

A THERMODYNAMIC STUDY OF THE ABSORPTION
REFRIGERATION SYSTEM.

With especial relation to domestic
machines of that type.

by

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INTRODUCTION.

The purpose of this thesis is to make a thermodynamic study of the absorption refrigeration process, developing such equations as may be of use in studying the process and making calculations relating thereto. In general, the technique which has been employed in dealing with this subject is new, and not in accordance with the current methods of treatment. The reason of the writer for devising this technique in dealing with the subject is that it enables one to better understand the actions of the process, and to better see the influence that the many variable conditions of the process have upon the performance of the machine. In short, the purpose of this thesis is to propose a new method of studying and making calculations concerning the absorption refrigeration process, which method, it is hoped, will be more useful than the current methods used in this connection, especially when the study or calculations made relate to the conditions of maximum efficiency and minimum cost.

It is to be mentioned here that the importance of the absorption refrigeration system is growing. This type of machine is now about to be introduced into the field of domestic refrigeration. With the coming of this new use of the absorption machine new problems of design at once present themselves, for the conditions of operation must of ne-

cessity vary greatly from those of machines now in use.
It is especially in connection with the problems of design for this new field that this work is intended to be of value.

Part I.

The principle of operation of the ammonia absorption refrigeration system is known, and is dealt with in many books, hence it will not be explained here.

EQUATIONS RELATING TO PROCESS.

In connection with the process the following equations apply:

$$N = \frac{1-X}{X-X_2} \quad (1)$$

where

N = Weight liquor to be circulated

X_1 = Upper concentration

X_2 = Lower concentration

$$\frac{T'}{T} = 0.466X + 0.656 \quad (2)$$

where

X = Concentration of solution

T = Absolute temperature of solution

T' = Absolute temperature of saturated ammonia corresponding to the pressure on the solution.

$$Q = 345(1-X) - 400X^2 \quad (3)$$

X = Mean concentration, $\frac{1}{2}(X_1 + X_2)$

Q = Heat developed when one pound of liquid ammonia is added to liquor of concentration X_2 increasing its concentration to X_1

Of the preceding equations, (1) is mathematically arrived at and is exact, while (2) and (3) are imperical, and only approximate. The approximation, however, is sufficiently accurate for practical purposes.*

EFFICIENCY OF ABSORPTION MACHINE.

There is no very adequate treatment dealing with the efficiency of the absorption process. The efficiency of the process, when considered as though the heat supplied were applied to a perfect engine driving a perfect reversed engine as a refrigerator, is readily derived, and an expression of the efficiency on this basis has been included in some works on refrigeration.** The inaccuracy of dealing with the efficiency on this basis is acknowledged. Nevertheless more appropriate means have not been introduced.

In the following there is given a method of studying the process on a somewhat different basis than is conventionally used, which method, admits more readily of the study of the process from the efficiency standpoint. A theoretical cycle, varying somewhat from operating conditions, is at first assumed, and the study made on the basis of this cycle. The main purpose of this theoretical

* See: Goodenough: "Principles of Thermodynamics", p. 59 - 64.

** See: Ewing: "The Mechanical Production of Cold", p. 26.

cycle is to afford a means of studying the process; and a method of dealing with the conditions of practice is later given.

The assumed theoretical cycle is as follows:

- (1) The concentration of the solution in all parts of the system remains constant, or rather, varies only by an infinitesimal amount. This occasions that an infinite amount of liquor must be circulated in order to drive off one pound of ammonia gas from the generator.
- (2) The exchanger is assumed perfect. That is to say that heat is exchanged from the liquor passing from the generator to the absorber, to the liquor passing from the absorber to the generator, with only an infinitesimal temperature difference in the two liquids. This will occasion that for each pound of ammonia gas circulated, one pound of liquor passing from the absorber to the generator must be taken through a separate passage from the exchanger. If all the liquor exchanged passed through the absorber there would be a temperature difference in effecting the exchange of heat, and this is not admitted in this cycle.
- (3) It is assumed that the work required to force the liquor from the low pressure side to the high pressure side of the system is accomplished by, in some manner, utilizing the work that is available due to the passage of the aqueous solution and the liquid ammonia in the reverse direction. It is assumed that these two amounts

of work are equal, and therefore balance each other.

(4) It is assumed that there is no water vapor driven off in the system.

Now that the cycle has been assumed, it may be said that the method used here is a comparison of this cycle with the previously mentioned perfect machine in which the heat supplied was utilized to run a Carnot engine which in turn drove a reversed Carnot engine as a refrigerator.

In the case of the perfect machine the efficiency of the machine would be the product of the efficiency of the Carnot engine and the coefficient of performance of the reversed Carnot engine used as the refrigerator,* or:

$$B = \frac{T_3(T_1 - T_0)}{T_1(T_0 - T_3)} \quad (4)$$

where B denotes the efficiency of the machine, T_1 the temperature of the heat supplied, which of course corresponds to the generator temperature, T_3 the lowest available temperature, and T_0 the cooler temperature. The above is the equation for the highest efficiency that any machine can have.

The reason that the preceding equation does not apply to the theoretical absorption cycle previously assumed is that there are losses due to irreversible actions which take place in the cycle. These irreversible

* Ewing: "Mechanical Production of Cold"
p. 26.

actions are four in number. It is of importance to know something of the magnitude of each of these losses and how they vary with conditions, for they relate directly to the efficiency of the machine. When the total available energy lost is known the efficiency of the cycle can then be determined from its relation to the efficiency of the perfect process. The following development gives the determination of the losses of the cycle and the efficiency of the cycle.

The connotations used are:

$T_0 =$ Lowest available temperature

$T_1 =$ Generator temperature

$T_2 = T_0 =$ Condenser temperature

$T_3 =$ Temperature of cold body

$T_4 = T_0 =$ Absorber temperature

(These connotations refer to liquid states
in the system)

1, 2, 3, and 4 denote respectively the states of the liquor in the generator, the liquid ammonia in condenser, the liquid ammonia in cooler, and the liquor in the absorber.

(These connotations refer to gaseous states
in the system)

1a denotes the gaseous state immediately after it is driven from the generator at generator temperature, 2a the

gaseous state immediately before it condenses in the condenser at condenser temperature, 3a the gaseous state immediately after it evaporates from the liquid in the cooler at cooler temperature, and 4a the gaseous state immediately before it is absorbed in the absorber at absorber temperature.

In this assumed theoretical absorption cycle the four irreversible processes, previously referred to, which result in a loss of energy are as given below:

Loss (a), - the loss in the passage from state 1a
to 2a,

Loss (b), - the loss in the passage from state 2
to 3,

Loss (c), - the loss in the passage from state 3a
to 4a,

Loss (d), - the loss in the passage from state 1
to 4.

Loss (a). In the passage from state 1a to 2a the superheated gas gives up heat above the lowest available temperature to external sources. The available energy dissipated in this process is:*

$$MC_p(T_1 - T_0 - T_0 \log \frac{T_1}{T_0}) \quad (a)$$

M = Weight of ammonia circulated

C_p = Mean specific of superheated ammonia heat

between generator temperature and absorber temperature under the existing pressure.

* See: Goodenough: "Principles of Thermodynamics", p. 63.

Loss (b). In the passage from state 2 to 3 there is a loss of available energy in as much as the liquid is cooled from T_2 to T_3 at the expense of absorbing the heat at the low temperature T_3 ; that is to say, heat flows from a body of one temperature to a body of another temperature which always results in a loss of available energy. If there is to be no loss of available energy in this passage, a reversed Carnot engine whose upper limit of temperature is T and whose lower limit is a variable limit ranging from T_3 to T_2 , must be used to extract the heat from the liquid, and this engine must be driven by a forward Carnot engine which receives a portion of the heat supplied to the system at the temperature T_1 and rejects its heat at T_0 . If the change from state 2 to 3 were effected in the above manner the available energy necessary to effect this change would be:*

$$MC' \left(T_0 \log \frac{T_0}{T_3} - T_0 + T_3 \right)$$

M = Weight of ammonia gas circulated.

C' Mean specific heat of liquid ammonia
between T_0 and T_3

The available energy actually utilized in effecting this change from state 2 to 3 is $MC' \frac{(T_0 - T_3)^2}{T_3}$, in as much as all the heat is absorbed at the temperature T . If from the above amount there be subtracted the available energy required in the perfect process of effecting the change, the result will be available energy dissipated

* See: Goodenough: "Principles of Thermodynamics", p.63.

in the process, which gives:

$$MC_1 \frac{(T_0 - T_3)^2}{T_3} - T \log_e \frac{T_0 + T_0}{T_3} - T \quad (b)$$

Loss (c). In passing from state 3a to 4a the available energy dissipated is:*

$$MC_2 (T_0 \log_e \frac{T_0}{T_3} - T_0 + T_3) \quad (c)$$

Loss (d). In the passage from state 4 to 1 there is a loss of available energy in as much as this change is effected at the expense of heat supplied at the temperature T_1 . The available energy actually used in effecting this change is $MC_1 \frac{(T_1 - T_0)}{T_1}$. The available energy which would be required if it were effected by a perfect process is:

$$MC_2 [T_1 - T_0 \log_e \frac{T_1}{T_0} - T_0]$$

Then the available energy dissipated in accomplishing this change is:

$$MC_2 \left[\frac{(T_1 - T_0)^2}{T_1} - T_1 + T_0 \log_e \frac{T_1}{T_0} \right] \quad (d)$$

The foregoing equations give the values of each of the four losses due to irreversible processes which occur in our assumed theoretical absorption cycle. Tables I, II, III, and IV give the numerical values of these respective losses for a number of conditions. These tables are of aid in studying this cycle.

If the sum of the losses which occur in the cycle for any given set of conditions, when a definite amount of ammonia gas is circulated, be determined, it is possible to calculate the efficiency of the cycle for the particular

* See: Goodenough: "Principles of Thermodynamics", p. 63.

set of conditions. The method of doing this is to find the amount by refrigeration effect by which the perfect process exceeds that of the theoretical absorption cycle for any set of conditions, and then substitute this lost refrigeration effect in equation (5), presently to be derived. The amount of the lost refrigeration effect is equal to the product of the available energy lost in the cycle and the coefficient of performance of a perfect refrigerator working between the limits of temperature T and T_1 . The reason that the above is true is that the available energy lost in the cycle would have to be utilized without any dissipation if the process were to be made perfect.

The relation between the efficiency of the cycle and the lost refrigeration effect occurring in the cycle is arrived at in the following manner. The connotations used are:

Q_3 Quantity of refrigeration effect produced by the circulation of one pound of ammonia gas,

Q_1 = Quantity of heat that must be supplied to generator to circulate one pound of ammonia gas,

Q'_3 Lost refrigeration effect, or the amount by which refrigeration effect of the perfect process exceeds that of the theoretical absorption cycle.

Other connotations are as before used.

From (4), the efficiency of perfect process equals:

$$\frac{T_3(T_1 - T_0)}{T_1(T_0 - T_3)} \quad (a)$$

The refrigeration effect of the perfect process by application of heat Q is:

$$Q \frac{T_3(T_1 - T_0)}{T_1(T_0 - T_3)} \quad (b)$$

The refrigeration effect produced by the theoretical cycle then is:

$$Q_3 = Q \frac{T_3(T_1 - T_0)}{T_1(T_0 - T_3)} - Q \quad (c)$$

$$\text{But, } B = \frac{Q_3}{Q_1}$$

Substituting in the above

$$B = \frac{T_3(T_1 - T_0)}{T_1(T_0 - T_3)} - \frac{Q_3}{Q_1} \quad (d)$$

$$\text{But, } Q_1 = \frac{Q_3}{B}$$

$$\text{Therefore } B = \frac{T_3(T_1 - T_0)}{T_1(T_0 - T_3)} - \frac{Q_3}{Q_3} \quad (e)$$

and clearing the above equation

$$B = \frac{T_3(T_1 - T_0)}{T_1(T_0 - T_3)(1 + \frac{Q_3}{Q_3})} \quad (f)$$

For the theoretical absorption cycle T_1 bears a relation between T_3 and T_0 . This relation is arrived at as follows:

From (2)

$$\frac{T_3}{T_0} = 0.466X + .656$$

$$\text{also } \frac{T_0}{T_1} = 0.466X + .656$$

X is the same for each case,

$$\text{therefore } \frac{T_3}{T_0} = \frac{T_0}{T_1} \text{ and } T_1 = \frac{T_0^2}{T_3} \quad (g)$$

Substituting this value for T_1 in (f):

$$B = \frac{T_3}{T_0(1 + \frac{Q}{Q})} \quad (5)$$

The value of Q is a very long and complex equation, as is seen by equation (6), below. This value is arrived at by multiplying the coefficient of performance a perfect refrigerator working between the limits of temperature T_3 and T_0 , by the sum of the four losses of available energy in the cycle. Thus, the expression is:

$$Q'_3 = \frac{T_3}{T_0 - T_3} \left\{ C'_1 \left(T_1 - T_0 - T_0 \log_e \frac{T_0}{T_1} \right) + \right. \\ \left[C'_1 \left(\frac{T_0 - T_3}{T_3} \right)^2 + T_0 - T_3 - T_0 \log_e \frac{T_0}{T_3} \right] + \\ \frac{C''_2 (T_0 \log_e \frac{T_0}{T_3} - T_0 + T_3) +}{2} \\ \left. \frac{C''_2 \left[\frac{T_1 - T_0}{T_1} \right]^2 - T_1 + T_1 + T_0 \log_e \frac{T_1}{T_0}}{2} \right\} \quad (6)$$

If the value of Q'_3 given in equation (6) were substituted in equation (5) the result would be a tremendously complicated equation. If, however, C''_1 be assumed equal to C''_2 , and C'_1 equal to C'_2 , the log quantities drop out and a simpler equation results. It is true that C''_1 is not equal to C''_2 , and also that C'_1 is not equal to C'_2 , but they are nearly enough equal that the substitution of a mean value for them in equation (5), which in turn is substituted in equation (6), will not greatly affect

the final value of B. It is to be remembered, however, that the equation so arrived at is approximate. It is found by working examples that the discrepancy of applying this equation to the assumed theoretical cycle ranges up to one percent as compared with results given by using equations (2) and (3). Equations (2) and (3), however, are only approximate and the results given by this following approximate equation, (8), are probably as accurate.

Using mean values for C'_1 and C''_2 , and C'_2 and C''_1 and substituting in (5) the following much simplified equation results:

$$Q'_3 = \frac{(T_0^2 - 2T_0T_3 + T_3^2)(C''_1 + C'_2)}{T_0 - T_3} \frac{T_3}{T_3} \quad (7)$$

where C'_1 and C''_2 are mean values respectively of C'_1 and C''_2 and C''_1 and C'_2 . Substituting in equation (6) the value of Q as given in (7), the result is:

$$B = \frac{T_0}{T_3} \frac{(1 + (C''_1 + C'_2) \frac{(T_0^2 - 2T_0T_3 + T_3^2)}{T_0 - T_3})}{Q_3} \frac{T_3}{T_0 - T_3} \quad (8)$$

Equation (8) might be employed to make calculation for a table giving the values of B, for this theoretical cycle, covering a wide range of upper and lower temperatures. Table (V) is such a table. The calculations involved in making this table can just as well be made by employing equations (2) and (3), and as before noted, will vary only slightly from the values given by using

equation (8). Equations (2) and (3) rather than equation (8) were used in making calculations for Table (V).

It is to be acknowledged that equation (8) is of theoretical importance only. As for its value in this respect, it shows that an equation for efficiency can be written which does not involve the heat of absorption of ammonia. It shows also that the efficiency must always be less than one, and that it approaches one as T approaches T . It is further to be observed from the equation that T and T are the principal variables which influence the efficiency, as the other terms of the equation vary rather slowly. Of more importance than the equation itself, though, is the enlightenment concerning the process which can be gained from studying its derivation. Tables I, II, III, IV, and V will be of value in studying the process.

Part II.

OPERATING CONDITIONS.

The actions which take place in the absorption process under operating conditions differ in four respects from those of the previously assumed theoretical absorption cycle. These differences are: (1) water vapor is driven off with the ammonia gas, (2) the exchanger is imperfect, (3) the concentration of the liquor entering the generator must be appreciably higher than that of the liquor leaving, and (4) all the heat may not be rejected at the same temperature. In explanation of (4) of the above, it was specified in the previously considered cycle that all heat be rejected at the lowest available temperature^{*}; while under operating conditions, the absorber may reject heat at one temperature, the condenser at another, and the liquid ammonia may be further cooled below condenser temperature before it passes the pressure reducing value.

The effect of the water vapor which is driven off from the generator along with the ammonia gas is that it absorbs considerable heat in being driven off, and later, when cooled, it unites with some of the ammonia gas and returns to the generator in the form of a liquor. The percentage content of water vapor above ammonia liquors for

^{*}Excepting of course, the heat which is rejected in cooling the superheated gas from generator temperature to condenser temperature.

various conditions has not been so definitely verified, but the results found by Mr. T. A. Wilson during his experiments in the above connection are likely the most dependable information at hand. Tables VIII and IX of the appendix are taken from Mr. Wilson's work*.

The loss due to water vapor, however, cannot be entirely determined when the percentages of water vapor and ammonia above liquors of various concentration are known, for this loss is dependent upon the construction of the machine. The following explanation of the actions which take place as a result of the presence of water vapor will show how the construction of certain units of the machine will affect this loss.

In the generator all the liquor is not at the same temperature; the liquor at the top is cooler and richer than the liquor in the bottom. It, however, is not a stable condition for ammonia liquors of different concentration to remain in contact in the same vessel, they tend to mix, forming one concentration. In the generator they do mix, and the rapidity of mixing is aided by any ebullition that takes place. It is desirable that the liquors mix as little as possible in order to be able to maintain a relatively low temperature at the top of the generator. If there were no mixing at all of the liquors in the generator and the con-

*See: Bulletin 146, University of Illinois Experiment Station.

centration gradually decreased toward the bottom as ammonia was driven off, the temperature at the top of the generator would be that corresponding to equilibrium, under the existing pressure, of the liquor of the concentration it has on coming from the analyzer. Under this condition all the gases leaving would theoretically be at the temperature existing at the top of the generator, and would contain the amount of water vapor corresponding to equilibrium of the strong liquor entering the generator under the existing pressure.

In practice the above ideal condition is not reached, but the vapors are at a lower temperature than that of the weakest liquor in the generator, and the water vapor too, no doubt, is less than the amount corresponding to equilibrium of the weakest liquor. The writer has been unable to find any information as to the conditions of temperature and water vapor content that exist at the top of the generator; likely they have not been investigated with any degree of precision. It is nevertheless true that the temperature at the top of the generator, for any set of conditions, will vary with the construction of the generator and the rate at which the operation is forced.

As the gases leave the generator they enter the analyzer and there give up some of their superheat and water vapor to the rich liquor trickling through the analyzer, with the result that ammonia gas is driven off from the rich liquor. Due to the above process the liquor leaving the ana-

lyzer is weaker than the liquor entering.

After leaving the analyzer the gas enters the rectifier. There it is cooled to a temperature only slightly above condensing temperature, and on cooling gives up practically all its water vapor content which unites with some of the ammonia gas and returns to the generator in the form of a rich liquor. It is commonly said that the water vapor condenses in the rectifier and then absorbs some of the ammonia gas forming a liquor. In reality, the liquor present absorbs the water vapor without its passing through the state of saturation, for there can be no saturated water vapor in the presence of ammonia liquor. The reason for the above is that the partial water vapor pressure above ammonia liquor of a given temperature is less than the saturation pressure for the same temperature. It may also be said of the analyzer that no water vapor condenses, but is absorbed by the strong liquor without passing through saturation.

The preceding discussion of the actions which take place in connection with the water vapor indicates that the actual loss due to its presence, will, for any set of operating conditions, vary with the construction of the machine. The analyzer cannot be made to function ideally, nor can the generator, but different degrees of effectiveness of each will be gained from different types of construction.

The loss due to the imperfect exchanger depends upon

the amount of weak liquor circulated, the difference between the absorber temperature and that of the weak liquor entering the absorber, and the specific heat of the liquor. The following equation applies, the specific heat of the liquor being taken as one.

$$L = (t_1 - t_2)w \quad (9)$$

w = Weight of weak liquor circulated.

t_1 = Temperature of liquor entering absorber.

t_2 = Temperature of liquor leaving absorber.

The above equation is true because it gives the heat which the exchanger failed to transfer, but would have, had it been perfect. This may be seen from the fact that the perfect exchanger delivers the weak liquor to the absorber at absorber temperature, and the above equation expresses the heat content of the entering weak liquor above absorber temperature.

The third of the respects in which the absorption cycle under operating conditions differs from the cycle assumed in Part I, namely, that the concentration of the liquor entering the generator is appreciably higher than that of the liquor leaving, occasions also a loss which does not apply to the latter cycle. This loss is seen from the fact that more heat is required to drive ammonia gas from a weak liquor than from a stronger liquor. This loss is taken into account by a theoretical cycle pertaining to operating conditions which is presently to be defined, and since it is thus accounted for its amount need not be determined.

CALCULATIONS RELATING TO PROCESS.

In the method which is here given for making calculations relating to the absorption process, the heat which is supplied to the system is divided into two parts, the heat which is required to carry out a theoretical cycle, which was above anticipated and now to be defined, and the heat consumed by the losses not included in that cycle. The theoretical cycle that is assumed is as follows:

- (1) There is no water vapor driven off in the system.
- (2) The exchanger is perfect.
- (3) The concentration of the liquor leaving the generator is appreciably less than that entering, a finite quantity of liquor therefore being circulated.

(4) The ammonia gas leaving the generator is at the temperature of the weakest liquor in the generator. (It is later shown how any deviation from (4) is taken care of.) The only respect which this cycle differs from that assumed in Part I is given in (3). The calculations of the heat required to carry out this cycle, as that in Part I, are made by using equations (2) and (3), and tables of properties of ammonia. An example showing the method of making the above calculation is later given in a problem which is worked.

The heat which is otherwise consumed than for carrying out the above cycle has been called lost heat for the reason that it in no manner aids in producing the refrigeration effect. The losses which occur are two in number, the loss due to water vapor, and the loss due to the imperfect exchanger.

The latter loss is definitely known, and can be calculated from equation (9). The loss due to water vapor, however, has already been said to depend upon the construction of certain units of the machine, and is not so definite. Reasonable assumptions of the actions that take place can nevertheless be made, and very approximate values of this loss may be calculated; or the amount of loss for various conditions may be determined by experimental tests upon the machine to which the calculations relate. In the problem which follows the probable actions are assumed and calculations of the loss due to water vapor are based on the assumption made. The problem illustrates the general method of making calculations of the above loss.

The heat which is supplied to the generator to produce any given refrigeration effect may be divided into three parts, (1) the heat which is required to carry out the theoretical cycle previously defined, (2) the heat lost due to water vapor, and (3) the heat lost due to the imperfect exchanger. The total heat to be supplied in any case is found by determining each of these three quantities separately and adding them together. The efficiency of the machine is the refrigeration effect divided by the total heat supplied. Thus:

$$B = \frac{Q_3}{K + l_w + l_{ex}} \quad (10)$$

where B = efficiency of machine, Q_3 = refrigeration effect, K = the heat which is required to carry out the theoretical cycle, l_w = the loss due to water vapor, and l_{ex} = the loss due to

the imperfect exchanger.

In the above method of making calculations relating to the absorption process, the heat which is required to carry out the cycle is separated from that which disappears in the losses of the system, and the losses are then divided according to the two sources of loss. This method shows where the heat which is supplied to the system goes, and throws better light upon what the efficiency depends. It is for the above reason that the writer claims advantage of this method over current methods that are used for making calculations relating to the absorption process.

THE DOMESTIC ABSORPTION MACHINE AND THE PROBLEM OF MINIMUM COST.

There are certain broad differences in the requirements which the domestic absorption refrigerator and the common ice-making absorption machine must meet, which differences necessitate greater refinement in designing the former machine and regulating its conditions of operation. The domestic machine burns gas which costs eight to fifteen times as much for a given heating value as does the coal burned by the ice-making machine. It also uses cooling water which is twenty-five to one hundred times as costly as that used by the former machine. On the other hand, the domestic refrigerator utilizes all the refrigeration effect produced, while the ice-making machine loses approximately half of its refrigeration effect before it is transferred to ice.

Also the domestic machine costs practically nothing for care and attendance, while this, and other costs of the ice manufacture amount to several times fuel and cooling water costs.

In addition to the above named features peculiar to the two machines, the domestic machine can generate steam at any pressure that may be needed, high pressure steam being just as cheap as low pressure steam; but the ice-making absorption machine seldom uses high pressure steam since it is more economical to first use the high pressure steam in a compressor type refrigerator and then use the exhaust steam in the absorption machine. The steam pressure, then, which is to be used in the generator is a problem to be solved, in the case of the domestic refrigeration, which is seldom met with in dealing with other machines.

For any domestic absorption machine having a given required lower temperature and a given temperature of cooling water available the two important conditions of operation which must be decided upon are the temperature at which the cooling water leaves the system and the steam pressure to be used in the generator. These conditions should be so adjusted that the machine will operate on the minimum possible cost; for minimum cost is the ultimate thing sought. A method of arriving at the operating conditions corresponding to minimum costs is given below.

The procedure that is followed is to write an expression for the total cost which applies to any operating condition and then determine the conditions conforming with min-

imum cost when certain other conditions are given. The cost of fuel in any case is: $\frac{c_f Q_3}{B}$ (a)

where Q_3 = refrigeration effect in B.T.U.s, B = efficiency of the machine, and c_f cost of heat per B.T.U. as supplied to generator. To get c_f the actual cost of the fuel per B.T.U. must be multiplied by the efficiency with which this heat is transferred to the generator. The heat in B.T.U.s which must be rejected to the cooling water is the heat supplied to the generator plus the refrigeration effect produced, which gives: $\frac{Q_3}{B} + Q_3$ (b)

The heat rejected to each pound of water is: $t_1 - t_2$ (c)

where t_1 = entrance temperature, and t_2 = exit temperature.

(The specific heat of water in the above is taken as one)

The cost of cooling water is:

$$\left(\frac{Q_3}{B} + Q_3 \right) \frac{c_w}{t_1 - t_2} \quad (d)$$

where c_w = cost of water per pound. The total cost for fuel and cooling water is:

$$C = \frac{c_f Q_3}{B} + \left(\frac{Q_3}{B} + Q_3 \right) \frac{c_w}{t_1 - t_2} \quad (11)$$

In making calculations, B for any particular set of conditions is found by equation (10) and substituted in equation (11), giving the cost for those conditions.

Let it be required to find the most economical operating conditions when the temperature of the cooling water available and the temperature at which the refrigeration effect is to be produced are given. The two conditions which must be determined are the temperature at which the cooling water should leave the system and the lower concentration

of liquor that should be used. The method is first to estimate one of the two unknown conditions, and using this estimated value, determine, by a series of trial calculations, the value of the other condition which gives the minimum cost. The condition which was estimated will not be exactly that corresponding to minimum cost, and this condition is then found by trial calculations, on the basis that the one previously found was correct. The process may be continued until the conditions are found which give the minimum possible cost. The length of the calculations which are necessary will depend upon how nearly right was the first estimated condition. The example which follows illustrates the method explained above.

Assume that the cooler temperature which is required is 15 degrees F., that the cooling water available is at 70 degrees F. and costs \$.20 per thousand gallons, and that gas having a heat value of 500 B. T. U.s per cubic foot costs \$1.10 per thousand cubic feet, and that 70 percent of the heat value is transferred to the generator. Assume also that the absorber temperature is 10 degrees higher than the cooling water leaving the absorber, that the condenser temperature is 10 degrees higher than the cooling water leaving the condenser, and that the liquid ammonia is 10 degrees higher than the cooling water available. The cooling water is assumed to enter the condenser in a counter-flow direction and then flow through the absorber which

is in series with the condenser.

A reasonable estimate of the temperature at which the cooling water should leave the machine for minimum total cost of operation would be 105 degrees, and the best lower concentration would be in the neighborhood of .25. The .25 being held constant for the lower concentration a series of values, beginning with 105 degrees, are tried for the temperature at which the cooling water leaves the system in order to find the temperature corresponding to minimum cost.

Cooling water leaves absorber at 105 F.

Absorber temperature 115.

The condenser temperature must be first estimated, and if after working the problem it is found to vary appreciably from the estimated temperature, the problem should again be worked with the new value for the condenser temperature. A fair estimate of the condenser temperature is 90 degrees.

By ammonia tables the refrigeration effect produced when one pound of liquid ammonia at 80 degrees F. is passed through a reducing valve and evaporated at 15 F. is 506.4 B. T. U.s.

By equation (2) the upper concentration is .366.

By equation (1) the strong liquor to be circulated per pound of ammonia gas circulated is 6.46, and the weak liquor circulated is 5.46.

The loss due to the imperfect exchanger is $20 \times 5.46 = 109.2$.

The generator temperature is by equation (2) 253 degrees F.

The value of the heat, K , which is required to carry out the theoretical cycle is the heat of absorption of liquid ammonia corresponding to a mean concentration of $(.25 + .366) / 2$ or $.308$ plus the heat content of the superheated ammonia at 253 degrees F. and a pressure corresponding to saturation at 90 degrees F. minus the heat of liquid ammonia at absorber temperature, which gives 771 .

Referring to tables VIII and IX and steam tables the loss due to water vapor is 341 B. T. U.s.

The total heat which must be supplied to the generator is $109.2 + 341 + 771 = 1221.2$.

The Efficiency, B , is 41.6 .

By equation (11) the total cost per B. T. U. refrigeration effect is $\$.0000100$.

By similar trials the total cost is $\$.00000923$ per B. T. U. refrigeration effect when the cooling water leaves at 110 degrees F. and $\$.0000127$ when it leaves at 120 degrees F.

From these trials it is found that for minimum cost the cooling water should leave at 110 degrees F. For these conditions the cost per 100 pounds ice making effect is 13.7 cents.

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APPENDIX

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Tables I, II, III, and IV give available energy in B.T.U.s dissipated in the respective processes (a), (b), (c), and (d) of Part I. T_3 =cooler temperature and T_0 =lowest available temperature.

TABLE I

T_3	T_0 70	80	90	100
5	3.03	4.25	5.73	6.75
15	1.92	3.08	4.25	5.26

TABLE II

T_3	T_0 70	80	90	100
5	5.14	6.90	8.50	11.5
15	5.56	5.02	6.15	8.0

TABLE III

T_3	T_0 70	80	90	100
5	2.53	3.17	4.16	5.00
15	1.84	2.62	3.28	4.14

TABLE IV

T_3	T_0 70	80	90	100
5	5.75	5.72	5.67	5.50
15	4.44	4.25	5.55	5.22

TABLE V.

EFFICIENCY OF ABSORPTION CYCLE DEFINED PART I
FOR VARIOUS CONDITIONS.

	T_0 70	80	90	100
T_3 5	76.1	72.0	66.9	63.9
15	81.5	76.5	71.5	68.0
25	87.1	81.0	76.4	71.7

TABLE VI.

VALUES OF HEAT OF ABSORPTION OF ONE POUND LIQUID AMMONIA IN AQUEOUS AMMONIA.							
X	Q	X	Q	X	Q	X	Q
.150	284.25	.175	272.38	.200	260.00	.225	247.13
.151	283.79	.176	271.89	.201	259.50	.226	246.60
.152	283.32	.177	271.40	.202	258.99	.227	246.08
.153	282.85	.178	270.92	.203	258.49	.228	245.55
.154	282.38	.179	270.43	.204	257.97	.229	245.02
.155	281.92	.180	269.94	.205	257.47	.230	244.49
.156	281.45	.181	269.45	.206	256.96	.231	243.97
.157	280.98	.182	268.96	.207	256.45	.232	243.43
.158	280.50	.183	268.47	.208	255.93	.233	242.90
.159	280.02	.184	267.98	.209	255.42	.234	242.37
.160	279.56	.185	267.49	.210	254.91	.235	241.84
.161	279.09	.186	266.99	.211	254.40	.236	241.30
.162	278.61	.187	266.50	.212	253.88	.237	240.77
.163	278.13	.188	266.00	.213	253.37	.238	240.23
.164	277.66	.189	265.51	.214	252.85	.239	239.70
.165	277.19	.190	265.01	.215	252.34	.240	239.16
.166	276.71	.191	264.51	.216	251.82	.241	238.63
.167	276.23	.192	264.01	.217	251.30	.242	238.08
.168	275.75	.193	263.52	.218	250.79	.243	237.55
.169	275.27	.194	263.03	.219	250.27	.244	237.01
.170	274.79	.195	262.52	.220	249.74	.245	236.47
.171	274.31	.196	262.01	.221	249.22	.246	235.92
.172	273.83	.197	261.51	.222	248.70	.247	235.39
.173	273.34	.198	261.01	.223	248.18	.248	234.84
.174	272.86	.199	260.50	.224	247.65	.249	234.30

X = Mean concentration

Q = Heat of solution

(This table is calculated
from equation (3)).

TABLE VI (continued)

VALUES OF HEAT OF ABSORPTION OF ONE POUND LIQUID AMMONIA IN AQUEOUS AMMONIA.							
X	Q	X	Q	X	Q	X	Q
.250	233.75	.275	219.88	.300	205.50	.325	190.63
.251	233.21	.276	219.31	.301	204.92	.326	190.02
.252	232.66	.277	218.75	.302	204.33	.327	189.42
.253	232.12	.278	218.18	.303	203.75	.328	188.81
.254	231.56	.279	217.61	.304	203.15	.329	188.20
.255	231.02	.280	217.04	.305	202.59	.330	187.59
.256	230.47	.281	216.48	.306	201.99	.331	186.98
.257	229.92	.282	215.90	.307	201.39	.332	186.37
.258	229.36	.283	215.33	.308	200.79	.333	185.76
.259	228.82	.284	214.76	.309	200.21	.334	185.15
.260	228.26	.285	214.19	.310	199.61	.335	184.54
.261	227.73	.286	213.61	.311	199.02	.336	183.92
.262	227.15	.287	213.04	.312	198.42	.337	183.31
.263	226.60	.288	212.46	.313	197.83	.338	182.69
.264	226.04	.289	211.89	.314	197.23	.339	182.08
.265	225.49	.290	211.31	.315	196.64	.340	181.46
.266	224.93	.291	210.74	.316	196.04	.341	180.85
.267	224.37	.292	210.15	.317	195.44	.342	180.22
.268	223.81	.293	209.58	.318	194.84	.343	179.61
.269	223.26	.294	209.00	.319	194.25	.344	178.99
.270	222.69	.295	208.42	.320	193.64	.345	178.37
.271	222.13	.296	207.83	.321	193.04	.346	177.74
.272	221.57	.297	207.26	.322	192.44	.347	177.13
.273	221.01	.298	206.67	.323	191.84	.348	176.50
.274	220.44	.299	206.09	.324	191.23	.349	175.88

TABLE VII.

PARTIAL PRESSURES OF WATER VAPOR ABOVE AQUA AMMONIA.

Pressures are in Pounds per Square Inch Absolute.

Temp. Deg. F.	MOLAL CONCENTRATION OF AMMONIA IN SOLUTIONS IN PERCENTAGES.						
	0	5	10	15	20	25	30
32	0.09	0.084	0.079	0.074	0.070	0.065	0.060
40	0.12	0.115	0.108	0.101	0.095	0.089	0.083
50	0.18	0.17	0.16	0.15	0.14	0.13	0.12
60	0.266	0.24	0.23	0.21	0.20	0.19	0.17
70	0.36	0.34	0.32	0.30	0.28	0.26	0.25
880	0.51	0.48	0.45	0.42	0.40	0.37	0.34
90	0.70	0.66	0.63	0.58	0.55	0.51	0.47
100	0.95	0.90	0.85	0.79	0.74	0.69	0.64
110	1.27	1.20	1.14	1.07	1.00	0.93	0.86
120	1.69	1.60	1.51	1.42	1.33	1.24	1.15
130	2.22	2.10	1.98	1.86	1.74	1.62	1.51
140	2.89	2.73	2.57	2.42	2.26	2.11	1.96
150	3.72	3.51	3.31	3.11	2.91	2.72	2.52
160	4.74	4.48	4.22	3.97	3.71	3.46	3.22
170	5.99	5.66	5.34	5.02	4.70	4.38	4.07
180	7.51	7.10	6.69	6.30	5.89	5.49	5.10
190	9.34	8.83	8.32	7.82	7.32	6.83	6.34
200	11.53	10.90	10.27	9.65	9.04	8.43	7.83
210	14.12	13.35	12.58	11.82	11.07	10.32	9.59
220	17.19	16.25	15.32	14.39	13.48	12.57	11.67
230	20.78	19.64	18.51	17.40	16.29	15.19	14.11
240	24.97	23.60	22.25	20.91	19.58	18.26	16.95
250	29.83	28.20	26.58	25.00	23.39	21.82	20.25

TABLE 1A (CONTINUED)

PARTIAL PRESSURES OF WATER VAPOR ABOVE AQUA AMMONIA.

Pressures are in Pounds per Square Inch Absolute.

Temp. Deg. F.	MOLAL CONCENTRATION OF AMMONIA IN SOLUTIONS IN PERCENTAGES.						
	35	40	45	50	55	60	65
32	0.056	0.051	0.047	0.042	0.038	0.034	0.030
40	0.076	0.070	0.064	0.058	0.052	0.046	0.040
50	0.11	0.10	0.094	0.085	0.076	0.068	0.059
60	0.16	0.15	0.13	0.12	0.11	0.097	0.085
70	0.23	0.21	0.19	0.17	0.15	0.14	0.12
80	0.32	0.29	0.27	0.24	0.22	0.19	0.17
90	0.44	0.40	0.37	0.33	0.30	0.26	0.23
100	0.59	0.55	0.50	0.45	0.41	0.36	0.31
110	0.80	0.73	0.67	0.60	0.54	0.48	0.42
120	1.06	0.97	0.89	0.80	0.72	0.64	0.56
130	1.39	1.28	1.17	1.05	0.95	0.84	0.74
140	1.81	1.66	1.52	1.37	1.23	1.10	0.96
150	2.33	2.14	1.95	1.76	1.59	1.41	1.24
160	2.97	2.73	2.49	2.25	2.02	1.80	1.58
170	3.75	3.45	3.15	2.84	2.56	2.28	1.99
180	4.71	4.33	3.94	3.57	3.21	2.85	2.50
190	5.86	5.38	4.91	4.44	3.99	3.55	3.10
200	7.23	6.64	6.06	5.48	4.93	4.38	3.81
210	8.86	8.13	7.42	6.71	6.04	5.34	----
220	10.78	9.90	9.03	8.17	7.31	----	----
230	13.03	11.97	10.91	9.87	----	----	----
240	15.66	14.38	13.12	11.86	----	----	----
250	18.71	17.18	15.67	----	----	----	----

TABLE 7 (CONTINUED)

PARTIAL PRESSURES OF WATER VAPOR ABOVE AQUA AMMONIA.

Pressures are in Pounds per Square Inch Absolute.

Temp. Deg. F.	MOLAL CONCENTRATION OF AMMONIA IN SOLUTIONS IN PERCENTAGES.						
	70	75	80	85	90	95	100
32	0.025	0.021	0.017	0.013	0.008	0.004	0.00
40	0.035	0.029	0.023	0.015	0.012	0.006	----
50	0.051	0.042	0.034	0.025	0.017	0.008	----
60	0.073	0.061	0.049	0.037	0.024	0.012	----
70	0.10	0.086	0.069	0.052	0.034	0.017	----
80	0.14	0.12	0.096	0.072	0.048	0.024	----
90	0.20	0.16	0.13	0.10	0.066	0.033	----
100	0.27	0.22	0.18	0.13	0.090	0.045	----
110	0.36	0.30	0.24	0.18	0.120	0.061	----
120	0.48	0.40	0.32	0.24	0.160	0.081	----
130	0.63	0.53	0.42	0.32	0.210	0.100	----
140	0.82	0.69	0.55	0.41	0.270	0.140	----
150	1.06	0.88	0.71	0.53	0.350	0.180	----
160	1.35	1.12	0.90	0.67	0.450	0.220	----
170	1.71	1.42	1.13	0.85	0.570	0.300	----
180	2.14	1.77	1.42	1.06	---	---	----
190	2.65	---	---	---	---	---	----
200	---	---	---	---	---	---	----
210	---	---	---	---	---	---	----
220	---	---	---	---	---	---	----
230	---	---	---	---	---	---	----
240	---	---	---	---	---	---	----
250	---	---	---	---	---	---	----

TABLE 8.

MOL PER CENT AQUEOUS CONCENTRATION IN AMMONIA WATER VAPORS.

[illegible]

TABLE 8 (CONTINUED)
MOL PER CENT AQUEOUS CONCENTRATION IN AMMONIA WATER VAPORS

Temp. Deg. F.	MOLAL CONCENTRATION OF AMMONIA IN SOLUTIONS IN PERCENTAGES.						
	35	40	45	50	55	60	65
32	0.856	0.514	0.335	0.216	0.151	0.109	0.0816
40	0.943	0.581	0.372	0.248	0.172	0.124	0.0914
50	1.060	0.652	0.434	0.290	0.202	0.148	0.1095
60	1.210	0.777	0.481	0.331	0.238	0.172	0.1290
70	1.390	0.873	0.569	0.383	0.266	0.205	0.1510
80	1.550	0.978	0.659	0.444	0.323	0.230	0.1750
90	1.730	1.100	0.742	0.505	0.366	0.267	0.2020
100	1.890	1.250	0.834	0.574	0.420	0.307	0.2290
110	2.110	1.370	0.932	0.644	0.466	0.347	0.2640
120	2.320	1.520	1.044	0.714	0.529	0.395	0.3020
130	2.550	1.690	1.160	0.811	0.596	0.444	0.3430
140	2.790	1.860	1.286	0.906	0.663	0.501	0.3840
150	3.080	2.040	1.410	1.004	0.741	0.558	0.4320
160	3.300	2.230	1.550	1.110	0.818	0.617	0.4800
170	3.580	2.430	1.700	1.220	0.904	0.689	0.5300
180	3.870	2.640	1.850	1.340	0.994	0.756	0.5860
190	4.160	2.860	2.020	1.460	1.087	0.830	0.6420
200	4.470	3.080	2.190	1.580	1.187	0.907	0.7010
210	4.780	3.310	2.360	1.720	1.272	0.983	-----
220	5.100	3.560	2.540	1.860	1.390	-----	-----
230	5.440	3.810	2.730	2.000	-----	-----	-----
240	5.780	4.060	2.920	2.150	-----	-----	-----
250	6.120	4.340	3.120	-----	-----	-----	-----

TABLE 9.

CONVERSION FACTORS.

Wt. Con- centration	Conversion Factor (K)	Wt. Con- centration.	Conversion Factor (K)
100	1.0000	45	0.9692
95	0.9972	40	0.9664
90	0.9944	35	0.9636
85	0.9916	30	0.9608
80	0.9888	25	0.9580
75	0.9860	20	0.9552
70	0.9832	15	0.9524
65	0.9804	10	0.9496
60	0.9776	5	0.9468
55	0.9748	0	0.9440
50	0.9720	--	-----

APPROVAL.

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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