this hitherto unreported phenomenon may be quite widespread. In a manner similar to other forms of upwelling, this mechanism should be a means of creating oceanic fronts and for bringing nutrients to the surface waters where they will enhance biological productivity in these ice edge regions when the sunlight conditions allow. In raising the deeper, more saline waters to the surface where they will be cooled and made denser, ice edge upwelling is a mechanism for deep and possibly even bottom water formation. This process could be important for removing heat from the ocean's depths and hence may be important in determining the world's climate.

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References and Notes

1. Some descriptions of the theory and observations of coastal upwelling are given in the following: R. L. Smith, *Oceanogr. Mar. Biol.* **6**, 11 (1968); C. N. K. Mooers, C. A. Collins, R. L. Smith, *J. Phys. Oceanogr.* **6**, 3 (1976); A. E. Gill and A. J. Clarke, *Deep-Sea Res.* **21**, 325 (1974).
2. The first published work on ice edge upwelling was the presentation of an analytical, homogeneous model by T. Gammelsrød, M. Mork, and L. P. Røed [*Mar. Sci. Commun.* **1**, 115 (1975)]. A. J. Clarke [*Deep-Sea Res.* **25**, 41 (1978)] produced a stratified model. Most of the comparisons with theory in this report are based on Clarke's model.
3. In late November 1977, K. Aagaard and A. Foldvik made a cruise in this region on the *Polarsirkel*.
4. H. Mosby, *Geofys. Publ. 12* (1938).
5. A CTD is an instrument which makes continuous measurements of conductivity, temperature, and depth as it is lowered through the water. With these measurements it is possible to calculate the salinity and density of the water as well as other variables.
6. The density anomaly of seawater may be written as $\sigma_\theta = (\rho_\theta - 1)10^3$, where ρ_θ is the potential density of the water in grams per cubic centimeter. Potential density is the density a water sample would have if it were raised adiabatically from the sample depth to the ocean's surface.
7. Y. Gjessing, in preparation.
8. The baroclinic radius of deformation (internal Rossby radius) in a two-layer fluid is given by $\sqrt{(gH\Delta\rho/\rho f)}$, where g is the acceleration of gravity, $\Delta\rho$ is the density difference between the layers, ρ is the average density of the layers, H is the depth of the surface layer, and f is the Coriolis parameter, that is, twice the rotation rate of the earth multiplied by the sine of the latitude. In this formula it is assumed that the total depth of the fluid is much greater than the depth of the surface layer. Although baroclinic radii calculated from this two-layer approximation may be different from those calculated from continuous theory by as much as a factor of 2, they are of sufficient accuracy for the purposes of this report. The upwelling varies away from the ice edge as $\exp(-|x|/a)$, where x is the distance from the ice edge and a is the baroclinic radius.
9. J. R. Buckley, T. Gammelsrød, O. M. Johannessen, L. P. Røed, in preparation.
10. We thank the director of the Institute for Continental Shelf Research (IKU) in Trondheim, Norway, for providing us with their integrated navigation system, a computerized satellite position-finding and navigation unit; T. Vinje of the Norwegian Polar Institute for interpreting the satellite images; and the captain and crew of the M.S. *Polarsirkel* for making the best of working under very difficult conditions. This research was supported by the University of Bergen.
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Thermoclines: A Solar Thermal Energy Resource for Enhanced Hydroelectric Power Production

Abstract. *The solar thermal energy stored in hydroelectric reservoir thermoclines is very large and greatly exceeds the gravitational hydroenergy of the surface water, even after limitations arising from the second law of thermodynamics have been taken into account. Greatly enhanced power production can be obtained at present hydroelectric facilities if heat engines are adapted to exploit this large thermal energy resource.*

We suggest here a technique for increasing the power output of conventional hydroelectric plants. The freshwater thermoclines behind normal hydroelectric plants contain thermal energy greatly in excess of the gravitational hydroenergy. Even after one takes into account the Carnot efficiency and the reduction below Carnot efficiency for real heat engines, the convertible energy expressed in equivalent "head" can exceed the average dam height in the United States by a factor greater than 4. The presence of power-conditioning equipment and power transmission lines makes present hydroelectric facilities ideal locations for heat engines that operate on the large freshwater thermocline energy source. Furthermore, there should be no negative environmental factors associated with power production by the application of heat engines to hydroelectric dam thermoclines. Thermocline data taken from three western reservoirs (Lake Mead, Lake Shasta, and Clair Engle Lake) are presented for illustrative purposes.

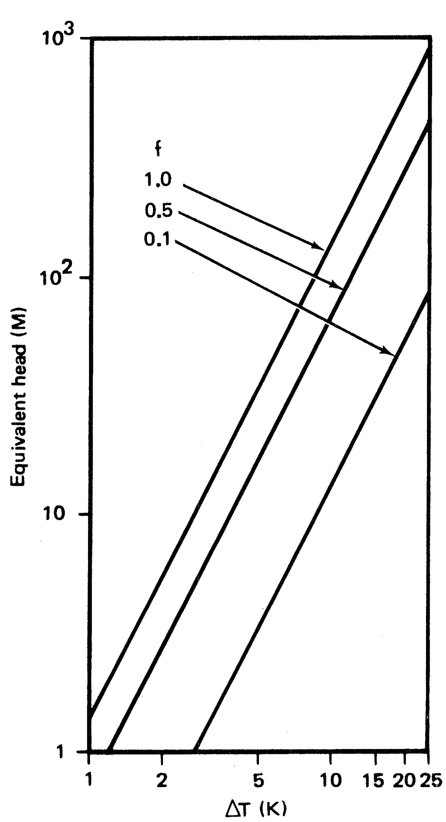
Vast quantities of absorbed solar energy are stored in the form of freshwater thermoclines behind hydroelectric dams. The mechanical equivalent of the thermal energy stored in water at a temperature difference ΔT can be expressed conveniently in terms of head if one sets the gravitational potential energy of the head, h, equal to the thermal energy

$$Mgh = MC\Delta T \tag{1}$$

where M is the mass of water, g is the acceleration due to gravity (9.8 m/sec^2), and C is the specific heat of water (4.18×10^3 J kg^{-1} K^{-1}). Equation 1 then becomes

$$\frac{h}{\Delta T} = \frac{C}{g} = 427 \text{ m K}^{-1} \tag{2}$$

or 778 feet per degree Fahrenheit. This value is very impressive when compared to the average head deliverable by a dam in the United States, which is only ~40



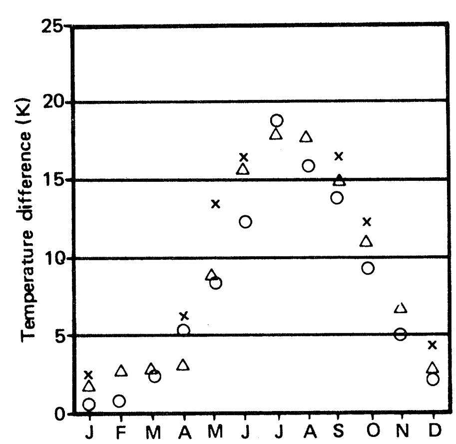


Fig. 1 (left). Equivalent head of converted thermocline thermal energy plotted as a function of the temperature difference between solar-warmed surface water and cooler deep water. The parameter f is the fraction of the maximum theoretical heat conversion efficiency (Carnot) at which a heat engine is to operate. Fig. 2 (right). Seasonal variations in the thermocline temperature difference in three western reservoirs: △, Lake Mead; x, Lake Shasta; and ○, Clair Engle Lake.

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m (130 feet). Thermoclines generally correspond to the stratification, with a surface water temperature 5 to 20 K greater than the water temperature 10 to 20 m below the surface. For a typical thermocline temperature difference of 15 K, the equivalent gravitational head is 6.4 km (12×10^4 feet). Therefore, it is apparent that the solar thermal energy stored in freshwater thermoclines substantially exceeds the energy stored in the gravitational potential.

However, not all of the thermal energy can be converted to useful mechanical or electrical energy. The maximum fraction of the thermal energy that can be converted to mechanical energy is given by the Carnot efficiency, and any real heat engine will operate at some fraction, $f < 1$ of the Carnot efficiency. For a ΔT between the warmer surface water temperature and the cooler deeper water, the equivalent head, h', for converted thermal energy is given by

$$Mgh' = MC\Delta T\left(\frac{\Delta T}{T}\right)f \qquad (3)$$

or

$$h' = \frac{C}{g}\frac{\Delta T^2}{T}f = 427\frac{\Delta T^2}{T}f \qquad (4)$$

where T is the temperature of the warm surface water, and $\Delta T/T$ is the Carnot efficiency.

As an example, for a heat engine that operates at 50 percent of the Carnot efficiency ($f = 0.5$), with a thermocline of 15 K and a surface temperature of 300 K, h' is

$$h' = 427\left(\frac{15^2}{300}\right)0.5 = 160 \text{ m}$$

The h' value is plotted against ΔT in Fig. 1 with the fraction of the Carnot efficiency at which the heat engine operates as a parameter. This convertible head, that is, the portion of the head that can be realized by the use of real thermal energy conversion systems, exceeds the hydropotential for the water in most hydroelectric facilities. Therefore, by adapting heat engines to hydroelectric facilities which possess appreciable thermoclines, it is possible to increase substantially the output power of such plants.

The thermocline application of hydroelectric facilities for heat engines is particularly appealing because power conditioning and transmission equipment are already installed at such sites. Another important consideration is that most modern hydroelectric facilities have water intakes at several reservoir elevations for the express purpose of attaining an output water temperature appropriate to the downstream usage (*1*). It would appear that this configuration would be advantageous for application to heat engines, because the hot and cold water intakes could be directed to the corresponding hot and cold sides of the heat engine and the water outputs could be mixed behind the heat engine.

To illustrate the magnitude and seasonal variations to be anticipated, we obtained thermocline data for three western U.S. reservoirs (Fig. 2). The data for Lake Mead were taken during 1977 (*2*), and the data for Lake Shasta and Clair Engle Lake are 3-year averages for 1973 through 1975 (*3*). As should be expected, the greatest temperature differences occur during the summer months, which also correspond to the times of peak power demand. For these three reservoirs, the temperature difference exceeds 15 K for approximately 3 months and exceeds 10 K for 5 to 6 months.

Our purpose in this report was to identify the thermocline energy source and to demonstrate the benefit to be derived from the utilization of this source at hydroelectric facilities. To properly exploit this thermocline source, effective low-temperature thermal energy conversion systems are required. Although a comprehensive discussion of low-temperature-difference heat engines is beyond the scope of this report, two possible systems for the thermocline application are the vapor-liquid phase Rankine cycle heat engine, currently being considered for Ocean Thermal Energy Conversion (OTEC) power plants (*4*), and the solid-state Nitinol heat engine, which, although in a primitive state of development, shows great technical and economic promise for effective low-temperature thermal energy conversion (*5*). There should be no negative environmental factors associated with power production by this application of heat engines to the thermocline energy resource.

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References and Notes

1. In some cases considerable retrofit expense has been incurred in an effort to provide temperature control of reservoir outlet water [see, for example, *Eng. News Rec.* **199** (No. 4), 18 (1978)].
2. The Lake Mead data were provided by R. D. Mason of the Boulder City office of the U.S. Bureau of Reclamation.
3. Thermocline data for Lake Shasta and for Clair Engle Lake were provided by R. Brown of the California Water Resources Department.
4. W. D. Metz, *Science* **198**, 178 (1977).
5. W. S. Ginell, J. L. McNichols, J. S. Cory, paper presented at the Intersociety Conference on Environmental Systems, San Diego, Calif., 10 to 13 July 1978; J. S. Cory and J. L. McNichols, paper presented at the 13th annual Intersociety Energy Conversion Conference, San Diego, Calif., 21 to 25 August 1978.
6. We thank R. D. Mason and R. Brown for supplying us with reservoir data.

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Paleocirculation of the Deep North Atlantic: 150,000-Year Record of Benthic Foraminifera and Oxygen-18

Abstract. *Benthic foraminiferal faunas in a piston core from 3331 meters at 44°N on the Mid-Atlantic Ridge show striking variations in the relative abundance of species.* Uvigerina peregrina, *which is broadly distributed today in the South Atlantic and in the Pacific in water that has been long isolated from the surface, is absent in the North and Equatorial Atlantic at depths occupied by highly oxygenated North Atlantic deep water. This species dominated the fauna at this site for much of the past 150,000 years. It is suggested that North Atlantic deepwater production was much reduced or eliminated at times of* Uvigerina peregrina *abundance, as a result of cooling and stratification of the Norwegian Sea surface, coincident with the times of the southward migration of the polar front in the North Atlantic.*

Studies of deep-sea sediments have shown that the temperature, oxygen isotopic content, and sediment sources (*1*) in the deep ocean have changed on a time scale of millions of years. These changes are due both to the drifting of the lithospheric plates through time and to changes in the thermal structure of the oceans. In particular, gradual cooling of the poles during the last 35 million years has led to a decrease in the temperature of the bottom water of the deep sea (*2*). On a shorter time scale, sediment cores provide the best record of fluctuating surface zooplankton and phytoplankton distribution, revealing the climatic fluctuations of the Pleistocene. Weyl and others (*3*) have proposed that these fluctuations of Pleistocene climate repetitively modified the deep circulation of