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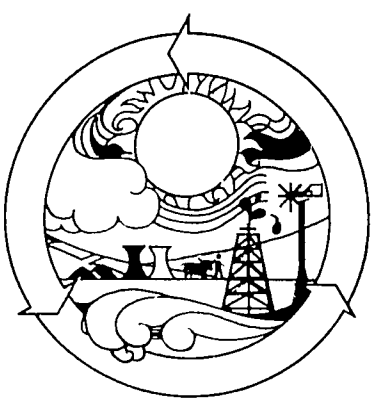

SOLAR ICEMAKERS FOR RURAL DEVELOPMENT: TECHNICAL PROSPECTS

David T. Isaak

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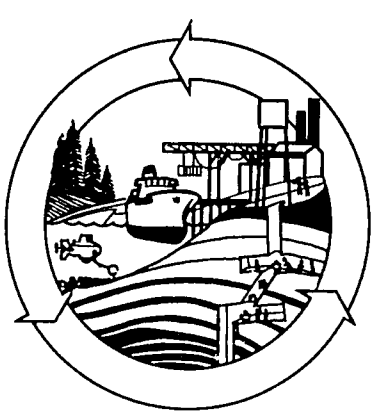

Energy for Rural Development
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SOLAR ICEMAKING FOR RURAL DEVELOPMENT:

TECHNICAL PROSPECTS

David Isaak

A preliminary report on research in progress as part of the inter-country Energy for Rural Development program, with support from the Agency for International Development

September 1980

INTRODUCTION

Refrigeration is not a necessity, but neither is it a luxury. Cooling to low temperature is required for the preservation of many foodstuffs and medicines, and is central to many commercial processes such as fishing (FAO 1977).

Solar refrigeration is an attractive technology. If solar radiation is harnessed to provide a cooling effect, the peak supply of useful energy will generally be coincident with the peak demand for refrigeration. A number of authors have emphasized the need for a solar refrigerator in the developing world (Anon. 1963; Merriam 1972). If the solar cooling effect is used to produce ice, one of the fundamental problems of most solar technologies--that of energy storage during low-radiation periods--is avoided. Ice is relatively transportable, is capable of storing cold at high density, and can be used to provide cooling in simple, inexpensive iceboxes. For the near term, an economical solar icemaker appears to be one of the most logical applications of solar energy in developing countries.

Despite the potential of solar icemaking technology, the literature on the subject is scanty. Many of the papers on the topic are published in conference proceedings or institutional papers with small circulations. Moreover, with the partial exception of a short review of general solar cooling presented at a conference in Saudi Arabia (Swartman, 1975), there is at present no general review or introduction published on the topic of solar icemakers. This in part may account for the slow rate of dissemination of information on the subject.

There are a number of theoretically possible means of converting solar radiation into cooling, including the use of photovoltaic cells or heat engines to provide power to conventional refrigerators. However, research on these topics falls naturally into the general field of solar power research within which developments will certainly have broader ramifications than their impact on refrigeration.

This discussion will be limited to devices that convert solar heat directly into cooling by condensation-evaporation cycles. The emphasis will be on refrigeration at or near the freezing point of water rather than temperature suitable for space conditioning. While space conditioning is an important application of solar energy in many parts of the world, the preservation of foodstuffs and medicines is a more critical issue.

technologies is followed by an introduction to refrigeration theory. Specific applications and problems are then discussed. An effort has been made to keep the discussion as nontechnical as possible, in the hope that the material may be undertood by those with limited background in engineering or the physical sciences. For those readers who do not wish to dwell on the technical details of solar icemakers, the two concluding sections of this report provide a summary of the potentials and economics of the technology as perceived at present.

A BRIEF HISTORY

The modern electric refrigerator is a "vapor compression" device, which uses mechanical power to provide cooling by the alternate compression and expansion of a refrigerating gas. Although this device has captured virtually all of the modern market, in the first half of this century it suffered serious competition from "vapor absorption" refrigerators—devices which were powered by heat (such as burning gas, coal or wood) rather than mechanical drive. The vapor absorption concept provides the basis for the modern solar icemaker.

Like so many "alternative energy" schemes, the history of vapor absorption refrigeration in the developed world is characterized by serious commercial development in the first quarter of this century, a sharp decline with the coming of rural electrification, and a renewed flurry of activity in the 1960s and 1970s.

Evaporative refrigeration effects were first studied by Faraday in 1824 (Daniels, 1964) using an ammonia-silver chloride system. By 1859, the French engineer Carre had developed a workable vapor absorption machine that met with little commercial success. However, for the Paris Exhibition in 1878, Mouchot connected it to a conoidal reflector in what must have been the first demonstration of solar icemaking (Butti and Perlin 1980).

By the 1920s, demand for refrigeration in areas remote from central power supplies had resulted in the manufacture of a large number of small ammonia-water refrigerators for home use. The design and operation of such devices is reviewed by Keith (1930). However, the combined impact of the depression of the 1930s and the extension of utility power into rural areas drove most of the small manufacturing firms out of business.

The late 1950s saw a revival of interest in unconventional sources of energy. At this time researchers began a more intensive investigation of vapor absorption cycles, with an eye to producing a workable solar icemaker. Initial research carried out at the University of Wisconsin (Williams et al. 1958; Chung and Duffie 1961; Duffie, Chung and Lof 1958), at the University of Ceylon (Chinnappa 1961, 1962), at Tashkent, USSR (Kirpachev and Baum 1954), and at the Laboratoire de l'Energie Solaire in France (Trombe and Foex 1957) laid the groundwork for current research on solar refrigeration, and by 1963 all the fundamental engineering concepts presently employed had been developed, including the use of ammonia-sodium thiocyanate (NaSCN) solutions (Chung 1963)

and the use of flat-plate collectors as generators (Chinnappa 1962).

Paradoxically, the interest in solar refrigeration has been both widespread and limited. Investigations of solar refrigeration have been carried out in the United States, France (Trombe and Foex 1957), Brazil (Oniga 1961), India (Chandra et al. 1977), Canada (Swartman, Ha, and Swaminathan 1975), Sri Lanka (Chinnappa 1962), Thailand (Exell 1978), Kenya, (Srivastava 1977), Pakistan (DeSa 1964),and the USSR (Vakhidov and Maksudov 1977). Yet it appears that not a single experimental device has been carried beyond the design stage to successful commercial development. Both individual researchers and research organizations have shown a tendency to limit their studies of solar icemakers, usually moving on to other topics after a short period of activity. For example, the University of Wisconsin Solar Energy Laboratory, once the leader in this field, is no longer investigating icemaking technology (J. A. Duffie, personal communication).

The situation has been further complicated because research results have not been widely disseminated. Although major journals such as Solar Energy have carried papers on solar refrigeration, the bulk of the research completed has been reported only at conferences or in private institutional offprints (such as the American Society of Mechanical Engineers reprint series). This has resulted in poor communication between interested research groups and has prevented widespread interest from developing in either the solar research community or the international funding organizations.

It is hoped that this paper, by explaining the fundamental principles of solar refrigeration and exposing the reader to the main references on the topic, can contribute to more widespread and coordinated research in this area.

REFRIGERATION PRINCIPLES I - MECHANICAL COMPRESSION CYCLES

To appreciate the workings of a vapor absorption icemaker, it is easiest first to understand the operation of the more common mechanical compression vapor refrigerator.

All vapor cycle refrigerators make use of the principle of evaporative cooling. At a given temperature and pressure, any substance undergoing a change from the liquid to the vapor state will absorb from its surroundings a characteristic amount of heat, Q_e, which depends on the amount of the substance and its latent heat of evaporation, ΔH_e, measured in kilojoules per kilogram of material. H_e is itself a function of temperature and pressure. Thus, at a fixed temperature and pressure, the heat absorbed from the surroundings is given by

$$Q_e = m\Delta H_e \qquad (1)$$

where m is the mass of substance vaporized.

Similarly, when a substance is condensed from the vapor to the liquid state, it gives off an amount of heat Q_{cond} to its surroundings. If the vapor

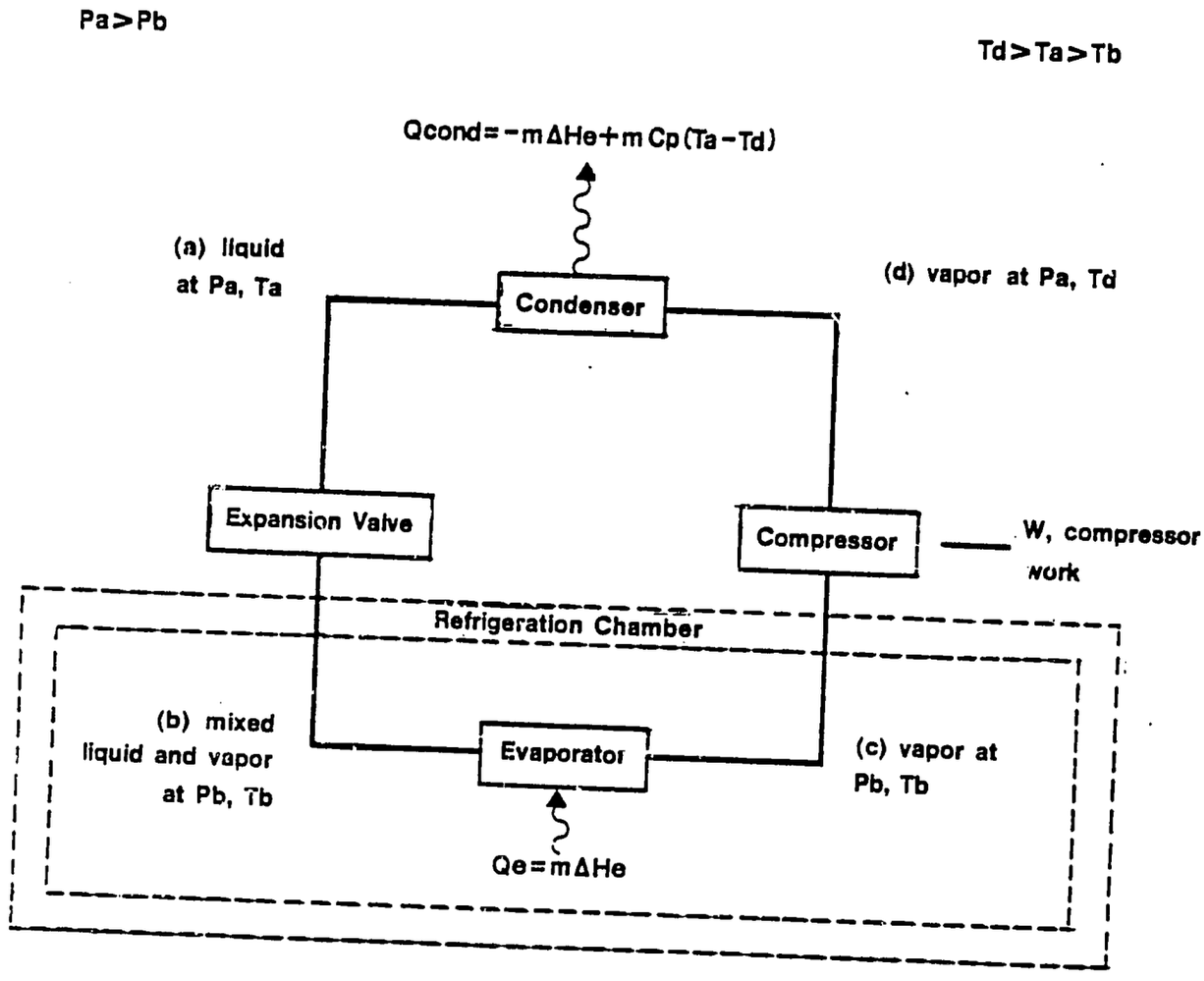

Fig. 1. Normal Vapor Compression Refrigeration Cycle.

is initially at a temperature T_i which is higher than its condensing temperature T_f, then the total heat exhausted to the surroundings is given by

$$Q_{cond} = -m\Delta H_e + m \int C \, dT \qquad (2)$$

where C is the heat capacity of the vapor in kJ/kg° C, and the negative sign indicates that the heat is being exhausted rather than absorbed.

In the case where the vapor cools at constant pressure, and C_p, (the constant pressure heat capacity) is approximately constant within temperature equation (2) is simply

$$Q_{cond} = -m\Delta H_e + mC_p (T_f - T_i) \qquad (3)$$

The twin phenomena of heat absorption during evaporation and heat release during condensation can be combined to produce a refrigeration cycle as shown in Figure 1.

At state (a) in Figure 1, a liquid refrigerant at pressure, P_a, and at approximately ambient temperature, T_a, is allowed to enter an expansion valve and flow into a region of reduced pressure, (b). In passing through the expansion valve, a portion of the liquid vaporizes, thus reducing the temperature of the mixture. The liquid in equilibrium with its vapor therefore enters the refrigeration chamber at reduced temperature and pressure, P_b and T_b.

Within the refrigeration chamber, the liquid-vapor mixture enters a series of evaporator coils. The liquid portion of the refrigerant absorbs heat, Qe, from the refrigeration chamber and evaporates to pure vapor at (c).

The vapor is then drawn off under suction by a mechanical compressor that raises the temperature of the vapor to a point above ambient, T_d, and returns the refrigerant to its initial pressure at (d).

The hot vapor is then led to a condenser, where it cools from T_d to T_a, and finally condenses, exhausting its heat to the surroundings. The total heat exhausted is the sum of the heat absorbed from the refrigeration chamber plus the work performed on the fluid

$$Q_{cond} = -m\Delta \cdot H_e + mC_p (T_a - T_d) = -Q_e - W \qquad (4)$$

This completes the cycle.

Unlike the thermodynamic efficiency of an engine, which is measured in work output per unit of heat input, the efficiency of a refrigerator is measured by the Coefficient of Performance (COP), expressed as the cooling achieved per unit of work input:

$$COP = \frac{Qe}{W} \qquad (5)$$

Note that this value is generally greater than unity; typical values for mechanical systems are in the range of 2 to 5.

By analogy with the Carnot Cycle of heat engines, we can identify a reversible path that defines the theoretical upper limit for the COP. Like the standard Carnot Cycle, the Carnot refrigeration cycle consists of two isothermal (constant temperature) stages (evaporation and condensation) and two adiabatic (constant energy) stages (expansion and compression). For any refrigerator that absorbs heat from a chamber at temperature T_2 and exhausts it to a heat sink at temperature T_1, the maximum value of COP is given by

$$COP_{carnot} = \frac{T_2}{T_1 - T_2} \qquad (6)$$

where T_1 and T_2 are both given on the absolute (Kelvin) temperature scale. For example, if the surroundings are at a temperature of 293° K (20° C), and the cold chamber is at 273° K (0° C), then the maximum value for the COP is the Carnot value, 273/(293-273) = 13.65.

It should be apparent from equation (6) that the efficiency of refrigeration rises as the temperature difference, T_1-T_2, is lowered. This is intuitively reasonable, as the temperature difference is essentially a measure of the amount of work that must be done. In practice, the temperature difference between the chamber and the ambient air is even more important than equation (6) would suggest, since the rate at which the chamber gains heat from the surroundings by conduction-convection is directly proportional to T_1-T_1.

Having shown how cooling may be achieved by alternate condensation and evaporation of a refrigerant, we may now discuss how this effect may be achieved by means of a heat source such as solar energy.

REFRIGERATION PRINCIPLES II - INTERMITTENT VAPOR ABSORPTION CYCLES

When two miscible liquids are combined, the mixture generally displays thermodynamic properties that are not directly deducible from the properties of the individual liquids. For example, for two liquids A and B it is not generally true that Volume (A) + Volume (B) = Volume (A+B). Solutions often display surprising behavior; their thermodynamic state cannot be established by simply specifying the temperature and pressure of the system.

However, some generic observations about solutions are of value. When a volatile liquid is mixed with another substance, there is a change in its vapor pressure; that is, at the same temperature, it exhibits a greater or lesser tendency to evaporate. For most miscible substances, the vapor pressure is lowered; in other words, the boiling point of the substance is raised. The reason for the lowering of vapor pressure is that the molecules of the substances are able to form closer associations in the mixture than were

possible in the pure substances alone, thus resulting in a lowering of their chemical potential. Since the molecules in the mixture are now more energetically "stable," they have less tendency to leave the solution as a gas.

The boiling point of such a mixture is a function of the relative proportions of the components and the pressure on the solution. As one substance boils out of solution, the relative proportions of the substances in the mixture change, thereby altering the boiling point. This situation is shown in Figure 2, where X, the mass fraction of component A, is defined as

$$X(A) = \frac{\text{mass of A}}{\text{mass of solution}} \qquad (7)$$

T_x is simply the boiling point of pure component A at Pressure P.

A whole family of such lines exists, one for each pressure on the solution. If the initial mass fraction of A is 0.5, and the vapor is allowed to boil off at pressure P_2, then a continued rise in temperature from 0° C will cause the system to follow the path shown in Figure 3. Only two points are of particular significance. At T_1, the composition of the solution begins to change, owing to a net vaporization of component A; and at T_2, all of component A is in the vapor state and its mass fraction is zero.

If, in Figure 3, the vapor generated by the heating of the solution were allowed to condense in an unheated chamber, then the pressure, P_2, would be determined by the temperature conditions in the unheated chamber. If the temperature in the unheated chamber is T_c, (the condensing temperature), then the resulting pressure on the solution is P_c, the condensing pressure.

Assuming that B is nonvolatile, then pure component A will be condensed to a liquid in the unheated chamber. In effect, heat has been used to purify component A out of the initial A + B mixture. From the previous section, it should be apparent that this pure substance may be used to achieve cooling via evaporation at a reduced temperature.

The means for achieving a refrigeration effect under these conditions are shown schematically in Figure 4.

Figure 4(a) shows a hypothetical mixture A + B in equilibrium with vapor A. Both chambers are in thermal equilibrium with the environment at $T_{ambient}$, and the internal pressure is P_1.

In 4(b), heat Q_{in} is applied to the generator, and the generator temperature rises to T_2. Since the vapor moves freely between the chambers, the pressure of both chambers rises to P_2. However, since the condenser chamber is not directly heated, the vapor in the condenser loses heat Q_{out} by conduction through the chamber walls. This results in a condenser temperature that is somewhere between the ambient temperature and the temperature of the generator, the exact value depending on the heat-transfer characteristics of the system.

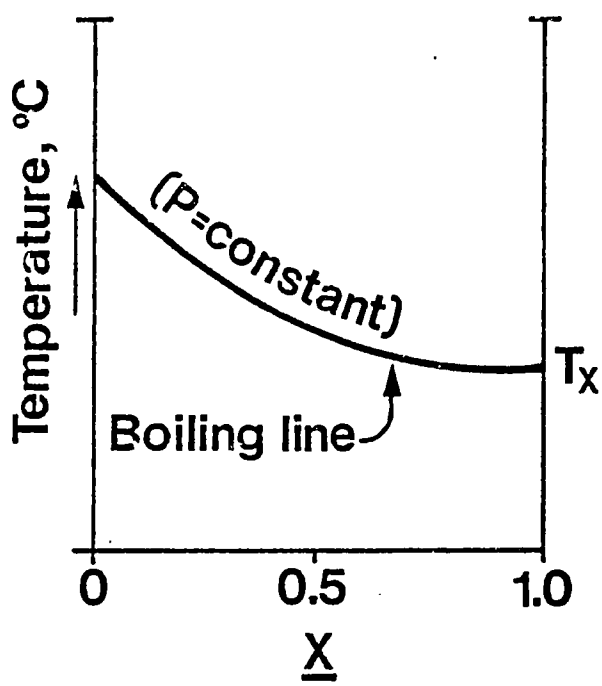

Fig. 2. Constant Pressure Boiling Line for a Binary Solution.

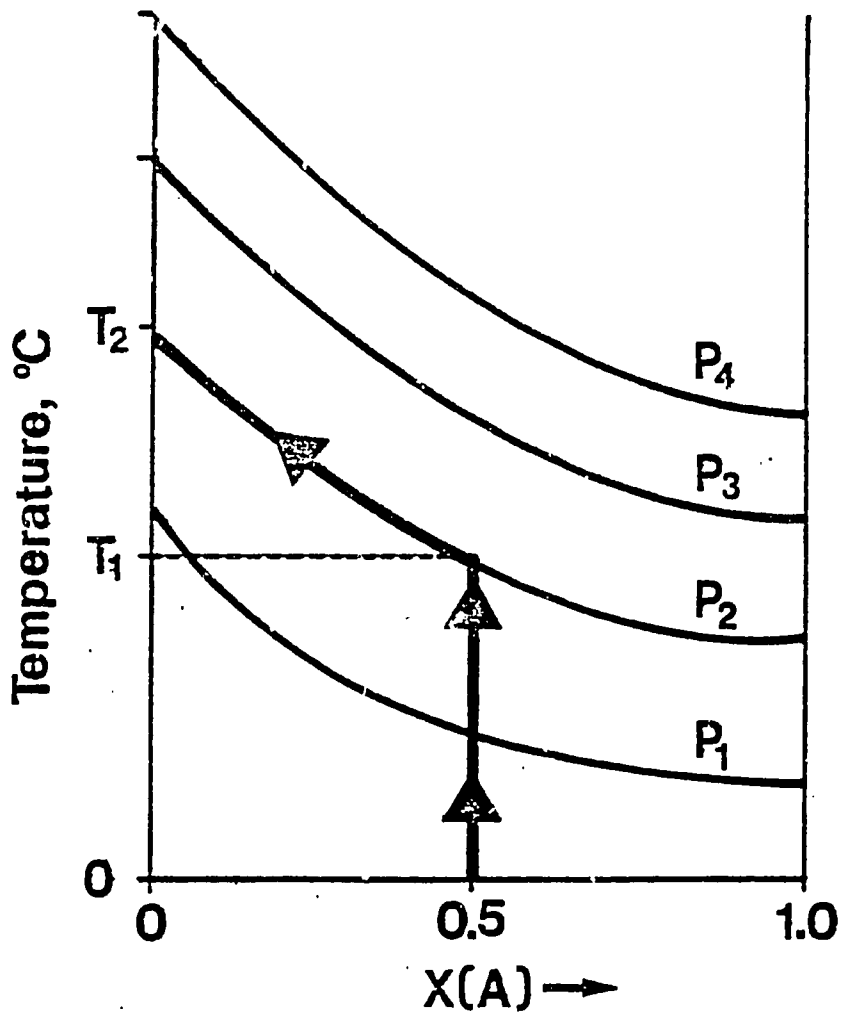

Fig. 3. Course of Boiling.

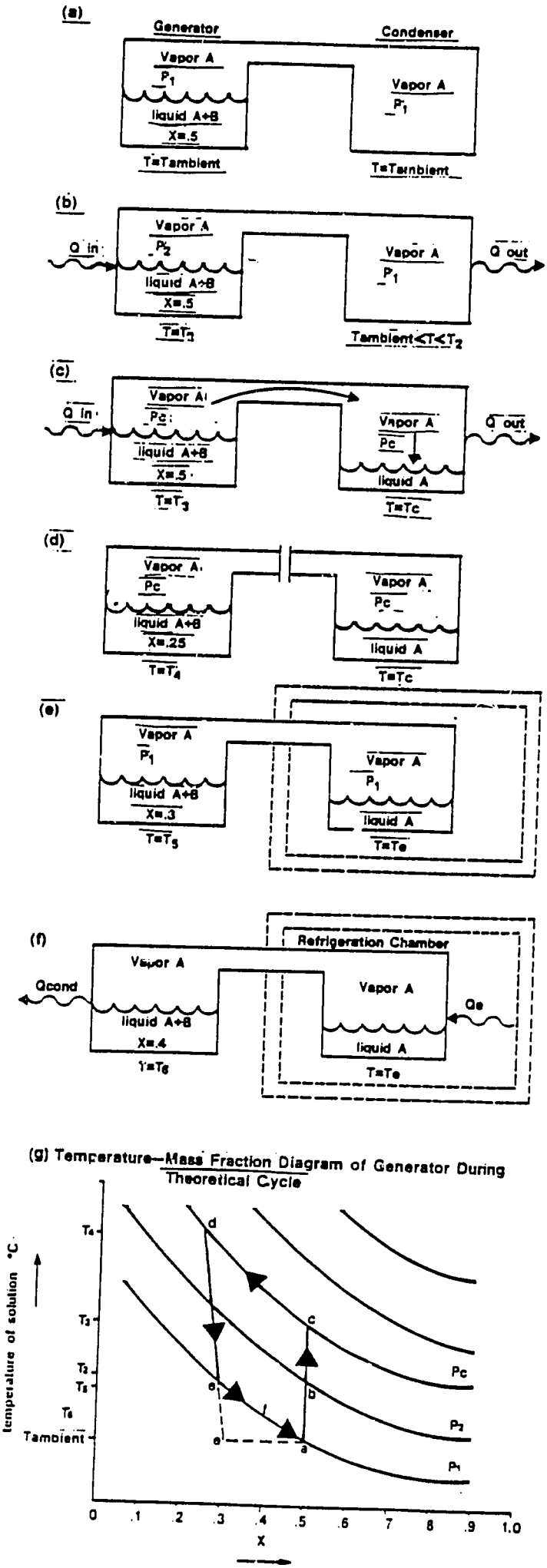

Fig. 4. The Vapor Absorption Refrigeration Cycle for Intermittant Operation

In 4(c), as more heat is added to the generator contents, a vapor pressure P_c develops and vapor begins to condense in the condensing chamber The value of P_c is a function of the temperature of the condensing chamber, T_c. The higher the temperature at which condensation must occur, the higher the pressure necessary to force condensation. Thus, to avoid unnecessarily high values of P_c, it is desirable to achieve large values of Q_{out} at the condenser, either by designing for large heat loss surfaces or by providing air or water cooling to the condenser's exterior.

From figures 4(c) to 4(d), vapor boils out of solution at a constant pressure P_c. The temperature of the generator contents continues to rise to a final high temperature, T_4, until heating is stopped. The condenser now contains a mass m of liquid A at temperature T_c.

From figures 4(d) to 4(e), the generator contents cool rapidly to T_5, and a small amount of vapor is reabsorbed into solution. The condenser is placed in a refrigeration chamber, and the liquid A "autocools" to the evaporating temperature, T_e, by vaporizing a small amount of mass, m_a.

Thus, the total amount of refrigerant available for useful cooling is $m_{ref} = m - ma$. The system has now returned to its initial pressure, P_1.

Figure 4(f) shows the system at some point during the actual refrigeration process. The liquid A vaporizes, removing heat, Q_e, from the chamber, and is reabsorbed into the solution in the generator. The generator continues to cool from T_5 to T_6, giving up to the environment not only the initial heat contained in the generator solution at T_5, but also the additional "heat of solution" produced by reabsorption of the vapor.

Finally, the system returns to state (a), thus completing the cycle. The useful refrigeration achieved is given by

$$Q_{ref} = m_{ref}\ \Delta He \qquad (9)$$

The entire cycle is summarized by Figure 4(g), which shows the cycle on a temperature-mass fraction diagram for the generator. The path (a) through (d) represents heating of the generator contents to drive vapor out of solution. The path (d) through (a) represents cooling of the generator and reabsorption of refrigerant into the mixture.

A useful index of cycle performance, similar to the COP for mechanical compression, is the refrigerating efficiency, n, where

$$n = \frac{\text{(heat absorbed by refrigerant (e) to (a))}}{\text{(Heat added to system (a) to (d))}} \qquad (10)$$

Thus, if Q_g is the total heat added to the generator from (a) to (d),

$$n = \frac{Q_{ref}}{Q_g} \qquad (11)$$

For solar refrigerators constructed to date, typical values of n are between 0.05 and 0.27(17). Thus, anywhere from 4 to 20 units of heat energy must be provided to a solar refrigerator to achieve a single unit of cooling. This compares rather unfavorably with the performance of a mechanical vapor compression cycle, where only 0.2 to 0.5 units of heat are required to achieve a unit of cooling. However, the solar devices have the twin advantages of being operable by low-grade heat and functioning in areas where electricity or other high-quality fuels are not available.

In the interests of nontechnical readers, the foregoing discussion has been simple and somewhat abbreviated. Those desiring a more thorough understanding of the theory of vapor absorption cycles may consult the excellent articles by Chinnappa (1961) or Sargent and Beckman (1968). and the chapter on vapor absorption in Threlkeld (1970).

REFRIGERANT/ABSORBENT COMBINATIONS

The choice of refrigerant and absorbent for absorption refrigeration is possibly the most important single consideration in designing an effective system. In the heyday of commercial vapor absorption refrigeration, the development of suitable refrigerant/absorbent systems was one of the priority research topics in the refrigeration industry. Hainsworth (1944) lists 180 refrigerant/absorbent combinations that were considered for use in vapor absorption refrigeration as of 1944.

Although a large amount of research effort has already been expended in pursuit of the perfect binary mixture, further research in this area would be fruitful—first, because chemical technology has advanced greatly since World War II and second, because earlier research dwelt on many systems that required operating temperatures greater than 210° C (Miller 1929), a rather high temperature for nonconcentrating solar systems.

Buffington (1949) considered the requirements of absorption refrigeration from an engineering viewpoint and produced a list of seven desirable properties for successful refrigerant/absorbent combinations. With the original language considerably simplified, the Buffington criteria are:

1. The solubility of the refrigerant in the absorbent should be extraordinarily high at absorption temperature and evaporation pressure (that is, the solution vapor pressure should have a large negative deviation from the Raoult's Law prediction). This allows a large amount of refrigerant to be stored in the least possible amount of solvent, a situation that minimizes the cost of equipment and absorbent and also reduces the amount of mixture that must be heated to the generation temperature.

2. Absorption of the refrigerant by the solvent should be rapid up to concentrations approaching the equilibrium value. If absorption of the vapor is too slow, the entire refrigeration process will be slowed, precluding the attainment of low temperatures.

3. A high percentage of the refrigerant should be recoverable from the mixture by distillation at the operating temperature.

4. The absorbent should be nonvolatile in the range of operating temperatures. If absorbent is carried into the condensation chamber along with the refrigerant, evaporation will be retarded and refrigeration reduced.

5. The viscosity of the solution should be low. This insures good heat transfer properties and also increases the rate of mixing during absorption.

6. The freezing points of any liquids involved should be well below the temperatures encountered during operation. Clearly, if the refrigerant freezes during evaporation or the absorbent freezes during absorption, the operation of the whole system will be adversely affected.

7. The system should be chemically stable under expected operating conditions. The refrigerant and absorbent must not undergo irreversible chemical reaction or decomposition. Moreover, neither the pure components nor the mixture should have a corrosive effect on the chambers, piping, and other parts of the equipment.

To Buffington's list, common sense dictates that we add:

8. The prices of the chemicals should be low. In general, the capital costs of absorption refrigeration systems are somewhat greater than for comparable vapor compression systems. If expensive chemicals are added to the basic equipment costs, the cost of the ice produced may become prohibitive.

9. The chemicals should be widely available in case recharging is necessary. While some downtime in operation in case of a leak may be acceptable, the chemicals should not be so esoteric as to require ordering from distant firms or foreign nations.

10. The chemicals should be relatively safe in the event of an accident. Chemicals should not be highly toxic or explosive in the expected concentrations.

11. The refrigerant should have a high latent heat of evaporation.

This produces a large refrigeration effect from a small amount of distillate, thereby minimizing equipment size and costs.

In spite of the large list of candidate chemicals for use in absorption refrigeration, only a few combinations have been proposed for use in solar refrigerators; virtually all of these use ammonia as the refrigerant. (The well-publicized lithium bromide-water system, which has found much favor in air-conditioning experiments, is not suitable for use in solar refrigerators. The refrigerant in this system is water at reduced pressure, largely precluding ice-temperature application. In addition, lithium bromide-water systems are poorly suited for operation where electricity for pumping is not available.)

Ammonia has a number of desirable properties. It is highly polar, thus displaying good absorption properties in polar solvents; it has a freezing point well below the freezing point of water; it is widely available, cheap, and its properties are well understood.

The disadvantages are that ammonia is corrosive to some metals in combination with certain chemicals, is explosive under standard atmospheric conditions in a certain range of concentrations, and is toxic if inhaled in large quantities. The cumulative experience of years of handling ammonia in industry and engineering makes it less dangerous in the hands of a technician than, say, an equal amount of propane; nonetheless, if the intention is to produce fairly large ammonia-based refrigeration systems for operation by unskilled or semiskilled workers, it is vital that safety be emphasized in both design and operator training.

The most common absorbent for ammonia is water, and a number of solar refrigerators operating on ammonia-water systems have been built and tested (Chinnappa 1961; Trombe and Foex 1957; Exell 1978; Giri and Barve 1977; Farber 1970). The obvious disadvantage of such a system is the volatility of water at elevated temperatures; some means of rectification is necessary if water is not to condense as part of the distillate. Some investigators have cited the expense of rectification equipment as an argument against the ammonia-water system; however, Exell et al. (1977) found that a simple 0.8 m vertical pipe provided enough rectification to achieve adequate performance in their tests, and Chinnappa (1962) found little if any carry-over of water from a boiler with just a few condensation plates.

Nonvolatile absorbents for ammonia that have been successfully tested include calcium chloride (Muradov and Shadiev 1971), lithium nitrate (Chinnappa 1961), and sodium thiocyanate (Swartman, Ha, and Swaminathan 1975). The most promising of these is sodium thiocyanate, the chemical properties of which have been exhaustively determined by Blytas and Daniels (1962). The reported performance of sodium thiocyanate as an absorbent is superior to that obtained by water under the same conditions (Swartman, Ha, and Swaminathan 1975). Whether this performance advantage (coupled with whatever cost savings result from the lack of a rectifier) outweighs the added cost of the sodium thiocyanate remains to be seen.

The only other refrigerant system to be thoroughly tested for solar icemaker applications is Refrigerant 21-glycol ether. The results of the tests were not encouraging; ammonia-water gave better performance, and the Refrigerant 21-glycol ether system requires large quantities of absorbent (Williams et al. 1958).

Some preliminary studies of silica gel as an adsorbent for methyl alcohol, acetone, or diethylamine were undertaken at the University of Wisconsin in the late 1950s (Salam, Chung, and Duffie 1958). Such systems deserve further investigation in connection with concentrating collectors capable of providing high (>200 °C) temperatures. The advantages of silica gel are its long operational life, its inert chemical behavior, and its complete nonvolatility.

In summary, while investigators have settled on ammonia-based systems as the basis for all present research in solar refrigeration, it is not clear that any of the refrigerant/absorbent combinations yet studied represent an optimum for solar applications. While continued testing and development of currently available systems should certainly be a priority, basic chemical research on potential refrigerant/absorbent combinations should be strongly encouraged.

BASIC DESIGNS AND OPERATION

The simplest solar refrigerator consists of two chambers connected by a pipe with a valve in the center of the pipe so that the chambers can be separated. This device, shown schematically in Figure 5, has been used with a parabolic reflector as a heat source to produce ice (Williams et al. 1958, Chung and Duffie 1961).

During the day, the valve is open, and ammonia vapor is driven from the generator to liquefy in the water-cooled condenser. When the bulk of the ammonia has condensed in the condenser, heating is stopped, the valve is closed, and the system is allowed to cool until evening.

At night, the condenser is removed from its water jacket and placed in the refrigeration chamber. The valve is then reopened, and the ammonia evaporates, withdrawing heat from the chamber and reentering solution in the absorber (Figure 6).

A more sophisticated version of the concentrating collector type of system is that built in 1956-57 by Trombe and Foex (1957). One of the earliest refrigeration designs, it is still one of the best. A schematic is shown in Figure 7.

The Trombe design allows for thermosyphoning, gravity, and boiling effects to move the richest ammonia-water liquid to the collector focus. Rich solution at (a) flows through a heat exchanger and into a heating tube, (b),

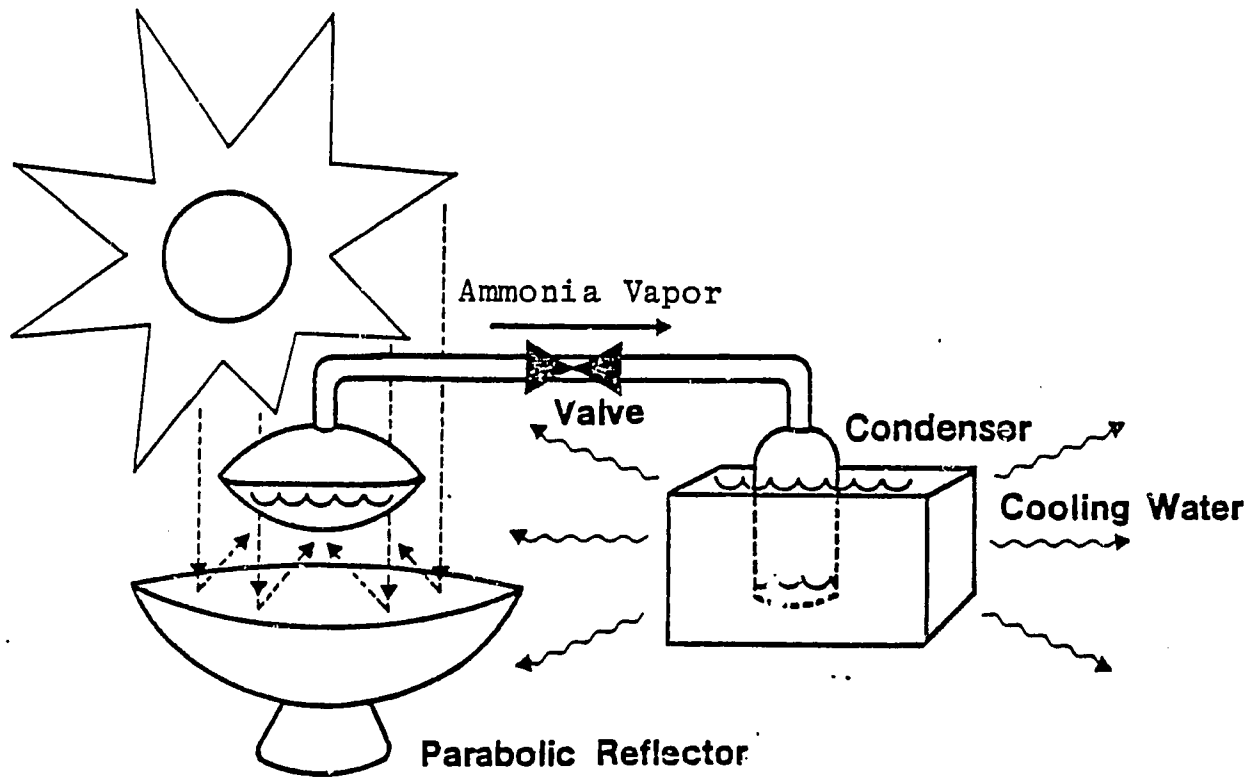

Fig. 5. Simple Vapor Absorption System During Heating.

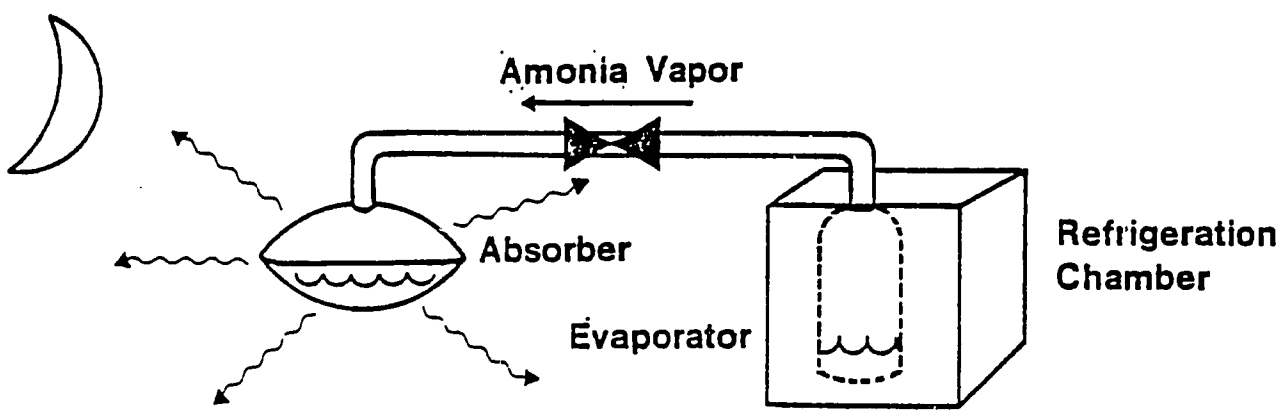

Fig. 6. Simple Vapor Absorption System During Refrigeration.

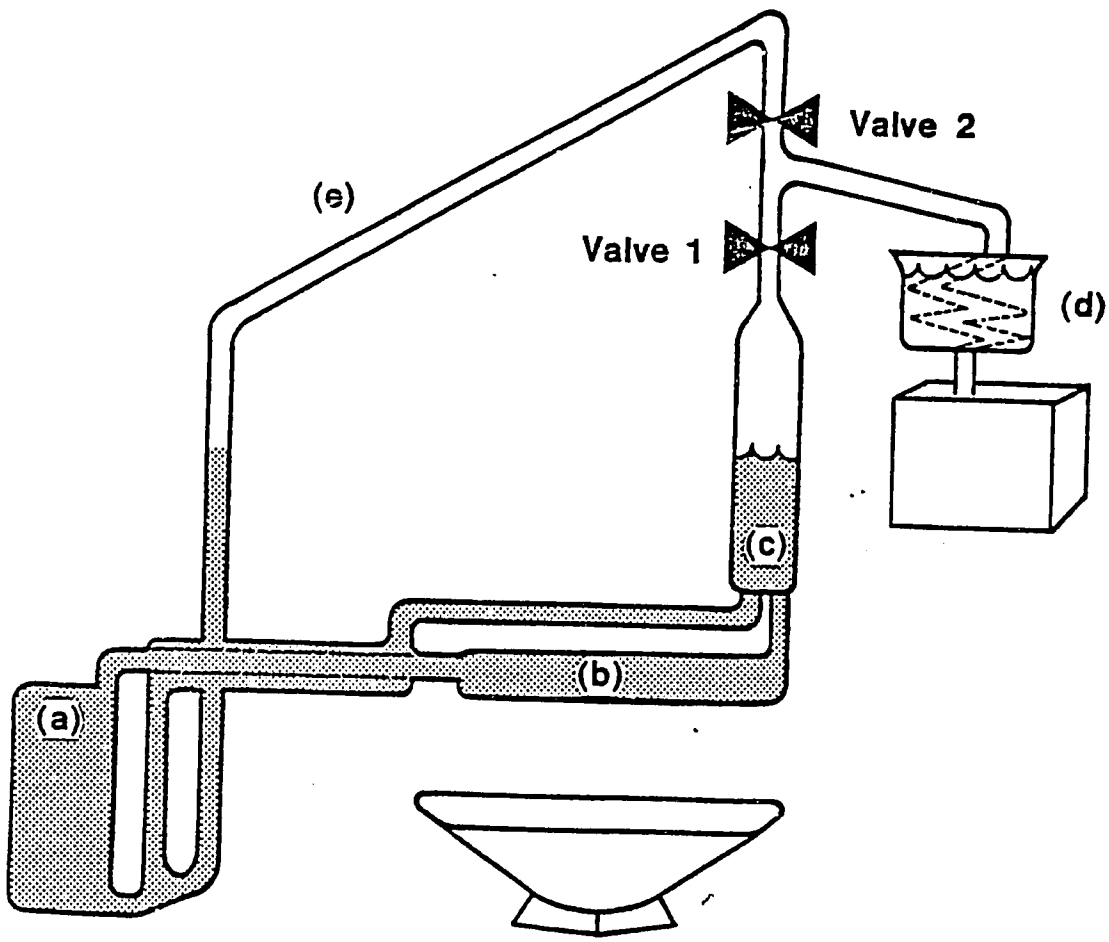

Fig. 7. The Trombe-Foex Solar Refrigerator.

that receives concentrated sunlight from a parabolic mirror. The heated fluid rises to the boiler, (c), and ammonia gas rises up the boiler tube (which, because of its size, acts as a rectifying column) through valve 1. The vapor is then led off to a water-cooled condenser, (d), and eventually to a refrigeration chamber.

The ammonia-water mixture circulates from the boiler back through the heat exchanger jacket (thereby preheating the incoming rich solution) and back down the return line to the base of the solution vat, (a). Since a solution weak in ammonia is denser than one rich in ammonia, the solution in the vat remains stratified, with the richest solution always entering the boiler.

Refrigeration is achieved by shutting valve 1 and opening valve 2 to allow the condensed ammonia to reenter solution via the return line, (e). Since the return line is at the base of the solution vat, the ammonia vapor is reabsorbed by the weakest solution present, thus hastening the reabsorption process.

The primary advantage of the Trombe design is that only a small fraction of the ammonia-water solution is heated at any one time; and the fraction that is heated is precisely the fraction that boils off its ammonia vapor the most readily. This results in a higher thermal efficiency than is found in most systems.

The foremost virtue of concentrating collectors is the relative ease ch which high temperatures may be attained. Their disadvantage is that they can effectively focus only direct radiation. In areas of the world where diffuse radiation is a major component of the total insolation, a significant fraction of the available solar energy is not captured if concentrating collectors are employed.

Since the temperatures needed for distillation of ammonia are moderate (70-100° C), it is possible to use a flat-plate collector as the heat source for a solar icemaker. It is possible to achieve this simply by using the flat-plate collector to generate hot water for a boiler, as suggested by Merriam (1974); however, it is more direct and efficient to incorporate the generator/absorber of the refrigerator as an integral part of the solar collector.

The first published results of a combined collector/generator appear to be those of Chinnappa (1962) in his experiments in Colombo. A schematic of this design is shown in Figure 8.

During heating, valves 1 and 2 are open and valves 3 and 4 are closed. Solar radiation is absorbed by the collector plate at (a). The heated ammonia-water solution rises in the collector tubes as a result of thermosyphoning and the formation of ammonia bubbles. Passing through the header, the ammonia vaporizes in the boiler, (b), passes the rectification plates at the top of the boiler, and is led to a water-cooled condenser, (c), where the ammonia liquefies and drains down to the evaporator, (d).

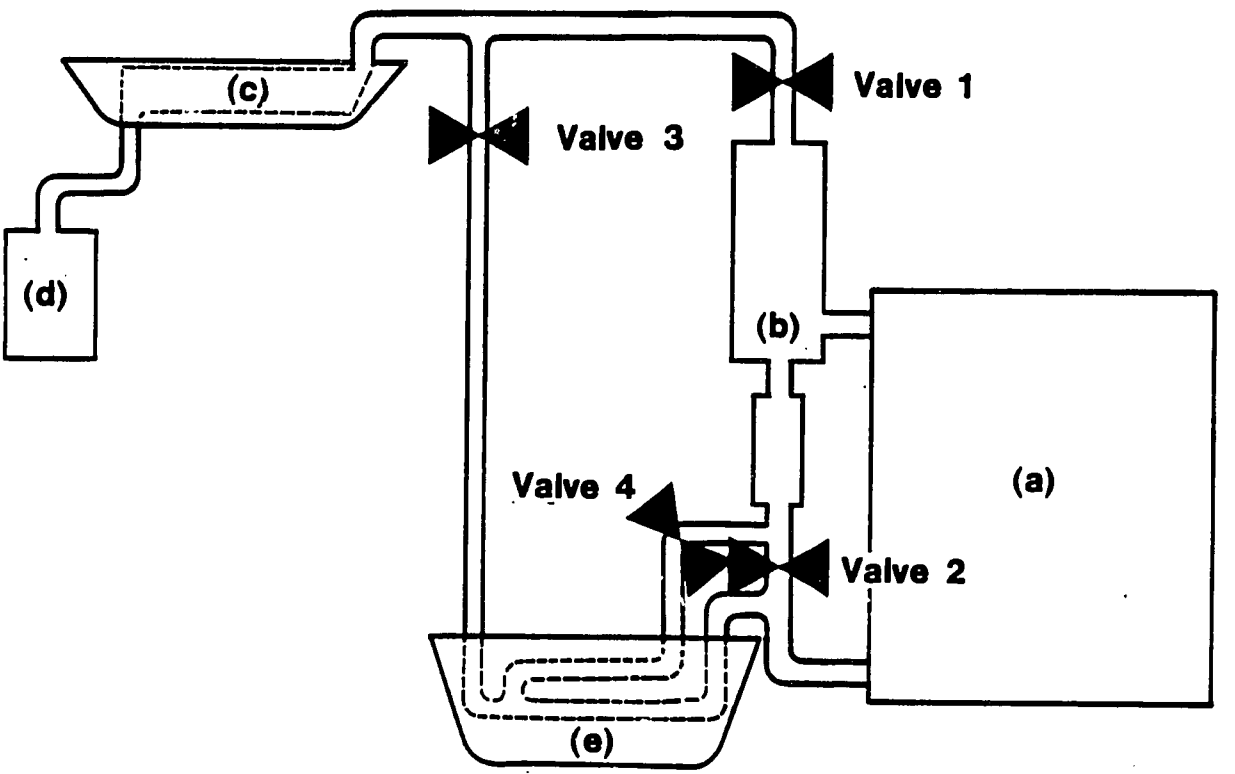

Fig. 8. The Chinnappa Solar Refrigerator.

The entire apparatus is cooled with all four valves closed. For refrigeration, valves 3 and 4 are opened. Ammonia vaporizes in the evaporator and reenters solution in the water-cooled absorber tube, (e). Circulation of the solution takes place by mixing and a small amount of thermosyphoning.

The Chinnappa design worked well although its performance was somewhat below that of earlier concentrating collectors in terms of refrigerating efficiency (see below). Since much of the interest in solar refrigeration has centered on the tropics, where the diffuse component of radiation is often large, the success of the flat-plate collector/generator as the heat source for a solar refrigerator stimulated a great deal of research by other workers in the field.

The design of an optimum flat-plate solar collector for any given application is a complex heat transfer problem. The fact that two phases (liquid solution and ammonia vapor) are often present within the collector tubing further complicates the issue. However, as in most collector design, the fundamental compromise is between maximizing collector efficiency (by increasing the number and decreasing the spacing of the tubes) and minimizing materials and weight. A theoretical development and analysis relating specifically to the design of collector/generators is given by Moore and Farber (1967).

Farber (1970) produced an excellent icemaking machine by modifying the basic Chinnappa design. An advantage of the Farber design is that it allows for continuous operation, with heating and refrigeration carried out simultaneously. The primary disadvantage of the Farber design is that it requires two centrifugal pumps, adding to the cost and limiting applications to areas where electric power is available.

Numerous other systems have been built and tested, most quite similar to the Chinnappa and Farber designs. The system that best reflects the current state of the art is that produced by Exell (1978) and Exell and his coworkers (1977). A schematic of this sytem is shown in Figure 9. The Exell design is similar in operation to other designs based on flat-plate collectors. The flat-plate collector/generator, (a), is identical to that of Moore and Farber (1967). During heating, valve 1 is open and valves 2 and 3 are closed. Ammonia rises through a tube that acts as a rectification column and passes into the water-cooled condenser, (b).

During refrigeration, valve 1 is closed and valves 2 and 3 are opened. Liquid ammonia passes into the evaporator, (c), through a heat exchanger, (d). The heat exchanger allows cool vapor leaving the evaporator to cool the incoming liquid, thus increasing the refrigerating effect. The flow of ammonia into the evaporator is controlled by an expansion valve. Ammonia leaving the evaporator returns via line (e).

The innovations in the Exell design are both simple and practical. First, an adjustable reflector is added to the collector to enhance the solar

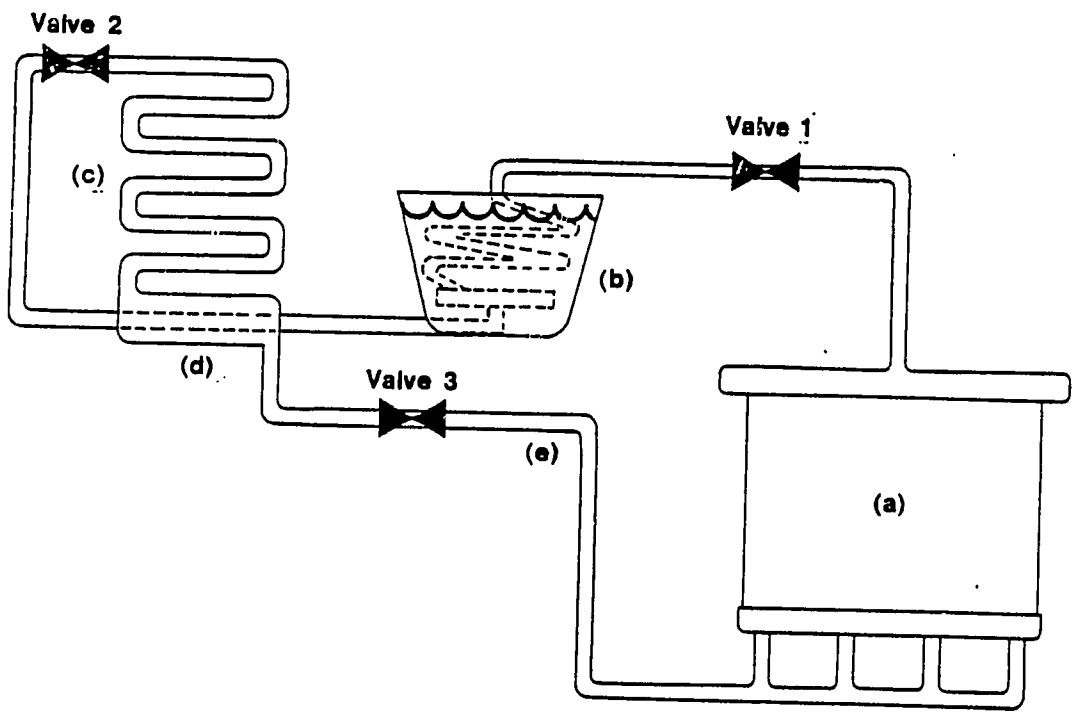

Fig. 9. The Exell Solar Refrigerator.

gain during heating. Second, the water tank is fitted with removable insulation, allowing the cooling water to be chilled by exposure to night air and isolated from daytime temperatures. Third, and most important, the cover plate on the collector is constructed for easy removal during reabsorption of the ammonia vapor, thus insuring that the heat of solution produced during reabsorption can be dissipated at a high rate.

Two operational questions remain only partly solved. The first is: How is the operator to know when to shut off the system during heating? Clearly, there needs to be some signal to the operator when a suitable amount of ammonia has been transferred to the condenser. Similarly, if the rate of heating drops off and ammonia begins to reenter the generator, it is desirable to isolate the condensed ammonia until the generator heats up again. Chinnappa (1962) used a spring balance on the evaporator to track the amount of ammonia accumulated. Exell et al. (1977) provided glass windows in the condenser, permitting the ammonia level to be observed. Khanna (1963) reports a rather ingenious indicator of performance long used in absorption refrigerators in India. These devices have a cap within the rectifying column that the ammonia vapor lifts in passing to the condenser. The vapor, in squeezing by the cap, makes a singing sound like a teakettle, indicating to the operator that distillation is proceeding properly. Incorporation of such a device along with some means (as above) of checking the ammonia accumulated would make it relatively easy for the operator to monitor the system's production.

The second operational question is: At what rate should the operator release ammonia from the condenser to achieve the optimum refrigerating effect? While this is indeed a technical problem, its solution is likely to be as much art as science. The operator will need to be able to assess when the absorber is getting too hot and to slow the rate of ammonia release until the solution cools. He must also recognize when the rate of cooling within the chamber is too rapid to be effective, with more energy used to drop the temperature of the refrigerant rapidly than to form ice in the cold chamber.

The operational parameters of solar icemakers, with monitoring during both heating and refrigeration on an almost continuous basis, make it likely that such systems will be operating as icemaking businesses or facilities rather than as home appliances. While neither the level of expertise nor the attention required of the operator is excessive, such operations are more in the nature of a job than a domestic chore. The image that some authors have of every home with its own solar refrigerator seems unlikely to be realized. More likely every home with its own icebox will be serviced every day or two by the village iceman.

PERFORMANCE

Assessing the performance of solar icemakers constructed to date is difficult for several reasons. First, investigators have not adopted a standardized means of reporting results. Second, the operating conditions under which performance is measured vary widely. Ambient temperature during

heating, ambient temperature during refrigeration, the rate of heating, and the rate of refrigeration all affect system performance.

The extent to which temperature may play a role in governing system behavior is only slowly being appreciated. While the experimental work of Swartman, Ha, and Swaminathan in Canada (1975) strongly suggests that the NH_3-NaSCN system offers significant performance advantages over NH_3-H_2O, the work of Flechon and Machizaud (1979) indicates that under expected tropical conditions the situation may be reversed; and the work of Eggers-Lura (1976, cited by Flechon and Machizaud 1979) suggests that NH_3-$CaCl_2$ may be the system of choice in many tropical areas.

In addition, comparing the performance of a parabolic reflector at one location with that of a flat-plate collector at another is a classic example of comparing apples and oranges. Not only are the characteristics of the solar flux different between locations, but expected response from the different collectors varies even under identical conditions.

Under the circumstances, the best measure of performance for different systems is probably the Total Coefficient of Performance. The Total COP is defined here as

$$\text{Total COP} = \frac{\text{(Cooling obtained)}}{\text{(Energy incident on collector)}}$$

The total COP is valuable in that it measures the system's overall effectiveness at capturing solar radiation and converting it into cooling. Thus, the Total COP includes the efficiencies of energy capture, conversion, and transfer as well as the cooling cycle performance.

Table 1 summarizes the features and performance of many of the systems constructed and tested to date. Most noticeable is the very high Total COP obtained by the Farber device. Part of this is because the energy delivered to the pumps was not reported and therefore was not included in the COP. But there is reason to believe that the performance of the Farber device is indeed above average; the continuous cycle involved tends to maximize possible ice production by the rapid recycling of ammonia back into solution for redistillation.

In areas where electric power is available, the additional cost of the pumps for the Farber system may be outweighed by increased ice production; however, the system would be in direct economic competition with more conventional refrigeration devices. Moreover, a recent analysis by Alizadeh, Bahar, and Geoola (1979) indicates that if chilling is desired where power is available, the more common lithium bromide-water chilling system may have performance advantages over NH_3-H_2O systems. It should also be noted that systems employing pumps or compressors are less suited to local manufacture or repair.

Excluding the Farber device, the Total COPs of the systems in Table 1

TABLE 1. Characteristics and Performance of Selected Solar Icemakers

Reference	Year	Collector Area, M^2	Refrigerant-Absorbent	Incident Radiation, MJ	Average Ice Production, kg/day	Total COP	Remarks
Parabolic collectors							
Kirpachev and Baum 1954	1954	76.5	NH_3-H_2O	1790*	130.0	.04-.08*	Standard industrial system driven by solar-heated system
Trombe and Foex 1957	1956	20.0	NH_3-H_2O	288.0	30.0-35.0	.04-.06*	
Trombe and Foex 1957	1956	1.5	NH_3-H_2O	21.6	6.0	.10-.13	Redesign of earlier system to minimize thermal inertia
Chung 1963	1962	1.1	NH_3-NaSCN	19.7	4.05	.08-.10*	
Flat-plate collectors							
Chinnappa 1962	1960	1.58	NH_3-H_2O	18.5	2.3	.054-.06	
Farber 1970	1969	1.44	NH_3-H_2O	41.5	18.5	.10-.20*	Requires two mechanical pumps to operate
Swartman and Swaminathan 1971	1971	1.62	NH_3-H_2O	26.8	—	.06-.08**	Difficulty with reabsorption; negligible ice production
Vakhidov and Maksudov 1977	1976	2.3	NH_3-H_2O	149.0	12.0-14.0	.04-.05*	
Exell 1978	1977	1.44	NH_3-H_2O	38.6	5.18	.073	Collector cover removable to enhance heat dissipation
Keizer 1979	1979	2.0	NH_3-H_2O	30.0*	4.0-5.0	.05-.08*	

*Author's estimate; based on inferences from data in original source.

**Inferred from estimated cooling ratios; ice production not reported.

are confined to the range .04 to .13. The flat-plate collector systems have a generally lower COP (.04-.08) than the parabolic systems (.04-.13), largely because higher temperatures are attainable with the latter devices. Taking into account the differential performances of the collector types, no general trend is apparent. Considering the aggregate amount of design and experimentation that these systems represent suggests that modifications in design are unlikely to produce major changes in performance in the near future. Well-designed flat-plate systems will probably continue to operate at a COP of about .07 to .08, while parabolic systems will probably operate in the range of .09 to .10.

More important than enhancing peak system performance is increasing the reliability of operation of existing designs. There have been a number of reports of difficulty with the rate of reabsorption of ammonia (DeSa 1964; Swartman and Swaminathan 1971; Swartman 1975). Whether this represents the effects of elevated absorber temperature, a limited vapor-solution interface, or the result of the formation of gradients in solution is not clear. But it is clear that even the best ammonia distillation system is of little use if refrigeration temperatures cannot be attained.

In this connection, it is worth noting that the use of a removable collector glazing appeared to eliminate much of the reabsorption problem in tests by Exell (1978) and Exell et al. (1977). It would be valuable to know if this would still be the case under other operating conditions. If the whole of the reabsorption problem centers on the rapid dissipation of the heat of solution, the answer to the problem may well be at hand.

The largest remaining technical question relates to the relative performances of the various system types under different climatic conditions. There may not exist a single, optimum system design. Research and development in this field would be greatly aided if four or five prototypical units, representing the full range of system configurations, could be provided to a number of climatically different sites for monitoring over a full year or more. The results of such a test could provide valuable data on the best system type for a particular climate and also provide a wealth of standardized operational observations that could greatly assist future design efforts.

ECONOMIC CONSIDERATIONS

Like virtually all nonmilitary engineering problems, the ultimate factor governing the application of solar icemakers is cost. While a solar icemaker has the potential of extending ice production to areas where conventional sources of power are not available, this is of little consequence if the product is so expensive as to be beyond the means of the average consumer.

Reliable figures on the cost of ice from solar icemakers are even more difficult to obtain than performance figures. Few authors report their construction costs, and the figures available are spread over such a range of

time that inflation and changes in exchange rates create problems in interpreting the numbers (Swartman and Swaminathan 1970).

From the cost estimates available (Chung and Duffie 1961; Exell 1978; Merriam 1974; Swartman and Swaminathan 1971), it appears that an icemaking capacity of 1 kg per day costs from US$150-250 in present terms. If this investment is amortized over 10 years, it indicates a cost of 4.1 to 6.8 cents per kilo of ice—excluding labor, debt service, and maintenance. This is three to six times the wholesale cost of block ice in many tropical urban centers (Exell 1978; Regina Santerre, personal communication). Prior to the great leaps in energy costs after 1973, the fuel and water costs of a large ice plant were about 20 percent of the operating costs in most areas (FAO 1975); at present, it appears that the energy component of wholesale ice cost is 20 to 40 percent.

In most developing economies it is expected that the rate of real fuel-price increase will outpace increases in wages and other goods. This indicates that the energy costs of ice manufacture will become an increasingly burdensome factor of production. However, the increases in the cost of ice will not grow as rapidly as the cost of energy. Even if the cost of solar icemakers could be cut in half, it seems unlikely that solar icemakers will become competitive with urban wholesale ice prices in the near future.

On the other hand, even modest reductions in the cost of solar icemakers could make the process competitive in some rural areas. The transport of ice over long distances is extremely expensive. Either costly refrigerated delivery must be provided or significant loss of ice is to be expected. In either case, the result can be a substantial increase in the unit cost of ice. In some areas, figures indicate that delivery and retail markup may approach 300 percent of the actual production cost of the ice, putting the costs presently paid by consumers at the bottom range of solar ice costs.

While the appropriate size for a solar ice factory is probably at the village size or larger (to minimize the labor per unit), large economies of scale in the cost of equipment should not be expected. In many types of small industrial equipment, an increasing capacity means an increase in the volume to surface area ratio for such items as boilers, tanks, and the like thereby reducing the materials inputs. But owing to the very nature of solar icemakers, large surfaces are needed for radiation capture and passive heat transfer processes. Most of the capital costs in solar icemakers appear to be proportional rather than declining functions of total capacity. Doubling the size of a single-family icemaker to serve two families would reduce the cost per unit of capacity, since with small devices the fixed costs (connectors, valves, intermediary piping) represent a noticeable fraction of the total cost; but doubling the size of a device designed for 100 families would probably have an insignificant impact on the cost per unit of capacity.

Although the price of ice from a solar unit may be competitive with local ice costs this does not make the product affordable. To be affordable, the ice must save more perishable food than the consumer could have purchased

with the money spent on ice. The need for rural refrigeration is sometimes supported by international figures on the amount of harvested food lost every year in the developing world. However, these figures include large amounts of grain lost to rats and other pests during storage. Solar icemakers are clearly not an answer to pest management problems in grain farming.

Farmers and fishermen in remote areas have already developed many kinds of food preservation such as salting, drying, and pickling. The advantages of refrigeration in such areas are not in displacing traditional means of food preparation, but in extending present diets to foods that are now little used because of preservation problems, as well as extending dietary diversity throughout the year.

At least as important as domestic applications of refrigeration in remote areas are the commercial possibilities. In many areas of the developing world one of the major constraints on increasing the production of perishables such as fish, vegetables, and dairy products is not the resource base but the limited size of the local market. If harvests can be increased, refrigeration of perishables can allow the export of surplus food to urban centers or other countries, bringing currency for development into the local economy. This is especially attractive in cases where a specialty resource exists with high demand on the world market.

An example is the prawn industry in Jaffna, located in northern Sri Lanka. Since prawns are a high-priced export item, it has proved economical to truck ice to Jaffna from Colombo--a trip of over 300 kilometers--ice the prawns, and ship them back to Colombo for export (Regina Santerre, personal communication). The ice use runs to a kilogram of ice for every kilogram of prawns.

Although the extent of the resource in Jaffna has been large enough to warrant the long-distance transport of ice, in many fishing areas of the developing world the resource is not large enough to arouse the interest of the urban export centers. But if ice were available in fishing villages to allow local storage of surplus catch, it might encourage entrepreneurs to arrange for cooperative transport and marketing of the catch from several villages.

The exact nature of a workable ice industry on the village level will vary widely with cultural and social factors. In some areas, the typical private enterprise model of ownership and operation may be appropriate; but in societies well adapted to collective management, economies would be achieved by operating the ice plant as both the source of ice for cooperative agricultural marketing and as a central cold store for domestic use.

Far too little attention has been paid to the problem of the infrastructure necessary to support a large number of dispersed ice plants. While simplicity, durability, and wide availabilty of construction materials have been stressed as critical design factors by most authors, such terms as "constructed from locally available materials by local labor" should be viewed with some skepticism. It is unlikely that many villages will have the

equipment necessary to fabricate or even repair a solar icemaker unless each can afford compressors, welding equipment, and other tools. Moreover, the "locally available materials" include steel pipe, sheet glass, and pressure-tolerant valves. Under these circumstances, manufacture and repairs must be centralized to some degree.

An efficient system of repair and maintenance is crucial to the whole scheme. Any ice plant is going to represent a substantial capital outlay relative to the resources of most villagers, and a system that does not function for want of repair is rapidly transformed from an asset to a liability. If, as seems likely, most villages cannot afford an entire repair system and an operator, some form of intervillage cooperation will be necessary to make local ice manufacture viable.

In summary, there are still a number of unanswered questions regarding the economics of solar icemakers in rural areas. Considerably more research needs to be done on social and cultural roles and the support system for such devices. While cost reductions in the manufacture of solar ice plants are important in encouraging their widespread adoption, the appropriate management systems are just as critical a consideration. The social and management aspects of the problem may ultimately prove to be more important than simple economics in the future of solar icemakers.

Experience in day-to-day operation is by far the best test of these concepts. Funding organizations should be encouraged to support construction of a few facilities in remote areas to determine the true value and difficulties involved in such projects.

DISCUSSION AND CONCLUSIONS

Despite the diverse groups that have investigated solar refrigeration over the past thirty years, solar icemaking remains a neglected technology. Although potentially workable devices have been tested at the laboratory level, it appears that no device has been carried from the laboratory into serious field testing.

There are many reasons for this. First, solar icemaking is one of the more abstract of the appropriate technologies; to many, the concept is counter-intuitive. Despite the extremely problematical nature of direct heat storage, many government planners are more inclined to become enthusiatic about a "logical" technology such as solar cookers than an apparent oddity such as solar icemakers. In fact, many researchers in solar energy are not acquainted with the vapor absorption cycle, and think of photovoltaic power when the topic of "solar refrigerators" is mentioned.

A second factor contributing to the neglect of solar icemakers is the extremely limited potential of the technology for application in the industrialized nations. The countries that expend the bulk of energy research funds have had little incentive to investigate this technology.

A final factor that has made solar icemakers a low-priority research item in most areas is that they are inherently a rural technology. While local ice production could have a significant effect on the process of rural development, the technology does not have much value in terms of dramatically reducing oil import bills or bolstering energy-short industries. Until recently, the problems of rural develoment have largely been ignored in favor of industrialization schemes. With new international attention being paid to rural development comes the hope that the potential of solar icemakers will at last be seriously and fully explored.

There is considerable room for technical innovation in solar icemaking. Unusual refrigerant/absorbent combinations still need to be studied; moreover, the operational characteristics of these refrigerants in various climatic regimes need to be recorded and tabulated. New materials and configurations should be explored with a view to reducing the capital-intensiveness of present designs. Means of fabrication and repair need to be examined critically for their applicability in rural areas.

In addition, other means of making ice in power-short areas should be explored. Although there seems to be no mention of it in the literature, there is no apparent reason that a wind machine cannot be coupled to a conventional compression refrigeration unit to provide direct mechanical drive (although the variable speed drive at the shaft will certainly introduce complications).

The social and economic aspects of local ice manufacture have never been adequately investigated. While concerned technologists have frequently raised this issue, it remains for agricultural economists and sociologists to outline in detail the problems and promises of the technology at the village level.

The central issue in solar icemaking technology at present is the encouragement and coordination of future research on the topic. To date there has been far too little interchange of results and ideas among scientists and engineers working at the design stage. The international agencies concerned with energy and development issues need to act to facilitate communication and dissemination of research results among the widely separated research groups investigating icemakers. Even a small conference dedicated solely to this issue could be of inestimable value.

It is almost cliche to conclude an article with a plea for "further study and increased funding in this area," but in few areas could such small expenditures so greatly accelerate the research process. Virtually all solar icemaker design to date has been conducted on extremely modest funding. While modest funding is perhaps the best policy in design work related to appropriate rural technologies, the amounts of money currently expended on solar icemaker research are too limited to perform the scaling-up and village testing of devices that will be needed in the near future. Even widespread testing of solar icemakers would entail very little capital outlay compared to many of the agricultural development schemes that are routinely experimented with around

the globe. The benefits of a serious design and testing effort would be large relative to the investment, not only in terms of the information gained but in terms of the research time saved in the laboratory.

Solar icemakers are but a small part of the solution to the world's energy problems and can hardly be expected to revolutionize the international energy picture. Nonetheless, unlike many solar technologies, solar icemakers appear to have many possibilities for near-term applications around the globe; and there is every reason to believe that access to ice would be welcomed by most peoples of the rural tropics.

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THE EAST-WEST RESOURCE SYSTEMS INSTITUTE is directed to the overall goal of understanding how nations can maintain adequate, equitable, and reliable access to resources. The institute consists of a broad study of three interrelated programs: Food Systems, Energy Systems, and Raw Materials Systems.

International research groups are collaborating with RSI staff to analyze and conduct research on these systems. A series of databases and information exchange facilities is now being developed to support their studies. On an interdisciplinary basis, the various teams will explore these problems stressing their interrelationships in both local and international terms in the Asian and Pacific region.

Food Systems conducts research on the institutional and policy aspects of improving food security in the Asia-Pacific region; examines the complex interactions of administrative, technological, and social issues involved in developing food systems in marginal areas; and explores alternate food systems with special emphasis on: food and the city, food systems based on water environments, and institutional and policy aspects of biological nitrogen fixation.

Energy Systems provides analyses of the vulnerabilities of nations to disruptions in the flow of fuels; collects and analyzes data on energy supply, demand, and flows, especially those in rural areas; evaluates alternative development policies on a variety of energy systems; and develops energy indexing methodologies and information exchange both within and among nations.

Raw Materials Systems is concerned with the identification and evaluation of policy and strategy options that will benefit nations from the exploration and development of their mineral resource potential. The main research areas are: mineral assessment for national planning, innovative government-transnational company arrangements, uncertainties in future commodity trade, and case histories of mineral projects.

THE EAST-WEST CENTER—officially known as the Center for Cultural and Technical Interchange Between East and West—is a national educational institution established in Hawaii by the U.S. Congress in 1960 to promote better relations and understanding between the United States and the nations of Asia and the Pacific through cooperative study, training, and research. The Center is administered by a public, nonprofit corporation whose international Board of Governors consists of distinguished scholars, business leaders, and public servants.

Each year more than 1,500 men and women from many nations and cultures participate in Center programs that seek cooperative solutions to problems of mutual consequence to East and West. Working with the Center's multidisciplinary and multicultural staff, participants include visiting scholars and researchers; leaders and professionals from the academic, government, and business communities; and graduate degree students, most of whom are enrolled at the University of Hawaii. For each Center participant from the United States, two participants are sought from the Asian and Pacific area.

Center programs are conducted by institutes addressing problems of communication, culture learning, environment and policy, population, and resource systems. A limited number of "open" grants are available to degree scholars and research fellows whose academic interests are not encompassed by institute programs.

The U.S. Congress provides basic funding for Center programs and a variety of awards to participants. Because of the cooperative nature of Center programs, financial support and cost-sharing are also provided by Asian and Pacific governments, regional agencies, private enterprise, and foundations. The Center is on land adjacent to and provided by the University of Hawaii.

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