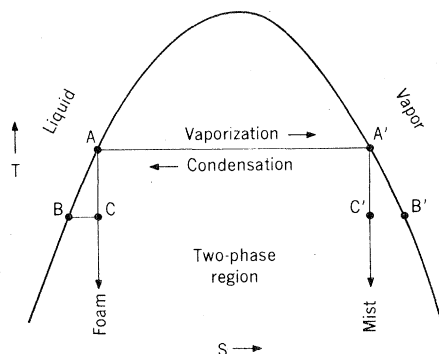


Fig. 1. Typical temperature-entropy (T - S) diagram.

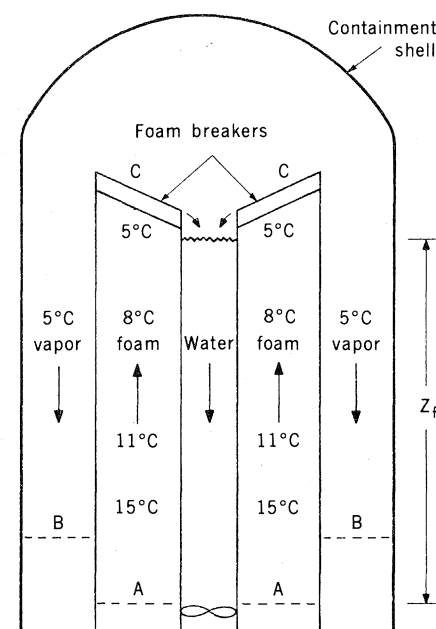


Fig. 2. Schematic diagram of a foam SSPP designed to generate a hydrostatic water head. The transition between the pure liquid and the liquid-vapor mixture (foam) in the warm seawater intake at 25°C takes place at A . This point is at about 30 feet (9 m) above sea level. The foam breaker at C separates 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.

compared to the density of the vapor, the fraction of the total volume which they occupy is exceedingly small. Accordingly we change the properties of a vapor only slightly by a small cooling, as from A' to C' . Only the optical properties are noticeably changed. We commonly call such a vapor a mist.

A slight cooling below the liquid branch, say from A to C , results in a correspondingly small mass fraction of the liquid vaporizing into small bubbles. Since the density of the vapor is very low compared to the density of the liquid, the fraction of the total volume occupied by the vapor may be very high. Thus, if we adiabatically cool water from 25° to 24°C, the mass fraction that vaporizes is only 0.00168, but this small mass fraction of vapor occupies 98.7 percent of the volume. The volume fraction of the liquid is so small that it is confined to the corners of the vapor cells. The pure liquid phase at 25°C has changed into a foam by cooling 1°C. More generally, we define a foam as a mixture of liquid and vapor in which the overwhelming volume percentage is in the vapor phase, the overwhelming mass percentage is in the liquid phase, and the vapor is contained in cells bounded by liquid films. The bulk of the liquid is contained at the corners of these cells.

With further cooling below 24°C, more liquid vaporizes, resulting in still smaller overall density, ρ . It is this extremely low density that gives rise to a remarkably large enthalpy change

$$\Delta H = \int_{P_A}^{P_B} \frac{dP}{\rho}$$

when the pressure is reduced from $P_A = 0.458$ pound per square inch (psi) (31,600 dyne/cm²), corresponding to the vapor pressure of water at 25°C, to $P_B = 0.126$ psi, corresponding to the vapor pressure of water at 5°C. This enthalpy change is just the area of the triangle ABC in Fig. 1 and is given by $\Delta H = -2.90$ joule/g. It is sufficient to raise the 1 g of water 972 feet (296 m). When the plant design is optimized to achieve the lowest possible capital cost per unit power output the actual head will be reduced below the theoretical value of 972 feet.

The thermodynamic quantities P , ρ , and ΔH are given as a function of T in Table 1. These quantities have been computed from steam tables (2).

We visualize a foam SSPP as depicted in Fig. 2. Consider that the air is removed from the device, so that only water (liquid and vapor) exists within. The seawater intake provides warm surface water at 25°C with a vapor pressure of 0.458 psi. The condenser temperature is brought to 5°C

Table 1. Properties of a foam having an upper limiting temperature of 25°C.

T (°C)	X (weight fraction of vapor)	P (psi)	ρ (g/cm ³)	ΔH (joule/ g)
25	0	0.458	1	0
24	0.0017	0.432	0.013	-0.0063
22	0.0052	0.383	0.0037	-0.061
20	0.00865	0.339	0.0020	-0.18
15	0.0167	0.247	0.00077	-0.726
10	0.0248	0.178	0.000385	-1.63
5	0.0320	0.126	0.000208	-2.8

by cooling with deep ocean water. This corresponds to a vapor pressure of 0.126 psi. There will be a flow of vapor from the warm water (25°C) to the condenser (5°C). However, if the water between 25° and 5°C exists as a foam, the flow of vapor from the warm region to the cool region will necessarily be accompanied by a flow of the whole foam structure. This foam structure consists not only of the individual foam walls, but also of the cell edges where two walls meet, and of the cell corners. The cell corners are of particular importance, for they hold the bulk of the fluid. If the liquid and vapor are separated by the foam breaker at the top of the tower, the liquid may be channeled into the central water column, where it is used to drive the turbine before being exhausted back into the sea.

The maximum height of 972 feet is attained only when the available enthalpy is all converted into potential energy. But under these conditions the foam rises with a velocity approaching zero, and hence no power is developed. The maximum power per unit horizontal area is developed when the foam breaker is at two-thirds of its maximum height, 648 feet. For this height

of the foam breaker, power is generated at the rate of 1.62 kw per square foot.

It is pertinent to ask how long the foam takes in rising 648 feet. This may be calculated directly from Bernoulli's equation

$$\int \frac{dP}{\rho} + \frac{1}{2} v^2 + gz = \frac{1}{2} v_0^2$$

where v is the velocity of the rising foam, z is the height the foam has risen, v_0 is the value of v at $z = 0$, and g is the acceleration of gravity. We take the differential of this equation

$$\frac{dP}{\rho} + v dv + g dz = 0$$

and multiply by ρ

$$dP + \dot{m} dv + g \dot{m} dt = 0$$

where \dot{m} denotes the mass flux, ρv . Since the mass flux is constant, this equation may be integrated to give

$$\Delta P + \dot{m} \Delta v + g \dot{m} \Delta t = 0$$

Upon substituting the appropriate constants into this equation, we deduce that Δt , the time required for the foam to reach the foam breaker at 648 feet, is 21 seconds.

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References and Notes

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3. We are greatly indebted to E. Beck for the opportunity of reading his patent disclosure (Navy Case 58,611). This work has been supported in part by the National Science Foundation, RANN (Research Applied to National Needs) division, under grants GI-39114 and AER73-07863 A02.

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Oxidation of the Carcinogens Benzo[a]pyrene and Benzo[a]anthracene to Dihydrodiols by a Bacterium

Abstract. *A mutant strain of Beijerinckia, after growth with succinate plus biphenyl, contains an enzyme system that oxidizes benzo[a]pyrene and benzo[a]anthracene to mixtures of vicinal dihydrodiols. The major dihydrodiol formed from benzo[a]pyrene was identified as cis-9,10-dihydroxy-9,10-dihydrobenzo[a]pyrene by comparison with a synthetic sample. Benzo[a]anthracene was metabolized to four dihydrodiols, the major isomer being cis-1,2-dihydroxy-1,2-dihydrobenzo[a]anthracene.*

Almost 200 years ago Percivall Pott reported a possible causal relationship between coal soot and the incidence of scrotal skin cancer in English chimney sweeps (1). Since that time several different polycyclic aromatic hydrocarbons (PAH) have been implicated as chemical carcinogens (2). Today, it is generally accepted

that the carcinogenic properties of PAH are only manifested after metabolic activation by microsomal monooxygenases. Arene oxides, the initial oxidation products of aromatic rings, in mammals are possibly the ultimate chemical carcinogens (3). The present study explores the fate of carcinogenic PAH on oxidation by micro-