1985

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Recommended Citation

Roux, J. A., "Experimental Investigation of a Solar Refrigerator Using Natural Zeolite" (1985). *Open-File Reports*. 94.
https://egrove.olemiss.edu/mmri_ofr/94

Open-File Report 85-5F

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1985

The Mississippi Mineral Resources Institute
University, Mississippi 38677

EXPERIMENTAL INVESTIGATION OF A SOLAR REFRIGERATOR USING NATURAL ZEOLITE

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A Final Report
Submitted to the Mississippi Mineral Resources Institute
for FY 85

MMRI Grant 85 - 5F G1144128

August 1985

ABSTRACT

Experimental Investigation of a Solar Refrigerator Using Natural Zeolite

The extreme pressure independent behavior of adsorption isotherms of the material known as molecular sieve zeolite, makes it favorable for a solid gas adsorption cooling system. The previous works on solar zeolite refrigeration had all used zeolites inside a flat plate solar collector. The objective of this research was to construct and then investigate the performance of a system which separates the zeolite from the solar collector. This would even make possible the use of industrial waste heat in producing the refrigeration effect.

Water was selected as the working fluid because of its large heat of vaporization. Furthermore, the heat of adsorption of water vapor on natural zeolites is lower than on synthetic zeolites. This results in a lower system cost since natural zeolites are less expensive, and an increased overall efficiency because of the lower heat of adsorption of natural zeolites. An apparatus was constructed and tested by circulating heated water through the zeolite tank. Data

pertaining to the adsorption and desorption properties of zeolites and the system performance were recorded.

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NOMENCLATURE

COP = Ratio of cooling effect to heat consumption of generator.

CP - Specific heat of water.

CPm = Mean ratio of cooling effect to incident solar flux.

Cz = Constant for the zeolite - water property equation.

Lc = Latent heat of condensation of water.

Lv = Latent heat of vaporisation of water.

md = Mass of water desorbed(lbm).

mz = Slope of constant mass line on log Pv vs 1/Tz plot.

mzd = Mass flow rate of water through the zeolite heat exchanger for the desorption process(lbm/min).

mza = Mass flow rate of water through the zeolite heat exchanger for the adsorption process(lbm/min).

Ma = Total water adsorbed in one cycle(lbm).

Pv = Vapor pressure (bar).

Tz = Zeolite temperature.

Ta = Temperature difference across the zeolite heat exchanger for the adsorption process.

Td = Temperature difference across the zeolite heat exchanger for the desorption process.

t = Time.

ta --Time at end of adsorption process.

td = Time at end of desorption process.

AH = Heat of adsorption (Kj/g).

Xz = Weight ratio of adsorbed water to solid zeolite.

CHAPTER I

INTRODUCTION

Increasing dependence on fossil fuels like coal and oil has led to the shortage of fuel supplies, commonly known as the ”energy crisis”. After the second world war oil was much cheaper than coal, which led most industries to change from coal to oil, thus increasing the demand for oil very sharply. The 1973 oil embargo followed by the increase in the price of oil created an uncertainity about the future of oil reserves. This led people to seriously start thinking about utilizing virtually inexhaustible forms of energy like solar and wind.

Solar energy could be used for a variety of applications(1) such as for :

a)heating water for domestic, industrial and agricultural purposes,
b)space heating and cooling,
c)refrigeration for preservation of food materials,
d)desalination of water,
e)cooking of food,

f)mechanical power production, and
g)electricity production.

The. major technical hurdle for solar applications is the intermittent nature of the resource. This leads to storage requirements which are not as much of a problem in non-solar applications. Solar energy systems require a favorable geographic location and finally, they need to be economically competetive with conventional systems.

Solar refrigeration has attracted a lot of researchers because it requires a relatively low temperature, which is possible by using ordinary solar collectors. The continous solar absorption system is the simplest and potentially most efficient. The generator and the absorber in this system perform the functions of a compressor in the mechanical vapor compression system. The main advantage is that it requires a very small amount of mechanical work. The large amount of heat input which it requires, compared to the work input to a mechanical vapor compression system can be economically attractive if the heat input is inexpensive such as waste heat or solar energy.

The two most common refrigerant/absorbent combinations are ammonia/water and water/LiBr. In the case of an ammonia/water absorption system the absorbent(water) is volatile and so additional equipment is necessary to rectify the generator vapor and increase the ammonia concentration. Moreover the hazards of using ammonia in residential applications have always been a major factor against the development of this system. The main advantage of this system is that it can be air cooled as opposed to the need of a water cooled condenser as with the water/LiBr system.

In the water/LiBr system the non volatility of LiBr eliminates the need for a rectifying equipment. Compared to the ammonia/water system, the water/LiBr system is simpler and operates with a higher COP for certain evaporator and generator temperatures. A practical COP of a commercial unit is in the range of 0.5-0.7 for ammonia/water and 0.6-0.8 for water/LiBr system (2). The primary drawback of the water/LiBr system is that it requires relatively high evaporating temperatures.

Unlike the continuous absorption system, the intermittent system can use either a liquid or a solid absorber. A typical adsorption isotherm (3) is shown in Fig.1 for :

a) Microporous adsorbents (zeolites, other carbons),

b) Carbons, silica gels etc.

Comparing (a) and (b), it is seen that zeolites have a very weak pressure dependence. It is this property which makes zeolites suitable for use in intermittent refrigeration systems.

Zeolites are natural and synthetic minerals made of silica and alumina. They are capable of adsorbing large quantities of a variety of refrigerant gases ranging from water vapor and ammonia to carbon dioxides and freons. According to Tchernev (4), for most of these gases, the saturation amount adsorbed is around 30 percent by weight. Adsorption and desorption are completely reversible so that the contour of a desorption isotherm follows that of adsorption. Since the heat of vaporization for water is the largest of any common refrigerant, the zeolite/ water vapor combination was used in Tchernev's work.

Dubinin and Astakhov (5) have derived a mathematical description for adsorption of vapors on zeolites, taking into consideration the interaction of molecules adsorbed with the adsorption centers of the zeolite, followed by volume filling of the zeolite voids. The exponential temperature dependence of gas adsorption by zeolites led to investigation of the use of molecular sieves for pumping gases in refrigeration cycles. Since desorption follows the adsorption contour, a small change in temperature will cause a large amount of desorbed mass of vapor resulting in a large increase in vapor pressure.

Dubinin, Kadlec and Zukal (6) carried out experimental measurements of the equilibria adsorption values of water on zeolite NaX in the temperature range 20 to 280 C. They obtained strong linearity of the constant mass lines on a log Pv vs 1/Tz plot. It was shown by Berry, Dubinin and Serpenski (6) that the linearity of the isosters was in agreement with the theory of volume filling of microporous adsorbents.

Chang (3) carried out a detailed thermodynamic analysis of a solar zeolite refrigeration system. He derived a zeolite property equation related to its heat adsorption value and desorption initiation temperature. The system performance was found to depend primarily upon the solar collector type and the zeolite adsorption properties. These adsorption properties depend on the adsorption pair and can be represented by the constant mass lines on a log Pv vs 1/Tz plot, Fig. 2. The parameters for the constant mass lines are slope, mz, spacing constant, Cz, and water mass concentration, Xi.

The heat of adsorption was found to be only a function of slope, mz. The slope had competing effects on the system performance, (a) The higher slope (lower desorption temperature) helps the system performance by operating at lower generator temperatures and hence higher solar collector efficiencies.(b) The higher slope (higher heat of adsorption value) lowers the refrigeration cycle COP and hence lowers the overall efficiency. The effect of non-uniform slope on the system CP is shown in Fig. 3, for three different types of collectors. The zeolite intermittent cycle was found to have a lower system performance than the water/LiBr system but had a wider operating range of heat rejection temperatures and could be used to simultaneously produce domestic hot water.

The intermittent nature of solar energy makes energy storage necessary in such a system. Shigheishi, Langford and Hollebone (7) showed that the energy storage by zeolites compared favorably with respect to the thermal capacity of water, stone and heat of phase change systems. Compared to the other solid adsorbents like silica gel, charcoal and alumina gel, the zeolites proved to be superior adsorbents. Zeolite 13X was found to be the best among the molecular sieves. Based upon experimental data from Refs. 6 and 8, Fig. 4 shows the heat of adsorption of water on zeolite 13X and NaX. At very low values of the water content, the heat of adsorption is very high reflecting the strong force with which the residual water is held.

To determine the effect of repeated adsorption and desorption on the zeolite adsorptive capacity, cycling studies were performed over a two month period (8). The results showed no significant deterioration either in the adsorptive capacity or in the structure of the zeolite. The dehydration rate measurements on 10 g samples of zeolite 13X revealed a rapid water desorption rate, with the majority desorbed in about 3 hours and only a marginal improvement thereafter. The room temperature adsorption isotherm was found to be an approximate step function with a maximum capacity of 33 percent by weight; thus corroborating Tchernev's finding (4) of about 30 percent. Almost 75 percent of the maximum capacity was reached at equilibrium pressures of less than 1 torr. Thus a zeolite adsorption system must be operated below atmospheric pressure.

Experiments on the speed at which water was adsorbed, indicated that upto a water content of 21 percent the rate of adsorption was very rapid with the pressure dropping to less than 2 torr in 2 minutes (8). As the preadsorbed amount approached the saturation value, the adsorption rate declined gradually. The rate of heat development was consistent with the rapid adsorption. It was found that under the conditions of the experiment, virtually all of the stored energy could be released at rates which are sufficient for practical utilization like space heating.

Most of the works discussed here have dealt with certain properties of zeolites which demonstrated the feasibility of a vapor zeolite adsorption system. Tchernev's (4) was the only work which demonstrated the working principle of a complete zeolite refrigeration system through an experimental model. His design consisted of zeolite inside a one square foot solar panel, which was tested with simulated solar radiation and with actual sunlight. An alumunium egg-crate-like structure with slotted pieces was found to provide the desired thermal conductivity. The results indicated that natural zeolite chabazite provides the most effective cooling with an overall engineering efficiency of over 45 percent, including collector losses. The efficiency on heating was found to be even higher -- 75 percent. In the heating mode, the condensed liquid was returned directly to the zeolite panel, bypassing the evaporator. The overall engineering efficiency was defined as the ratio of the heat of condensation of the water desorbed during a given time period to the radiant energy incident on the panel during that period. Based on the results of the solar panel, a demonstration module was constructed from nine one-square-foot panels. The results were consistent with those obtained with the single panel.

In the present work an experimental model using natural zeolite was developed, which could run in a refrigeration as well as a heat pump mode. Unlike Tchernev's model, the present design does not restrict itself to heat input in the form of solar energy and hence does not require the manufacture of an entirely different collector assembly, as suggested by Tchernev. Since long term energy storage by zeolites has been found to be feasible, the zeolite is separated from the heat source which could either be solar energy tapped by a standard flat plate solar collector or waste heat in any form which could be economically used to heat the zeolite.

Data pertaining to the system performance were recorded. The system was tested with a natural zeolite from Arizona. The transient system pressure and temperature were measured. The COP of the system with respect to the heat input as well as with respect to the power required to run the pump were calculated. The amount of water adsorbed by the zeolite and the rate of desorption were measured. These, together with the transient temperature and pressure in the zeolite tank were used to study the performance of the zeolite. Finally, a cost estimation of the entire system was done.

CHAPTER II

STATEMENT OF THE PROBLEM

Zeolites are natural and synthetic minerals made of silica and alumina. There are some 34 different varieties of natural zeolites which are found among volcanic rocks and in large clay deposits. The synthetic zeolites are made by synthesizing gels of appropriate composition in an alkaline environment. The mineral structure is rather open but tightly linked electrostatically charged tetrahedra of silica and alumina. These silica and alumina tetrahedras connect in a limited number of ways, thus creating pores and inner cavities with diameters ranging from 3 angstroms to about 10 angstroms. The negative charges of silica and alumina are partially balanced by the metal cations such as sodium or calcium, which are relatively loosely bound within the large voids in the framework. This structural porosity is the reason for the low specific gravity of the minerals, as well as the ability to serve as molecular sieves. When a zeolite particle has been activated by heating, its inner cavities are virtually empty. It is then ready for adsorption. The zeolite framework carries a net charge which attracts polar molecules such as water. Over a large pressure range zeolites can adsorb and desorb water vapor when cooled and heated respectively without any structural damage. It is this property which makes zeolites attractive for use as a non-mechanical compressor in an adsorption refrigeration system.

A solar powered zeolite refrigeration system is depicted in Fig. 5. It consists of two separate loops. The left loop is evacuated and is composed of a zeolite tank, a condenser, a water reservoir and an evaporator, all of which have water vapor circulating through it intermittently. The right loop is at atmospheric pressure and consists of water circulating within a heat exchanger coil in the zeolite tank, a pump and a solar collector. The solar collector can be replaced by any heat/waste heat source which could be economically used to heat the zeolite.

During the day time, the water circulating in the right loop heats up the zeolite by transferring heat from the solar collector to the zeolite tank. The zeolite being heated, desorbs water vapor to the condenser. The vapor pressure thus increases and the water begins to condense when this pressure equals the vapor pressure of water at ambient temperature. This heat of condensation could be used to provide domestic hot water during the daytime.

During the night time, the water circulating through the right loop takes the heat from the zeolite and convectively loses it to the atmosphere, thus cooling the zeolite. Being cooled, the zeolite adsorbs water vapor from the evaporator. As the water vapor is adsorbed by the zeolite, the vapor pressure decreases. When the vapor pressure decreases to about 0.1 psia (5 mm Hg), the water in the evaporator begins to boil. The evaporator tank is heavily insulated so that when the water boils, it takes the latent heat of boiling from the rest of the water in the tank, thus lowering the temperature in the tank. By controlling the quantity of water in the tank, even ice could be produced. The ice produced at night melts during the day, thus maintaining the refrigerated space at a constant temperature. The melted water will be cooled to ice again during the next night time cycle.

Assuming ice to be formed at 0 C, 1 Ibm of water on evaporation will produce about 7 Ibm of ice (heat of vaporization of water is 540 BTU/lbm and heat of melting of ice is 80 BTU/lbm). By controlling the amount of water in the evaporator, the system could operate either as a chilled water unit or a freezer.

An experimental model to demonstrate the working principle was constructed. This study deals with the design and performance of the system under actual operating conditions.

CHAPTER III

APPARATUS

The system flow diagram and details of the zeolite tank are shown in Figs. 6, 7 and 8. As can be seen from the flow diagram, the zeolite tank, condenser and the evaporator constitute the main components of the system. The zeolite tank, with a flat lid on top, is 18 inches in diameter and 27 inches tall. It is constructed of carbon steel and designed for a pressure range of 0 psi inside and 15 psi outside. The tank is painted black both on the inside and the outside.

The zeolite was packed in eleven PVC(polyvinyl chloride) canisters (Fig. 7), which were placed in the tank. The two most important factors which led to this particular heat exchanger design were: (a) the zeolite temperature, which should be high enough for desorption and (b) ease of diffusion of water vapor within the zeolite mass. The PVC canisters were 4 inches in diameter and 24 inches long. To increase the surface area of the zeolite mass exposed to the water vapor, 36 holes 2 inches in diameter were cut on each of the canisters. A standard metallic window screen was used to line the inside of the canisters, to prevent the zeolite granules from falling out through the holes. A 0.5 inch diameter PVC tube drilled with approximately 300 holes each 0.25 inches in diameter, and lined on the outside with metallic screen, was placed in the center of the canisters, thus creating additional vapor passage. A 0.25 inch copper tube, coiled in a circular helix of 3 inches in diameter and a pitch of 0.5 inch, was placed concentrically inside each of the canisters. This constituted the heat exchanger. Both ends of the canisters were capped. The top cap had two holes drilled for the inlet and outlet of the heat exchanger coils and one hole for the center tube. The bottom cap had (one centering hole for the center tube. The heat exchanger coils in all the 11 canisters were connected in series with brass tube to tube couplings. Two holes for the water inlet and outlet to and from the heat exchanger coils were drilled on the side of the tank. Three more holes of 0.25 inch diameter were drilled on the side to insert thermocouple probes to measure the zeolite temperature and the vapor temperature inside the tank. The vapor line to and from the zeolite tank extends from the center of the lid. The tank was insulated with R—11 (3.5 inch) fiberglass insulation. The total weight of zeolite in the tank was 95 pounds.

The evaporator was a carbon steel tank 3-5 feet long and 14 inches in diameter. It was placed inside a 6ft*2ft*2ft styrofoam chest and was also insulated with R-11 (3.5 inch) fiber glass insulation. The condenser was composed of 3 feet of uninsulated 0.5 inch copper tubing and a graduated glass jar 3.25 inches in diameter and 14 inches in height. It also serves as a reservoir. The interconnecting tubing was 0.5 inches diameter copper tube, covered with tube insulation.

Water was heated by passing it through 40 feet of 0.25 inch diameter coiled copper tubing, which was placed directly on a gas burner. This, was used to simulate a solar collector or a waste heat source. The water exiting from the zeolite tank was drained off. This system puts a constraint on the maximum water temperature that could be achieved, namely 100 C. It is possible to increase the temperature by adding antifreeze to the water and circulating it by a pump instead of draining it out. Increasing the water temperature would increase the maximum zeolite temperature, thus resulting in a larger quantity of desorbed water, which would increase the COP of the system.

Temperature measurements were made at the ten locations shown in Fig 6. The thermocouples were given a one point calibration check before being used. This was performed by measuring the temperature of boiling water. All thermocouples used were iron-constantan (J) type. They were connected to an Omega model 2116A digital thermocouple readout. This instrument can handle a total of ten thermocouples.

Leak checking of the zeolite tank and the evaporator tank under vacuum was performed prior to assembly. Suspecting a possible outgassing of the paint and the zeolite, the tank was pumped on by a vacuum pump for several days at a stretch.

All of the above apparatus was assembled as shown in Fig 6. The entire system was then evacuated and each component was leak checked by isolating it from the rest of the system using the valves as shown in the figure. Pressure measurements were then carried out by a manometer .'

Before charging the system with water, the zeolite tank was heated to drive out the water present in the zeolite in the natural state. To cool the zeolite, the gas burners were turned off and cold water from the main water line was passed through the coils. The system was charged by adding a known quantity of water in the glass reservoir. When the zeolite is cooled down, it absorbs the water from the reservoir. Water was added in stages until the zeolite stopped absorbing.

On being heated throughout the day, the zeolite desorbs water vapor which is condensed in the reservoir. The water from the reservoir is then drained into the evaporator. Cold water is passed through the heat exchanger in the night cycle to cool the zeolite. The zeolite then adsorbs the water from the evaporator. The vapor pressure in the evaporator is lowered and this causes the water to boil. Since the evaporator is well insulated, the temperature of the water decreases steadily, thus producing a cooling effect.

The following chapter contains the data pertaining to the performance of the system with the zeolite and a discussion of the results obtained.

CHAPTER IV

RESULTS AND DISCUSSION

The refrigeration results presented in this chapter correspond to a simulated waste heat source. At this stage of the experimental work, it was important to observe the change in the physical state of the working fluid in the evaporator at the end of the adsorption cycle. Hence it was decided to use the glass reservoir as an evaporator in the adsorption process: this was accomplished by insulating the 3.25 inch diameter glass reservoir with R - 11 fiberglass insulation. The actual metallic evaporator tank was not used at this stage. Because of the glass evaporator it was possible to accurately record the quantity of water actually adsorbed during the adsorption process.

Upon being heated, the zeolite desorbs the water vapor, which is condensed in the glass reservoir. During the refrigeration process, the zeolite, after being cooled by circulating cold water through the heat exchanger coils, begins to adsorb the water vapor from the evaporator. Because of the insulation around the evaporator, the energy for evaporation comes from the water itself resulting in cooling of the water and subsequent ice formation in the evaporator.

The index of system performance is the ratio of heat extracted during the evaporation of water in the adsorption process to the heat added to the zeolite in the desorption process, as a function of time,

$$CP_{mr,i} = \frac{\sum_{i=0}^{t} m_{d,i} L_v}{\sum_{i=0}^{t} \dot{m}_{zd,i} C_p \left(\frac{\Delta T_{d,i} + \Delta T_{d,i-1}}{2}\right)(t_i - t_{i-1})} \tag{1}$$

The numerator in Eq. 1 represents the heat extracted in the adsorption process in the form of heat of vaporization of water. Since the evaporator was insulated, the quantity of water adsorbed as a function of time could not be recorded in the adsorption process. To calculate the system performance as a function of time, the quantity of water desorbed by the zeolite was used. The numerator in Eq. 1 thus assumes that all the water which was desorbed, would be adsorbed by the zeolite in the adsorption cycle.

The denominator in Eq. 1 represents the heat added to the zeolite by circulating hot water through the heat exchanger in the desorption process.

Table I presents the data collected during a sample refrigeration run. Figures 9 and 10 show the system performance as a function of time and the average tank temperature respectively; the efficiency is based on Eq. 1. From Fig. 9, it can be seen that the efficiency curve tends to flatten out after about 6 hours and that the rate of increase is almost linear for about three hours. Since the efficiency is based upon the quantity desorbed, it can be seen that heating the zeolite beyond 8 hours would not serve any useful purpose. The dynamics of the process are quite fast and thus the system is suitable for intermittent operation where a heating and cooling cycle could be performed in a 24 hour period. This is of great significance if solar energy is to be used for heating the zeolite, since the period of useful solar insolation is limited to around 8 hours. Figure 10 shows the efficiency curve as a function of the average tank temperature. Since there was no probe inserted in the zeolite mass, the average tank temperature was used to get an approximate value of the zeolite temperature.

For a fixed condenser temperature and fixed heat of adsorption, the two most important factors which govern the quantity of water desorbed are (a) the zeolite temperature and (b) the mass concentration at the beginning of desorption, Fig. 11 (Ref. 3). In the present case only about 4 lbs of water was charged in the zeolite after the tank was heated and evacuated. The charging was performed by letting the zeolite adsorb the water from the reservoir. Since the zeolite was not saturated, the constant mass line at the beginning of desorption would be further to the right on a Tv - Tz plot similiar to the 13X - water plot in Fig. 11. This in turn would require a higher zeolite temperature to begin condensaion. It is seen from Fig. 11 that increasing the zeolite temperature would increase the number of constant mass lines crossed, which in turn would increase the mass of water desorbed.

In the present experimental configuration, the maximum zeolite temperature was constrained by the boiling temperature of water at atmospheric pressure. Figures 12 and 13 show the quantity of water desorbed as a function of time and average tank temperature respectively. It can be seen from Fig. 12 that after the water starts condensing, the curve is quite linear for about 3-5 hours after which it starts to flatten out, indicating a decrease in the rate of desorption. This is because of the extermely slow increase of the zeolite temperature after about 4 hours of heating. From Table I it can be seen that the rate of increase of the average tank temperature decreases considerably after about 4 hours.

Figures 14 and 15 show the pressure variation during the desorption and adsorption cycles respectively. The condenser temperature attained was assumed to be in equilibrium with the pressure measured in the desorption process. A higher condenser temperature would decrease the system efficiency. For the pressure range shown in Fig. 14, the condenser temperature varied between 33 C and 36 C. The pressure during the adsorption process, Fig. 15, was between 1.5 and 2.5 mm Hg. The ability of the zeolite to maintain a very low pressure is an indication of the "pumping action" of the molecular sieves. A low partial pressure in the evaporator results in boiling of the water at very low temperatures, thus producing a refrigeration effect. It is thus seen that when the zeolite is at ambient temperature, it can adsorb large quantities of water vapor even at low partial pressures. On the other hand, when the zeolite is heated, it desorbs most of the water vapor even at high partial pressures corresponding to high condenser temperatures. Thus the difference in adsorbed gas between the high and the low temperature states is large. This corroborates the property of extreme pressure independence of the adsorption isotherms for water vapor on zeolite(Ref. 4). It is this property which accounts for the superiority of the zeolite system over the conventional sorption refrigeration cycles.

At the end of the adsorption process, a cylindrical block of ice was observed in the evaporator. Because of the cylindrical shape of the evaporator, the ice formed on top prevented further evaporation of water from below, resulting in a frozen - lake - type situation. As shown in Table I, the amount adsorbed was only 0.4 Ibm. This was found by taking the difference of the water levels at the beginning of the adsorption and after the ice melted. A part of the adsorbed water mass was a result of the sublimation of ice to vapor. The adsorption of less than 0.4 Ibm of water was enough to form a small block of ice which prevented further evaporation of water from below the ice.

System Sizing

The cooling load for a typical 2000 square feet house in the month of June is around 72000 KJ/day (Ref. 3). The COP of a normal household central A/C unit can be taken as 2.0. Assuming the amount of water adsorbed to be the same as the amount desorbed, that is about 1.6 lbm(0.73 Kg), the amount of cooling produced is, 0.73 Kg * 2453-7 KJ/Kg = 1791-20 KJ. The latent heat of vaporization of water is 2453.7 KJ/Kg.

The mass of zeolite is 95 Ibm (43 Kg). Therefore, the amount of cooling effect per Kg of zeolite is 42 KJ. Hence the mass of zeolite required to take the cooling load of the house is about 1700 Kg (3740 ibm).

CHAPTER V

Conclusions

The possibility of using natural zeolite to achieve a refrigerating effect was demonstrated by producing a small quantity of ice in the evaporator. The efficiency of such a system was found to be approximately 30 percent. The desorption and the adsorption rates were found to be suitable for the operation of an intermittant zeolite refrigeration system. The zeolite maintained a very low pressure of less than 0.1 psi (5 mm Hg) in the evaporator during the adsorption process. This was necessary in order to maintain a low temperature in the evaporator and was an indication of the strong ”pumping action” of the zeolite.

It was found that the boiling mechanism had an important role to play in the refrigeration process. Increasing the nucleation sites for boiling by lining the inside surface of the glass evaporator by metallic screen increased the evaporation rate. Ice was formed at a rate faster with the screen than without the screen.

The system behavior was found to be very sensitive to the presence of residual gases or air in the circuit. The presence of residual air or even a small leak would decrease and eventually stop the condensation process. It was found to have a similiar effect during the adsorption process. The rate of evaporation was reduced to an extent which prevented any ice formation in the reservoir. Monitoring the pressure readings during the adsorption and desorption process is thus very important. For example, a pressure much higher than the vapor pressure of water corresponding to the condenser temperature during the desorption process indicates the presence of residual air or gas or even a possible leak in the system.

Though technically feasible , the cost effectiveness of such a system needs further study. Since most of the literature published on the characteristics of zeolites deal with synthetic zeolites, the performance of a refrigeration system using a synthetic zeolite like 13X should be investigated. The use of Mississippi zeolite would give a basis of comparison with the performance of the present system with the natural zeolite from Arizona.

Since the behaviour of the zeolite permits it to be operated as a heat pump, the investigation of the system in this mode should also be done. In this mode, the evaporator is not used. The heat is collected as heat of condensation in the condenser in the desorption process and as heat of adsorption in the zeolite tank in the adsorption cycle. The possibility of using this system both for cooling and heating makes it very attractive.

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TABLE I

Refrigeration Data ---------------- August 15 1985.

Time (Hours)	Inlet Water Temp (Deg C)	Outlet Water Temp (Deg C)	Qty Desorbed (Ibm)	Avg Tank Temp (Deg C)
0.0	25.00	25.00	0.0	27.00
0.50	95.00	78.00	0.0	34.33
1.00	95.0	83.00	0.04	46.00
1.50	94.00	85.00	0.17	54.00
2.00	95.00	87.00	0.33	60.00
2.50	97.00	89.00	0.49	64.00
3.00	97.00	90.00	0.65	67.33
3.50	97.00	91 .00	0.79	70.00
4.00	96.00	91.00	0.92	71.67
4.50	96.00	92.00	1.03	73.67
5.00	90.00	90.00	1.14	74.67
5.50	95.00	91 .00	1.23	75.00
6.07	93.00	90.00	1.31	75.33
6.50	91.00	90.00	1.37	75.67
7.00	93.00	91 .00	1.43	76.00
7.50	95.00	91.00	1.48	76.67
8.00	90.00	89.00	1.53	76.67

Mass Flow Rate of Water = 1.125 Ibm/min.
Total Energy Input = 5510 Btu.
Amount of Water adsorbed = 0.40 Ibm.

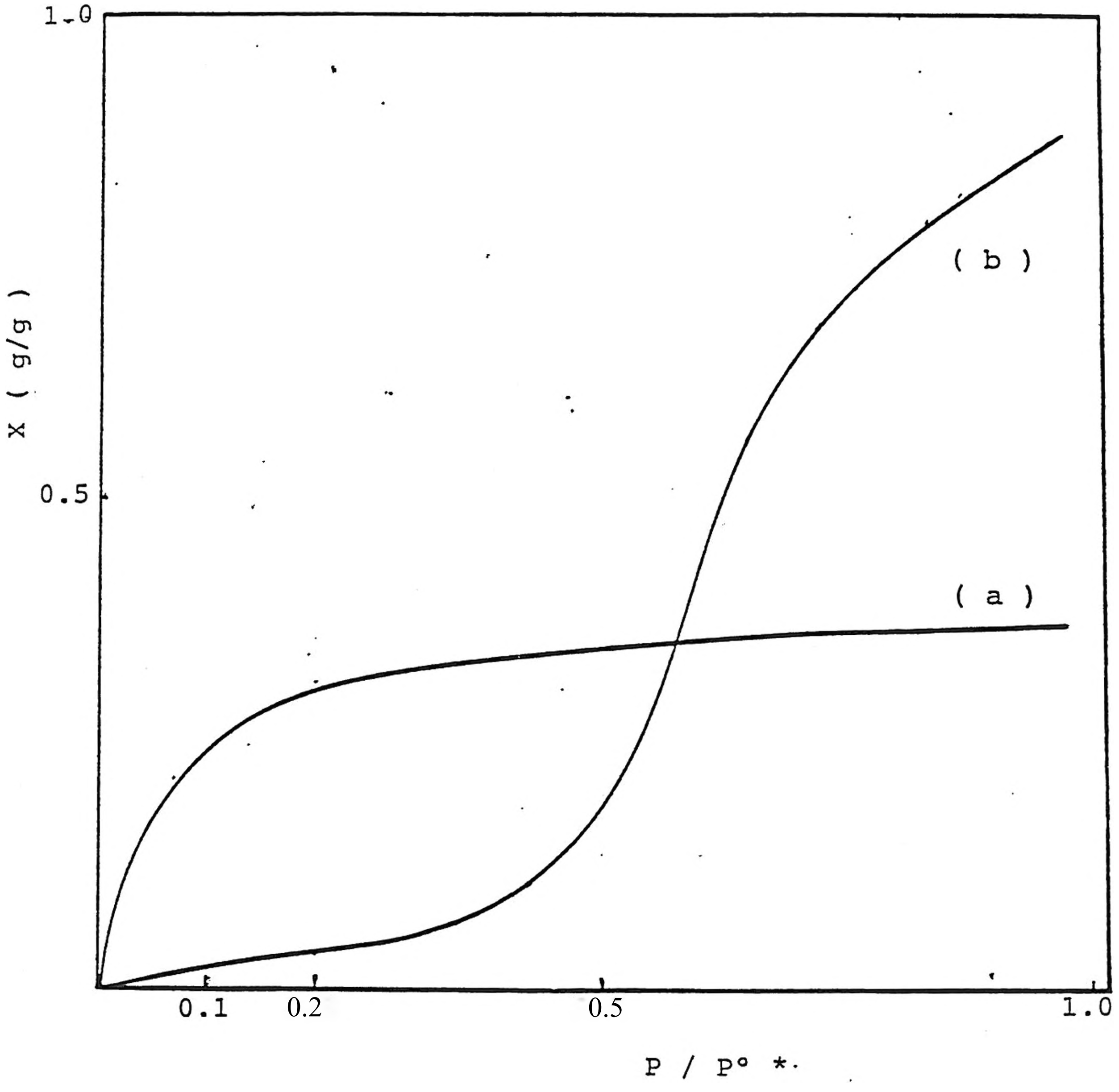

Fig. 1 Typici Isotherms for Absorbed Mass Versus the Vapor Pressure (Ref. 3).

* P is the Pressure above Absorber Fluid.
P_o is the Saturated Pressure Corrsponding to
Temperature of Absorption.

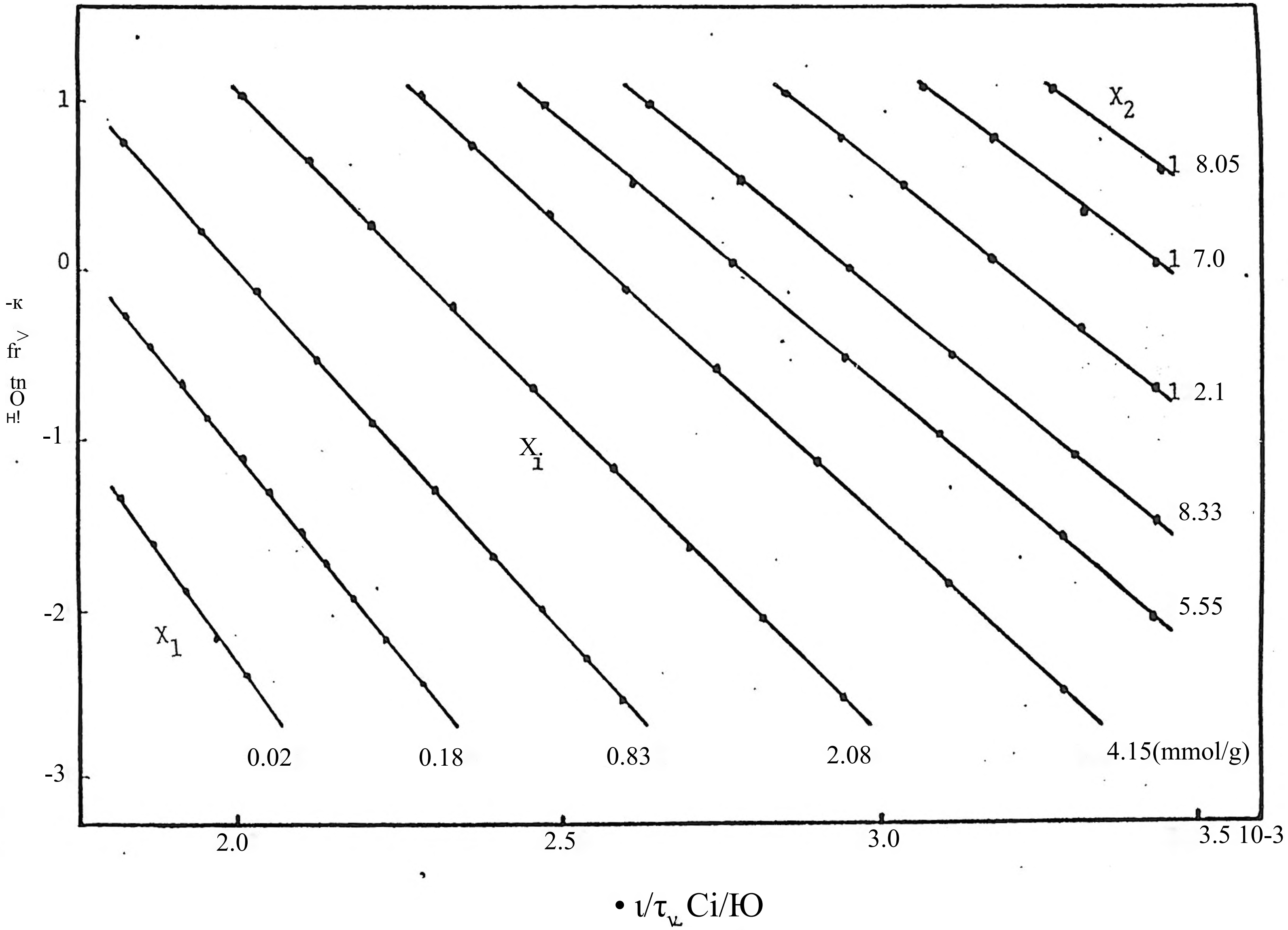

Fig. 2 The Log P Versus 1/T_g Plot for Zeolite NaX-Water
Pair from Expermental Data. ' (Ref. 3)
*P_y (mm Hg)

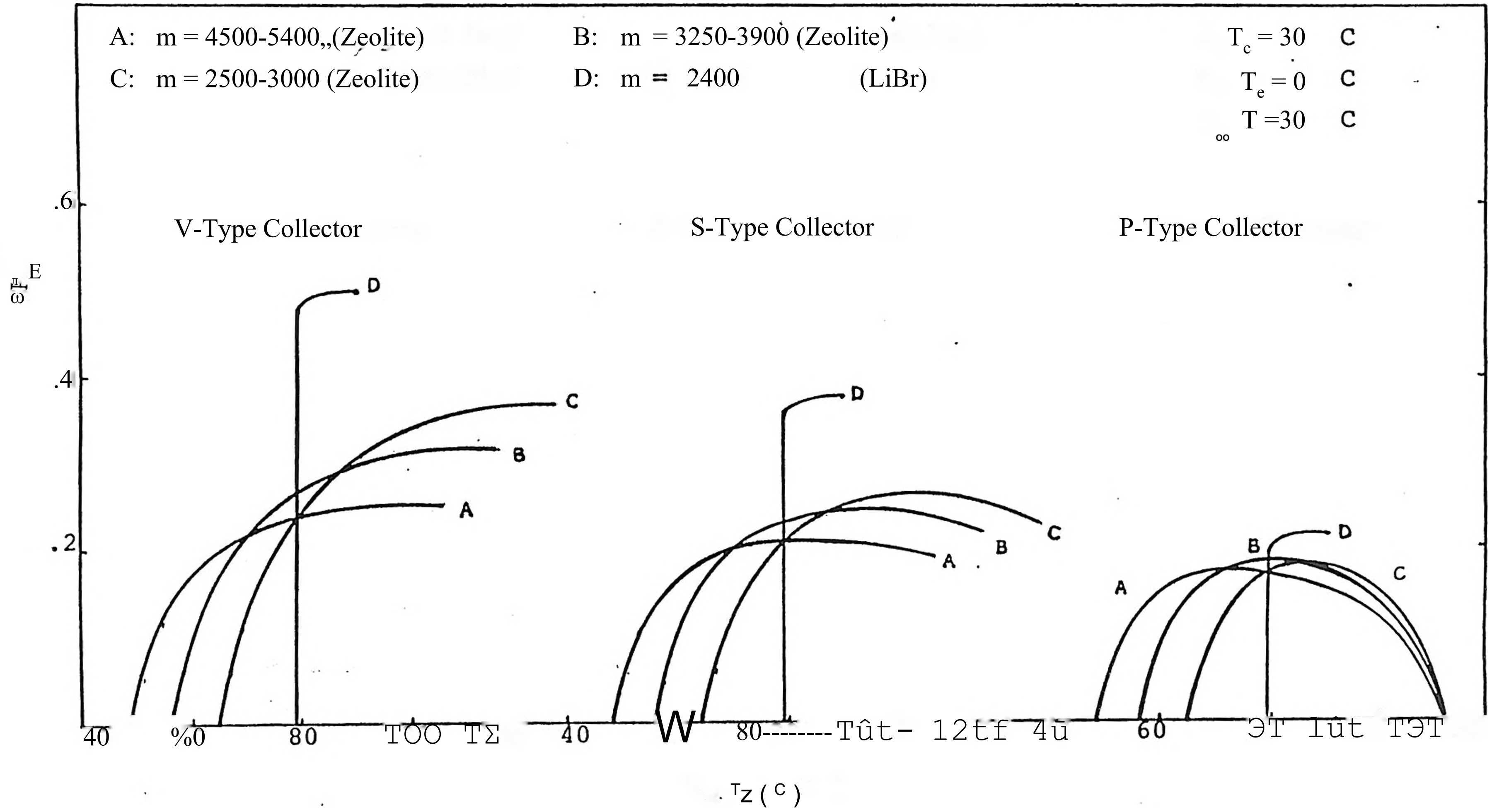

Fig. 3 Comparison between Zeolite-Water Intermittent and LiBr-Water Continuous Cycles(Ref. 3)·

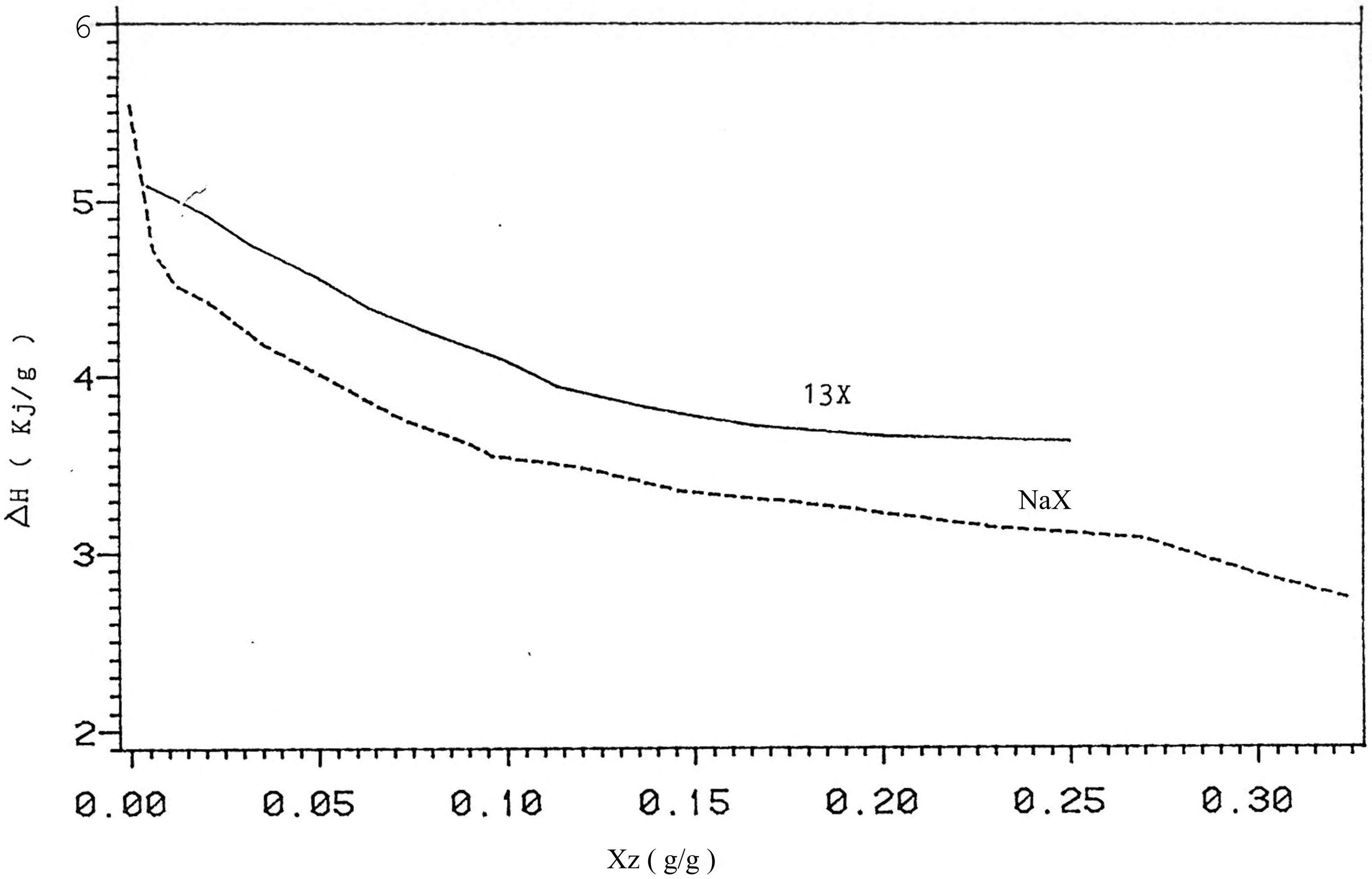

Fig. 4 Heat of adsorption as a function of amount of adsorbed water vapor

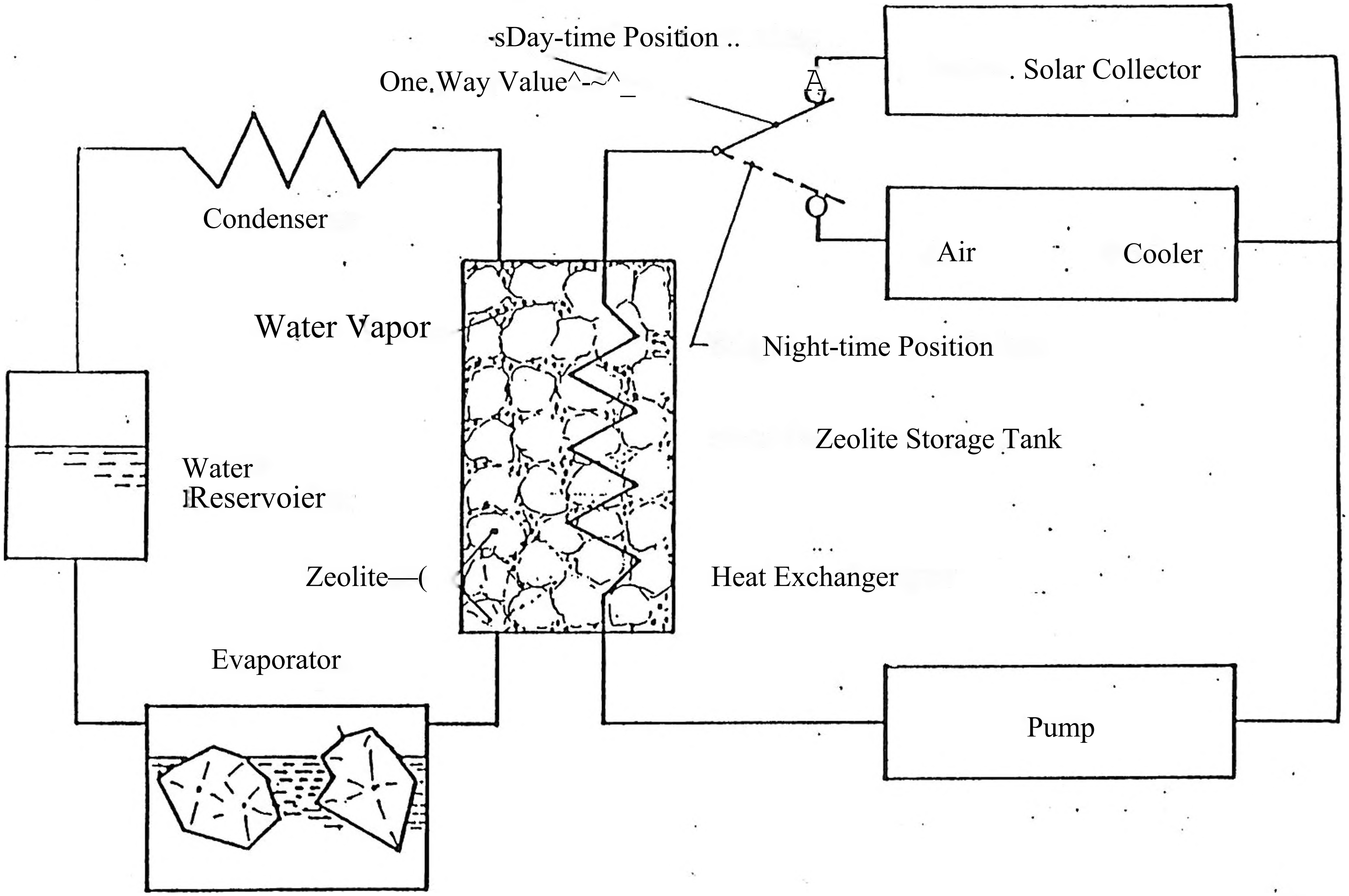

Fig. 5 The solar zeolite absorption refrigeration system(R$_{e}$f. 3)

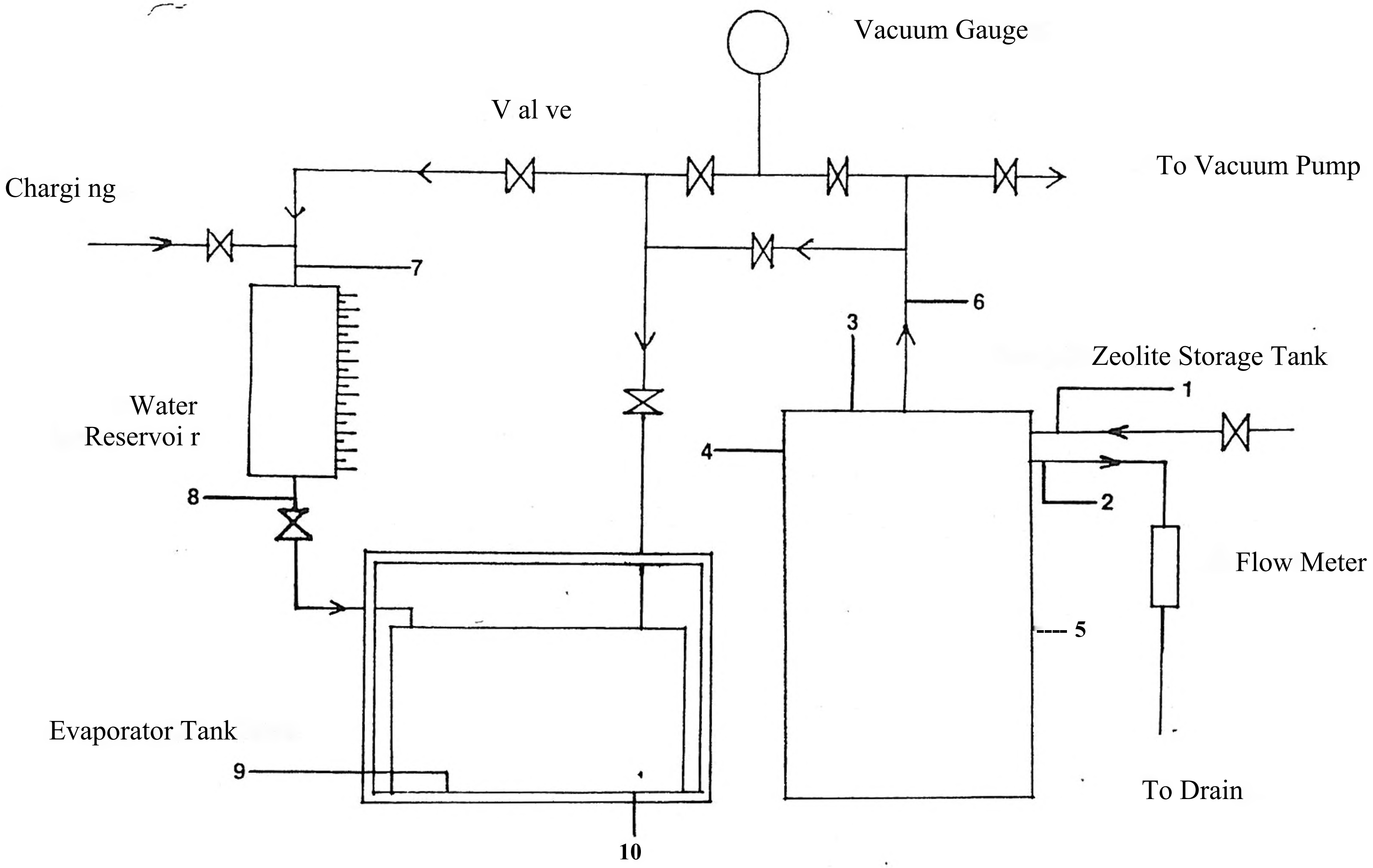

Fig. 6 The System Flow Diagram.

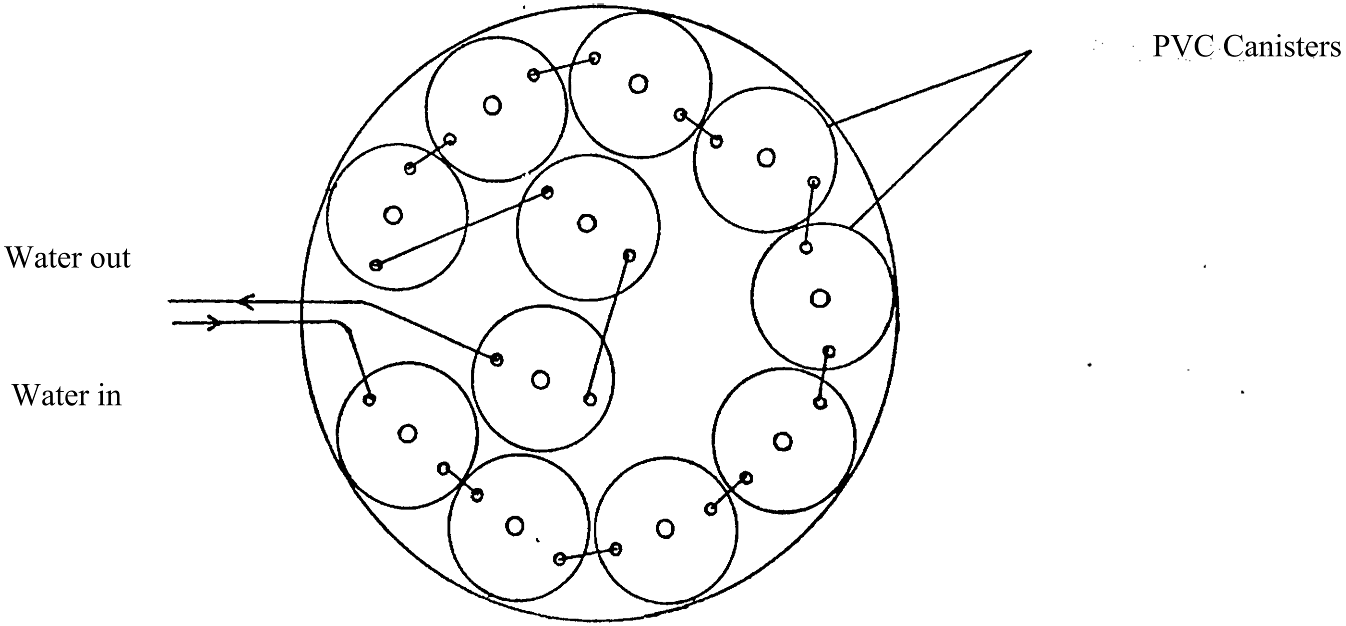

Fig. T Arrangement of the PVC canisters in the zeolite tank.

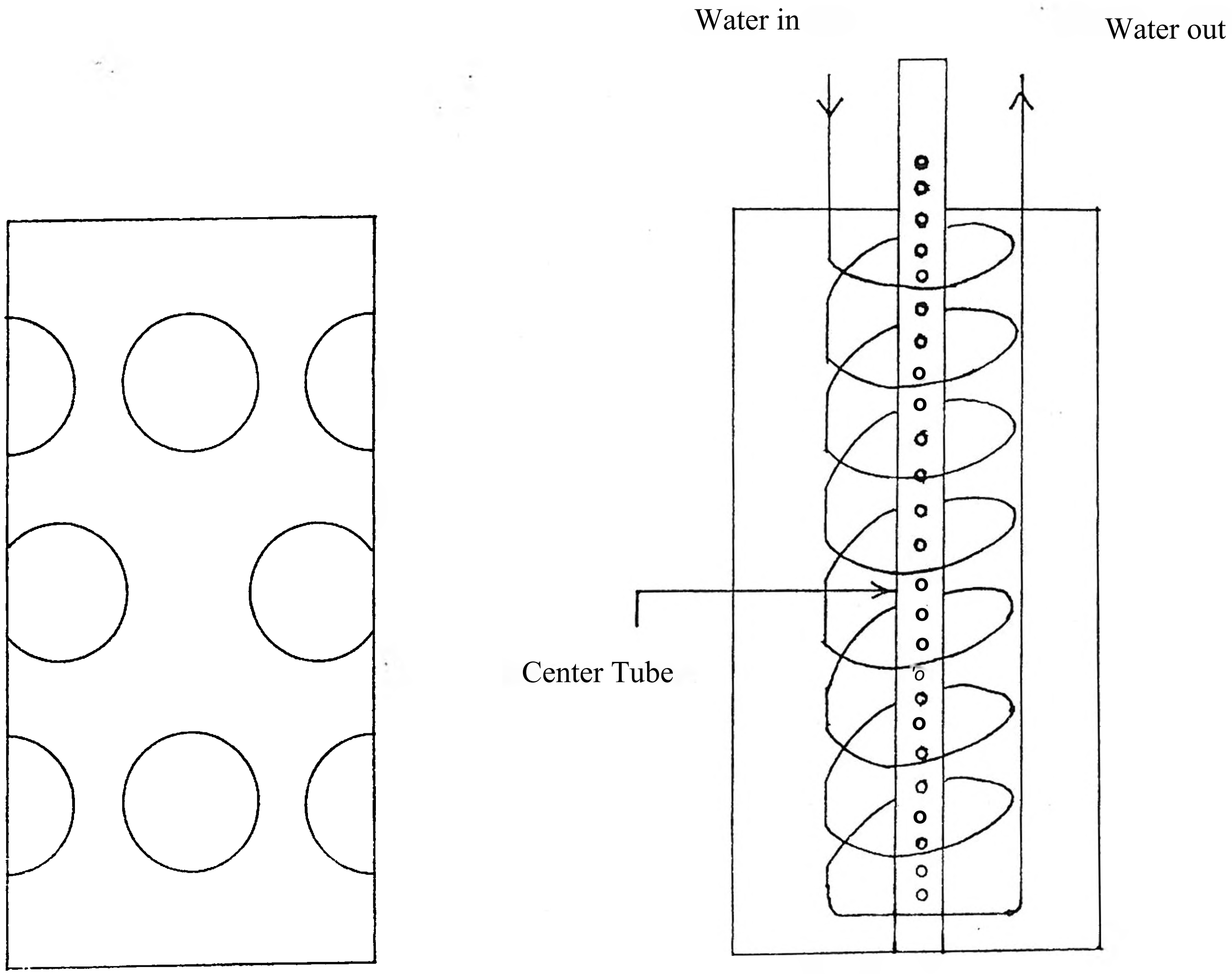

Fig. Ó Details of the heat exchanger.

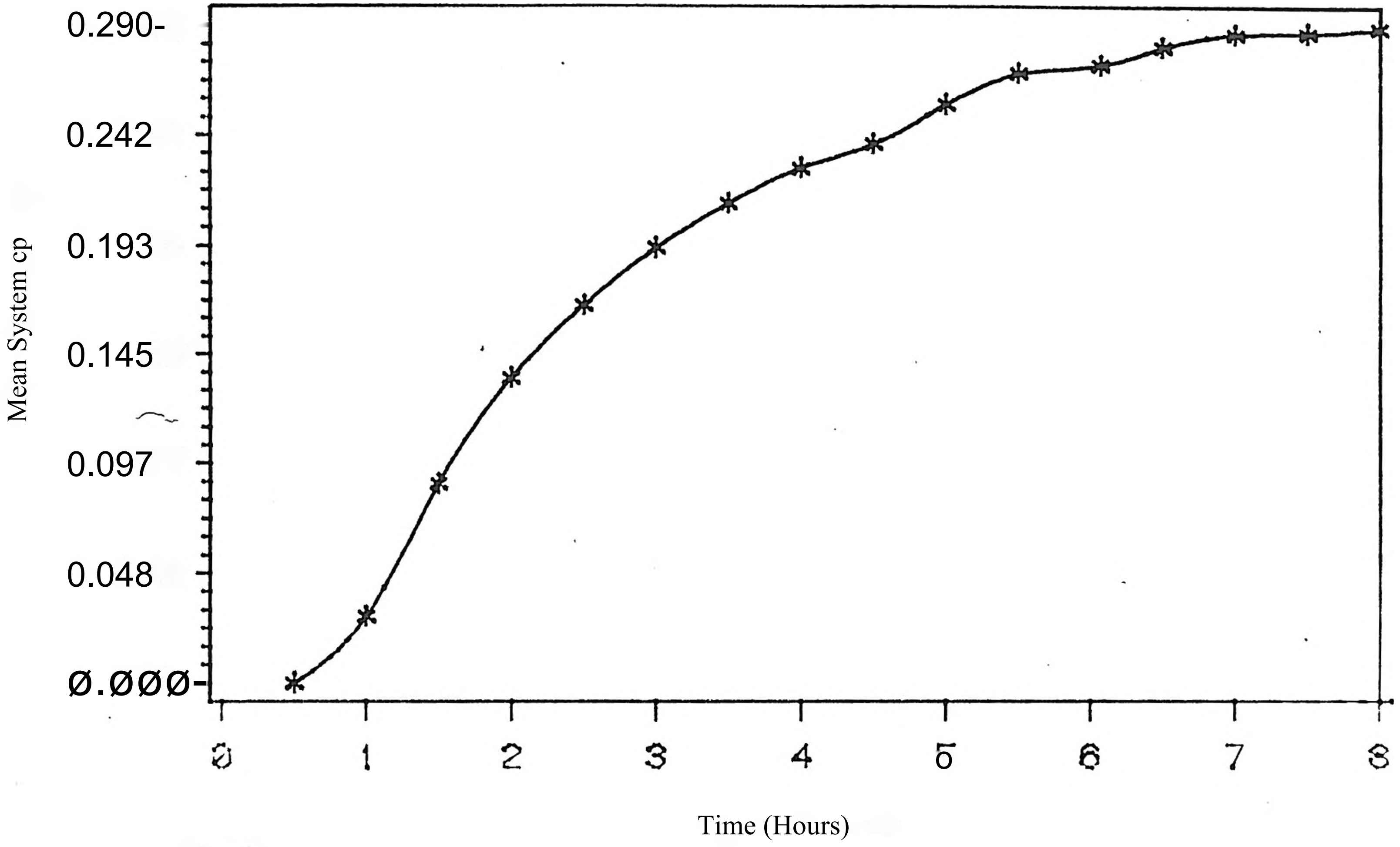

Fig. 9 Mean system CP versus cycle time in refrigeration mode.

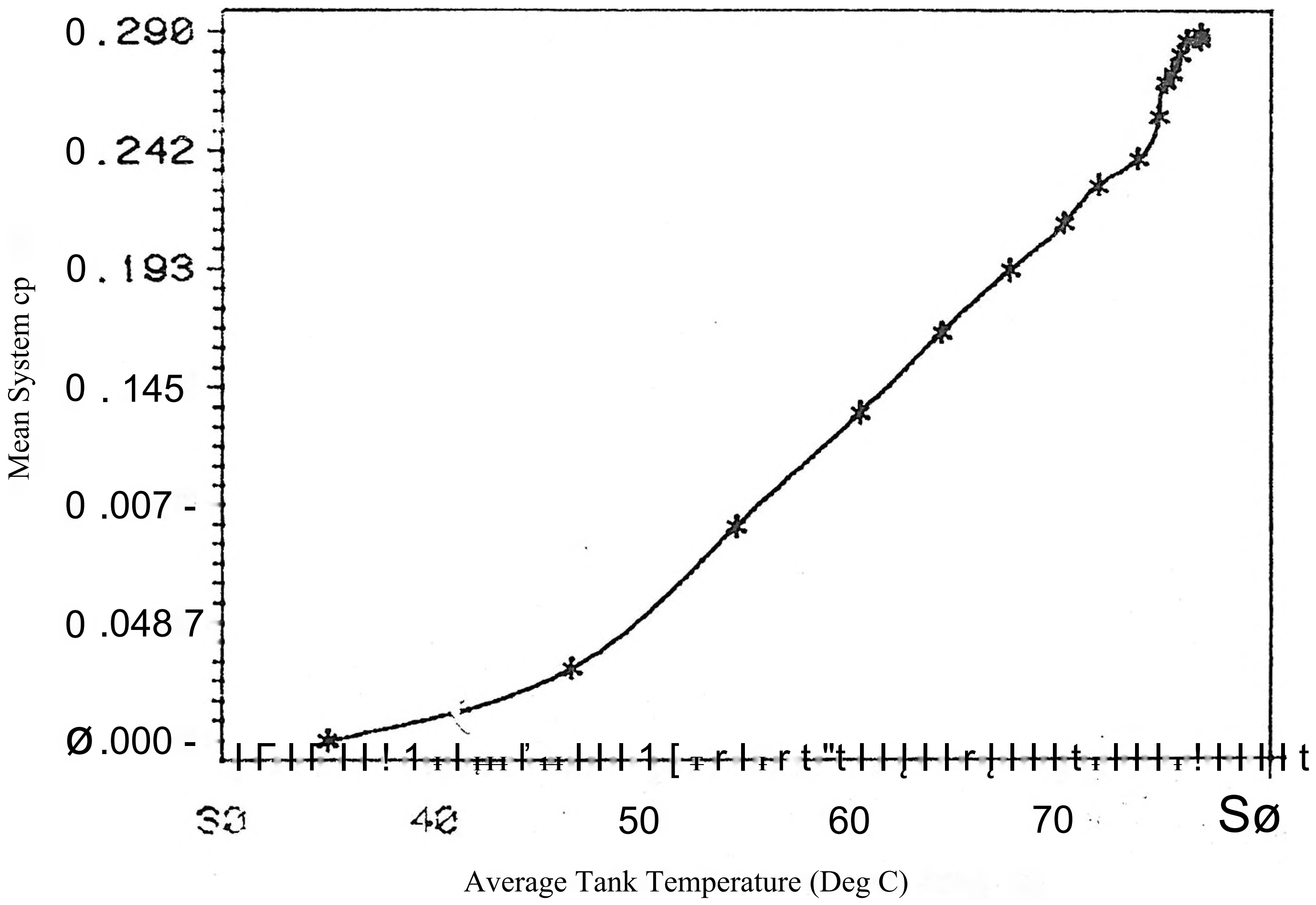

Fig. 10 Mean system CP versus average tank temperature in refrigeration mode.

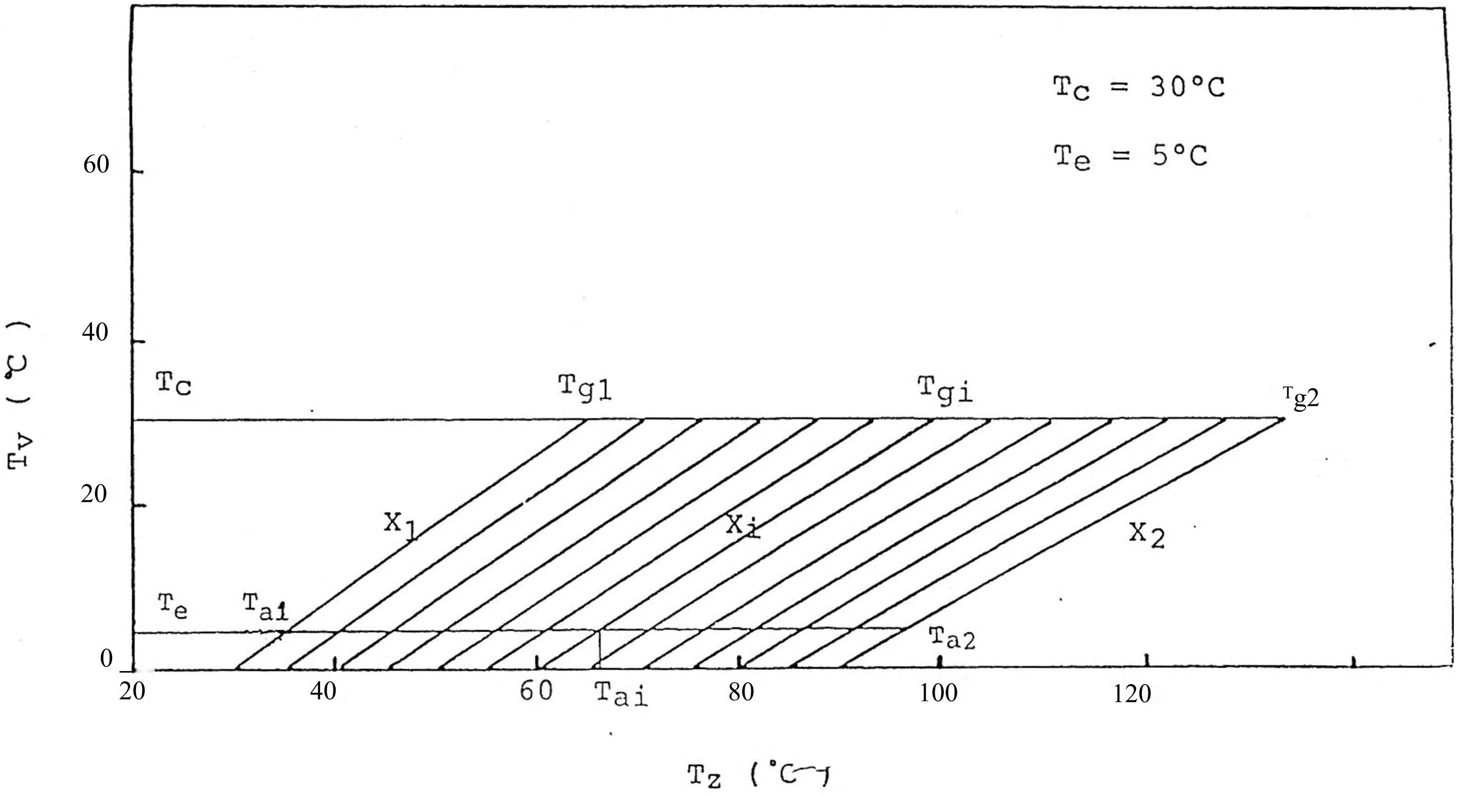

Fig. 11 Tv versus Tz Plot for Zeolite (13X) - Water Pair (Ref. 3)

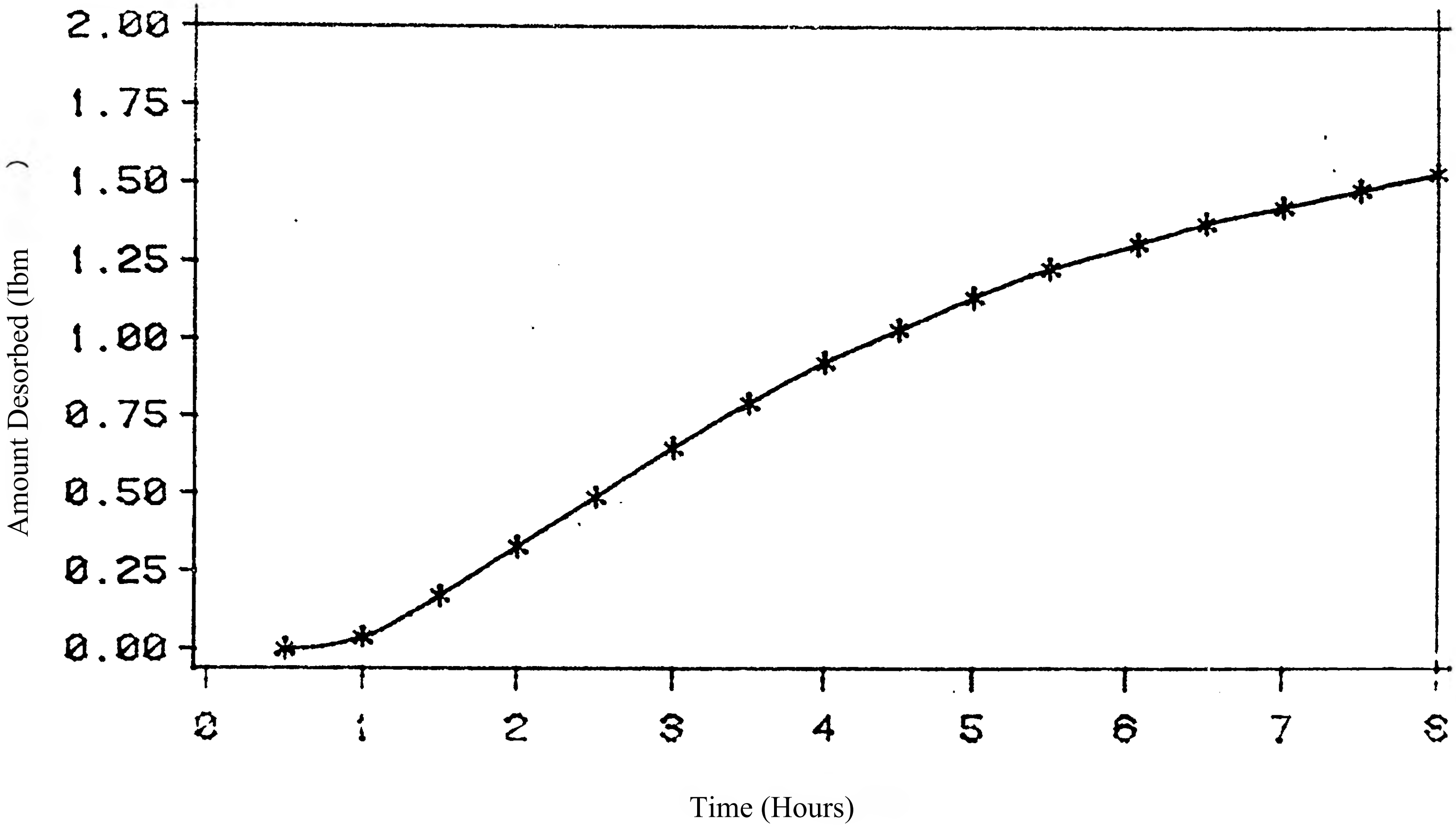

Fig. 12 Amount desorbed versus cycle time in refrigeration mode.

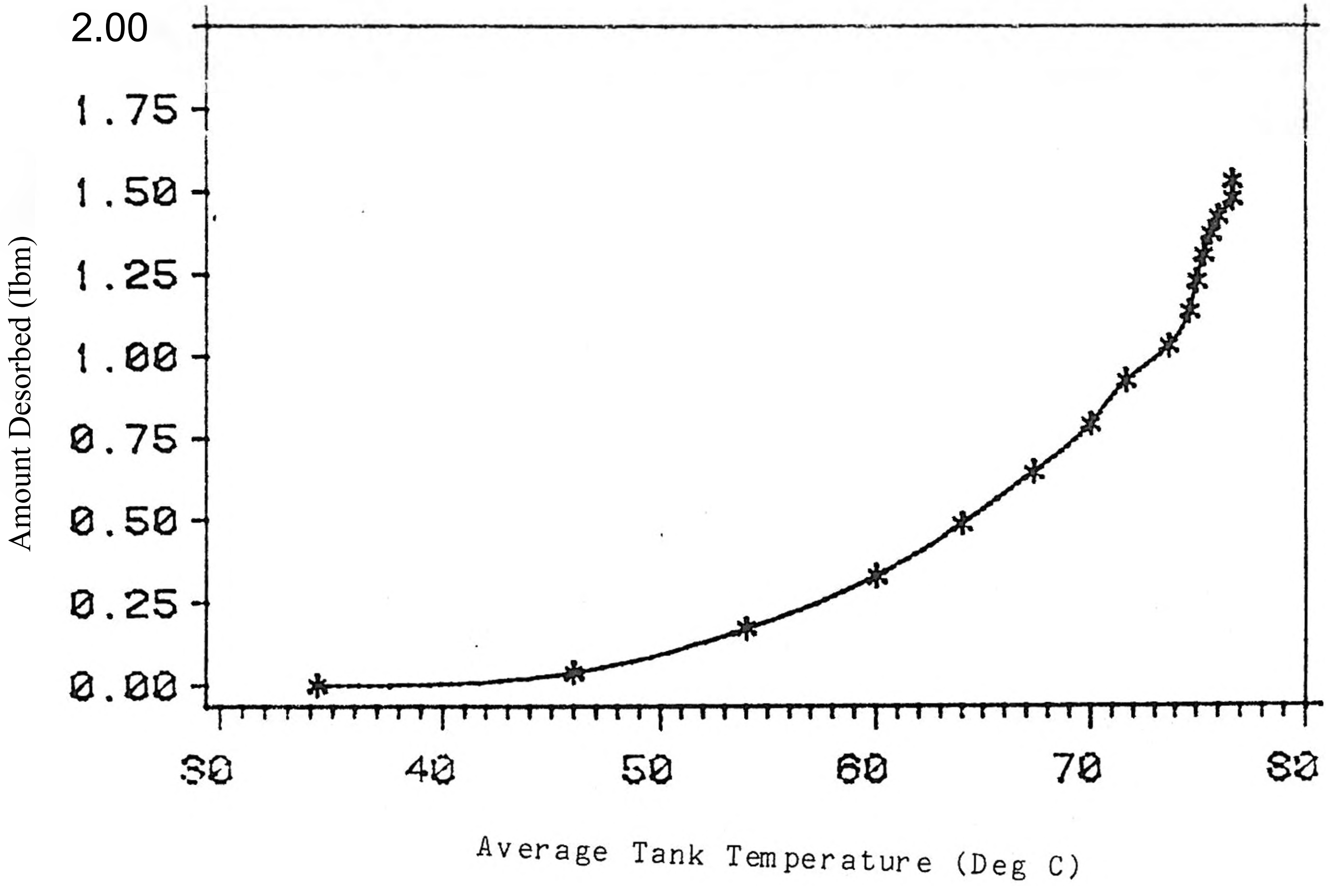

Fig. 13 Amount desorbed versus average tank temperature in refrigeration mode.

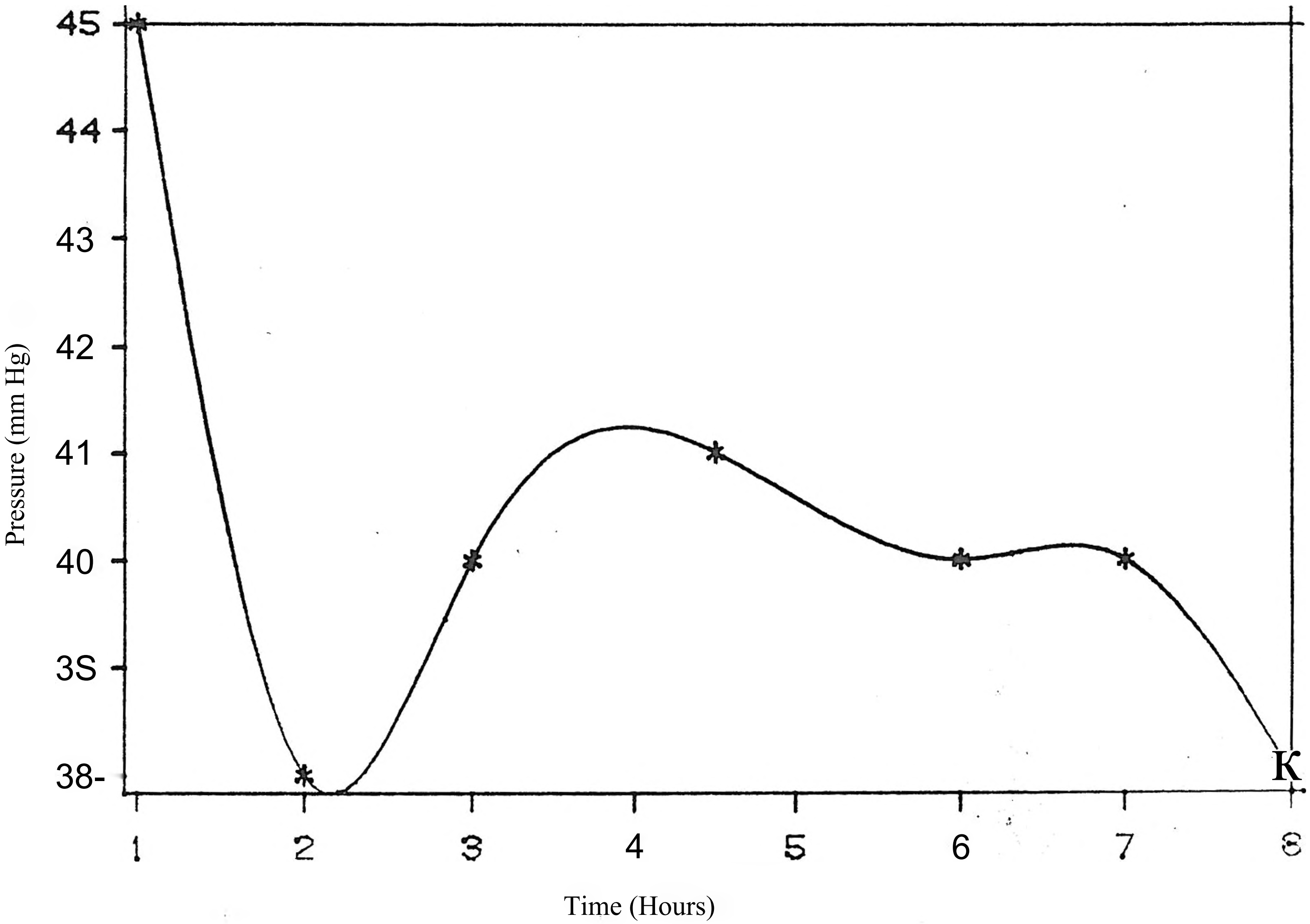

Fig. 14 System pressure versus cycle time in refrigeration desorption.

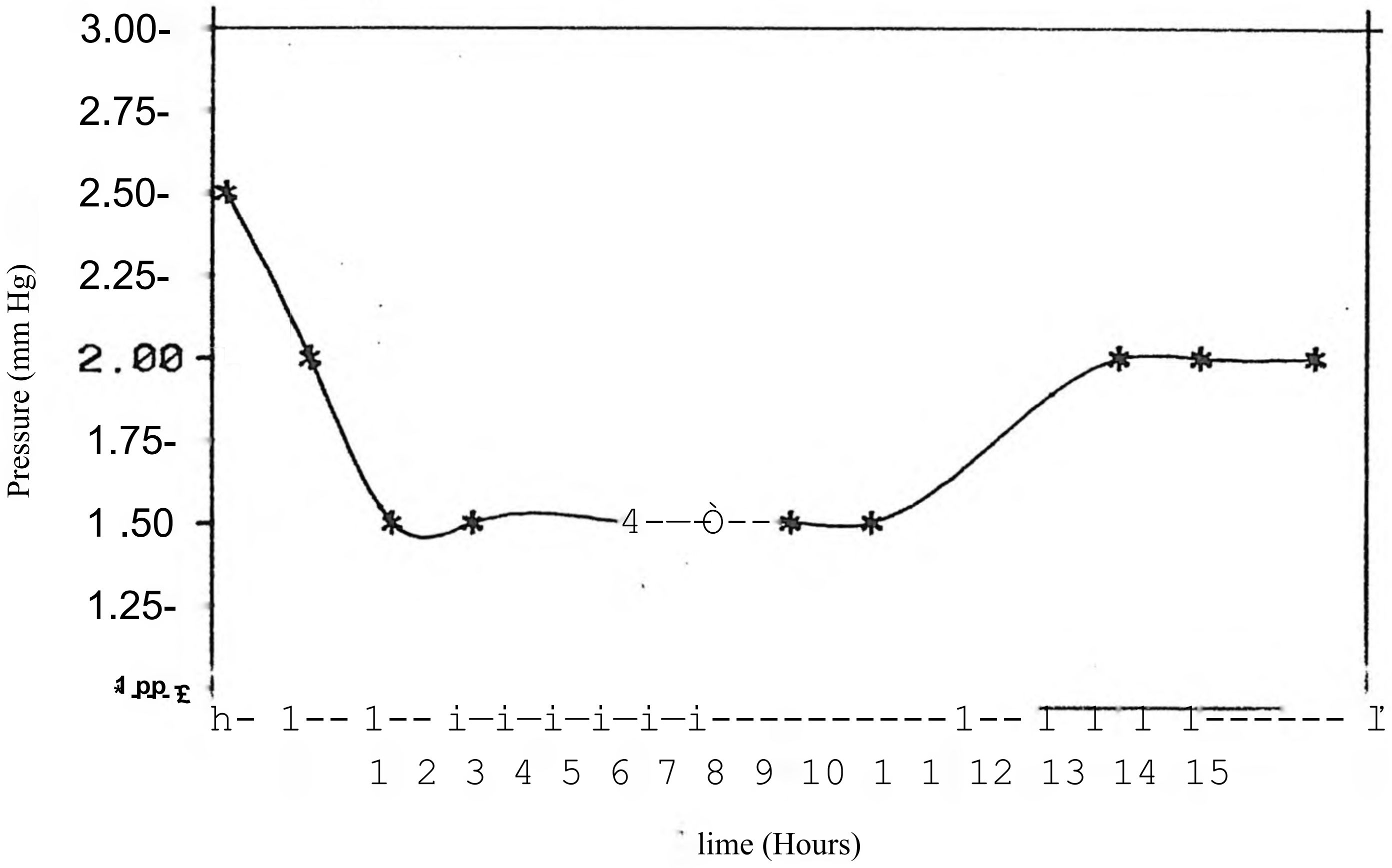

Fig. 15 System pressure versus cycle time in refrigeration adsorption.