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SOLAR HEAT COLLECTOR IN NEW ENGLAND

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William S. von Arx

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TECHNICAL REPORT

*Prepared for the Department of Commerce,
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04-7-158-44104.*

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Approved for Distribution

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Summary

The modified 20 metric ton, 20 m² area Bloch-Tabor brine pond built on the premises of the New Alchemy Institute, Hatchville, Massachusetts, under Woods Hole Oceanographic Institution auspices has been in operation since early October 1976 through one of the coldest winters in recent New England history. Despite a "cold" start in October 1976 the core temperature declined only to 24° C in January-February 1977, reached a summer peak of 58° C in August 1977 and is now showing seasonal decline. Generally speaking, the pond has maintained a temperature about 20° C above ambient; showing only very sluggish responses to weather changes and a smooth response to seasonal changes of insolation and average wind speed.

The pond, though small, has been operated in an unsheltered mode to see whether very large ponds (too large to be covered) could perform usefully in New England. As a result the open pond not only suffered evaporative losses and wind-mixing of the fresh water cap overlying the brine, but, when iced over, collected snow. Exposure to the elements also permitted accumulation of leaves, pollen, and dust on the surface which cast shadows. Almost daily cleaning was necessary but easily done with a drop

of dishwashing detergent on the surface and a scoop net. The pond operated at an average efficiency of 24% (total daily output/daylight input $\times$ 100%).

The pond differs from the Bloch-Tabor design in utilizing coal as a black body absorber and brine concentrations of Calcium Chloride Hexahydrate near 45% to raise the refractive index to 1.42 and thus enhance the "fish-eye" or whole-sky radiation-trap effect. As a result the pond could acquire and trap radiation on cloudy as well as clear days to such good effect that it is difficult to distinguish between clear and overcast days in the recording thermograph records. Rainfall has a cooling effect from which recovery is rapid, and also "tops up" and freshens the sweet water cap over the brine. Precipitation has just about balanced evaporative losses from the surface since excesses overflow and $P - E$ is generally positive in New England.

The experiment has been generally successful from the physical point of view (radiant heating of homes, for example), but its biological performance is marginal in mid-winter. Tropical species of plankton feeders, such as *Talapia*, grow best in water temperatures near 27° C which the pond at 24° C cannot supply in the coldest months. Anaerobic digesters for bioconversion of organic wastes into high grade fuels and fertilizers operate best at 35° C which, again, are not within the capabilities of the pond in mid-winter. Water plants, algae and the nitrogen-fixing bacteria associated with *Azolla* (water ferns) survive and reproduce at 24° C and can thus be held over in winter, but 30° C or so would improve their vitality. Obviously, some form of increased heat storage capacity, with very long time constants, is required.

As a result of these findings and experiences an altogether different approach to solar heat collection and storage has been developed in which the heat excesses of summer are collected and stored below ground for use in winter: the annual-cycle, groundwater heat storage system. Preparations are being made to drive wells to and into the phreatic zone so as to pump several hundred-thousand gallons of cold groundwater to the surface for solar heating to about 45° C in summer, and return the heated water to the groundwater table for storage as a warm, buoyant lens for heat recovery in winter. The practicality of such a plan has been given careful study with much help from the geologists, hydrologists, and environmentalists of the U. S. Geological Survey, Environmental Protection Agency, and the National Water Well Association. Computer models of the "thermal onion" developed around heat storage well and heat recovery expectations have been made at the ETH, Zurich, Switzerland which suggest that a pilot experiment would provide valuable proof of the principle and indicate the scope of its applications.

A much more serious constraint on brine pond usage is environmental. The concrete tank holding the pond survived the pressure of foot-thick ice without damage, but subsequent bulldozer operations near the tank undermined its footings. This provoked the thought that a serious leak in a large hypersaline pond could discharge brine into the vadose zone and eventually contaminate groundwater to such an extent that the water quality of wells in the vicinity would suffer for years. For this reason the present experiment has been terminated. Clearly, brine ponds should be built only in places where they do not impose an environmental threat, as in connection with marine aquaculture tank or polder heating where inadvertent salt leakage would be of no consequence.

Theoretical and experimental study of the physics of brine pond efficiency indicates that the 20 m², 20-ton experiment just concluded, represents the lower limit of practical size. Theory suggests that a more nearly optimum pond would be about 10,000 m² (one hectare) in area and 3 m deep with a much more gentle pycnocline developed in the upper 1 m. The pond should be quite fresh in the upper 20 cm and reach higher salt concentrations below the 1 m level. Since the coal layer tends to be neutrally buoyant at 40% brine concentrations it thus becomes involved in convection and shades the bottom layers. A lower salt concentration would prove advantageous in terms of heat collection and heat storage capabilities. Wave and wind-stirring action on a large pond would have to be suppressed, possibly by floating a grid of wooden booms on the surface. Large solar ponds are being studied at the Dead Sea Works in Israel. It would be very instructive to conduct similar experiments in the less favorable climate of New England.

SEASONAL PERFORMANCE OF A BRINE POND SOLAR HEAT COLLECTOR
IN NEW ENGLAND

There is an abundant supply of natural energy in this world (see Table 1) but the problem is to convert it into useful forms in simple ways.

New England and the Canadian maritime is a cloudy, energy-starved part of the world where heat and power are expensive and highly treasured commodities. In the absence of direct sunshine much of the time, there is, even so, an abundance of light, heat, and power available in the diffuse radiation from the sky. The experiments have been made which utilize that natural resource throughout the year, by integrating the direct and indirect solar flux in an optical trap. The principles involved are these:

For purposes of biofuel production, space heating or cooling and numerous other applications, low grade heat can be produced by trapping sunlight in brine ponds (see H. Tabor, 1961). Both the direct beam and diffuse radiation from sunlight suffers refraction toward the normal. In this way the illuminated hemisphere of the sky can be seen from below the water surface as a "manhole" containing a compressed image of the sky from horizon to horizon. Beyond the rim of the manhole the upwelling light suffers total reflection at the free surface and is thus trapped and eventually absorbed and converted to heat by the blackened bottom and sides of the tank which conduct heat to the water volume. By this means a volume of water (or other liquid) can absorb daylight and store its heat.

Table 1

ESTIMATES OF POWER LEVELS IN NATURAL PROCESSES

	World Total Power Watts
Direct solar (incident)	10^{17}
Direct solar (at earth's surface)	10^{16}
Photosynthesis (marine)	10^{14}
Photosynthesis (arable lands, forests)	10^{13+}
Ocean thermal power (tropical) (polar?)	10^{13}
World power demand at present	10^{13}
Bioconversion (plant residues, manure)	10^{12} (gas only)
Bioconversion (garbage, sewage, pulps)	10^{12} (gas only)
Surface wind power (Trade Winds) (atolls)	10^{12} (steady)
Surface wind power (middle latitudes)	10^{12} (variable)
World total rainfall (including oceans)	10^{12}
Hydroelectric power (rivers)	10^{11}
Hydroelectric (evaporative sinks, Red Sea)	10^{11}
Human metabolism (present population)	10^{11}
Geothermal ("ring of fire", mid-ocean ridges)	10^{10}
Tidal flow	10^9
Evaporative exchanges (Med, Red Sea)	10^9 (KE of inflow)
Kinetic energy of Gulf Stream, Kiroshio	10^8
Ocean surface waves at coastlines	$10^6/\text{km}$

NOTE: The table above results from a study of the energy involved in geophysical processes (including gravitation), biological and botanical processes (including those induced by man); ranking these processes by order of magnitude of their world total power; and studying those points in each natural cycle where man may intervene to extract power, return it to the natural system, and estimate the probable disturbance(s) produced by his so-doing. A further object is to establish the power level at which man may survive indefinitely within the limits imposed by the natural energetic regimen. For details see W. S. von Arx, 1974, Energy: Natural Limits and Abundances, Trans. Am. Geophys. Un. (EOS) Vol. 55, No. 9, 828-832.

The efficiency of trapping is dependent upon several factors, namely; a clean free-surface, a tank with a suitably blackened bottom and side walls to convert visible radiation into heat, low rates of heat loss through the tank walls, heat storage in the bottom, and low evaporation from the free surface. Radiative losses through the free-surface tend to be small because the warmed water emits mainly in the long wavelength region of the infrared to which ordinary water is nearly opaque. But matters can be improved if two layers are employed, the bottom layer being a brine of high density so that convection cannot penetrate to the free surface, and of high refractive index so that the apparent angle of subtense of the manhole (defined by the critical angle of total reflection) be made as small as possible.

The physics of this situation is like that of the "fish eye" camera and is given by Snell's Law,

$$n \sin I = n' \sin I'$$

when n is the refractive index of water (about 1.33); n' that of air (effectively 1.00); I is the angle of incidence of the ray passing from water to air; and I' is the angle of refraction. As the angle of incidence increases, I' will also increase because n/n' is greater than unity. Eventually, I' will reach 90° , and if I is still further increased total reflection will occur and the angles I and I' will thence forward remain equal (the "Mirror Law" applies) and the ray is "trapped," as shown in Figure 1.

While an open tank cannot track the solar diurnal motion, it does collect both a component of the direct beam and the hemispheric integral of diffuse light from the sky. Both are partly reflected. The

EARTH (HEAT STORAGE)
 Critical angle reached when $n \sin I = n' \sin 90^\circ = n'$.
 Total reflection occurs when I crit is exceeded.
 Mirror Law then applies, i.e., $I_v - I$ crit

Note: I crit for brine ($n_v - 1.4$) is ca 45° , but is never reached because grazing ray at free surface is bent to enter brine at $I = 48.6^\circ$ by fresh water layer.

reflection coefficient for a quiet water surface ranges widely from about 2% at normal incidence to 3.4% at 50° then increases rapidly to 13.4% at 70°, 34.8% at 80° and virtually 100% at grazing incidence. This means that in addition to the cosine of the zenith angle of the sun there is an increase of reflected light as the sun approaches the horizon. For this reason lightly overcast skies may be almost as effective emitters as the sun on perfectly clear days. Indeed, measurements of whole-sky illumination show that insolation varies by a factor of only a little more than two under clear and overcast skies during the same season.

In colder months of New England winter the fresh water layer of the solar pond freezes. While the ice is new and clear the reflection coefficients for open water apply. But as the ice grows white or becomes snow-covered, not only is its albedo high at all angles of incidence but the light that does penetrate is attenuated and diffuse. Measurements under snow-cover indicate that transmission losses may be reduced by as much as 80% but that the diffusion of incoming specular radiation causes the light level to be almost independent of the solar zenith angle. This effect lengthens the period in which the (attenuated) direct rays can be absorbed rather than specularly reflected.

Description of the Experimental Pond

Figures 2a and 2b show the right cylindrical, insulated brine pond of 20 m³ capacity that has been built on the premises of the New Alchemy Institute, Hatchville, Massachusetts, and coupled by a wind-electric driven heat-exchanging system to the New Alchemy polyculture structure which they call the "ARK". The ARK experiment is directed toward the

Pond in Concrete tank 20m² area, 1.2m deep
Styrofoam insulation on sides

FIG 2a

FIG. 2b

closed-cycle production of fish protein and edible plants of mainly sub-tropical varieties which require heat during periods of radiational cooling at night and during periods of heavy overcast. The brine pond prototype is being studied as one means of collecting, storing and delivering solar heat to the ARK when direct sunlight is unavailable. (Successive reports on the ARK experiment are to be found in the annual issues of the Journal of the New Alchemy Institute of which Volume 4 (1976) is in preparation.)

In late September 1976 ground was broken for the construction of the solar pond in the form of a concrete tank 1.15 m deep, having a surface area of 20 m². The side wall of the tank was wrapped in 2-in thick styrofoam insulation before backfilling but the bottom was not insulated so that the dry ground beneath the tank could provide additional heat storage volume. The pond wall was fitted with a spiral manifold of 1-1/2 in. EMT heat-exchanger tubing carrying fresh water, and electrically connected to a sacrificial cathode of zinc mounted in the center of the pond. Next two metric tons of pea-size semi-bituminous coal were placed on the bottom and the tank half filled with tap water. Trouble was immediately apparent because coal for shipment overland is required by the EPA to be coated with crude oil as a dust suppressor. The tank was drained and detergent applied to remove the oil - a very messy and time-consuming process which required much stirring and seemingly endless skimming of sludge from the surface.

Once clean, the coal was again flooded and stirred thoroughly to remove trapped air and the tank refilled to the half depth level. Next, some five metric tons of calcium chloride were added to form a very dense brine, the heat of solution evolved being used to supercharge the

concrete bottom and subsoil with about 10^6 BTU of heat. A temperature of 42° C was reached, and convection swept the coal into the volume to produce an opaque, jet black mixture. After a week the coal began to settle out and the brine temperature dropped to about 32° C. Fresh water was added and an additional 3 metric tons of calcium chloride dissolved thus filling the tank to a working depth of 1 meter at a brine concentration of 40% by weight. Convection produced a virtually uniform mixture of brine and coal at about 29° C, which was then covered very carefully with a cap of fresh water 15 cm thick. The pycnocline thus produced remained fixed at 1 meter above the bottom since 1 October when the final fresh water capping was done.

By mid-November the coal settled out and the brine above became crystal clear. The refractive index in the brine layer was everywhere greater than 1.4, as expected, and varied with temperature. Under overcast skies the brine layer convected as a single cell, rising in the middle and sinking at the walls of the pond. Under bright mid-day sun the convection sometimes broke up into Benard cells of varying sizes and shapes but settled back into the simpler single cell mode in late afternoon. Owing to the unusually cold and stormy weather of the past fall the brine layer of the pond did not achieve its expected rate of temperature increase but held about constant at 24° C even through stormy overcast periods. The thermal losses were therefore just about equal to the solar gains as winter approached. The fresh water cap, on the other hand, changed temperature with and by nearly the same amount as the air temperature, even having developed a skim of ice during early frosts. Two cm below the ice the fresh water temperature was measured to be 4° C which indicates a state of stable stratification and that a

skim of ice serves to prevent wind-driven overturning in the fresh water layer. The fresh water layer thus serves as a mechanical as well as a radiational barrier against heat losses and from the hot brine below it.

Effects of Cold Winds and Precipitation

Experience shows that a thin layer of ice on the fresh water layer proves to be no obstacle to the performance of the pond, but is actually a benefit. In sub-freezing weather, which may be very windy, the fresh water layer is overturned by the wind and there is some upward mixing of salt; enough to make the fresh water layer "taste" of salt. These effects are greatly reduced by placing a wind break of concrete blocks on the wall of the pond to make the air flow turbulent and generally slower. Ripples and seiching were almost eliminated. When a skin of ice forms, the overturning stops. As the ice thickens the salt is frozen out and returned to the brine layer. Upon melting the once frozen layer becomes sweet to the taste and the screening effect of the fresh water layer is thus fully restored. Ice produced by nocturnal cooling is generally clear and no serious barrier to the next day's incoming radiation, but the refractive index of ice is slightly (1.31 vs. 1.33) lower than that of liquid water in which case the critical angle of total reflection is increased. When the ice grows thick, scattering from trapped bubbles and reflections from crystal boundaries raise the albedo of the surface layer to produce an observable net loss of radiative influx. These unfavorable effects suggest that a transparent cover could help matters, but would prove troublesome and expensive on large ponds. When ambient temperatures are above freezing the fresh water layer alone forms an effective cap and rainfall seems to be generally sufficient to compensate for evaporation.

When the solar pond surface does not freeze but is exposed to snow, sleet, or graupel, these solids float. If they form a transparent slush and are allowed to remain on the surface to melt, the heat of fusion is drawn from the fresh water layer, cooling it eventually to 0° C. Figure 3 shows the resulting thermal profile measured during the late fall-early winter of 1976-77. It is interesting to note that fresh water of maximum density (at 4° C) was found as little as 2 cm below the surface.

Rainfall at low temperatures poses still another problem. Each raindrop penetrating the free surface creates a powerful little ring vortex which moves swiftly downward into the fresh water volume where it bounces off the pycnocline and eventually mixes away as it loses energy through viscous drag and expansion. The fresh layer of the solar pond is thus cooled from top to bottom by a chilling rain and the thermal gradient between the brine and fresh water layers becomes less steep and the upper part of the brine layer suffers some heat loss.

Yet rainfall has some advantages. It replenishes evaporative losses from the fresh water layer, and when heavy enough, causes the pond to overflow thus carrying away accumulations of leaves, pollen, dust, and hay. These materials can also be concentrated by simply reducing the surface tension of the pond with a drop or two of dishwashing detergent and scooping them out with a dip net. (The effect of this detergent film is spectacular.) When the pond is iced over, the wind clears off such debris as fast as it accumulates.

It seemed unfortunate, at first, that funding and procurement delays postponed the start of this experiment until early winter conditions

FIG. 3

prevailed. But this, instead, makes the critical point that the brine pond can hold its own against severe climatic adversities...and indeed even show small gains of heat storage on favorable winter days. It seems probable that once enough time has passed for earth beneath the pond to have warmed up to an equilibrium temperature of about 16° to 20° C that a representative value of its heat storage capacity (measured with reference to the weekly average air temperature) is about 16 therms (1 therm = 10^5 BTU). But this is not a useful statement of storage because the air temperature varies with season. If the heat storage is recalculated with reference to a fixed temperature such as 20° C the mid-summer heat reserve is 33 therms while that of mid-winter is 3.5 therms.

Control Experiment vs. Brine Pond Performance

In addition to the insolation measurements made regularly with an Eppley pyranometer for the Environmental Science Laboratories at W.H.O.I., and a daily record of insolation made with a Beaufort recording pyranometer at the site of the brine pond, the heat producing effects of both direct and diffuse radiation have been made with a pair of black, liquid-filled embossed steel panels each of 2 m² area. One panel was mounted vertically on the north wall of a lean-to greenhouse with no glazing or insulation beyond that of the greenhouse itself to measure "functional" heating under those conditions. This panel operated most effectively during the interval between the two months preceding and the two months following the winter solstice. During this period it collected between 11,000 and 18,000 BTU/day. The other panel was mounted outside the greenhouse at an angle of 10° plus the latitude

(42° N), backed by a 2-in thick panel of urethane foam insulation, and glazed by two layers of light-diffusing acrylic paneling (made for overhead fluorescent light fixtures) spaced apart by 1/2-in. This collector was most effective from the autumnal to the vernal equinox and yielding between 14,000 and 22,000 BTU/day depending on weather conditions. Running in parallel the two panels (total area 4 m^2) collect between 18,000 and 36,000 BTU/day. Neither panel was steered to track the sun's diurnal motion or changing declination. Solar tracking could have increased their maximum output to 44,000 BTU/day. It was observed that though the maximum output of the panels is less than optimum and least on cloudy days, the noon peak of heat collection on overcast days was usefully broadened by two or three hours before and after the sun's meridian passage as is the case for the pond.

The pond is essentially a horizontal plate collector, but, owing to the refraction of light entering the water, the zenith angle of the apparent sun is considerably less than that of the true sun so that there is very little wall shadow on the pond floor. This refraction has the effect of "tilting" the pond and of providing a semblance of solar tracking, while at the same time the pond is accepting the hemispheric integral of diffuse radiation from the whole sky. While the refractive "tilting" toward the source of specular radiation is of some consequence, the $\cos Z$ effect of foreshortening remains and dominates its collection efficiency. These and the effects of air temperature are shown in Figs. 4a,b.

The rate of heating of the pond depends upon its starting temperature. The maximum rate of temperature rise observed was 1.2° C/day which means that just under 100,000 BTU were collected and stored per day; close to $5,000 \text{ BTU/m}^2/\text{day}$. In that the pyranometers and flat plate

FIGURE 4a OPTIMIZATION OF COLLECTOR TILT ANGLE

FIG. 4b.

collectors measured the incident radiation at about $20,000 \text{ BTU/m}^2/\text{day}$, the pond collection efficiency is therefore about 25% (24% when exact figures are used).

Future Developments

Higher collection efficiencies (and storage capacities) can be expected by making the pond deeper and the pycnocline less steep. A recent paper by Gad Assaf (Solar Energy, 1976, 18:293-299) recommends such changes in design, especially for solar lakes where wall shadow effects are of little consequence. A 20 m^2 pond probably represents the lower limit of size in which the foregoing physical principles may be tested. The upper limit of size is probably determined by the design of the heat transfer system used to withdraw heat from the brine pond and deliver it, without salt contamination, to the site or apparatus being heated. This heat exchange problem is important, difficult and requires exhaustive study. Heat storage over periods in excess of a few weeks is also necessary because a small pond collecting heat in summer could, with semi-annual time-constant storage, do the work of a pond ten times bigger in winter. For this reason much thought and planning has gone into the annual-cycle, groundwater heat storage system concept. Briefly, this involves pumping groundwater to the surface for solar heating in summer and return of the heated water to the phreatic zone for storage as a buoyant "thermal onion" from which summer heat can be recovered in winter (Fig. 5). Werner and Kley of the Institut für Geophysik, ETH, Zurich, have done some preliminary experiments, developed a computer model of such a heat storage well system and reported their findings in

FIG. 5

AN ANNUAL CYCLE GROUNDWATER HEAT STORAGE SYSTEM

Journal of Hydrology, 34 (1977) 35-43. Experiments on suitable solar heat collector designs, pumping systems, studies of possible heat losses through evaporation into the vadose zone and of pre-heat and advective losses have been given some attention here.

Practical Applications

Solar heat is essentially (and most economically) considered as a resource adapted to domestic and commercial space heating loads requiring temperatures well below that of boiling water but very large thermal capacities. Household heating and hot water, greenhouse heating, aquacultural pond heating, bioconversion systems and so on, all demand heat in the range between body and scalding temperatures, i.e., 35 to 50° C. These temperatures are easily reached by a brine pond in summer or simply by laying out a black hose filled with water under the summer sun. The question is then how much solar collector area should be provided?

(a) Household heating

Taking the figure of 24% as the representative collection efficiency an unsheltered brine pond in the latitudes of New England and that such a pond can maintain an internal temperature some 20° C above ambient it can be expected to collect and deliver at least 5,000 BTU/m²/day at "body temperature" in mid-winter. A small house (100 m² plan area) requires about 500,000 BTU/day for space heat and hot water. To meet 100% of the household demand a pond area of 100 m² would be required, i.e., a pond area equal to the plan area of the house. The space heat demand could be met by radiant heat plumbing which operates satisfactorily when interior surface temperatures are held between 15 and 20° C, that is, near skin temperatures. Domestic hot water supplies would require added

heat to reach 50° C or so but since the heat demand for hot water is normally only 20% of the household total demand and the "cold" water supply is already warm the fuel demand could be reduced by about 50%. In the end, then, the fuel demand for a small house could be reduced by 90% in mid-winter if the pond area equals the house plan area. To stretch the thought one step further; if the "body temperature" water from the pond could also be used to supply the low grade heat needed to operate an anaerobic digester fed with sewage, garbage, and garden waste it seems likely that the methane-hydrogen produced might supply the high grade fuel needed for hot water heating and cooking ... and the digester sludge returned to the garden as fertilizer for food production. This system approach is visionary and most applicable to open country or suburban living, but it is a germinal possibility that deserves rigorous practical and economic study.

(b) Greenhouse heating

The temperature at which a greenhouse is run depends very much on what is being grown, and may range from 15° C for vegetables to 30° C or more for tropical flowers. In either case it is far more efficient to heat the plants than the whole greenhouse. Heat delivered at the proper temperatures through a grid of pipes buried under an inch of sand or earth (and possibly isolated from the growing soil by a sheet of durable plastic) can provide a micro-climate in which the roots are warm and the foliage made both warm and moist by the rising water vapor which also produces gentle ventilation so essential to healthy growth. Growing benches are convenient, but beds on the greenhouse floor are thermally more efficient.

A greenhouse is itself a solar collector by day and often must be vented to avoid overheating. At night the heat loss through a single layer of glass is characteristically near $20 \text{ BTU/hr/m}^2/^{\circ}\text{C}$ difference between inside and outside air temperatures. The laps of glass panes sometimes open enough on windy nights to leak warm air especially near the ridge and increase the heat loss rate. But if the plants are warmed from below the ridge temperature may fall considerably without causing crop loss except near the walls and ends where cold air drainage is severe. Plastic covering under slight positive pressure serves to reduce both radiative and advective heat losses. This and growing bed heating can reduce the windy night heat demand by as much as 50%.

The heat demand of a commercial greenhouse on a windy, mid-winter night can be enormous; approaching $1000 \text{ BTU/m}^2/\text{hr}$ through bare glass. In a 14 hr night, or nearly 15 hrs from dusk to daylight, the total demand can be $15,000 \text{ BTU/m}^2$ of glass. But by plastic envelope greenhouse shrouding and bed heating rather than whole house heating the crop will survive the night with a heat supply of $5,000 \text{ BTU/m}^2$ of growing area. Since this is about the yield of a solar pond, area for area, it should be possible to run a commercial growing operation in winter almost totally by solar heat; using low pressure steam or hot water lines only in emergencies or at greatly reduced demand. Even if bare glass, whole-house heating were employed, bed heating by solar collectors could cut fuel demands by at least 30%.

In one small-scale experiment a "cool" (10°C) greenhouse has been operated successfully with an area for area solar collector and bed heating system with only 20% emergency supply. The latter was essentially automatic, being provided by a wind-driven electric generator coupled

to a resistive load in the hot water heat storage tank. On windy nights the wind chill was balanced by wind generated heat.

The heat requirements of a greenhouse cannot be stated in BTU generalities but must be taken with reference to an optimum growing temperature and the quantity of heat (in BTU) required to maintain the plants at or close to that temperature. Some daily cycle of temperatures may be desired as is the cycle of light and darkness, or even of humidity, to control germination, fruiting or blooming to meet harvesting or cutting schedules. Commercial growers are acutely aware of these requirements. Now power failures, fuel costs, and shortages add to their concerns. The autonomy of solar and wind-power heating is appealing to greenhousemen and deserves our best efforts to provide the means for utilizing these heat control resources with time constants of at least several days duration built in as design criteria.

(c) Aquacultural heating

The rate at which carbon is fixed in aquaculture is dependent on water temperature as well as the availability of light and balanced nutrients. Open air ponds or polders, like greenhouses, are horizontal solar collectors but have more heat storage capability. Unfortunately the higher the pond temperature and lower the relative humidity of the night the greater is the heat loss due to evaporation and radiation to the night sky.

Heat must often be supplied as well as power for stirring operations. For example, a local aquacultural pilot experiment consumes some 6,000 gal of fuel oil and 50,000 KWh of electric power each month. This amounts to about 30-million BTU/day and would require a solar pond area of 6,000 m²

to be run by solar energy alone. Since there are losses in heat transfer and conversion from thermal to mechanical power a pond area of $10,000 \text{ m}^2$ or 1-hectare would more likely be required: a large but not unmanageable size.

The need for mechanical power in aquaculture lies in pumping and stirring operations. Since the solar pond produces only low grade heat it would seem worthwhile to study the feasibility of employing Rankine cycle engines which run at low thermodynamic efficiencies and are physically quite large but can be effective when operated with Freon or ammonia as the working fluid. Rankine cycle engines date from the last century when 10 to 50 HP units were produced.

Alternatively it may be more practical to convert some of the biomass to high energy fuel (hydrogen and methane) through anaerobic digestion to run ordinary internal combustion Otto cycle engines. The sludge from digesters is very fertile and can be returned to the growing polders to "pay back" the debt of used biomass. But body temperature heat is required to maintain the endothermic microbiological digestion process. Here it would be appropriate to borrow solar heat and return that which is recovered by combustion to the growing ponds as available heat.

Site Limitations

A cautionary remark is appropriate here. A brine pond, though simple and relatively inexpensive, poses an environmental threat if it leaks. Brine discharged into the vadose zone will eventually reach the groundwater table and contaminate potable water in nearby wells. Such contamination could persist for years and migrate down the hydrologic gradient. This consideration should restrict brine pond use to areas where groundwater is already too badly contaminated to be used for human or

agricultural purposes, or in areas where seawater floods the phreatic zone. Their use in connection with maricultural polders or incubation tanks is appropriate. In this connection it is hoped that some day a full hectare brine pond 3 m deep with perhaps 2 m of sea water concentrate as the brine and a 1 m graded pycnocline can be built on a seacoast in middle latitudes to work out the niceties of physical design.

Inland, it seems necessary to provide alternative solar collector systems such as hose grids or spirals. Studies of black EPT hose arrays in sunlight during the past summer show that temperatures of 47° C can be reached at mid-day in one hour. If the hose lengths are spaced one diameter apart on a north-south grid both shading and sun angle fore-shortening by earth rotation are minimized. The cost of unsheltered hose arrays is less than half that of the least expensive commercially available flat plat collector, area for area, and since the temperatures attained are less than the softening or melting temperatures of PVC or polypropylene, these inexpensive materials may be used even in low pressure flow systems.

Concluding Remark

These simple, preliminary experiments on solar heat collection, storage and utilization have demanded that a whole set of new technological premises be coupled to existing knowledge of astronomical and terrestrial systems. It is a fresh and imperative challenge; intriguing and engrossing. Man's future depends on his mastery of these tentative enterprises. Taking the course that sophisticated thought leading to simple, decentralized, inexpensive and durable systems is best, and that man can arrange his social needs to fit into, rather than control, the

natural order, he may survive with some dignity. Read the recent book Ecology and the Politics of Scarcity, Yale, Porter Prize thesis by William Ophuls, 1977, published by W. H. Freeman, San Francisco, for some brilliant insights; and add then, the thought as Paul Valery puts it, "The trouble with our time is that the future is not what it used to be."

Bibliography

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