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FOUR METHODS FOR COMPETITIVE PRODUCTION OF FRESH WATER THROUGH SOLAR DISTILLATION

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ABSTRACT

It is entirely possible that the problem of obtaining competitive fresh water from saline water will not be solved in a sudden breakthrough by any new scientific discoveries of principles, mechanisms, or even new materials, but will have to be solved by engineering application, extension and combination of existing concepts and materials. This paper develops several such engineering combinations using solar energy for the separation, which it is hoped will lead to designs providing fresh water from sea water at costs quite competitive with natural fresh water and with water from other conversion methods. Preliminary designs seem to indicate that these hopes can be realized at present for several of the methods and that probable improvements in plastic films could make another method competitive also.

INTRODUCTION

Solar radiation is used as an energy source for the following reasons: 1) because it is the only energy available (in space or on the beach); 2) because it is available at a very high temperature (solar furnaces); 3) because it is the cheapest source of energy; 4) novelty on misapplication. The third case has by far the greatest potential but is surprisingly unimportant at present due to the dilute nature of the energy and the very large area required to collect commercial quantities of energy. The energy can be concentrated by reflectors, but the cost of constructing reflectors seems prohibitive for competition with other large scale sources of low quantity heat. A cheaper way of collecting the energy for transport is to use a cheap fluid such as water liquid or water vapor to collect the energy, since it can be readily moved to the point of application. One of the most likely applications of this energy would be the distillation of the water itself and indeed solar distillation of sea water has received considerable attention. All methods of solar distillation considered in this paper will use very large basins of the sea water to collect the heat and the basins will in general be as nearly natural as possible. The methods will differ in how the energy is retained in the system and how it is used in distilling off the fresh water product.

The various methods result from an initial choice of approach to the problem and assumptions concerning the problem. For the first method the heat will be used directly to vaporize the water throughout the basin and a clear plastic film barrier will be used to prevent the loss of the vapor to the air while premitting the solar radiation to pass to the basins.

It will be assumed that the cost (square foot, year of life) for this plastic cover will be sufficiently low that competitive fresh water can be produced in a single effect still providing the cost of the plastic were made the major cost of the design. This requires that the costs other than plastic, such as a fresh water collecting troughs, sealing the barrier edges, and of heat transfer must be made relatively small, but that the plastic film barrier itself could serve as the condensing surface. The second method makes the counter assumption that the plastic film costs alone are excessive for the production of competitive water unless the energy collected can be used more efficiently as in multiple effect evaporation. This involved additional expenses for the heat transfer, which must be more than made up for by the increased production of water. The third method eliminates the plastic cover entirely and carries the heat in liquid water only, to separate evaporation where the heat is used for the vaporization and fresh water production. Vaporization of the heating water is prevented or at least restrained by the addition of a molecular layer of organic to the free surface. The efficiency of heat collection would be reduced but the evaporation could be multiple effect. The final method speculates upon the possibility of reducing heat collecting costs to a minimum by removing all restraints from the water surface and using the air to carry the moisture. It requires a sizeable difference between wet and dry bulb air temperatures, rather constant wind direction and a lack of excessive air turbulence. These conditions seem less restrictive when one considers that a large fraction of the worlds desert area are bathed by the trade winds and that in these locations the air is often dry.

METHOD I

Our first approach will be to formulate a simple design in which the cost of collecting and using the solar energy for the distillation of water will be minimized. Functionally it will be similar to current designs as shown in Figures 1 and 2. The heat will be collected in large basins of water, the heat will be used directly to vaporize water and clear plastic covers can serve both to contain the vapor and to cool and condense the vapor.

Basins

In current designs, such basins would be covered by a black plastic waterproof layer on top of insulation in order that a large fraction of the incident radiation would be absorbed and that the heat would not be lost. It is true that the heat loss by seepage of heated water from the basins could be quite serious, but heat loss by conduction into the ground from large, reasonably constant temperature basins would be quite negligible in steady state operation. Since net seepage of water into the basin in an amount equal to or less than that distilled would result in absolutely no heat loss, we shall dispense with both water proofing and insulation by placing our basins below mean sea level in areas normally under water, such as lagoons, bays, on even off beaches. Considerable flexibility in choice results from the fact that the operating depth of the basins is not important to steady state heat economy and that the basins need not be level. Two or more inches in mean operating depth is desirable in order to keep the temperature reasonably constant both day and night and more than a few feet is

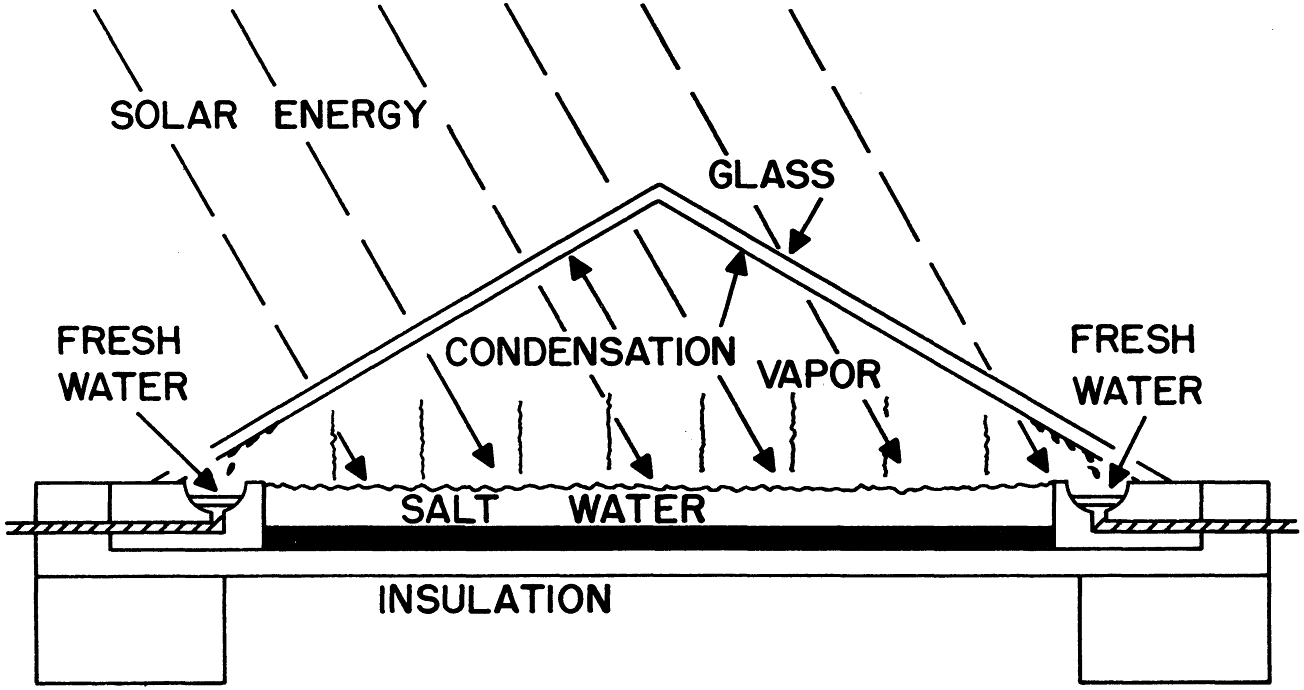


Figure 1. Lof Type Glass Covered Solar Still.

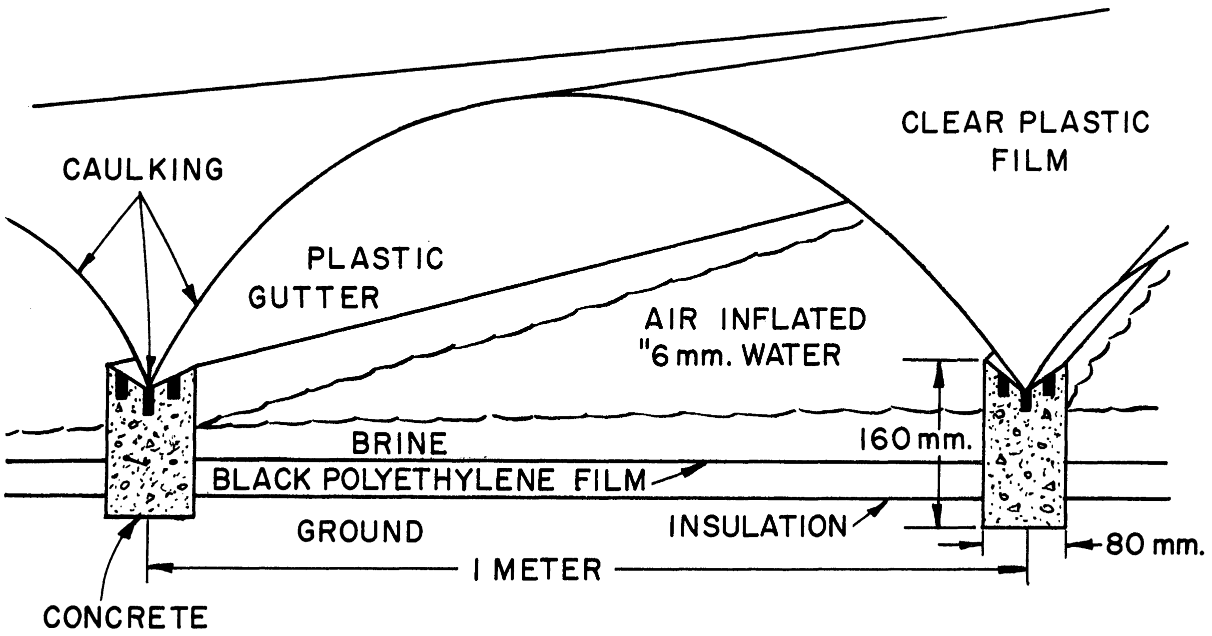


Figure 2a. DuPont Plastic Covered Still.

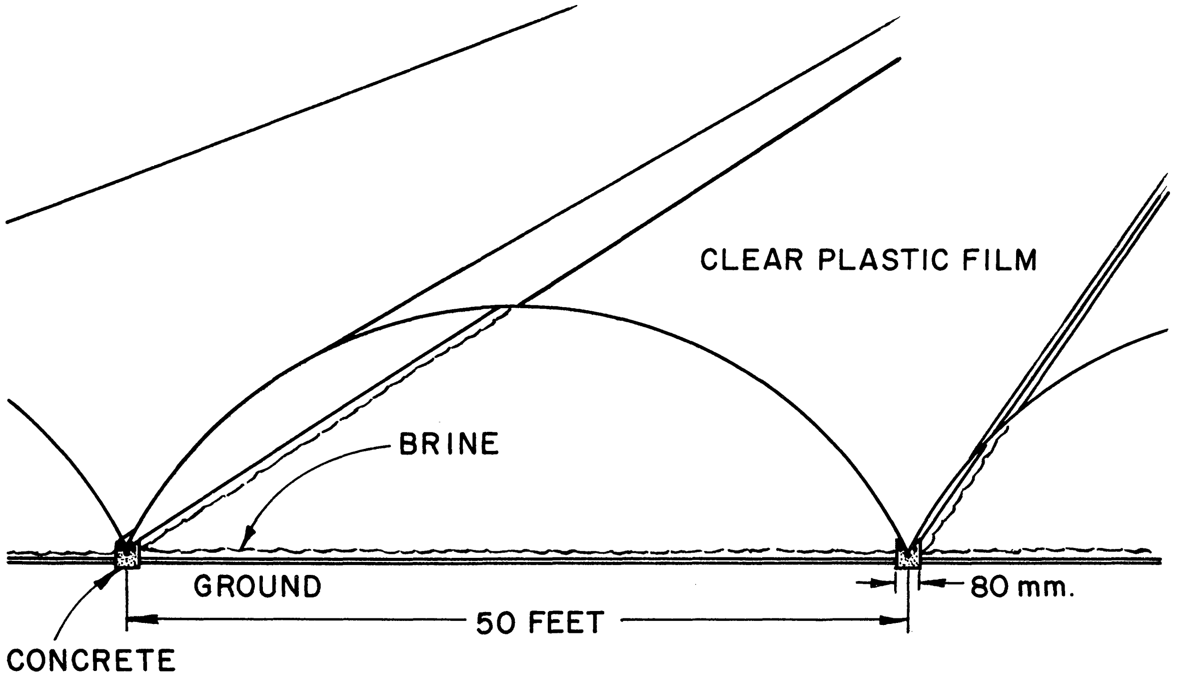


Figure 2b. Proposed Large Scale Single Effect Still

undesirable as it makes subsequent construction more difficult and increases the time required to reach steady state. It is still desirable to blacken the basin floors, but this alone can be done cheaply by depositing either a black natural organic silt, if available, or carbon black.

Plastic Vapor Barriers

A transparent plastic cover would serve to pass the solar radiation and prevent the loss of the water vapor to the outside, and as it would be cooled by the outside air, it could also serve to condense this vapor and direct the condensate into the fresh water collecting troughs bounding the basins. The troughs will also provide a means of anchoring the edge of the plastic cover and sealing it against vapor loss. In current designs such as Figure 2, the construction of the troughs and the vapor tight sealing of the plastic barrier to the trough represents a major expense, but, since these costs for any trough design will decrease in essentially inverse proportion to the basin's linear dimensions, we will make these costs relatively small by using large unit basins. The maximum economical size of such basins, as well as their optimum shape, is determined by considerations involving chiefly the plastic barrier whose material costs plus fabrication and erection costs will be the dominant factor in the total costs.

The first consideration is that the force of the wind on the plastic surface will increase in proportion to the linear dimension of the surface along the direction of the wind's movement. Thus increasing the basins dimensions will require either a proportionate increase in the thickness and therefore weight and cost of the plastic film or else a periodic reinforcement of the plastic film. Since steel provides the needed strength far more cheaply than any transparent plastic film it is planned to use steel wire to reinforce the plastic film. The second consideration is that large sections of plastic film can be manufactured only as strips of limited width but of virtually any length. These considerations combined suggest that the plastic film strips can be most easily fabricated into wide and possibly very long periodically reinforced rectangles by sealing a number of these strips together edge to edge and sealing the reinforcing wire into this seam. Considering the extent of plastic to be so fabricated, it would pay to design and construct special equipment to seal strips from a number of rolls together simultaneously on the plant site as the combined sheet is being erected. Figure 3 illustrates this type of equipment. If these wider sheets were not then of sufficient width, a number of these could be passed through the fabricating equipment for a second time producing a still wider sheet. Guiding these wider sheets through the equipment would be made easier if a wire had been sealed in the edges of each combined sheet on the first pass.

With such very long and fairly wide reinforced plastic sheets, the shape of the basins themselves should be of necessity long and rectangular, and the plastic canopy would be erected in the shape of a long prism whose cross-section might vary from triangular to semi-circular. A suggested cross-section may be seen in Figure 4. The taunt wires determine the general shape and a slight air pressure produces the curvature between the wires. The wired will be supported and anchored at the ends of the basins and for very long basins the wires would also be supported at intermediate points by concrete poles, possibly guyed erect. Erection would be greatly simplified by the presence of the wires, especially since these could extend out the edge of the plastic and be attached to a winch or a drawbar of a tractor.

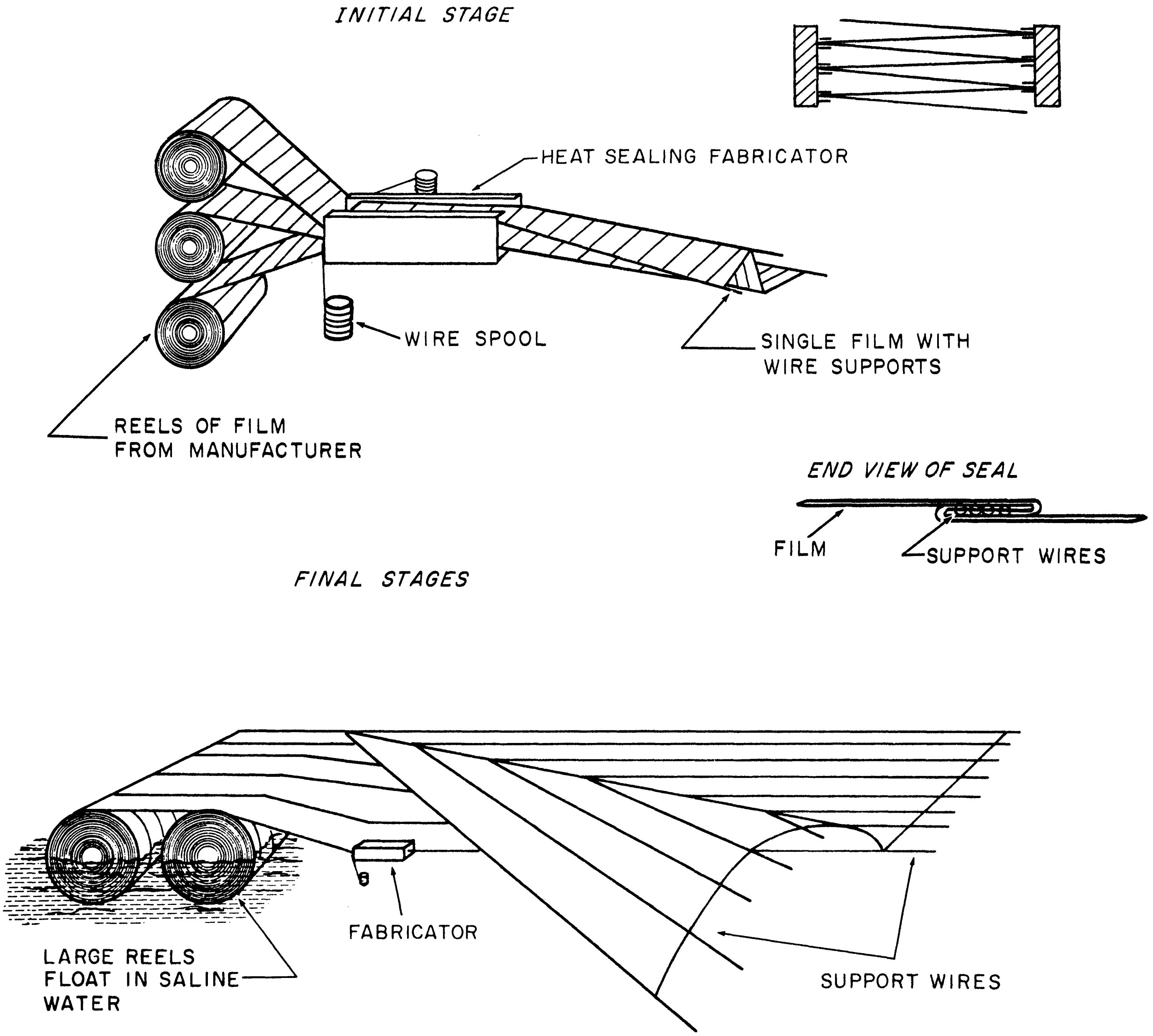
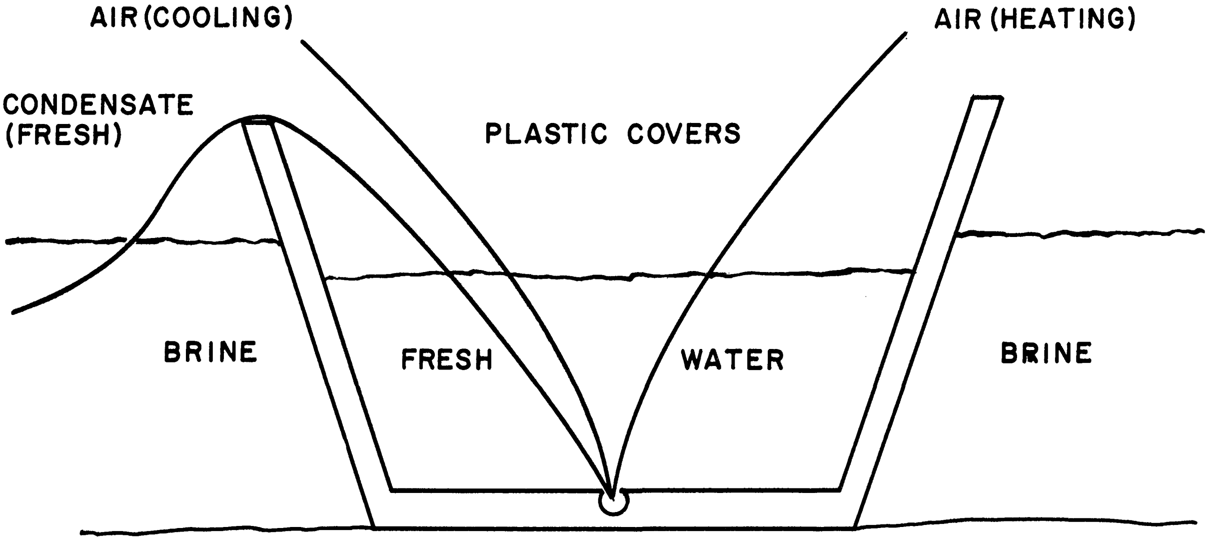
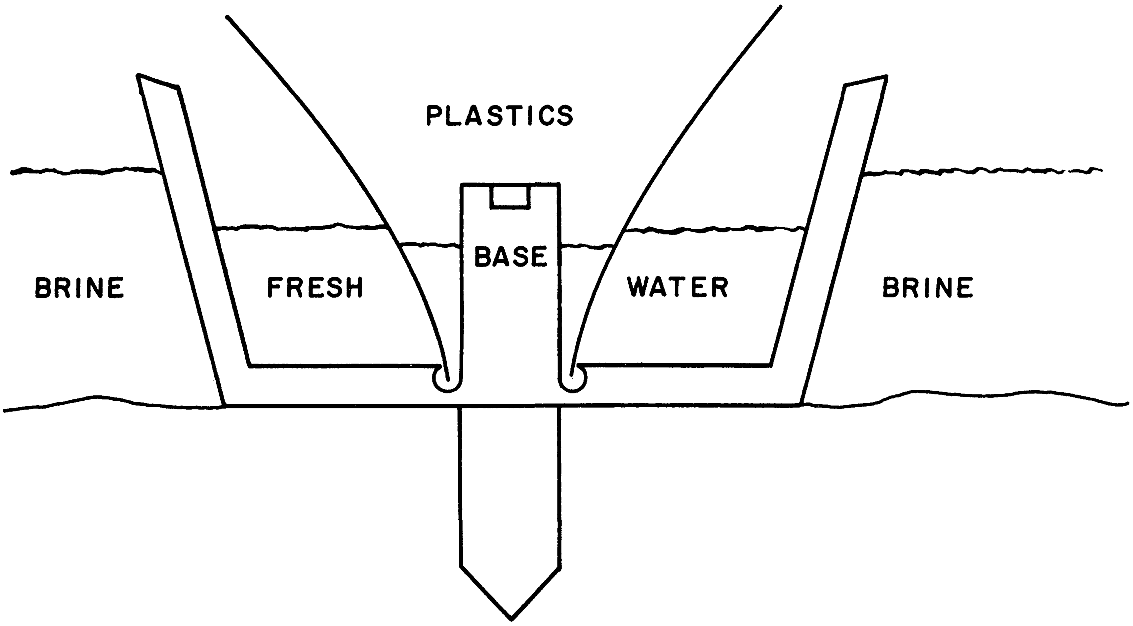


Figure 3. Heat-sealing fabricator preparing large single film.

DETAIL OF FRESH WATER TROUGH



GENERAL SECTION



SECTION INCLUDING BASE FOR SUPPORTS

Figure 4. Detail of Trough.

Troughs

Fresh water collecting troughs can be very simple concrete structures a foot or two deep and a foot or three wide occasionally pinned to the ground and with a groove along the center provided for the occasional anchoring of the reinforced plastic edge. A vapor tight seal for the plastic will be obtained whenever the water surface in the trough is above the edge of the plastic edge. The construction of these troughs using forms would be simple, rapid and cheap and the subsequent installation of the plastic during its erection would be extremely simple. This design would expose the surface of the fresh water to the outside air allowing some evaporation but as the surface would be relatively small, the evaporation would not be greatly noticed. There are some advantages to adding an interior light plastic trough through which the entering sea water could be passed in order that this sea water rather than the fresh water can serve as the sealing fluid and in order to preheat the entering sea water.

As previously mentioned, the considerable expense of waterproofing the basin floor can be eliminated by placing the basins below sea level on land previously covered by the salt water. It might be noted that the depth of the water is not critical and merely affects the time required for the basin to reach some steady state operation. The basin floor would be blackened to increase the absorption of radiation but this can also be done cheaply by using readily available black silt. The interior removal of water by evaporation can easily provide the hydrostatic head required for water flow into the basin and indeed a small part of this flow would probably be provided by natural seepage through the sands.

Alternant Design

Use of steel reinforcing wires as provided allows the use of much larger basins without excessive thickness and therefore cost for the plastic film, but even so 3 to 5 mil thick plastic must be used if the units are to withstand winds of hurricane force. In addition the concrete supports must be relatively frequent and thoroughly tied in place for the structure as a whole to withstand hurricane winds. It would actually be considerably cheaper to provide not one but two surfaces of which only the upper surface would be exposed to the hurricane winds since this upper surface could be made relatively flat resulting in a great decrease in the force of the wind on it. Such a structure is shown in Figure 5. This additional surface and the intervening air space would effectively restrict the heat loss required for the condensation of the vapor but loss could be provided by coupling sections such as this with the ordinary cells previously mentioned. Presumably a certain amount of forced convection would be necessary in order to get the vapor into the single layer condensing cells, but this would be offset not only by savings from the cheaper two surface sections but also by reduced heat losses. The radiation and convection losses from the two surface sections would be greatly reduced and although the resulting higher vapor pressure of water vapor in the condensing sections result in a slight increase in radiation losses from these sections this would be cancelled by a slight decrease in the convection losses. Another possibility would be to use the two surface sections only and provide for condensation by the addition of metal heat transfer surfaces chilled sufficiently by cold sea water. As the heat transfer coefficients of this type

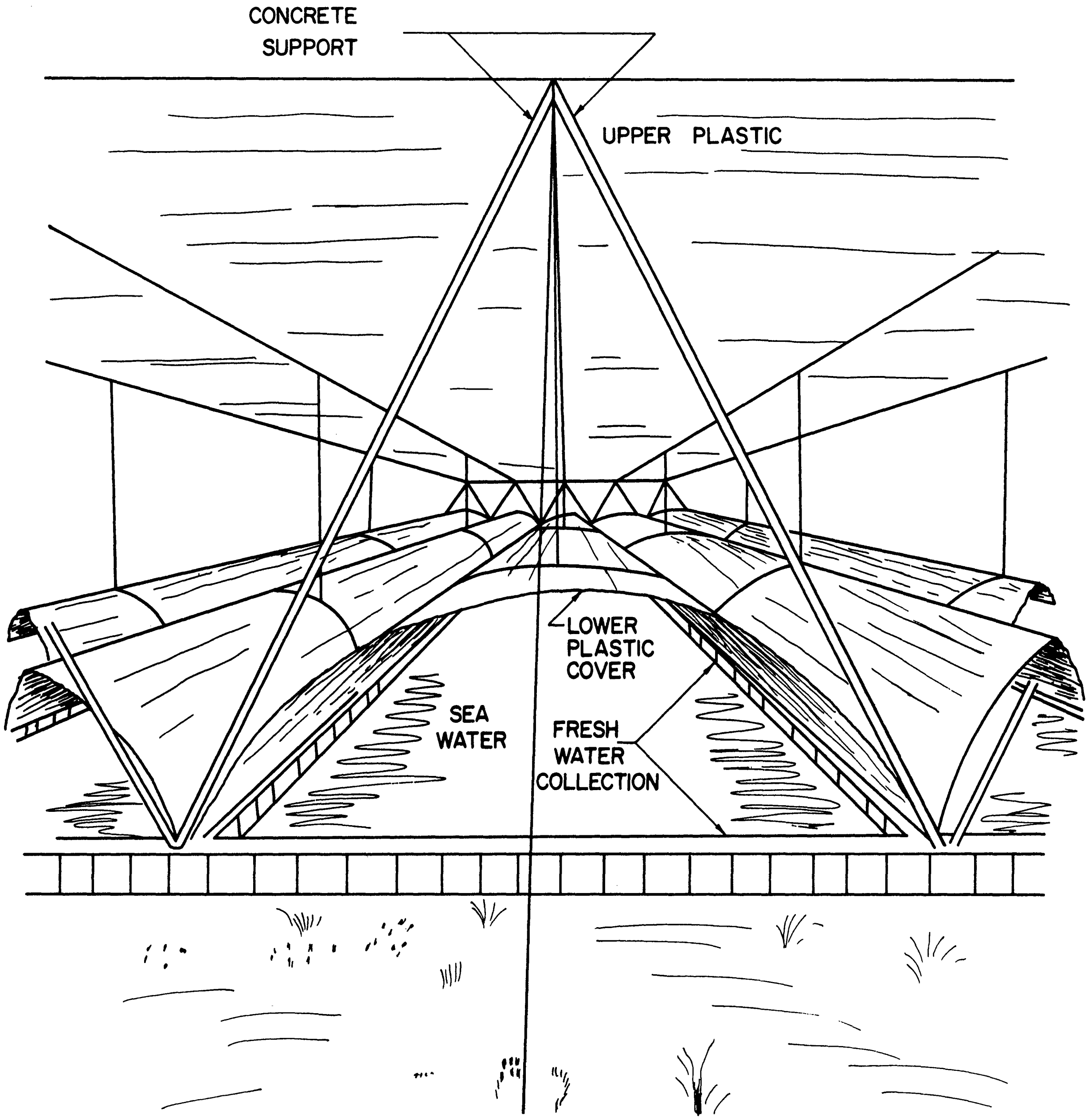


Figure 5. Proposed "Insulated" Heat Collecting Basin.

of surface would be much greater than for the plastic cooled by the air, the amount of surface would be a great deal less. Additional advantage is that some of the sea water so heated could be used as feed water to the sections resulting in additional heat economy. To carry this to the extreme that a majority of the heat of condensation is recovered require, however, considerable expense and will be dealt with in the next section, Method II.

METHOD II

Method II differs from Method Ib only in that the emphasis is shifted from collecting, conserving and using the solar energy at the lowest overall cost to using the energy more effeciently on the presumption that the resulting increase in water production will more than balance the increased equipment cost and the increase in complexity of the overall system. Multiple effect evaporation and/or multi-stage or continuous counter current flash and condensation will be considered as the means of obtaining this increase in efficiency.

As any heat discharged on the plastic cover will not be available for multi-stage utilization even when fresh water is formed, it will be necessary to minimize this heat by the use of two or more layers of infrared absorbing plastic film with infrared absorbing gas between the layers as shown in Figure 5 and discussed in Method Ib. The heat collected can be carried to the point of utilization entirely in the liquid or entirely in the vapor, but we shall use a combination of both. The liquid will move primarily due to the leveling effect of gravity to replace that evaporated, but would be pumped out of the multiple effect evaporators. The vapor will move to the heat transfer surface partially or largely because of its condensation, but it will be necessary to pull the noncondensible out of the evaporator and blow them back into the basins.

Radiation Losses

Operation of much of the water basin area at or near the normal boiling point of the salt solution reduces markedly the blower horsepower required, increases the first heat-transfer coefficient, and permits use of more stages of evaporation and/or reduction in the heat-transfer surface required. But at these high temperatures, the heat losses and especially the radiation losses become quite serious, and measures to reduce these losses must be considered. The "transparent" covers, each of which offers a major barrier to heat loss by conduction and convection may also be a major barrier to radiation losses* if the region of transparency were limited to above 2 microns (including the visible, the ultraviolet, and the near infrared, 95% of the sun's radiation) and the covers were opaque to radiation below 4 or 5 microns (95% of black-body radiation at 215°F is below 4.7 microns). Fortunately, all organic materials have an extensive absorption spectra if the infrared which can be made more complete for a particular plastic by a coating with different groups. Even more effective than absorbing the infrared is reflecting it back to the source. Roughing the upper surface of a plastic film should serve to reflect considerable amounts of the radiation from below without greatly reducing the incident radiation from the sun. The major disadvantages attending the use of additional layers of transparent plastic to reduce the radiation losses are that the plastic cost, which is already the major cost of the plant, will be increased in proportion to the number of layers, N, while the heat saved per additional layer will only be proportional to $1/(N^2-N)$. Another disadvantage is that each additional layer will increase the reflection and loss of the incident solar radiation.

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*If there were no convection, and if each layer absorbed completely the radiation falling upon it, N layers would reduce the radiation losses to $1/(N+1)$ of that lost with no layers present.

Absorption and partial return of the radiant losses by the gas between the layers is in many respects a superior method because it results in no reflection of the incident solar radiation, and because the gas offers a continuous thermal gradient and continuous absorption and partial return and can therefore offer the equivalent of many layers of plastic. The disadvantages are the low density and therefore weaker absorption, the simplicity of possible gases resulting in a less extensive absorption spectru, and finally the fact that the gas is free to circulate. The easiest absorbing gas mixture to obtain and maintain in this space is CO_2 saturated with water vapor, which can be obtained from the filtered and possibly washed exhaust of the diesel or natural gas motors powering the blowers. Additional organic materials either in the exhaust or otherwise added could help fill the windows in the CO_2, H_2O spectrum.

Night-time radiation losses can be almost eliminated by use of very shallow water in the basins so that the heat can be quickly extracted by the evaporator at nightfall. This heat extraction can be made more rapid by increasing the blower power and by reducing the number of evaporator stages at nightfall. The radiant losses can be reduced even more rapidly by draining the hot water from the extensive shallow basins into a small deep basin so that the heat can be extracted in a more leisurely and efficient manner. The hot water would be replaced in the shallow basins by a fresh charge of sea water. The disadvantages are that the operating time for the evaporators is curtailed and that the basins must be carefully leveled. This eliminates the use of natural lagoons and bays with extensive preparation.

Multiple Effect Evaporation

It would be entirely possible to use standard shell and tube heat exchangers for the multiple effect evaporation, but it is quite possible that a custom unit of new design would be more economical. Such a design must either have lower first costs, a longer life or less maintenance expense, produce more, or some combination of these. Lower first cost and long life suggests the use of concrete for the structure exclusive of the heat transfer surfaces. For the heat transfer surfaces long life will be sought by the use of expensive corrosion resistant alloy or metals and low cost sought by using membrane thin sheets for the heat transfer surfaces. These sheets could be stretched drum tight to form sloping plane heat transfer surfaces over which the brime would flow as it was being boiled. Several of these heat transfer surfaces could be packed in per foot of height. An alternant method of mounting these surfaces which does not permit tight packing is to leave considerable slack in the sheet and allow it to form its equilibrium hydralic shape. Both cases are shown in Figure 6 showing a possible evaporator design.

Operationally the evaporator will consist of two types of sections: One, the flash and deposition section will use the heat of the water to stage-wise flash a certain amount of vapor and will also provide large relatively stagnant volumes under favorable nucleation conditions in which the salts can deposit as their concentration exceeds their solubility. The second or heat transfer section will be used to condense the vapor from the flashing sections in the outside basins and from higher temperature stages and transfer this heat of condensation to the boiling brine. The evaporation units will operate entirely under vacuum with no noncondensables present. It will only be necessary to pump out the liquid fresh water and concentrated brine since the temperature differences and condensation

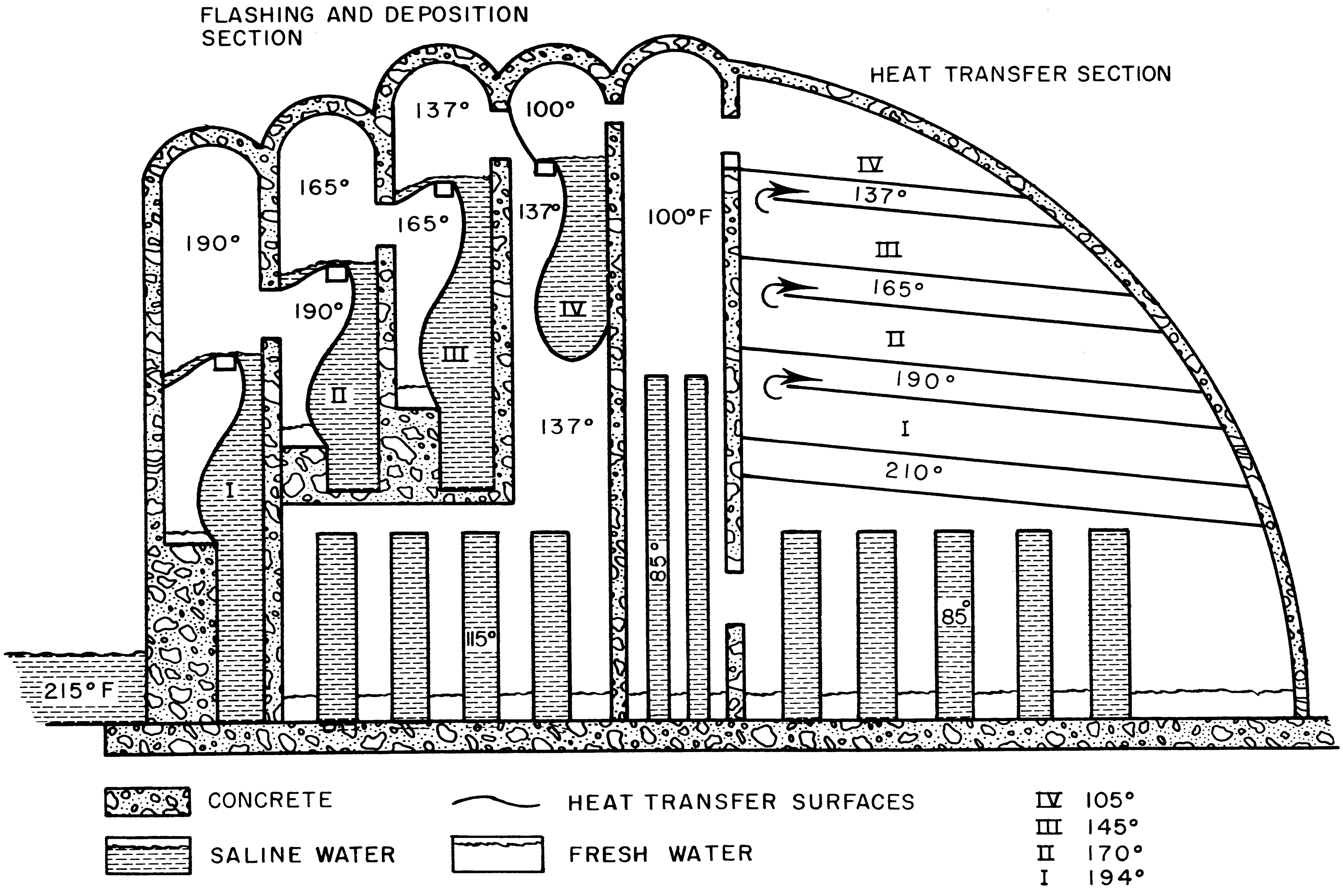

Figure 6. Multistage evaporator.

will move the pure water vapor entirely and the liquid water will be pulled into the evaporator and from stage to stage by the progressively higher vacuum. It will, however, be necessary to remove the noncondensables from the section exposed to vapor from heat collecting basins. Referring to Figures 6 and 7, water will enter flashing section 1 where it will be flashed some 10 or 15° provide a working Δt for the next heat transfer section which uses the external vapor as a heat source, and to remove the noncondensables from the solution. Part of the vapor flashed would then be recompressed to make possible the removal of the noncondensables. In this flash chamber, any supersaturation with respect to calcium or silica in the case of the more dilute brine or with respect to the valuable salts for more concentrated brine will have a chance to be relieved before entering the next stage, heat transfer section 1, in which the heat from the condensing vapor produced in the heat collecting basins is transferred to boil the brine. Following this stage, the water passes upward into the next stage which provides for deposition of any supersaturation and for flashing of the water to a lower temperature. This pattern will be repeated until the last heat transfer and flash stages are reached at which point the cool sea water is used to remove or recover the heat. As large a fraction of this sea water as possible will be entering sea water in order to increase the overall heat economy of the unit. Another advantage of this type of flashing units is that they can be used to produce pure solid salts relatively convendently through multiple crystallization at the varying temperatures within the units. This would, of course, result in increased cost for piping in order that streams could be mixed and thus crystallization controlled, and would result in a considerable decrease in thermal efficiency.

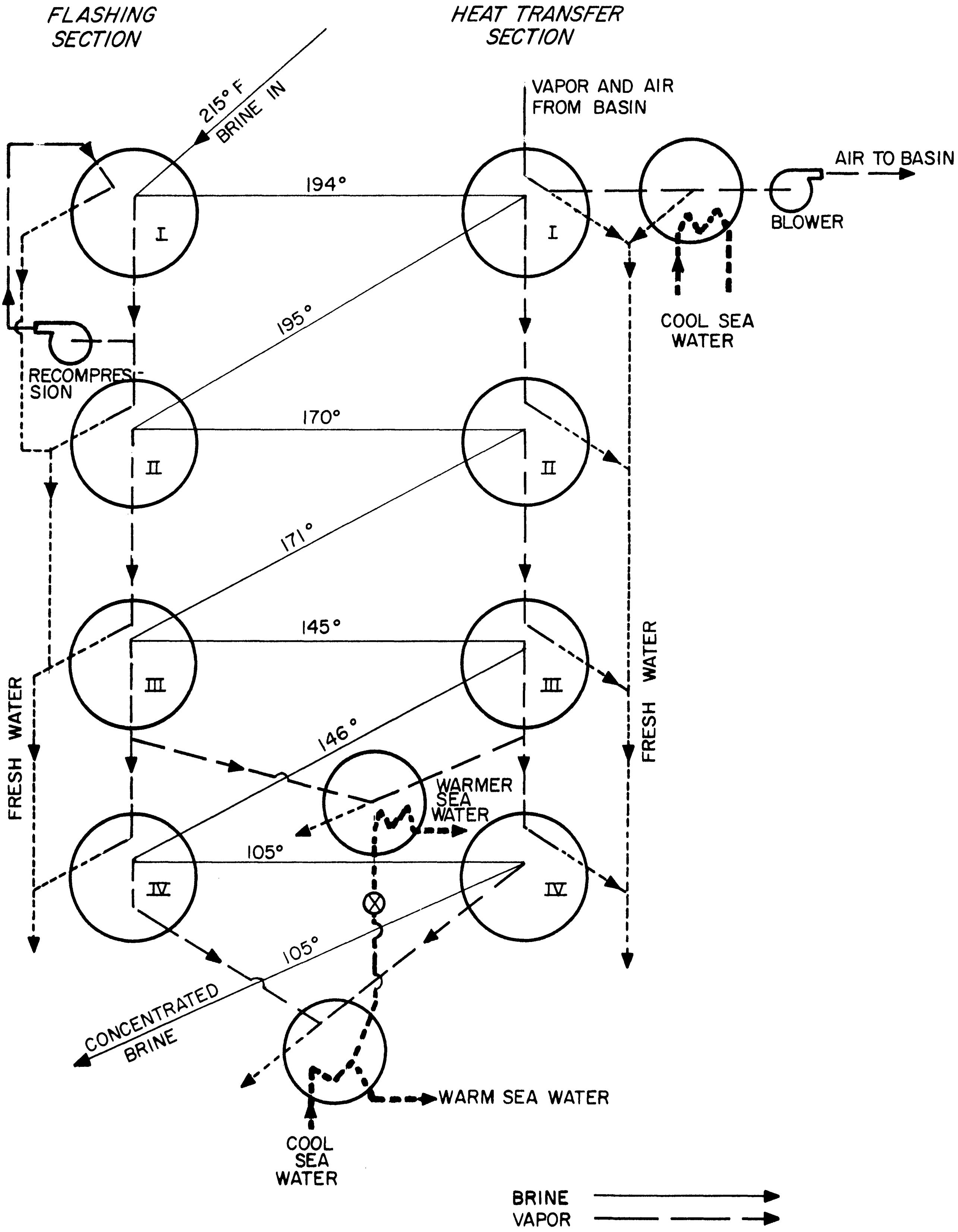

Figure 7. Schematic of multistage evaporator.

The solid products can be easily removed from the flashing and deposition chambers merely by providing sufficient depth in these chambers for a barometric leg. Figure 10 shows a schematic view of solid salt products being removed from such a deposition chamber.

A high efficiency in utilization of the energy can also be obtained if the heat of condensing the vapor could be largely absorbed by the evaporating brine. This could be attained by blowing cool air over the heating brine from the fresh sea water to the hotest brine and then passing this hot highly humidified air back over the heating brine in the reverse direction to cool the air and condense the vapor. The excess heat will be discharged into the cool ocean or bay and the solar energy will provide the heat for the separation and the heat and humidity driving forces needed. A heat transfer surface must separate the air being cooled from the brine being heated so that the fresh water condensed can be collected. Tremendous areas are required for the necessary heat and mass transfer but tremendous areas are available in the heat collecting basin. The problem is to provide the heat transfer surface cheaply. A design using clear plastic film is shown in Figure 10. Such a design would probably be cheaper in first costs than the evaporators but the operating costs would be greater due to the large quantities of air that must be blown.

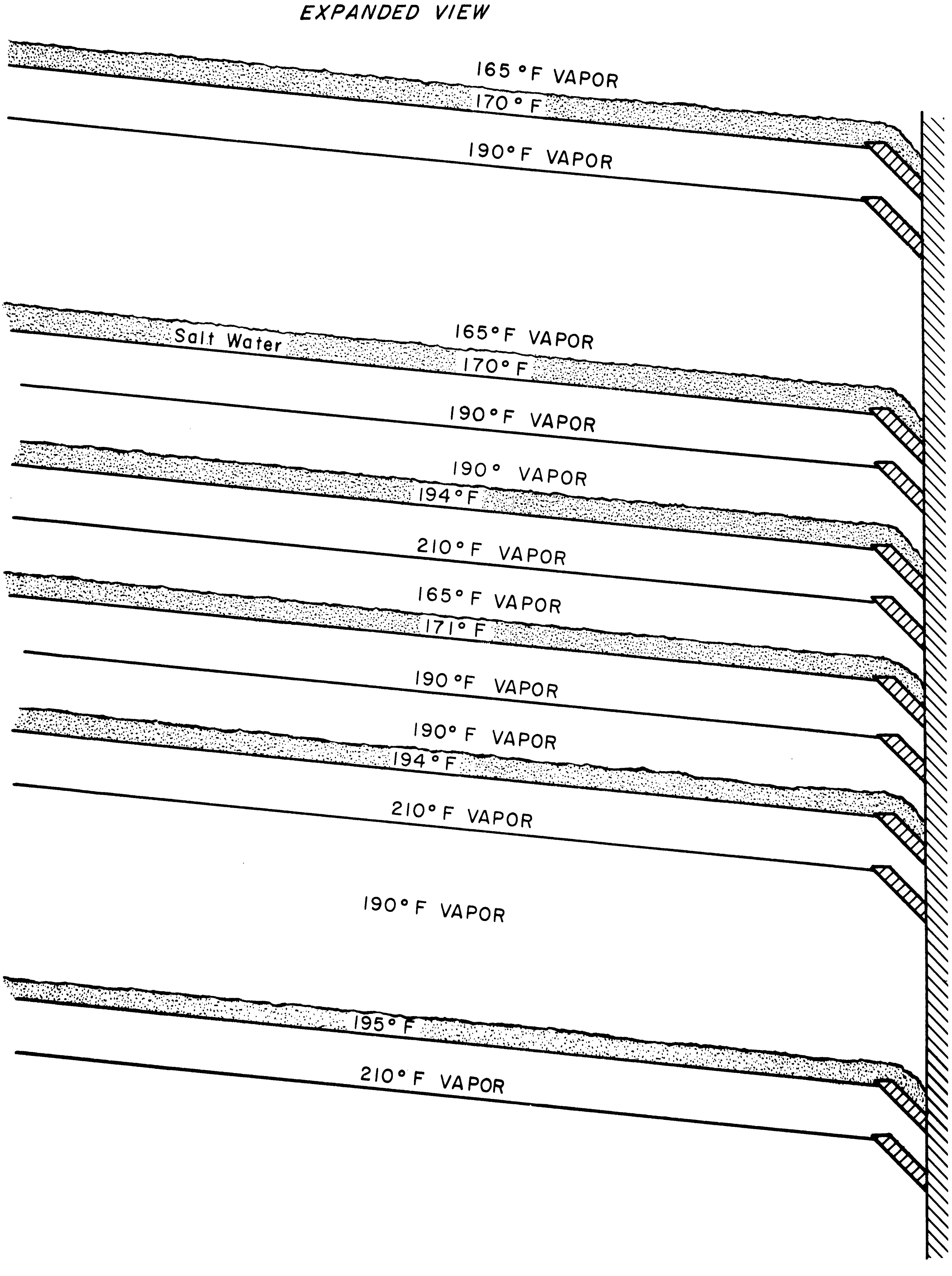

Figure 8. Heat-transfer section.

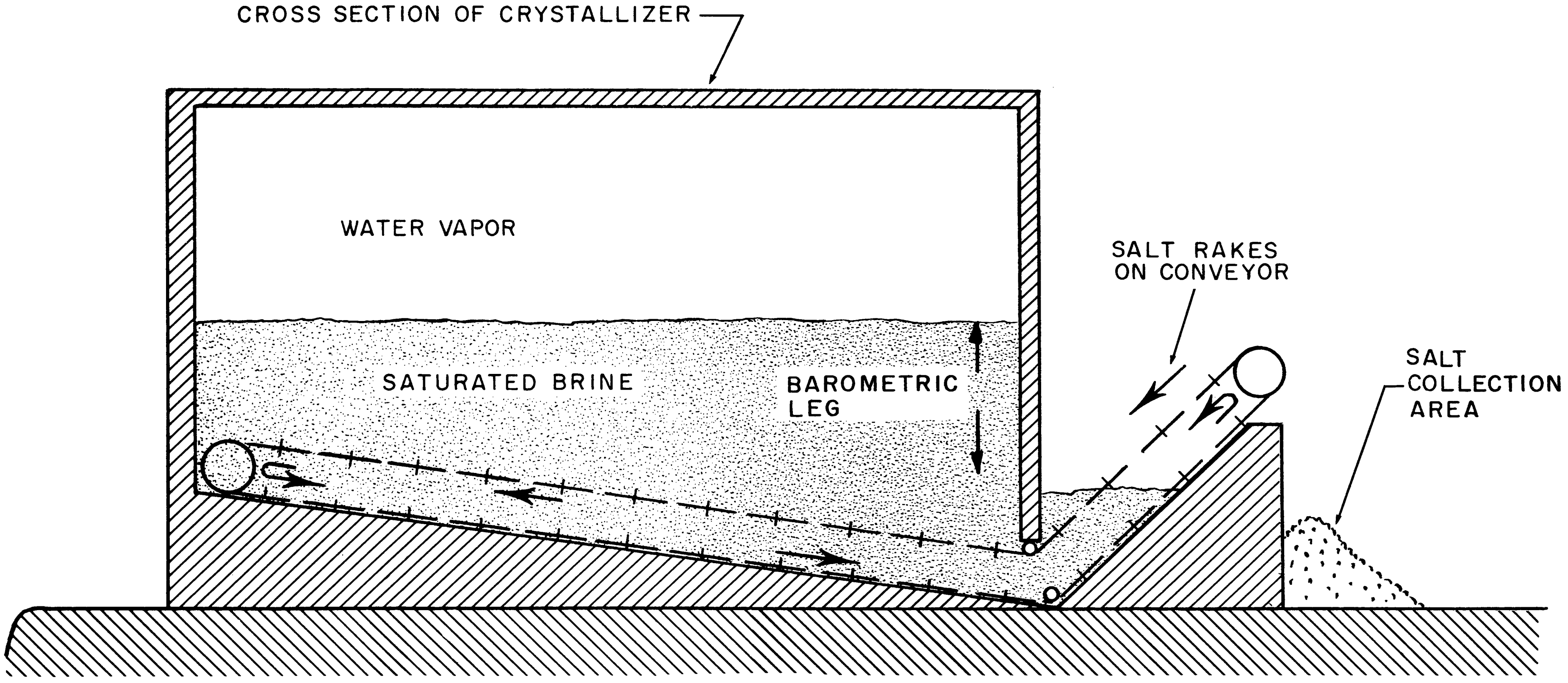

Figure 9. Salt removal from evaporator.

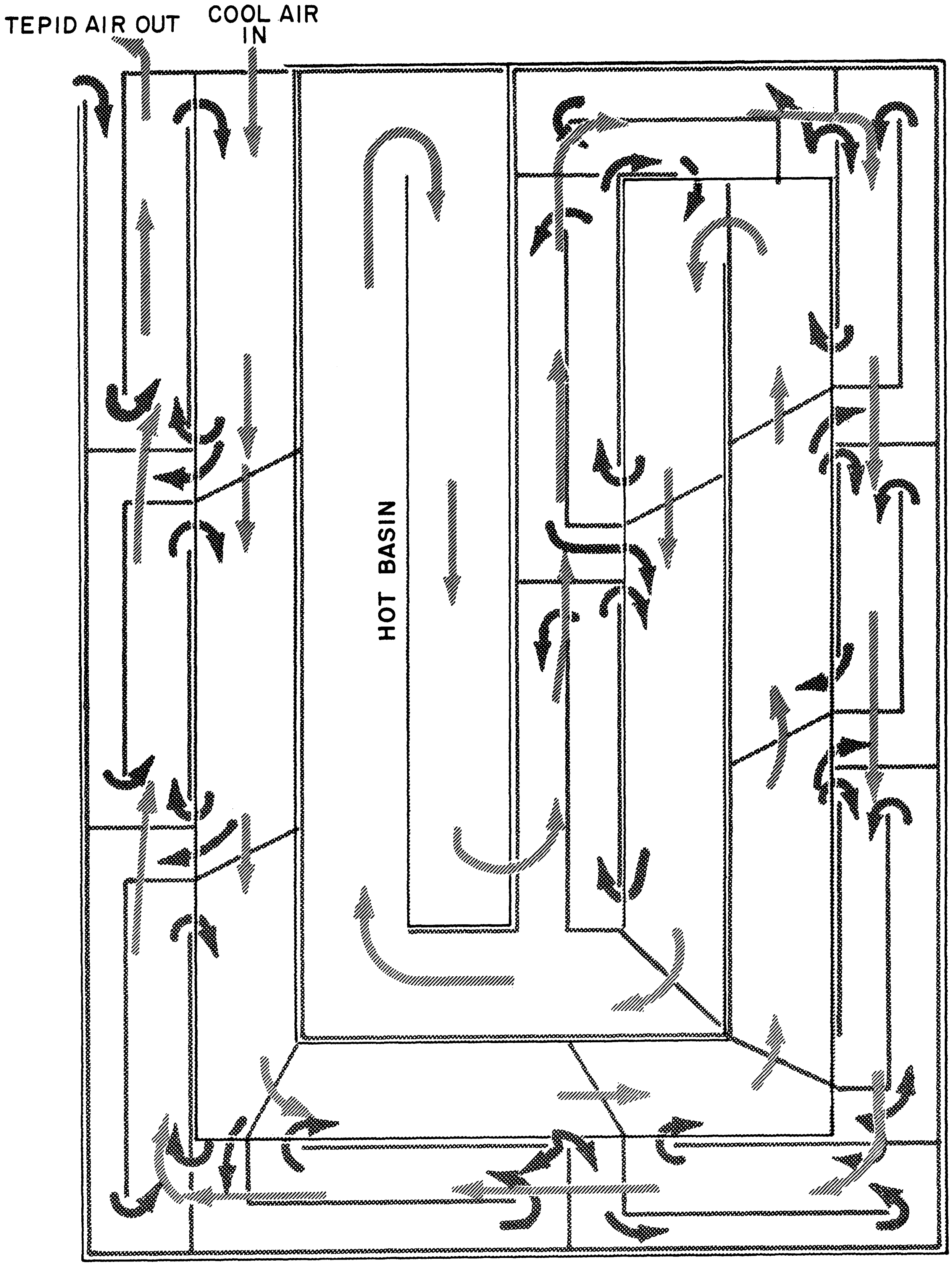

Figure 10. Continuous Countercurrent Heat Exchange.

METHOD III

The approach in this method is to assume that the plastic film is too expensive to be used to cover the heat collecting basins. As the plastic film serves merely to prevent the heat collected in the water being lost to the atmosphere, the question arises as to what extent can the water be heated without interposing this plastic film. Since most of the heat loss is normally carried by the vaporization of the water, the prevention of this vaporization will allow the water to be heated to a reasonable temperature. This vaporization can be prevented by covering the surface of the water with a very thin layer of nonvolatile organic material such as a molecular layer of alcohol. This heated water could then either be fed directly or be fed after further heating in plastic covered basins to multiple effect evaporators as previously described. The sole difference would be that in this case there would be no vapor from the outside. The only vapor that would be available for multiple effect evaporation would come from the flashing itself. Further since the temperature of the water could not be raised as high, the number of stages of evaporation would be considerably reduced. However, so would the cost of the heat.

METHOD IV

Let us reach deep into the blue sky for the final method which, if it can be developed, would be suitable only for truly monsterous installations. It would use large natural basins of untreated sea water and would use the air to carry the moisture from the heated water to the collecting surface and would require a dry air in order that an inversion layer could be produced above the water surface which would help prevent the mixing of this air with the air above. Assume steady desert winds at 110° dry bulb and 75° wet bulb.

As this air approached our humidifying and heating area it would be sprayed with fresh sea water on an extended front, cooling and saturating the air and providing a source of cold water for the condensation. This air would then be more dense than that of the air above it until after it had reached either 100° at saturation or some slightly higher temperature at a somewhat reduced humidity. Up to this point, therefore, we need not worry about losing the air to the upper atmosphere and fresh water could be produced from this air at this point by means of the water previously cooled. Greater efficiency would result, however, if we could hold on to this air somewhat longer and humidify it still further. Therefore, somewhat beyond the point at which the air would reach 100° we might wish to add restrictive devices such as vertical plane barriers to impede the development of circulation currents or to cover the area with a network of very long fine wires or nylon threads, or if these were not sufficient we might consider spraying it with heated water from hot basins to more rapidly saturate the air and to weigh it down with fine water droplets and salt particles. After a further period of heating and humidification, it would again be necessary to spray it with the hottest water to remove the salt particles and to raise the humidity still further. Following this it might be separated from the upper air by a plastic film until the condensing surfaces were reached. These condensing surfaces could be a spray of cold fresh water which would be cooled by heat exchange with the cool sea water and recycled to remove the moisture in the air. It would be necessary in such a design to make a wind movement itself provide for most of the water movement including that of the cool sea water, but in the system described a considerable amount of pumping would be required for the sprays. A system such as this would require a great deal of detailed and careful study considering all possible factors before it could be seriously proposed, but it might be attractive in certain areas (i.e. the Red Sea).