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TECHNOLOGY APPRAISAL:
UNCONVENTIONAL REFRIGERATION

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Refrigeration is a technology which, except for air conditioning, is strikingly underutilized in the developing countries. This is most easily explained by the simple fact that the poor, and particularly the rural poor, cannot afford the high costs of refrigeration equipment, that electricity is unavailable or too expensive, or that their traditional technologies obviate the need for refrigeration. These explanations appear sound until one reflects that refrigeration technology developed in respone to a dynamic situation in Europe and America that is to some degree shared by the developing countries today. Specifically, the rapid urbanisation of the 'developed' countries during the 19th century, created a high demand for perishable food, that could no longer be satisfied by the farmers and fishermen in the immediate vicinity of the cities and towns. The rapid development of dairy farming, of commercial fisheries, and, in the 20th century, of vegetable cropping was made possible by refrigeration and a progressive improvement in the transport infrastructure. Similarly, in the developing countries, by producing high-value foods in the rural areas, and by getting them to the urban markets in good condition, rural incomes can be significantly increased. It is the purpose of this assessment to determine the potential roles of several unconventional refrigeration technologies as a means of reducing the cost and increasing the benefits to the rural populations of ice production and refrigeration.

In addition to its application to the preservation of food, refrigeration has many uses in food processing. The exclusion of impurities and moisture from agar agar, and the processing of coconut cream into oil and whey are two applications that fall within existing ATI projects. The condensation of highly volatile oils (scents) is made more efficient or altogether possible by sub-ambient condensation. The drying of foods and other products that are susceptible to damage from

overheating or mold growth can be carried out rapidly and with high energy efficiency by recirculating dehumidified (chilled/reheated) air. The storage of human and animal vaccines or of biological cultures used in medicine, food processing, and increasingly in agriculture usually necessitates refrigeration. Many fundamental operations in chemistry require sub-ambient temperatures for the distillation, crystalisation, or precipitation of reaction products and for the control of reaction rates.

Despite the many opportunities that a refrigeration technology could generate in a particular situation, there are certain technical and economic issues that must be addressed in assessing its viability, and some important constraints to the development of a Project that involves unconventional refrigeration technology. First, refrigeration is like many other technologies in the respect that its efficiency, defined in terms of the amount of 'cold' that can be produced per unit of energy expended, tends to increase with system complexity, size, and cost. Therefore, except in certain situations which will be the focus of the following assessment, the conventional, off-the-shelf refrigeration technology tends to have the lowest running costs, and becomes more economic with increasing plant size or capacity. This technology requires equipment made to extremely precise specifications and with high quality materials and generally utilizes expensive chemically synthesized working 'fluids'. Its manufacture is not therefore easily undertaken by small firms in developing countries. This is perhaps the greatest incentive for identifying those situations in which the simpler technologies may be competitive.

The unconventional technologies may be of interest where mechanical energy is extremely cheap, or where mechanical (or electrical) energy is very expensive, or entirely unavailable. These two extremes may favor, respectively, the relatively inefficient mechanically driven technologies, or the heat driven refrigeration technologies that were common during the late 19th and early 20th century in Europe and America. Cheap mechanical power may be available in connection with micro-hydro plants that are underutilised, or operated intermittently, as for grain milling or food processing. The heat driven technologies can be competitive in rural locations where utility power is costly, unreliable, or unavailable,

where natural gas or agricultural wastes are at least five times cheaper, per BTU of fuel value, or where there is sufficient waste heat, as from the exhaust of an engine. In these cases, the feasibility of using one of the unconventional technologies must be assessed by carefully comparing its initial and life-cycle cost with that of an electrically or mechanically driven freon compression unit of similar capacity and operating temperatures, and by factoring in the relative liklihood and cost of service interruption. The cost of service interruption may be low in a plant that is exclusively used for the production of ice, and that has ice storage capability, but may be extremely high when the plant is used for the storage of frozen foods. Modern refrigeration plants can be characterised as extremely reliable, or nearly as reliable as the grid electricity to which they are connected, but may be very difficult or impossible to repair in a rural location. When used for the storage of large quantities of frozen food, redundancy and auxiliary power should be included in the cost of conventional plants.

The production of ice, and its utilisation for the chilling of perishable foods, is a relatively safe, reliable, low-capital refrigeration technology. Prior to the development of mechanical ice-making equipment during the last half of the 19th century, ice was harvested from lakes and rivers in winter, and stored in enormous insulated houses to be used in summer. Efficient railway cold-storage cars, which received block ice from overhead loading stations, block ice refrigerated trucks, and domestic 'ice boxes' were originally developed to handle this natural ice, but continued to be used with artificial ice long after the advent of mechanical refrigeration. Indeed, the principal application of mechanical refrigeration remained for many years the production of block ice. The advantges of ice chilling for the short-term storage and transportation of meats, dairy products, and fish, relative to freezing such products, are particularly important in the context of a developing country:

a. frozen foods deteriorate very quickly upon thawing; they are therefore less suited to an unreliable cold chain,

b. the use of ice means that only the ice producer needs refrigerating equipment; the consumers, transporters, and distributors need only insulated containers or vehicles. Thus the capital and operating costs, and the import content of an ice-based refrigeration system, can be much lower.

Applications for ice which are prevalent economic activities in the lesser developed countries include the transport and vending of fish, milk, and dairy products, fermented beverages, fruit juices, and meat.

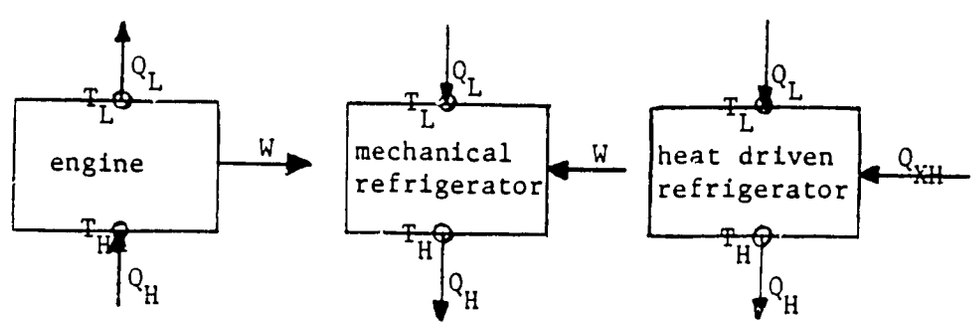
I. General Characteristics of Refrigeration Technologies

Refrigeration is the process of displacing heat from a cool place to a warmer one. The refrigerator removes heat from objects placed within it, and also removes the heat which leaks into it by conduction through the walls and, to a lesser extent, by convection of air through the occasionally opened door, convection of air in 'dead' spaces inside the walls, and radiation across such spaces. By removing such heat, it maintains a lower temperature inside than out. In this respect the refrigerating 'machine' is like a bilge pump which, in the process of discharging water from the hold of a ship, maintains a water level in the bilge which is lower than the level of the sea. Both the bilge pump and refrigerating machine are driven at the expense of energy from an external source. This expenditure is necessary to move water and heat in the direction opposite the direction in which they normally move, i.e., from a higher to a lower elevation or temperature.

Generally, mechanical energy is used for 'pumping' heat. This is because far less mechanical energy is needed to move a certain amount of thermal energy against a specific difference in external and internal temperatures, than would be needed if thermal energy were used under the same conditions. Since electricity is the medium of energy transmission that predominates in the developed nations, and since electricity is convertible with almost equal efficiency into mechanical energy or heat, it is mechanical energy that is generally used for refrigeration. However, one of the unconventional refrigeration technologies permits heat to be used directly, that is without any moving parts, to produce 'cold', and, despite its inefficiency, its simplicity, reliability, and flexibility in the choice of fuel, recommend this technology for use in certain situations. In fact, because most electrical energy is produced by the combustion of fuels of various kinds, and the conversion of heat thereby generated into electricity is itself inefficient, the efficiency of the heat-driven refrigeration technologies can be almost as high as

the overall efficiency of the process of converting heat to 'cold' through the intermediary of mechanical, electrical, and then mechanical energy. The loss of 60% to 70% of the energy contained in oil or coal during its conversion to electrical energy in a modern electric generating plant results in a price for electricity that is commonly three to five times the price of the energy contained in that oil or coal. Since a heat driven cold stroage or ice making plant can burn agricultural wastes costing potentially far less per unit of heat than oil or coal, it may be more economic than the modern mechanically-driven refrigerator.

The relationship between the heat and mechanically driven refrigerators, or 'heat pumps', and devices, like gasoline and diesel engines, power plants, and jet turbines, which convert heat into work, is portrayed below:



T_H and T_L denote, respectively, the temperatures of the hot and cool bodies, media, or spaces with which the machines interact, while Q_H and Q_L denote the quantities of heat that are exchanged between the machines and these media. W denotes the work that is used or produced in the process, while Q_{XH} is the quantity of heat that is used in the process of driving the thermal refrigerator.

An engine does work by consuming heat from fuel burned at a high temperature, and by exhausting a part of that heat to the environment at a lower temperature. The difference between the heat available from the fuel and the total heat released to the environment equals the amount of work that the engine can theoretically deliver. No engine can produce work without exchanging heat with two different external bodies that are at different temperatures. The efficiency of a 'heat engine' is the ratio of the amount of work that it can do to the amount of heat that it recieves from the warmer of the two bodies, which is usually burning fuel, in order to do that work. The maximum efficiency theoretically attainable in a heat engine increases as the diffence between the temperature of combustion

or 'heat addition' and the temperature of the exhaust or 'heat rejection' increases:

$$\text{efficiency} = W/Q_H = (T_H - T_L)/T_H$$

The efficiencies of diesel engines and power plants, as well as other heat engines, can be estimated from this formula if the temperature(s) at which heat is added to and rejected from the engine are known.

A mechanically driven refrigerator or 'heat pump' works, as previously mentioned, by moving heat from a lower to a higher temperature at the expense of mechanical work. It is nothing but a heat engine operating in reverse, since all of the arrows indicating direction of energy flow are reversed vis-a-vis the heat engine. In fact, some devices, including the Sterling cycle, or hot air engine, can function both as engines and refrigerators. The efficiency of a refrigerator is, however, defined differently than the efficiency of an engine, because the purpose of a refrigerator is different. Its efficient is called the 'coefficient of performance' and can be estimated from the following formula:

$$COP = Q_L/W = T_L/(T_H - T_L)$$

The coefficient of performance increases as the difference between the temperatures 'outside' and 'inside' the refrigerator decreases. An air conditioner can pump more heat than a commercial freezer, per unit of electricity used, because it pumps the heat from approximately $15^oC(288^oK)$ to 25^oC (298^oK), instead of from -15^oC (258^oK) to 25^oC. According to the above equation, and using the assumed numbers, a freezer will pump 6.45 times as much heat as the electrical energy consumed, while the air conditioner will pump 28.8 times as much. Various losses and temperature drops cause the COP's of real refrigerating machines to be between 25% and 50% of these values.

The heat driven refrigerator is distinctly different from the heat engine and heat pump in the respect that the 'pumping' is done by a heat driven distillation process, instead of by a mechanical pump. The temperature at which the heat is supplied can be fairly low, but must be significantly above the temperature of the environment into which the pumped heat is rejected. The coefficient of performance of such machines is defined as the ratio of the heat pumped from inside the refrigerator to the heat required to do that pumping:

$$COP = Q_L/Q_{XH}$$

The heat that drives the refrigerator is denoted as Q_{XH} because it is at a temeperature which is 'extra high', relative to the temperature, T_H, of the environment into which the heat is released.

For reasons which will be discussed in more detail in the section on heat driven refrigeration, the COP of these devices has a theoretical limit that is less than one. The exact value of the COP of a particular design can only be determined by a complete and detailed analysis. However, literature on well designed machines manufactured in the 1870's provide fuel consumption data indicating COP's in the range of .25 to .35. Modern, sophisticated units have been designed for COP's in excess of .5, corresponding to a fuel consumption of one kilogram of biomass for every ten kilograms of ice produced.

Refrigeration capacity, whether used for ice making, for fish freezing, or even for air conditioning, is always measured by the quantity of ice that, when melted, would generate the equivalent cooling effect. One ton per day of refrigerating capacity equals 200 BTU/minute or 288,000 BTU per 24 hours, since the melting of a pound of ice requires the addition of 144 British Thermal Units of heat.

I. Mechanically Driven Refrigeration Technologies

A. Vapor Compression Refrigeration

Modern refrigeration technology is overwhelmingly dominated by the vapor compression machine. The widespread availability of reliable electric power in the developed countries, and the high efficiency of the vapor compression machine, dictate its choice in most applications.

The vapor compression refrigerator works by moving a vapor, or evaporated liquid, through a cycle of different pressures and temperatures that result in its condensation to the liquid form, and re-evaporation to a gas. This is illustrated in figure 1. The machine consists of two coils or arrays of tubing, one located inside the refrigerated space, and one outside, plus an electrically or mechanically driven compressor. The compressor recieves the refrigerant vapor at a low temperature from the coil that is situated inside the refrigerated space (called the cold coil or evaporator), and compresses this vapor. The vapor does not condense inside the compressor, because both its temperature and pressure rise. The vapor then enters the coil of tubing that is located outside the

refrigerated space where its increased temperature enables it to lose heat, through the conductive walls of the tubing, to the air outside the refrigerator. It is at this time that the vapor, its temperature falling in relation to its pressure, condenses to form a liquid. The external coil (called the hot coil or condenser), is connected back to the internal or evaporator coil by way of a small orifice or valve, which restricts the flow of the liquid and enables its pressure to drop to the pressure existing in the evaporator. The drop in pressure that the liquid experiences as it passes through the orifice causes it to evaporate, thereby making up the vapor leaving the evaporator on its way to the compressor. The evaporation of liquid refrigerant inside the evaporator requires the absorbtion of heat from the refrigerated space by conduction through the walls of the evaporator tubing. The refrigerated space is thereby kept cold.

A number of different liquids have physical characteristics that make them suitable for use as refrigerants. The freons (flouro-chloro-carbons) are the refigerants of choice today, because their chemical stability enables them to remain effective for very long periods of use, even in safe proximity to the electric windings of the freon cooled compressor motors used in domestic refrigerators. Unfortunately, the great stability of freon also causes it to accumulate in the environment, where it eventually reacts with and destroys atmospheric ozone. Ammonia was widely used during the first half of this century and, although it performs nearly as well thermodynamically, it is somewhat reactive and presents a moderate health and fire hazard. Nonetheless, ammonia has a strong odor, and its leakage is therefore easily detected. It is easily and cheaply produced as an intermediary step in the manufacture of nitrogen fertilizers, and is naturally released to the environment as a product of anaerobic fermentation. It should therefore be considered an acceptable choice for commercial refrigeration systems manufactured in developing countries. Sulfur dioxide and carbon dioxide were somewhat commonly used as refrigerants during the early part of the twentieth century, but the former is extremely toxic, and the latter requires extreme pressures, and thus expensive equipment, to cause condensation at ambient temperatures.

Vapor compression refrigeration machines are very efficient because the quantity of heat released to the environment during the condensation

of a kilogram of refrigerant is, under most conditions, much greater than the amount of mechanical energy required to compress the refrigerant to a temperature above the temperature of the environment (ambient temperature), at which it can release this heat. The actual coefficient of performance of a small commercial ice making machine, of about one ton per day capacity, would be between 1.5 and 2.0, corresponding to an energy consumption of approximately one kilowatt-hour of electricity per 10 kg of ice produced. For air conditioning and other applications requiring cold at above $0^{o}C$, the COP of vapor compression increases dramatically, and, except in certain circumstances favoring evaporative cooling, it is the technology of choice.

The superiority of vapor compression refrigeration for applications, like ice making and the freezing of foods, which require relatively low temperatures, depends primarily upon the cost and reliability of the necessary mechanical (or electrical) power. If grid electricity is not available at a prospective site, it will be necessary to determine whether the intermittency of the existing electric service, and the purpose for which the refrigerator is used, necessitate the installation of an auxiliary engine or diesel-electric generator to operate the plant. In some countries, even the grid power is sufficiently unreliable to warrant installation of auxiliary power on food freezing or cold storage facilities. In such situations, it is important to assess the availability of low cost biomass, or coal, which might favor the installation of a heat-driven refrigerator. On the other hand, in countries which depend substantially upon hydro power for their grid electricity, and have unused capacity, it is likely that electrically operated vapor compression refrigeration is the most economic alternative, whatever the availability of agricultural wastes or other low cost biomass. A small vapor compression machine would make excellent use of an underutilized micro-hyro installation, for community preservation of food, ice production, and food processing.

There are few developing countries in which the production of vapor compression refrigerators would be feasible or economic. The compressors used in domestic refrigerators, freezers, and air conditioners are very simple but precise devices which are low in cost because of the advanced production technologies associated with their large scale manufacture. The compressors used in small commercial refrigeration units are reciprocating (piston) as opposed to rotary compressors, and the manufacture of

relatively low-speed single stage units could be economic in the more populous developing countries, and is certainly practiced by several of them. The fabrication of the heat exchangers (condenser and evaporator) is certainly feasible at a very low level of sophistication, but there are benefits to be obtained from large scale manufacture both with respect to the cost of production and the performance of such components. It is very difficult to seal refrigeration systems against the leakage of freon and ammonia, and a high level of quality control in the selection and processing of raw materials, in machining, welding, brazing, and assembly are needed to prevent losses of refrigerant.

B. Air Compression Refrigeration

One of several technologies which was fairly important during the last decades of the 19th century, and first decades of the 20th century, when refrigeration technology was undergoing a wild free-for-all of inventive and entrepreneurial activity, was the air compression refrigerator. Like the vapor compression cycle, the air compression cycle generates cold by alternately compressing and expanding a gas. Unlike the vapor compression cycle, the air compression cycle uses a gas which is not compressed to its point of liquifaction, or condensation, but which is simply compressed enough to quickly lose its heat of compression to the environment. Although notoriously inefficient, bulky, and expensive, this technology was used for many years for storing provisions on ship board and in other situations where the toxic and potentially explosive qualitites of ammonia could not be tolerated.

Two types of air compression refrigerators were developed: a closed cycle unit in which the air was contained at high pressure, maintained at low moisture content, and recycled inside the machine, and an open cycle unit which aspirated air from and exhausted air directly to the cold storage room. Both of these units had a large compression cylinder, which compressed the air, and a smaller expansion cylinder,which expanded the air and provided some of the mechanical energy needed for operating the compressor. A long circuit of pipe submerged in water connected the compression and expansion cylinders, and cooled the air to ambient temperature so that it would leave the expansion cylinder at a temperature well below ambient.

By comparison with the vapor compression refrigerator, the compressed

air machine has several important deficiencies, and two potentially interesting advantages. Since air does not change phase during the operation of the compressed air refrigerator, it gives up and absorbs relatively little heat. Therefore, a very much larger quantity of air must be compressed in the air compression than in the vapor compression machine, and the former must be larger and more costly than the latter to deliver the same cooling capacity. Because air is a poor conductor of heat, and because the heat exchanger tubes must be large in the air compression refrigerator to reduce frictional losses, the heat exchangers must be huge to provide sufficient cooling. The combination of these frictional losses, losses during the compression and expansion of the air, and inefficiencies in the cooling of the air due to its lack of conductivity, cause the air compression machine to be extremely inefficient, having a COP of less than .25. However, the air compression refrigerator needs no special refrigerant, eliminating the problem of toxicity and flammability. Furthermore, and perhaps of some importance, is the possibility of generating hot and cold temperatures simultaneously, and of varying these temperatures at will. Opportunities exist for greatly reducing the cost of the air compression refrigerator, and for improving its efficiency, by using a water piston air compressor which simultaneously compresses and cools the air. This could be driven either by a water piston engine (Humphrey pump), which shares the same piston in a U-tube configuration, or by water power using the hydraulic ram principle.

II. Heat Driven Refrigeration Technologies

A. Ammonia Absorption Refrigeration

Until electricity became a widely available and low cost commodity in America and Western Europe, the market for refrigerating equipment was shared by two strongly competitive technologies: the ammonia compression and the ammonia absorption machine. Since each factory, however small, was obliged to produce its own motive power, technologies which required little mechanical power could compete with those which, though possibly more efficient or productive, needed to be run by a costly steam engine. Unlike the ammonia compression machine, the ammonia absorption refrigerator could directly utilize heat from a low pressure boiler, not requiring the high pressure boiler, steam engine, and compressor employed

in the compression plant. Furthermore, the absorption refrigerator could even be driven by heat derived from the exhaust steam of a steam engine, and many were therefore installed in large cold storage and ice making facilities to increase the efficiency and output of their steam engine driven compression refrigerators.

The ammonia absorption refrigerator depends upon the high solubility of ammonia in water, and the lower boiling point of ammonia, for its refrigerating effect. This is shown in figure 3, illustrating the simplest 'discontinuous' ammonia absorption refrigerator. The device consists of two containers, each of which serves two different functions depending upon whether the refrigerator is in the first or second 'phase' of its operating cycle. In the first phase, shown by figure 3 (a), the first container, containing a rich solution of ammonia in water, is heated to a temperature enabling the evaporation of the ammonia, but too low to cause the water itself to boil. The ammonia vapor is condensed in the second bottle, which is cooled by a bath of water maintained at ambient temperature. When the evaporation of the ammonia is nearly complete, both of the containers are submerged in water baths at ambient temperature. Because ammonia vapor has a very high affinity for water, ammonia vapor in contact with the surface of water in the first bottle will begin to redisolve in the water as the system cools down to ambient temperature. The 'absorption' of ammonia vapor by the water causes the pressure of the system to drop so that the evaporation of ammonia in the second container continues, even as its temperature falls well below ambient. The evaporation of ammonia in the second container requires heat to be drawn from the surrounding water bath and results in the formation of ice around the container.

The device described above was invented in the early nineteenth century and was in fairly widespread use for domestic refrigeration and medical applications during the late nineteenth and early twentieth century. Called the 'icy ball', it was simple, reliable, and low in cost, and could keep a well insulated ice box cold with daily use. Its efficiency and, at about one kilogram of ice per two hour cycle, its output were, however, very modest.

By 1870 the thermodynamics of the ammonia absorption machine were understood in great detail, and a number of manufacturers were producing fairly sophisticated and efficient commercial ice-making machines. Most

of these machines operated 'continuously', meaning that each component of the system served only a single function, and that every part of the machine remained always at a more-or-less constant and optimal temperature. Both the capacity and the efficiency of these machines were thus much improved over the icy ball or larger discontinuous absorption refrigerators. The operation of a continuous absorption machine is illustrated in figure 4. A fairly important disadvantage of the continuous refrigerators was the need for a pump to recirculate the rich ammonia-water solution that accumulates in the absorber back to the generator. Since the power consumption of the pump is very small, it was possible in ice making plants of less than ten tons per day capacity to drive the pump manually. Nonetheless, this was onerous work, and many manufacturers instaled tiny steam engines to operate the pump. One particularly innovative manufacturer discovered that the ammonia vapor leaving the evaporator could be used to drive the pump, before being dissolved in the absorber. An important advantage of this design, called the Wallicely 'Automotrice', is that the pump operates at a speed that is proportional to the flow of gas from the evaporator, resulting in a relatively constant concentration of ammonia in the solution returning to the generator from the absorber.

The equipment used in a small (300 kg/hr.) turn-of-the-century ice making plant is illustrated in figure 5, taken from an early 20th century french encyclopedia on refrigeration technology . Not shown in the drawing are the low pressure boiler, which burns the fuel and generates steam to operate the ammonia generator, or the ice storage room. It is feasible to integrate the generator and boiler into a single unit, thereby reducing the size of the plant and somewhat increasing its fuel efficiency, but the availability of suitable off-the-shelf boilers, and the desire to simplify maintenance and control of the generator and other equipment, encouraged the isolation of these components. Also not apparent in the illustration is the considerable cooling water requirement of the ammonia absorption plant. The several cubic meter per hour cooling water requirement can be met by recirculating stream or pond water, or, in a dry climate, by expending some of a relatively small volume of water in an evaporative cooler. Air cooling of the condenser and absorber is feasible, but greatly increases the size and therefore the cost of these components.

The feasibility of using low-value agricultural wastes to fuel ammonia absorption refrigerators, their immunity to unreliable or costly electric service, their susceptibility to local manufacture, and the economic opportunities that rural ice-making capability would appear to generate have stimulated numerous initiatives in this area. The Asia Institute of Technology reported in 1984 their construction of a discontinuous ice maker having a capacity of 50 kgs. per day, and susceptible to local manufacture at a cost of 3000 dollars. A number of Indian technical institutes have developed solar powered absorption refrigerators, but the very high initial cost and low output of these devices continue to render them uncompetitive with more conventional alternatives. A retired American refrigeration engineer, Paul Speer of Dallas, Texas, whose convincing advocacy of absorption refrigeration as a tool for the development of tropical rural economies led to the writing of this Appraisal, has established an incipient network of potential developers and users of the technology. ITDG's Intermediate Technology Development Services has performed testing and demonstration of an icy ball refrigerator in Nepal and Kenya as a means of improving the storage of vaccines.

The efficiency or coefficient of performance of an ammonia absorption refrigerator tends to increase with system sophistication and, to the extent that sophistication is related to scale, with its size, as well as with the skill of the operator. The icy-ball and larger discontinuous ammonia-water absorbtion machines would tend to have a COP of about .1, equivalent to the consumption of about one kilogram of biomass for every two kilograms of ice produced. Obtaining higher efficiencies requires that water vapor produced during the evaporation of ammonia from solution in the generator be recondensed and returned to the generator before it reaches the condenser, where it would otherwise absorb some of the ammonia vapor. The use of heat exchangers to perform this function and to minimize the heat requirement of the generator by recovering heat from other components of the system permit the COP to be increased to .35, equivalent to the production of seven kilograms of ice per kilogram of biomass burned. The COP is theoretically limited by the ratio of the energy used to evaporate a kilogram of ammonia to the energy needed to dissociate that ammonia from water <u>and</u> cause its evaporation:

$$COP = Q_e/(Q_e + Q_a) = .4 \text{ (approximately)}$$

The limit is approximate because it depends upon the specifications of the particular refrigerator for which it is calculated. A paper presented by Xu Shi-qiong of the Shanghai Fisheries College, Shangai, China and George Pigott of the Institute for Food Science and Technology of the University of Washington, Seattle, Washington, to the American Society of Agricultural Engineers analyses a double absorber refrigeration system in which the theoretical limit is exceeded by providing some of the energy needed to dissociate the ammonia from water by using a second absorber. The calculated COP of this unit is .54, equivalent to the production of over 10 kg of ice for every kg of biomass consumed.

The significant gains in system efficiency that can be realised through proper design, including the introduction of additional heat exchangers, sufficient heat exchange surface, and indirect firing of the generator, make the choice of a best design rather complex. A component which increases the initial cost of the unit may well be justified, even if the fuel is cheap or free, because it increases the output of the plant by more than the cost increase associated with the component. In addition, improvements which reduce the energy consumption of the plant also decrease the amount of cooling water that it requires.

Although the efficiencies of ammonia absorption machines appear poor by comparison with the compression refrigerators, it should be remembered that the efficiencies of the absorption machines are defined in terms of the quantity of heat, rather than the amount of mechanical energy, that is used to produce a given refrigerating effect. Since three to five units of heat energy, in the form of fossil fuel, are usually used to produce a single unit of mechanical energy, the COP's quoted for mechanical refrigeration should be divided by three to five in making a meaningful technical or economic comparison of heat and mechanically driven machines. If this is done, the more efficient ammonia absorption machines would appear to be competitive, in terms of energy consumption, with the mechanically operated vapor compression refrigerator. The absorption machines are particularly competitive when freezing fish or in other applications requiring very low temperatures, since the COP of mechanical refrigerators decreases at such temperatures. In applications requiring relatively high temperatures, like cold cellars

and air conditioning, the absorption chillers are less likely to be competitive, unless the energy required to drive them is available as waste heat from another process, like the generation of electricity.

The manufacture of ammonia-water absorption refrigerators can be undertaken by unsophisticated metal fabrication workshops having the following capabilities:

- arc welding and flame cutting of mild steel
- soldering and brazing
- rolling of 4 to 6 mm steel sheet into cylinders
- coiling of steel pipe
- turning and drilling of fairly large flanges and other parts
- threading and tapping of pipe and pipe fittings
- casting of iron (optional)
- stamping and punching of sheet metal (optional)

The production of absorption refrigerators would likely be undertaken by a job shop in response to custom prepaid orders, until sufficient demand for a specific design could warrant continuous or serial production. The heat exchangers, whether coil, shell and tube, double tube, or atmospheric, would be simple, modular units permitting a refrigerator of varied capacity and temperature capability to be built by assembling low-cost standard units. The recirculating pump could be a suitably modified off-the-shelf reciprocating (piston) water pump, driven by hand, by a small electric motor, or by a steam or ammonia vapor expansion cylinder. The discontinuous machines do not require a pump and may be a better first product for a small manufacturer, but their relatively low efficiency and capacity tend to make them uncompetitive for commercial applications. The Asia Institute of Technology estimated the cost of producing its prototype 50 kilogram per day capacity freezer at $3000.00 in 1984, while an american engineer, Harry Fischer (PO Box 445, Maggie Valley, North Carolina), has developed a 230 kg/day intermittent ice maker which he estimates to cost between 8000 and 10,000 dollars (1986). While these estimates may be somewhat inaccurate, it is certain that continuous machines of the same physical size as the above designs, and costing 25% to 50% more, could produce more than twice as much ice.

B. Other Types of Absorption Refrigerators

A number of absorption refrigerators use other combinations of vapor and absorber than ammonia and water to improve the efficiency

of the absorption cycle. Bromide and lithium are a combination used in heat driven air conditioning units that are commercially manufactured, but are unable to generate low enough temperatures for ice production.

The well-known Servel gas or kerosene powered refrigerators are continuous ammonia absorption machines that operate without a recirculating pump. These machines utilize hydrogen gas to lower the vapor pressure of ammonia in the evaporator and thereby lower the temperature at which the ammonia will evaporate, without requiring a drop in pressure to occur between the condenser and evaporator. The hydrogen also serves to transport the ammonia vapor to the absorber by circulating in a convection loop between the evaporator, which is the highest and coldest component of the system, and the absorber. Water is still used to absorb the ammonia vapor, thereby extracting it from the hydrogen gas, and releasing its heat of vaporization at above ambient temperature. Although simple in principle, requiring no moving parts, the 'superimposed hydrogen' ammonia absorption refrigerator is not susceptible to manufacture by unsophisticated workshops. In addition to being extremely flammable, the hydrogen will tend to leak through welds that are anything less than metalurgically perfect. This leakage, though slow enough to present no hazard, will quickly result in a loss of performance.

III. Other Refrigeration Technologies

Refrigeration to temperatures slightly above $0^{o}C$ can be achieved by technologies less complex than those described above that depend upon accellerating the evaporation of water. In dry climates, the evaporation of water can be accellerated by breaking a stream of water into fine droplets, by pumping the water at high pressures through small orifices, or by centrifugally accellerating a film of water on a quickly rotating serrated disk. The chilling effect produced by the evaporation can be transferred to the area to be cooled simply by circulating the air that carries the evaporated water through the refrigerated space. Only a tiny amount of mechanical energy is needed to pump the water or spin the disks that enhance the evaporation process, and to blow ambient (dry) air through the evaporation chamber. This process is known as pulverised water refrigeration.

The above process may be applied in more 'normal' or humid climates

if the water is evaporated in a chamber that is entirely closed and is kept under vacuum. The temperature at which water will evaporate or boil decreases as the pressure of the water vapor thereby produced is decreased. At one atmosphere of pressure, water evaporates at 100°C, but the temperature at which water evaporates approaches 0°C as the pressure of the vapor is reduced to zero. In the so-called steam jet vacuum cooler, shown in figure 6, the vacuum is maintained by a jet of steam emerging from a nozzle at high velocity, and accellerating the vapor around it. Both the original steam and the vapor produced in the evaporation tank are condensed by contacting water at ambient temperature that is circulated through pipes in a condenser, and are thereby recirculated to the steam generator and evaporator sprayheads. Most of the water emerging from the spray heads does not evaporate and this chilled water is circulated to the space or object to be cooled. The steam jet vacuum cooler is an interesting technology where moderately high pressure steam is already available, as in an industrial or electrical generating plant, and cooling at temperatures above 2°C is required. The high energy and cooling water consumption of this device is likely to render it uncompetitive in situations where mechanical or electrical energy for powering a vapor compression refrigerator is available, reliable, and reasonably priced. Where neither electricity nor steam are available, and the cost of the boiler must be fully attributed to the cooler, more detailed analysis is needed to compare the costs and benefits of the ammonia absorption and steam jet vacuum cooler for temperatures above 2°C.

Sufficient chilling for the storage of root crops and other purposes can often be achieved in an underground vault, though this is particularly effective in temperate climates, where there is a wide variation in the seasonal temperature. In a dry climate, a combination of evaporative cooling and below-ground storage may be very effective means of refrigeration. The evaporative cooling effect can be achieved by cultivating a lush and well-watered crop above the vault, or by shading the area above the vault, and covering it or enclosing it, with damp cloth.

IV. Conclusion

The successful application of the refrigeration technologies

described above requires more than a good choice of the method used for producing cold. It often requires the ability to properly design and construct well-insulated cold rooms according to their particular function, the ability to build easy-to-handle, durable, and efficient ice freezing cans, brine tanks, and related equipment, and a knowledge of how to process, package, and transport the refrigerated product. Therefore, the unconventional refrigeration technologies are most likely to be successfully promoted by firms which are specialised in the installation and maintenance of commercial refrigeration equipment. The existence of such firms in a country, and their informed interest in an unconventional refrigeration technology are good indications that the technology may have a market. The nature, volume, and geographic distribution of sales of commercial refrigeration equipment, for purposes other than air conditioning, may help to identify immediate markets for an unconventional refrigeration technology.

On the other hand, the above approach may fail to take into consideration the need and potential market for refrigerating capability in villages without electricity, where refrigeration has been unavailable, if not totally unknown. This market, which is the principal reason for investigating unconventional refrigeration technologies, may be assessed according to the following factors:

i. the importance of trade between the villages and an urban center;

ii. the existence of surplus production, or the feasibility of surplus production of perishable food products in the villages during part or all of the year;

iii. the effectiveness of traditional food processing/preservation technologies in delivering that surplus to the urban center(s), or in preserving a seasonal surplus for year-round local consumption;

iv. the loss of value, both monetary and nutritional, that occurs due to the present processing/storage/transport/distribution methodology by comparison with one using the preferred refrigeration technology;

v. the relative cost to consumers of the chilled or frozen product vis-a-vis the cost, on a comparable (i.e. dry weight) basis of the traditionally processed product, and the relative size of the markets for the two products;

vi. the competitiveness of the small rural producer of a frozen/

chilled product, given the costs of raw materials, labor, energy, and transport incurred by the rural and urban producers;

vii. the existence of group/individual entrepreneurial experience in the villages, sufficient to manage the economic activity that would support and rely on the refrigeration technology.

Assuming that the preferred refrigeration technology for a particular application cannot be produced within the villages themselves, it is necessary to market the technology in a manner that suggests or demonstrates to the villagers how the technology can become a profitable investment. Small ice-making plants are probably the best application of modern refrigeration technology in rural areas because:

i. the owner/operator of the ice making equipment does not have to be involved in those activities that generate income by consuming ice, thereby facilitating profitable operation of the equipment;

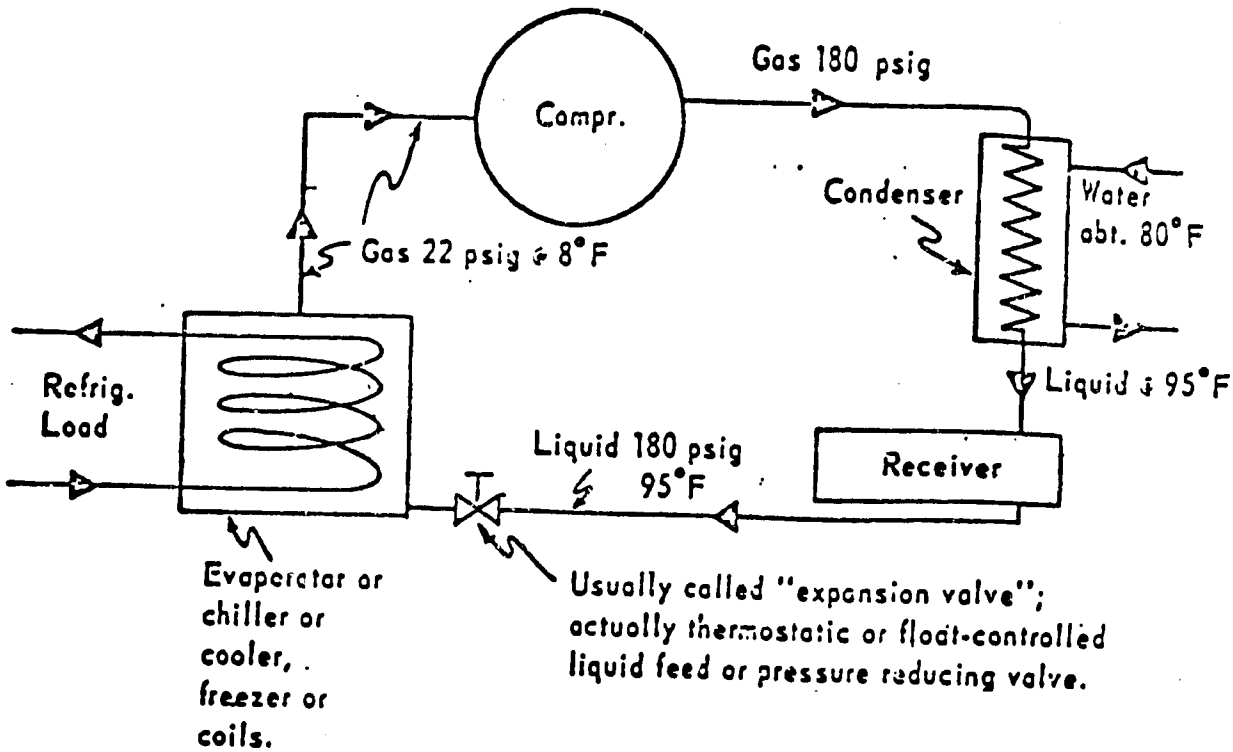
ii. benefits accrue to everyone involved in the distribution of ice, or of chilled food, in addition to those who produce the food and benefit from increased demand, and the plant owner himself;

iii. as previously mentioned, the chilling of food is a safer, easier, and more reliable method of short-term preservation than freezing; and

iv. if the refrigeration technology is heat-driven, local farmers can benefit by supplying biomass to fuel the plant.

Thus, under certain conditions, and especially where there is an important external market for a perishable food product, villages can realise important gains in income and employment through the use of appropriate refrigeration technology. Projects which can demonstrate these effects using equipment that is reliable, affordable, and locally manufacturable can have important and permanent beneficial effects on a very large rural population.

TYPICAL NH_3 CYCLE



Determining Refrigerating Effect:

Total heat of gas @ 22 psig = 614.2 BTU/LB.
Heat of liquid entering chiller @ 180 psig = 148.9 BTU/LB.
Refrigerating Effect = 465.3 BTU/LB.

Definition of a ton of refrigeration:

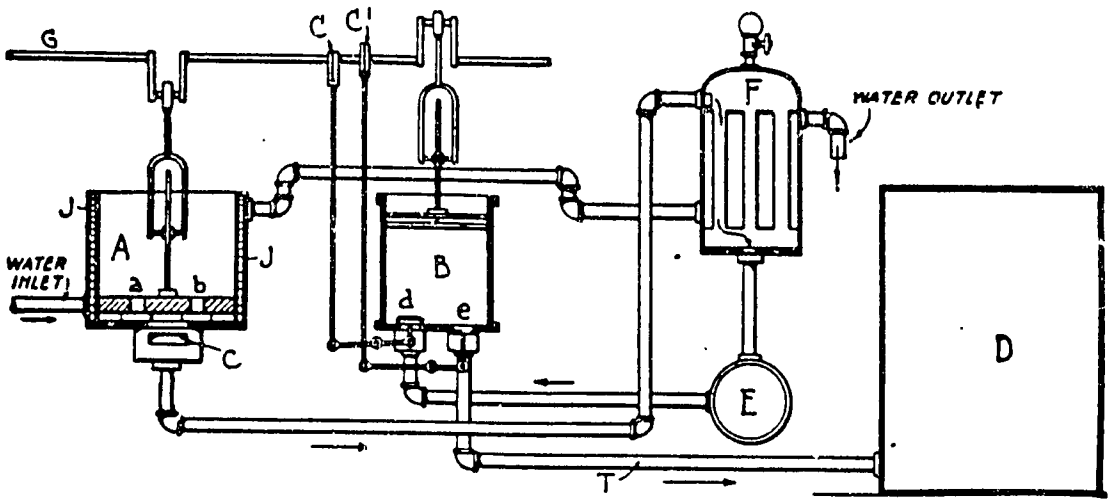
One ton refrigeration = 200 BTU/MIN.
=12,000 BTU/HR.
=288,000 BTU/24 Hrs.
=heat given up by melting 2000 lbs of ice in 24 hrs.

Determining Compressor Capacity:

Lbs. NH_3 evap/min./ton refrig. = $\frac{200}{465.3}$ = 0.43 lbs.
Cu.ft./lb.NH_3 @ 22 psig = 7.65 cu.ft.
Cu.ft.min./ton refrig = 0.43x7.65 = 3.29 cfm

For 100 ton unit need 329 CFM actual capacity at 22 psig intake and saturated temperature

FIGURE 2: Operation of the Open Cycle Air Compression Refrigerator



A - air compression cylinder

a, b are intake valves

c is the exhaust valve

B - air expansion cylinder

c, c' are the excentrics or cams that operate the valves

d is the intake valve

e is the exhaust valve

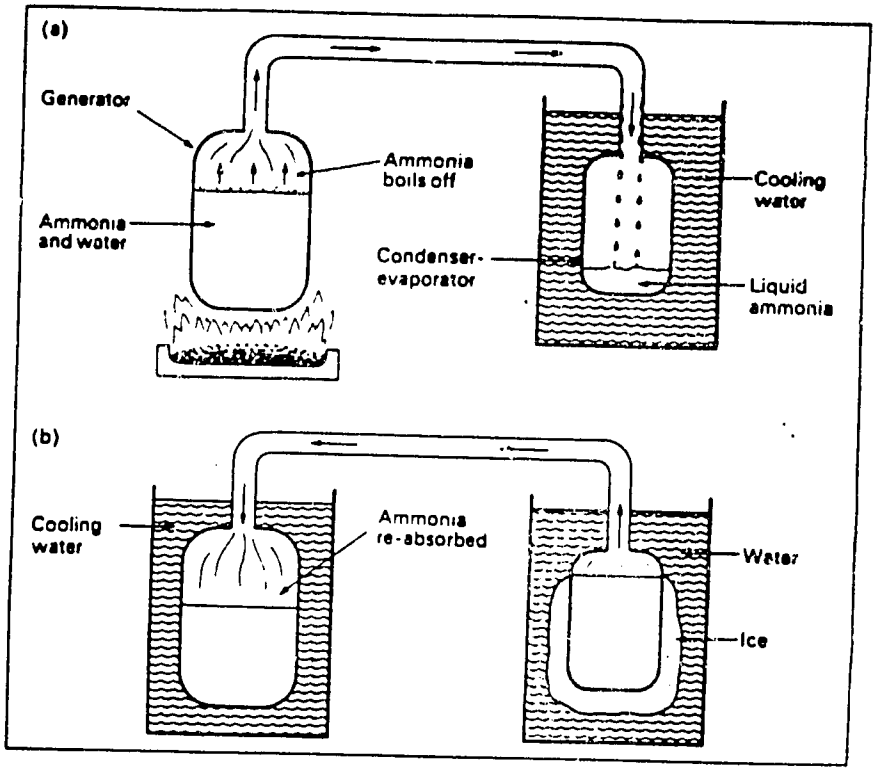
D - cold storage room or freezing compartment

E - high pressure air tank

F - high pressure air cooler

From: the Cyclopedia of Engineering, Volume 5, of the American Technical Society, Chicago, 1920

FIGURE 3: Operation of the Discontinuous or 'Icy Ball' Absorption Refrigerator



How the icemaker works: ammonia is boiled off the ammonia/water solution, and is collected in the cooled condenser. The burner is withdrawn, the ammonia gasifies once more and re-absorbs into the water. In vaporising, the ammonia turns some of the surrounding water to ice.

From: ITDG - ITIS Project Bulletin entitled: 'Completing the Vaccine "Cold Chain" - Field Testing a Portable Icemaker in Kenya' Ref. 60/1/30

FIGURE 4: Operation of the Continuous Ammonia Absorption Refrigerator

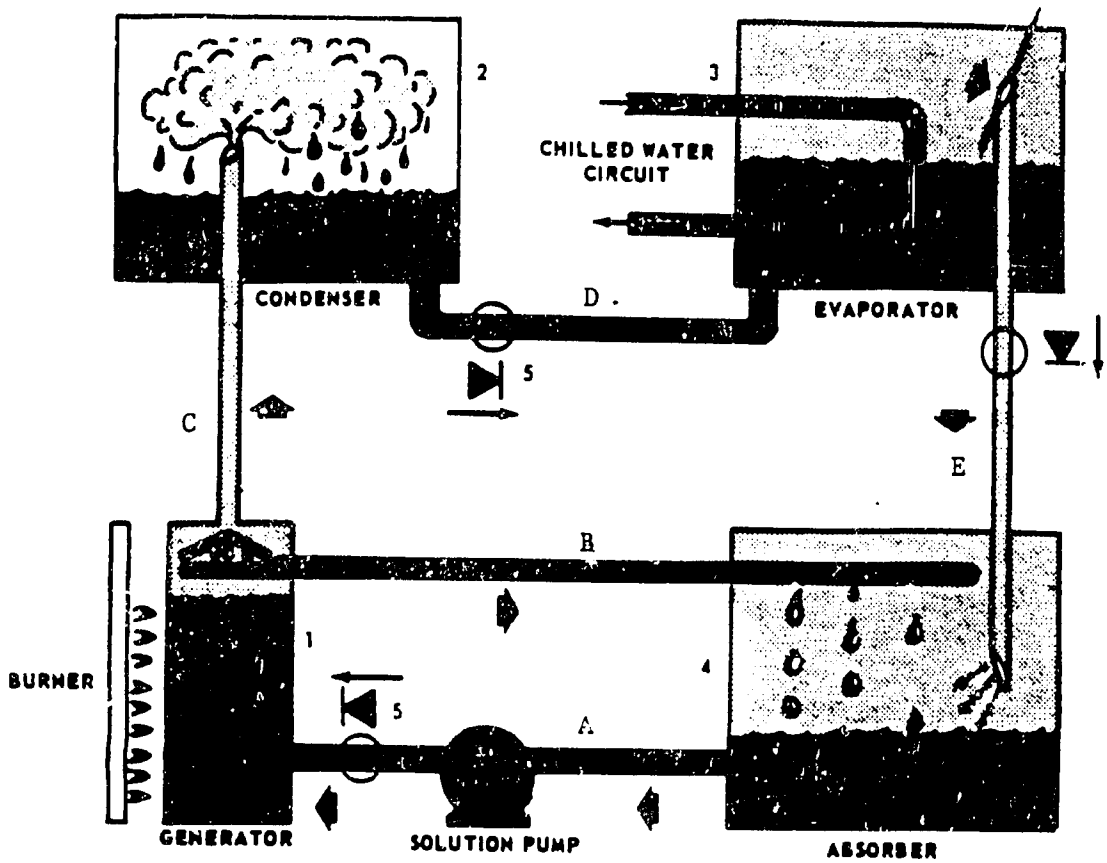


Fig. 16-4. Continuous absorption system uses pump to maintain pressure difference between low-pressure side and high-pressure side of system. Same pump transfers strong-in-ammonia, weak-in-water solution. 1—Generator. 2—Condenser. 3—Evaporator. 4—Absorber. 5—Check valves. (Arkla Air Conditioning Co.)

A - 'rich' solution, having a high (25 - 40%) concentration of ammonia in water

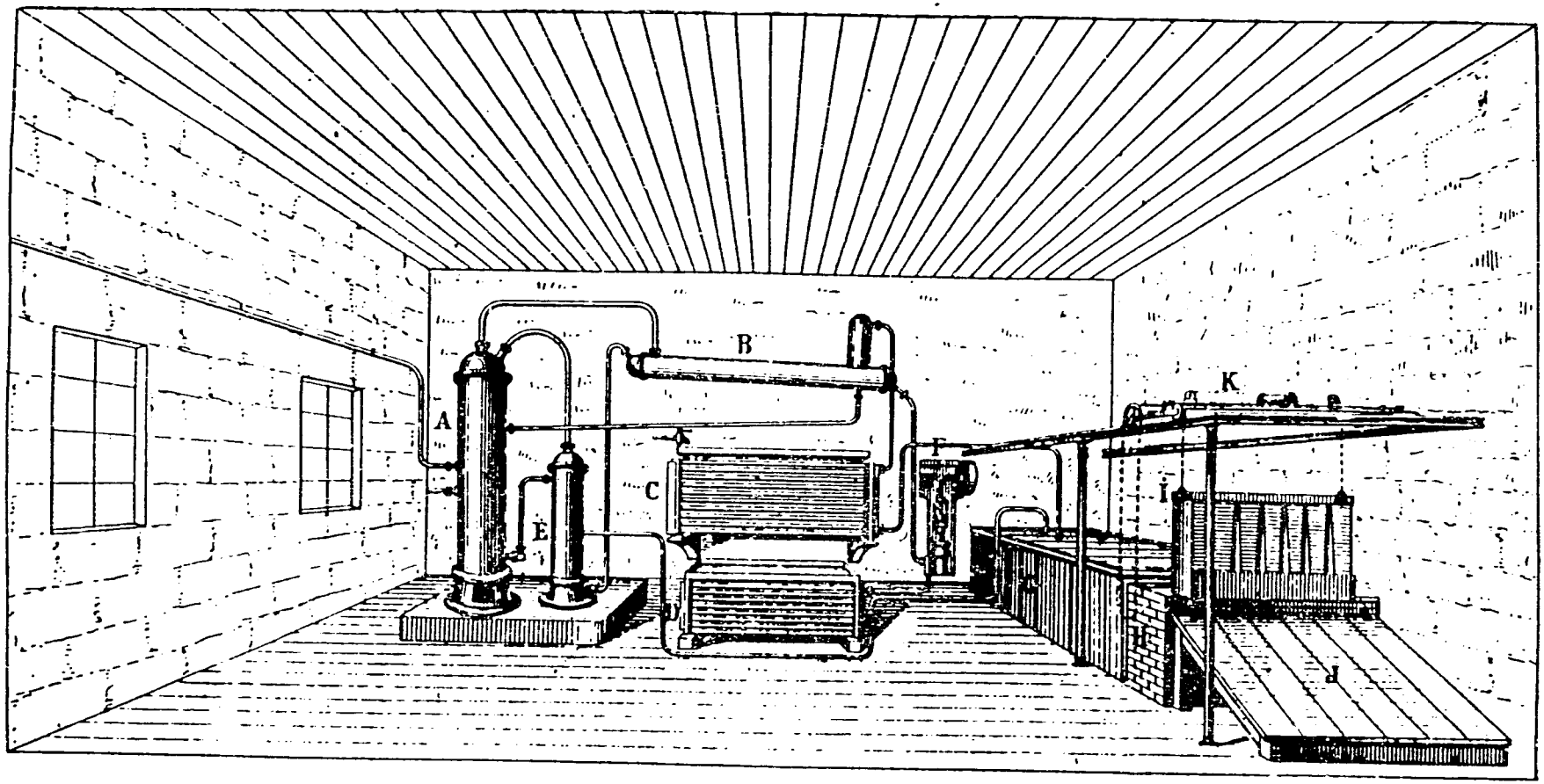
B - 'weak' solution, having a low (10 - 20%) concentration of ammonia in water

C - ammonia vapor at high pressure (app. 10 atm) and temperature (app. 240°F)

D - ammonia liquid at high pressure (app. 10 atm) and near-ambient temperature

E - ammonia vapor at low pressure (0.6 atm) and temperature (-30°F)

FIGURE 5: Appearance of turn-of-the-century small ammonia absorption ice making plant (capacity = 300 kg/hr)



A - Generator

B - Rectifier or Dephlemegator for removing water from ammonia vapor

C - Condenser

D - Absorber

E - Heat exchanger or Regenerator, for preheating rich ammonia-water solution before entry into generator by using heat from weak solution leaving generator

F - manual rich solution pump

G - brine tank, containing ammonia evaporator pipes and ice cans

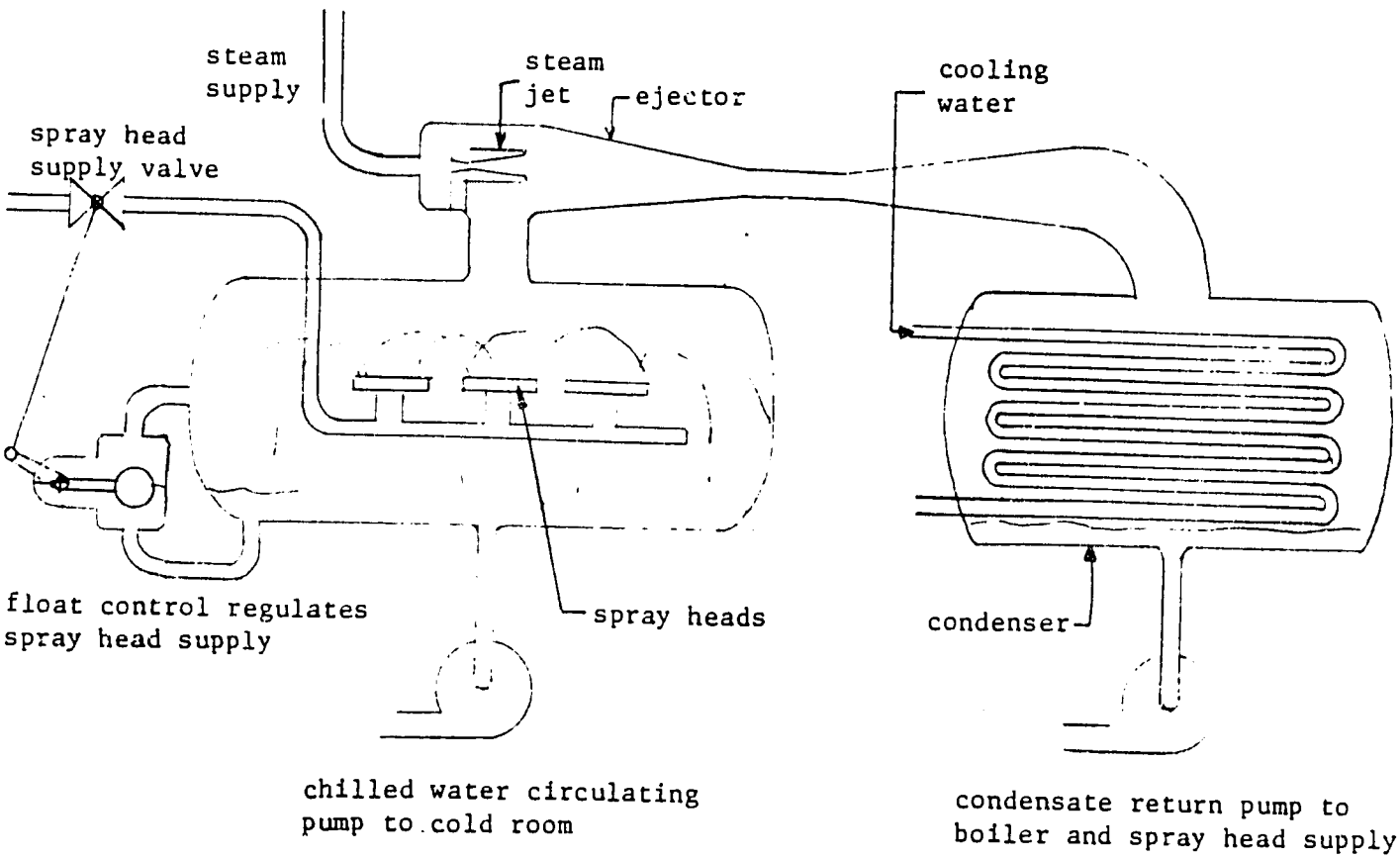
H - warm water tank for releasing ice blocks from cans

I - ice can assembly

J - incline plane for unloading ice

K - hoist for lifting ice cans from brine tank

FIGURE 6: Steam Jet Vacuum Cooler



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This paper explores the reasons why some unconventional refrigeration technologies might be economically viable for use in rural areas. A number of these technologies are described and illustrated, including mechanically driven and heat driven refrigeration technologies. It is concluded that under certain conditions, especially where there is an important external market for a perishable food product, villages can realise important gains in income and employment through the use of appropriate refrigeration technology. Projects which can demonstrate these effects using equipment that is reliable, affordable, and locally manufacturable can have important and permanent beneficial effects on a very large rural population.

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