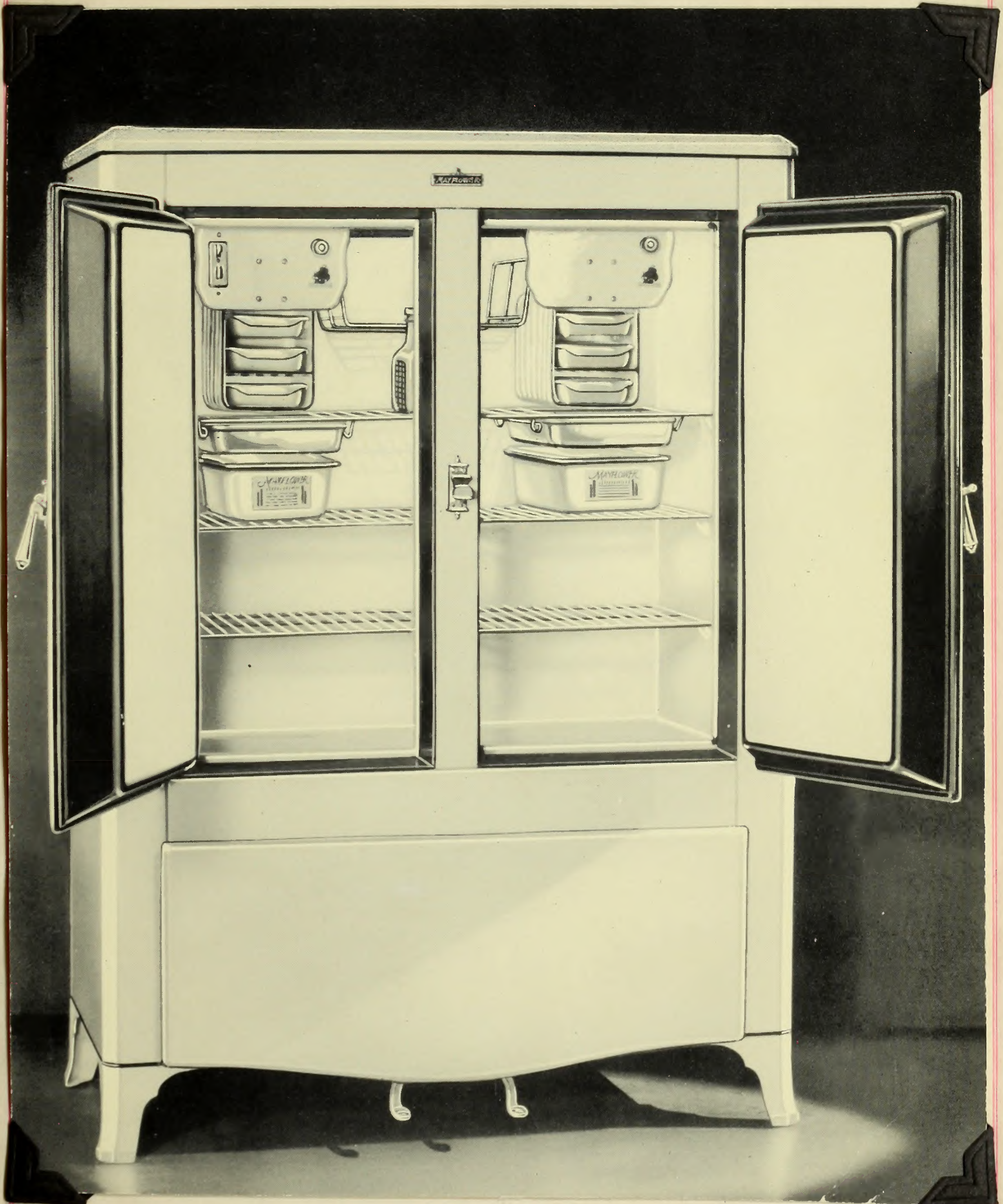
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BOSTON UNIVERSITY

GRADUATE SCHOOL
Thesis

THEORY OF HOUSEHOLD REFRIGERATION

by

Robert F. Lyons
(B.M.E. Northeastern University 1932)

submitted in partial fulfilment of the
requirements for the degree of

Master of Arts

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INTRODUCTION

The object of this thesis is the presentation of the theory underlying the operation of household refrigerating machinery, the properties and values of principal media used in modern machines, and a brief history of refrigeration. The method of treatment has been to present a comprehensive treatise on the phases of operation of the two major systems of refrigeration, the compression system and the absorption system; the air system being now obsolete has not been treated in this thesis.

I wish to thank Professor Norton A. Kent of Boston University for suggestions in the writing of this thesis; Professor Alfred Ferrettie of Northeastern University and P. A. Celander of the American Society of Refrigerating Engineers without whose valuable help this thesis would have been impossible. I also have drawn a great deal of material from pamphlets, catalogues, etc. which many of the refrigerating companies have sent to me.

I hope that those reading this thesis may gain as much from it as I have gained in the writing of it.

Boston, 1934 Robert F. Lyons

CHAPTER I

HISTORICAL INTRODUCTION TO REFRIGERATION

HISTORICAL INTRODUCTION TO REFRIGERATION

The purpose of refrigeration is the promotion of health and comfort. Health is improved by the proper preservation of food; comfort is enhanced by the preparation of frozen delicacies, the cooling of theatres, and the air conditioning of homes. Strange as it may seem to those of us who have always known the comforts of refrigeration the widespread use of refrigeration is less than 100 years old and really exists nowhere even today except in the United States. Perhaps this is partially responsible for the statement which is sometimes made that during the last 100 years the average life of man has been increased from 35 to 55 years. Whether this is true or not, it is at least partially confirmed by the figures of the Metropolitan Life Insurance Company,* which show that during the last 14 years there was a gain of 4.7 years in the expectation of life for the general population of the United States. Of course this is not all due to refrigeration but it seems unfair not to allow refrigeration to assume part of the credit for this improvement in health.

In both ancient and medieval history there are instances where refrigeration is spoken of but these are interesting as isolated instances not representative however of its general use. The Egyptians are said to have cooled water in shallow trays of porous material on beds of straw by evaporation. One of the Greek poets wrote a poem criticizing his host for not cooling his wine with snow. Both Alexander the Great and Nero had boys, slaves, who did nothing but climb to the snow

* Refrigeration Past, Present and Future

lines of the mountains after snow. Catherine de Medici took with her to France an Italian cook who knew how to make frozen delicacies. In the seventeenth century the French Government took over the control of refrigeration by granting licenses for the distribution of snow and ice. This however raised the prices so high that the government was forced to relinquish control. As these instances will indicate, there was absolutely no widespread use of refrigeration. However in Europe and in America particularly in the rural districts, foodstuffs were cooled by lowering them into wells, springs and damp cellars.

In America, where refrigeration has its widest and most general application, the first record of delivery of ice to a home was in 1802. The most notable instance of the early use of refrigeration for the promotion of health was in 1805 when Frederick Tudor made the first commercial shipment of ice from America to Martinique in the West Indies, to control a scourge of yellow fever.

After the construction of the first large ice house in America in 1805 there grew up rapidly an industry which harvested the ice of our Nothern states and shipped it to the South in sailing vessels. As early as 1850 the city of New Orleans consumed as much as 50,000 tons of ice annually.*

Meanwhile, in England and Europe experiments were being made. In this day of electric refrigeration it is most interesting to recall that Faraday, the father of our electrical science might also be called the father of mechanical refrigeration. While working in the Royal In-

* Motz, William G.
Principles of Refrigeration

stitute in London in 1824, he discovered that ammonia vapors which had been condensed by compressing and cooling would, when the pressure was removed from the liquid, boil violently, and become cold. This is, of course, the basic principle of the compression and absorption machines. We may say then that mechanical refrigeration dates from 1824 (although in 1755 temperature-pressure relations of certain refrigerating fluids were observed). During the next forty years many experiments were performed and many experimental machines were constructed such as the vacuum machine, etc.* The turn toward the modern machine was made in 1834 when the first compression machine was invented. This was a crude ether compression machine, but was the first machine to produce refrigeration or ice in commercial quantities by mechanical means. This was a product of our own Massachusetts inventor and engineer, Jocob B. Perkins.

We may still say that the United States is the birth place of mechanical refrigeration, for in 1850 John Gorrie, an American, produced refrigeration by means of the cold air machine.[2]

However five years later in 1855 the first absorption machine was invented. This was a crude affair but it was the forerunner of the modern absorption system. This system was developed by FerdinandCarrè of France. (One of the refrigerants, carriene, that I will discuss in the chapter on Refrigerants was named after him, although it is used in a compression machine). A steam coil for distilling off the ammonia was not used until 1865 and in the same year the first transparent ice was made, from distilled water, in the United States. During the Civil War a blockade

* Motz, William G. Principles of Refrigeration
2 Stevenson, A. J. Refrigeration:
Journal of the Franklin Institute Vol, 208 Aug. 1929 No.2

runner brought one of these Carrè machines from France to New Orleans. This machine was ordered because of the shortage of natural ice in the Southern States, the supply from the North being cut off by war. At that time the small amount of ice available in the South sold at five cents per pound.

In the years of 1873-1875 the first successful ammonia compression machines were introduced by C. P. Linde of Germany and David Boyle of the United States. In 1887 the first successful year-round shipments in refrigerator cars were made by G. F. Swift.*

In spite of these developments refrigeration was progressing at snail's pace and probably would have continued developing slowly if it had not been for the serious shortage of natural ice which occured in 1890. The art of refrigeration had almost come to a standstill but because necessity is the mother of invention the general public began to see for the first time the possibilities of mechanical refrigeration. Thus to this prank of nature we may accredit the impetus that started the phenomenal development and utilization of mechanical refrigeration in the United States.

Another important happening in the same year was the publication of the first trade journal in the world devoted exclusively to ice and the refrigeration industry.

One of the first small refrigerating machines was produced around 1900* when a French monk Abbè Audiffren designed a hermetically sealed compression type refrigerating machine. Strangely enough it is

* Motz William G. : Principles of Refrigeration

still one of the best small machines. It is said that some of these machines are still running in France after thirty odd years of service and they never have been refilled with oil or gas. The machine looks like a dumbbell with air cooled corrugated vanes. When the dumbbell is rotated * one end grows cold abstracting heat and the other end becomes hot giving up heat to the medium that surrounds it. The compressor hangs on a pendulum and power is transmitted by friction drive without using the usual direct drive and stuffing box that I shall describe more fully in the chapter on compressors. I was unable to obtain a print of the apparatus that was sufficiently clear to enable me to describe the principle involved more fully.

Fifteen or twenty years ago designers in America began to experiment with small machines. Most of these were compression machines modeled after the large ice plant machines.

In Europe, particularly in Germany, the development of the small machine followed the absorption principle. Rumpler and Otto both worked on this type machine which was the forerunner of our modern Electrolux, manufactured by the Servil Corporation.

In France there was a rather interesting minature absorption machine developed. A bottle of concentrated sulphuric acid is connected to a carafe of water. By means of a hand-operated air pump the air is removed from the system whereupon, because of the great affinity of sulphuric acid for water vapor, the water vapor pressure is reduced to such a point that it evaporates rapidly, and the latent heat of evaporation

* Stevenson, A. J. : Refrigeration

freezes the remaining water solid in approximately sixty seconds.

As the basic principles underlying the operation of refrigeration apparatus were discovered and brought out before the year I890 it was only necessary to develop the many improvements in design and operation in the succeeding years in order to provide means for universal application as is indicated by the few preceding cases that I mentioned. Many improvements have been incorporated into the design of the compressors. More efficient methods of condensing the discharged gases were brought out. Fittings, accessories were improved and at present attempts are being made to standardize them. Thus at the present time the ways and means of producing refrigeration have been so improved that it can be practically applied to many processes in the industrial world in an efficient manner.

Few people realize how large and important a factor the use of refrigeration has become in the industrial and economic activities of human life. Approximately 200 separate industries depend more or less upon mechanical refrigeration for the production of some commodity. Although most of the earlier applications were in artificial ice plants, the requirements of industrial enterprises as packing houses, cold storage warehouses, breweries, creameries and dairies, ice cream manufactures, etc., have made the application of refrigeration quite universal. In the industrial plants the equipment is valued at $I,280,000,000 (exclusive of buildings) and a capacity of I, 255,000, tons of refrigeration daily. (The commercial unit of refrigeration is the quantity of heat required to

melt a ton of pure solid ice per day into water at 32° F and 14.7 pounds per square inch atmospheric pressure and is termed the standard commercial ton of refrigeration and has a value of 288,000B.t.u. per 24 hours (or 3.34B.t.u. per second).

At present over 104 companies are manufacturing domestic or household refrigerating machines.* There are a great many different types, a rough classification of which is given as follows;

Vapor compression machines:	
a) Conventional type using stuffing box and electric motor	46
b) Using stuffing box and electric motor	1
c) Stuffing box eliminated by inclosing the motor in the machine	17
d) Stuffing box eliminated but motor outside	7
Total	71
Absorption machines	22
Compressed air machines	4
Unknown	7
Total	104

* Refrigerating Past, Present and Future;
General Electric Company

CHAPTER 2

REFRIGERATING MEDIA

REFRIGERATING MEDIA

Refrigeration has been defined as the cooling of substances below the temperatures of the surroundings by the extraction of heat from the substances. This definition implies that a substance of a lower temperature than the material to be cooled is used to extract the heat from the material in question. The substance that absorbs the heat from the material to be cooled may be termed "refrigerant". The working substances or refrigerants of mechanical refrigeration systems may be considered collectively as refrigerating media. These refrigerating media may be classified in three groups with respect to the manner of absorption of heat. In the first group are those which cool the material by absorbing their latent heats of evaporation. These refrigerants are liquefiable vapors such as ammonia, carbon dioxide, sulphur dioxide, methyl chloride, ethyl chloride etc. In the second group are those which cool by absorbing their sensible heats. These are air, calcium chloride brine, sodium chloride brine, etc. In the third group are solutions which contain absorbed vapors of liquefiable media. The solutions are really the carriers of the liquefiable vapors which produce refrigeration by the absorption of their latent heat. This type of refrigerant will be more fully explained in the chapter on the Absorption System. Aqua ammonia or a solution of water plus ammonia is an example of this type of

medium.

The possibility of using a refrigerant depends on a great number of factors. The suction and discharge pressures P_1 and P_2, the chemical properties, the upper and lower temperatures T_1 and T_2 and the physical properties.

The correct suction and discharge pressures must be employed to give proper upper and lower temperatures. This is an important factor in choosing a refrigerant. If the upper temperature limit is be be taken as 68° F. and the lower temperature limit as 14° F. the pressures for three of the refrigerants are as follows;*

Refrigerant	NH_3	SO_2	CO_2
Suction pressure in lbs /square in.	41.7	14.7	380
Discharge pressure in lbs /sq. in.	124.7	47.6	825
Volume taking that of CO_2 as unity	4.4	12.0	1

From this table it is evident that carbon dioxide requires very high pressures. This requires heavy pipes, special cylinders, special fittings, stuffing boxes, etc.

Since the boiling points of the various refrigerants are different a refrigerant may always be selected that will give a sufficiently low temperature.

The chemical properties of the working fluid are important in the proper selection of a refrigerant because of two consid-

* Grunow Service Manual: Grunow Company

erations. In the first place the refrigerant must not have a corrosive action on the various metals which go to make up the system. Although refrigerants in their pure state do not attack the metals used in the systems generally, such foreign matter as water and oils in combination with the refrigerant may produce corrosion. In the second, these fluids must have a strong chemical bond in order to withstand the repeated evaporations, condensations, absorptions and dissociations of the various cycles of operation. In the compression system the refrigerants may show a tendency to disintegrate because the temperatures are always high at the end of compression.

The physical properties are of course the most important points upon which to judge a refrigerant. Pressure as indicated above plays an important part in the design of the compressors. The specific volume per pound of the vapor at the refrigerator pressure determines the amount of piston displacement. This of course determines the size of the household unit and so this must be kept as small as possible. The magnitude of the latent heat of evaporation and the density per cubic foot affect the quantity of the medium to be circulated to produce a given refrigerating effect. The critical temperature of a vapor is that temperature above which it is impossible to condense the vapor by application of pressure alone. Since the temperature of the saturated vapor in

the condenser is several degrees above the temperature of the condenser cooling water, it is evident that the critical temperature must be considered in relation to the maximum temperature of the cooling water.

The general requisites then for a good refrigerant are as follows*;

a) A high latent heat as well as a high ratio of latent heat to the specific heat of the liquid in order to produce a large refrigerating effect per cycle of operation.

b) A boiling point at ordinary atmospheric pressure low enough to obtain the temperature desired.

c) A condensing temperature at relatively low pressures.

d) A high critical temperature.

e) A low specific volume of vapor.

f) A low ratio of compression.

g) A non-corrosive action on metals.

h) A stable chemical composition.

i) A non-inflammable and non-explosive nature.

j) An inoffensive odor, non-injurious to health.

k) A low cost of production.

A survey of the most important refrigerants will show how each has certain characteristics that make it valuable as a refrigerant.

* Hull, Harry Blair: Refrigeration

Ammonia

Ammonia is harmless ordinarily to iron and steel but will attack copper and copper alloys. Hence, these metals cannot be used in the construction of the system. A solution of ammonia and water such as used in the absorption machines may have a corroding action on iron and steel, as stated above, in the presence of foreign matter. The critical pressure and temperature is I690 lbs and 273.2° F. Since the critical pressure and temperature are high, warm condensing water may be used. Ammonia will disintegrate into nitrogen and hydrogen at 900 F. so that is advisable to always keep the temperature below 300 F. in order to reduce to a minimum the formation of permanent gases. Ammonia will burn above 900 F. but not with the force of an explosion. It is somewhat dangerous to life due to its corrosive and suffocating action. However it gives a warning when leaking that is not harmful but disagreeable to the extent that one is quite aware of it before it becomes dangerous. The compression of the vapor follows the law

$$PV^{I.28} = \text{Constant}$$

where P is absolute pressure in #/sq. ft. and V. is volume in cubic ft. Ammonia requires only medium pressures and temperatures in the working cycle.

Carbon Dioxide

Carbon dioxide is harmless to iron, steel, and copper the metals employed in the design of refrigerating equipment. Its critical temperature is 88.4°F and the corresponding critical pressure is 1071 # abs. therefore comparatively cool condenser water must be used. The chemical bond of the molecules is strong and the gas is non-combustible. Due to its small specific volume, or the large weight per unit volume the refrigerating effect per unit of displacement is large. This means that the compressor cylinder may be made comparatively small for a given tonnage. It however requires excessively high pressures which means steel compressor cylinders, special fittings, packings etc. The compression of the vapor follows the law

$$PV^{1.3} = \text{Constant}$$

It has only a suffocating action on life.

Sulphur Dioxide

Iron, steel, and copper may be used in the construction of a unit using sulphur dioxide. However all moisture must be excluded from the system as it forms an acid when mixed with water. Its critical condition lies at 311° F and 1160 lbs. pressure. The chemical bond is strong and it is non-combustible. The volume needed for the usual amount of a unit of refrigeration is large and therefore sulphur dioxide needs large compressors. However the pressures are quite low.

The expansion follows the law

$$PV^{1.26} = \text{Constant}$$

It is somewhat dangerous to life because of its suffocating action.

Methyl Chloride

This refrigerant is neutral to iron, steel, and copper as long as it is not decomposed. The critical temperature is 286.9° F. and pressure I073 lbs. abs. It is non-combustible at room temperature but will burn if ignited with a flame. The compression of the vapor follows the law

$$PV^{1.20} = \text{Constant}$$

Methylene Chloride - (Carrene) (Boiling Point I03.64° F)

This refrigerant has been extensively used by the Carrier Engineering Company with centrifugal compressors. It is also known as dichloromethane. Methylene chloride is a low boiling chlorohydrocarbon having the chemical formula $CH_2 Cl_2$. It is a colorless water-white liquid at ordinary atmospheric conditions. Its critical temperature is 473° F. At high temperatures it breakes down into phosgene ($CO Cl_2$), chlorine (Cl_2), and hydrochloric acid ($H Cl$). Therefore it is usable at low temperatures but has a corrosive action at high temperatures, due to the hydrochloric acid.

Dichlorodifluoromethane or F-I2 ($C Cl_2F_2$)

This refrigerant approaches nearly to the ideal re-

frigerant and was studied by Sw rtz and developed by Dr. Thomas Midgley, the originator of ethyl gasoline. The chemical reaction used in its manufacture is

$$3C\,Cl_4 + 2Sb\,F_3 \xrightarrow{SbCl_5} 3C\,Cl_2\,F_2 + 2Sb\,Cl_3.$$

When pure dry antimony trifluoride ($Sb\,F_3$) is brought into contact with carbon tetrachloride ($C\,CL_4$) in the presence of small amounts of antimony pentachloride ($Sb\,CL_5$) fluorine substitutes for chlorine in the carbon tetrachloride: since fluorine substitution lowers the boiling point of the resulting compound by about I26°F.

A study made by Bureau of Mines (Report of Investigations, 30I3) shows that F-I2 is non-toxic. Animals can withstand for long periods of time a concentration of 20% by volume.

The boiling point at atmospheric pressure is 2I.7°F. It freezes at a temperature of -3II°F, and the latent heat of evaporation at atmospheric pressure is 72 B.t.u. per pound. The weight of refrigerant circulated per minute per ton of refrigeration is much higher than for other common refrigerants. However as the specific volume is much lower than for the other common refrigerants the theoretical piston displacement for dichlorodifluoromethane runs about I.69 times as great as for ammonia. In the case of sulphur dioxide the piston displacement is only about 62.6 %, and for methyl chloride only 85% as large.

Dichloroethylene

This refrigerant is a low boiling chlorohydrocarbon with the formula $C_2 H_2 Cl_2$. The boiling point at 14.7 pounds is 122 F. The freezing point 70° F. This refrigerant is used with centrifugal compressors. It is explosive and not particularly suited for household units.

Trichloroethylene

This is another refrigerant used with centrifugal compressors. It boils at 188° F. at atmospheric pressure. The latent heat of evaporation at atmospheric pressure is 104.5 B.t.u. per pound. The freezing point is 126° F. It is used for dry cleaning as well. It has a high relative displacement as compared with the other refrigerants and is used in only a few systems.

There are four more refrigerants about which little is known at present but which are under experiment. They are Ethane ($C_2 H_6$), Propane ($C_3 H_8$), Butane ($C_4 H_{10}$) and Isobutane ($C_4 H_{10}$).

The refrigerants, then, used in household systems are ice, sulphur dioxide, ethyl chloride, menthyl chloride, ammonia, carbon dioxide, (not common in America but used extensively in Europe), butane, isobutane and dichlorodifluoromethane. These refrigerants may be classed in two groups inflammable and non-inflammable. The non-inflammable are carbon dioxide,

sulphur dioxide and dichlorodifluoromethane. The remainder of the group may burn when mixed with air. Not all of the above group are widely used but the most common are sulphur dioxide, methyl chloride, dichlorodifluoromethane.

CHAPTER 3

PRINCIPLES OF THE COMPRESSION SYSTEM

PRINCIPLES OF THE COMPRESSION SYSTEM

In all mechanical refrigerating machines using a liquefiable fluid, (called the medium) the working substance is placed in such a condition that it will absorb heat from a material at a temperature below that of the atmosphere. After the absorption of heat it is placed in such a state that it will give up the absorbed heat and the heat added during the process to a water supply at a temperature higher than that of the refrigerator. This is the general principle underlying the operation of refrigerating machines using a liquefiable fluid.

The cycle of operation of the compression system has four principle phases. In the first phase, the refrigerant absorbs heat from the material of low temperature. This is done by maintaining a certain pressure on the medium so that the boiling temperature is a few degrees below the material of low temperatures. The heat then flows by natural tendency into the boiling refrigerant, causing it to be entirely evaporated. In the second phase, the vapor of the medium is compressed from the low pressure in the evaporator to a pressure such that the temperature of the condensing medium is a few degrees above the temperature of the available water supply, which temperature is always several degrees above that of the

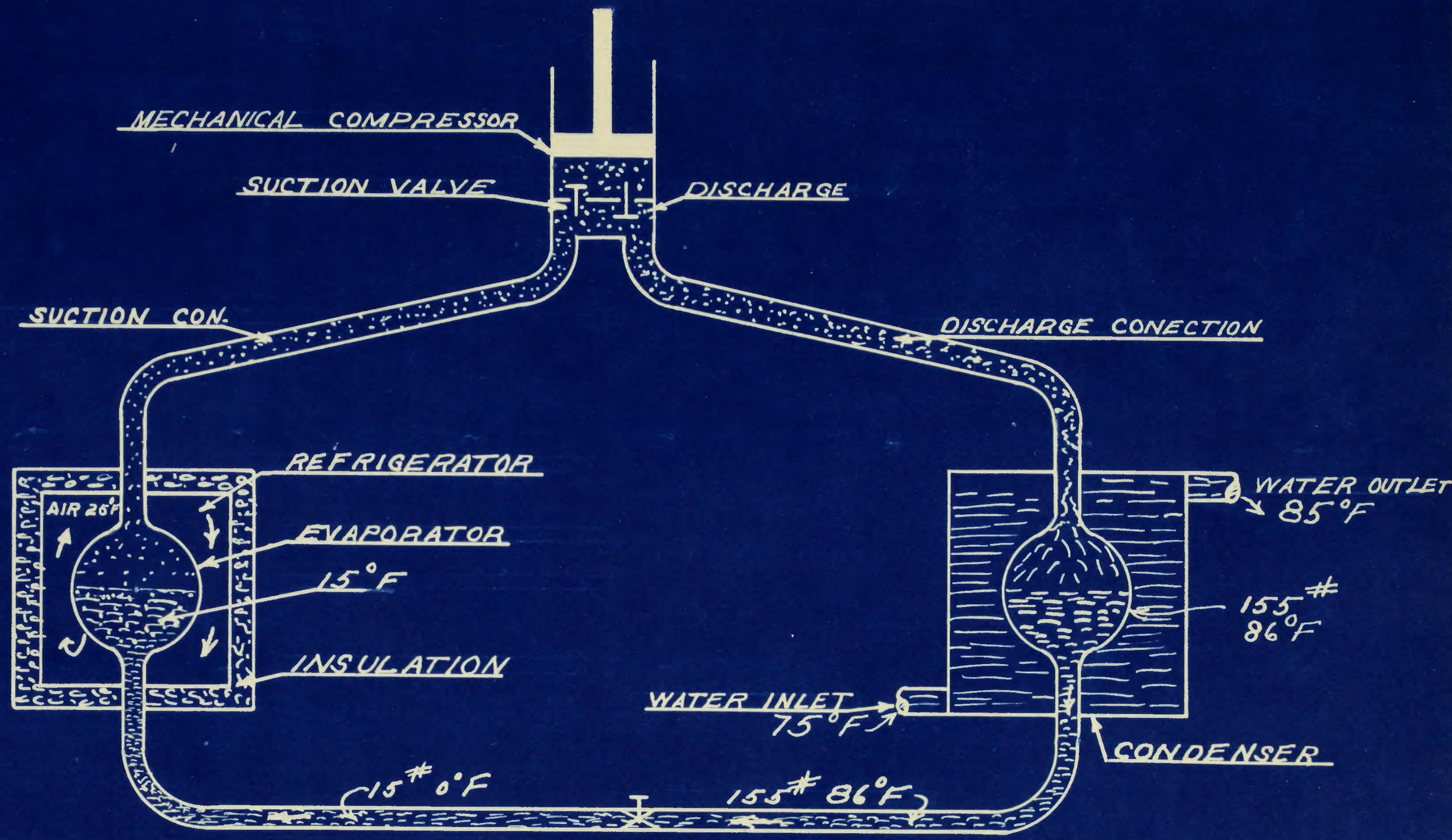
refrigerator (i.e. the evaporator). In the third phase, the heat in the refrigerating medium, that is, the heat absorbed in the evaporator and the heat added during compression, flows by natural tendency into the condensing water. The removal of this heat cools and then liquefies the medium. In the fourth phase, the medium is placed in such a condition that it will again absorb heat from the material of low temperature. This is accomplished by reducing the pressure of the liquid of the medium as it leaves the condenser to the pressure existing in the evaporator by means of the throttle valve, commonly termed expansion valve. The expansion valve reduces the pressure so that the temperature of the condensing fluid is a few degrees above the temperature of the condenser water, or air if it is an air cooled machine. The function of the expansion valve is to throttle the pressure of the refrigerant from the high pressure in the condenser to low pressure in the refrigerating coils. The liquid refrigerant is allowed to pass through a small orifice in the expansion, or throttle valve. The throttling through the valve takes place without the addition or extraction of heat. Therefore the "heat content" remains constant (providing that the velocity of the refrigerant is the same before and after passing through the valve).

The general principle underlying the operation of

this system depends upon the temperature-pressure relations of the refrigerating media. The fundamental principle lies in the physical law that states when the pressure of a refrigerant is increased, the temperature of its boiling point is raised in proportion to the increase of pressure, and conversely, when the pressure is reduced the temperature of the boiling point is likewise lowered. If the refrigerant in its liquid state is exposed to a temperature above that of its boiling point the temperature will increase until the boiling point is reached. It then boils, or evaporates, into a vapor at a constant temperature which depends upon the pressure of the medium. Likewise if a refrigerant in its gaseous state is exposed to a temperature lower than that of its condensing point the temperature will decrease until the condensing point is reached. It then condenses into the liquid state at constant temperature which depends upon the pressure.

Figure 1* shows the operation of a compression system using the liquid refrigerant ammonia. Any other liquid refrigerant would follow the same process but with differant temperatures and pressures. The properties of ammonia were obtained from the "Bureau of Standards" Tables of Properites of Ammonia, published by the Department of Commerce. The tables for ammonia are the most accurate to date. The properties of the other refrigerants are still not complete; many of the relations

* After Motz; Principles of Refrigeration



ELEMENTARY COMPRESSION SYSTEM

THEORY OF HOUSEHOLD REFRIGERATION
COMPRESSION SYSTEM
DRAWN BY — R.F. LYONS
FEB. 1934 PLATE I

Figure I

are still under experiment. The cardinal properties obtained from these tables are;

Temperature, degrees Fahr.

Pressure in pounds per sq. in. abs.

Specific volume in cu. ft. per lb.

Heat contents in B.t.u. per lb.

Entropy

The range of the tables is from temperature -60 F. and pressure 5.55# / sq. in. to temperature $+$ 125 F. and pressure 307.8 # / sq. in.

Referring again to Figure I, the compressor piston reduces the pressure in the cylinder on the up stroke somewhat below that in the evaporator, causing the vapor to flow from the evaporator into the compressor cylinder. The pressure in the evaporator is determined by the temperature desired in the refrigerator, therefore if a box temperature of 25 F.° is required the temperature of the boiling ammonia in the evaporator must be about 5° F. in order to cause the heat in the air of the evaporator or box to flow into the ammonia. The pressure corresponding to 5° F is about 17.58 lbs. per square inch gauge. Now, the compressor discharges the vapor from the evaporator into the condenser under high pressure. The pressure of the vapor in the condenser must be such that the condensing temperature of the ammonia is a few degrees

above the temperature of the water or air in order that the heat will flow from the ammonia into the water thus condensing. The initial temperature of the water may be 75° F. and may increase to 85° F. in absorbing heat as it passes through the condenser, then the temperature of the condensing ammonia may be 86° F. The pressure in the condenser corresponding to a condensing temperature of 86° F. would be approximately 155 lbs. per square inch gauge. Therefore our "high pressure side" must be at 155 pound pressure or in other words our compressor must compress the ammonia vapor to 155 lbs. per square inch in gauge before it goes to the condenser in order that it will condense. If air is used the temperature of the surrounding air must be estimated and the correct compression pressure found so that the vapor will have the right condensing temperature. In the diagram the liquid ammonia under a pressure of 155 lbs. and at a temperature of 86° F. passes to the regulating or expansion valve. The function of this valve is to throttle the pressure of the liquid ammonia from the high pressure in the condenser to the low pressure in the evaporator. After passing the regulating valve it has a pressure of 15 lbs. gauge and a temperature of 0°F. The liquid then flows to the evaporator to be re-evaporated. Hence by repeated evaporation, compression, condensation, and throttling the fluid may be used over and over again. The temperature of the

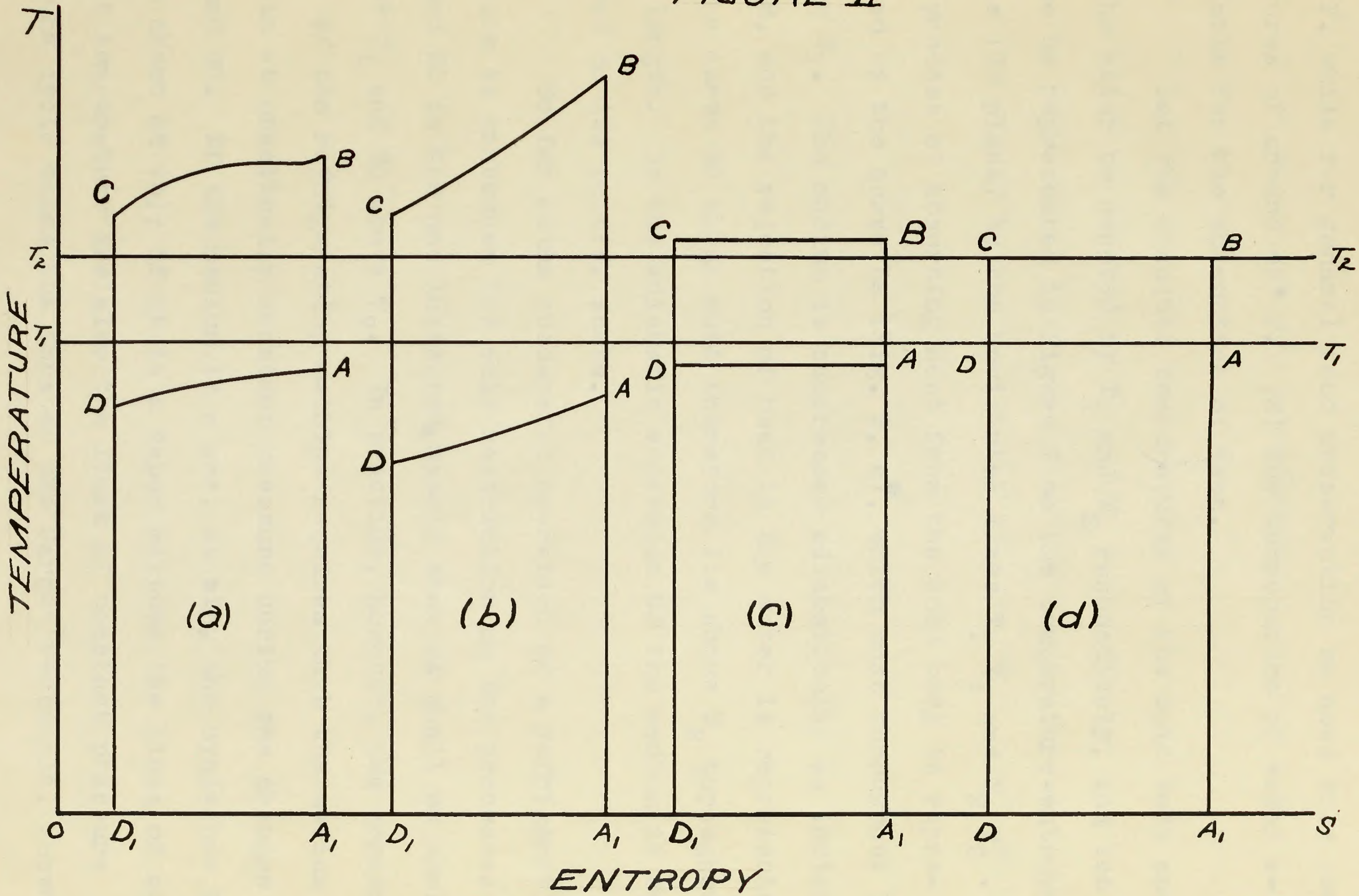
evaporator then is controlled by the expansion valve and the compressor which must also be regulated for changes in temperature.

The thermodynamics of the compression system is the reverse of the heat motor as the medium takes heat from the cold body and rejects heat to a body of higher temperature. The object sought in refrigeration, or the "production of cold" is the maintenance of the temperature of a body at a point lower than the temperature of surrounding bodies and no matter however well insulated the cold body may be, heat flows into it from the surroundings at higher temperature. It is then necessary to maintain a system that will cause the continuous removal of heat. The heat taken from the cold body must be rejected to some other body at a higher temperature. This second system we will consider as water although air is used in most household units; the medium after compression is put in contact with water, which absorbs the heat taken from the cold body and also additional heat, the equivalent of the external work required to drive the machine.

In the investigation of the refrigeration process we have two temperatures of first importance; and these are fixed by conditions of operation. (I) The temperature of the cold body, which is determined by the character of the service; thus for ice cubes we require a temperature below

PLATE II

FIGURE II



TYPICAL REFRIGERATION CYCLES PLOTTED ON THE Ts PLANE

32° F. while for general food preservation we need only temperatures of around 45° F. (2) The temperature of water available for the absorption of heat.

Let the absolute temperatures of the cold body and of the water be denoted by T_I and T_2 respectively, and let these be represented in Figure 2 on the temperature-entropy plane (TS plane) by the horizontal lines T_I T_I and T_2 T_2 . The process of absorbing heat from the cold body is represented by the curve DA (Fig. 2, a)*, which must throughout lie below T_I. The medium is compressed adiabatically as indicated by AB, and the rejection of heat to the water is represented by the curve BC which must therefore lie above T_2 throughout its length. By the adiabatic expansion CD the medium is returned to its initial state.

So far as the successful operation of a refrigerating machine is concerned the only restriction on the processes DA and BC is the one indicated, namely that DA shall be wholly below T_I and BC above T_2. In practice, however, the construction of the refrigerating machine requires that the medium remain at practically constant pressure during the changes DA and BC. If the medium is a gas, as air, the cycle has the form shown at (b); if it is a vapor mixture the lines of constant temperature are also the lines of constant pressure and the cycle takes the form of the Carnot rectangle, shown

* Goodenough, G. A. : Principles of Thermodynamics

at (c).

In each cycle the area $D_I DAA_I$, represents the heat taken from the cold body, that is, the useful effect, and the area ABCD represents the work required. It is evident that the ratio of the heat removed to the work supplied is greater for the vapor cycle than for the gas cycle. From the point of view of economy a gas is a poor medium for a refrigerating machine.

The refrigerating machine absorbs the heat Q_1 from the cold body, receives the work W from an external source and rejects the heat

$$Q_2 = Q_I + AW$$

(If we denote by Q the heat converted into work and by W the work thus obtained we have the equation for the first law of thermodynamics

$$W = JQ \text{ or } Q = AW$$

in which J denotes Joule's equivalent and $A = \frac{I}{J}$. If Q is expressed in B.t.u. and W in foot pounds, J = 777.64 and A is its reciprocal). This heat Q_2 is rejected to the warmer body. The useful effect is the heat Q_I, and the expense which is to be made as small as possible depends upon W. It is evident that the larger Q_I is, compared with W, the more efficient is the refrigeration process. The ratio $\frac{Q_1}{AW}$ may

therefore be taken as a measure of the efficiency of the machine, This ratio is called the "coefficient of performance" and is denoted by β.

With given temperatures T_I and T_2, the smallest possible work is required when the cycle is a rectangle as ABCD (Fig. 2, d) with the isothermals coinciding with T_I and T_2. The ideal coefficient of performance β_0 for this case is

$$\beta_0 = \frac{\text{area } D_I DAA_I}{\text{area } DABC} = \frac{T_I}{T_2 - T_I}$$

The efficiency of a refrigerating machine may be defined as the ratio of its coefficient of performance to this ideal coefficient, that is

$$\eta = \frac{\beta}{\beta_0}$$

Thus the ideal coefficient of performance depends upon the temperature difference $T_2 - T_I$. The smaller the temperature difference can, be made the larger the coefficient; hence the heat is absorbed from the cold body at as high a temperature as is permissable and the temperature of the medium during rejection of heat is kept as low as possible.

The performance of a refrigerating machine may be expressed in terms of the heat removed from the cold body per horsepower hour of work expended. Since one horsepower hour is equivalent to 2546 B.t.u., the product 2546 β gives the heat removed per hour per horsepower.

CHAPTER 4

PRINCIPLES OF THE ABSORPTION SYSTEM

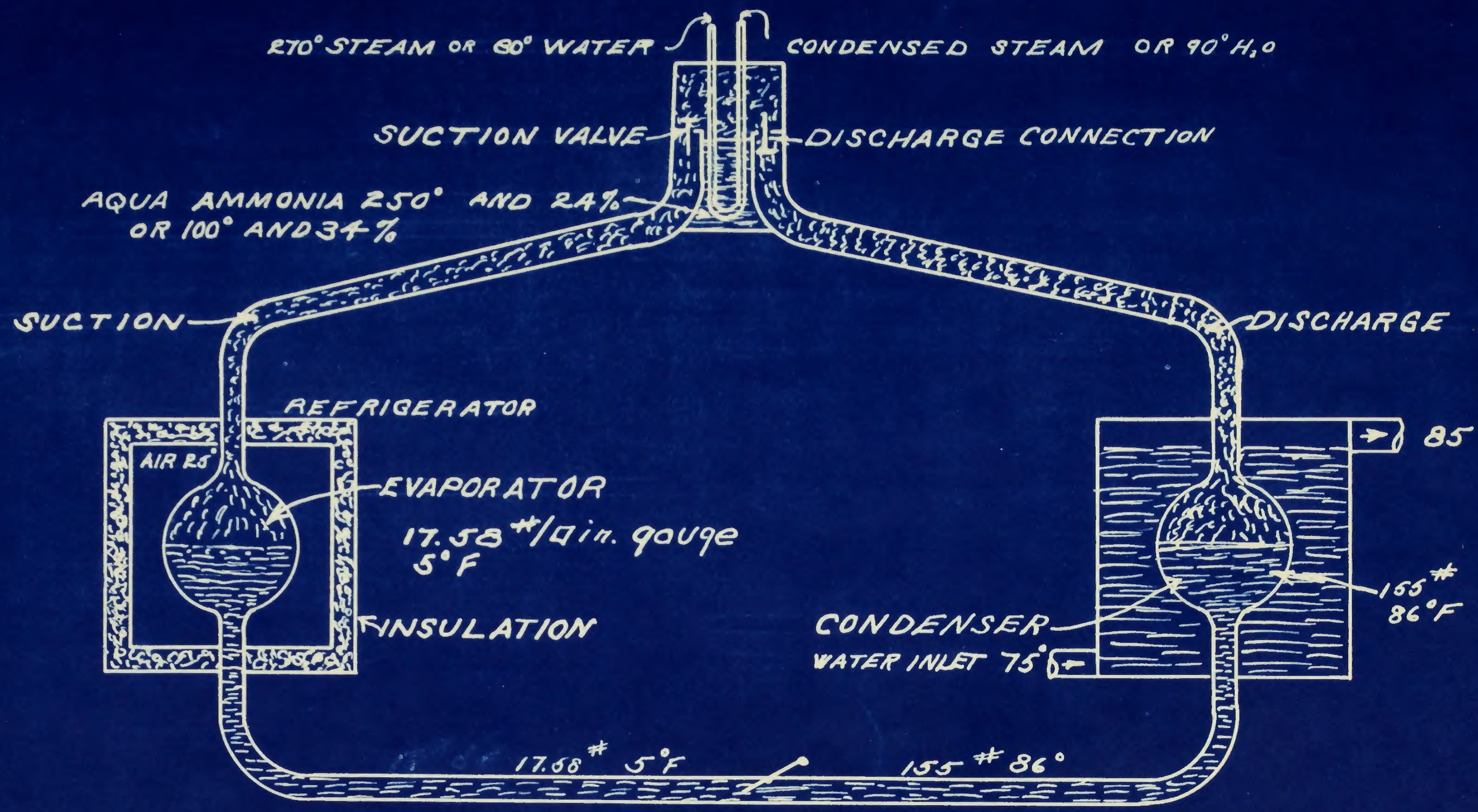
THE ABSORPTION SYSTEM

The general principle underlying the operation of the absorption refrigerating system is the same as that of the compression system. The working substance is placed in such a condition that it will extract heat from the refrigerator and after this extraction of heat, the working substance is placed in such a condition that it will give up the heat from the refrigerator and heat added during the process to a material warmer than that of the refrigerator space.

In the compression system, the vapor from the evaporator in the refrigerator is compressed from low pressure to high pressure by mechanical means, while in the absorption system the pressure is increased by the application of heat to a liquid which contains the disolved vapors from the evaporator.

Thus, water absorbs or dissolves the ammonia vapor from the evaporator at low temperature and pressure, and then it is made to give up or distill off the ammonia vapor at a higher temperature and pressure. This is the principle underlying the absorption part of the absorption system.

The cycle of operation of the elementary absorption system is as follows; the ammonia vapor from the evaporator is dissolved in a weak solution of ammonia and wa-



THE ELEMENTARY ABSORPTION SYSTEM

THEORY OF HOUSEHOLD REFRIGERATION
THESIS —— ROBERT LYONS
PLATE III —— MARCH 1934

ter, which is called weak aqua ammonia. This absorption of the vapor takes place in the absorber, and since there is a change of state from vapor to liquid the latent heats of condensation and absorption are liberated. This heat is taken out by water. Thus the weak aqua ammonia becomes strong aqua, due to the absorption of ammonia from the evaporator. The strong aqua is then pumped from the absorber into a still or generator, in which, by the application of heat, the ammonia is distilled into the condenser. The resulting weak aqua is piped back to the absorber to re-absorb ammonia again and thus complete this part of the cycle. The diagram of the simple cycle is given in Figure 3. By comparison with the elementary compression it will be seen that the two figures are alike but for the method of compression. From Figure 3 it will be noted that the elementary absorption system has a condenser, expansion valve, and evaporator, similar to the compression system.

The complete cycle of operation of the absorption refrigerating machine is shown in Figure 4.* The condenser operates in the same manner as in the compression system. The temperature of the air or water, determines the condenser pressure while the area of condensing surface also has bearing on the magnitude of the pressure. As in the compression system the temperature of the water or air rises a few degrees in passing through the condenser, and there is a small temp-

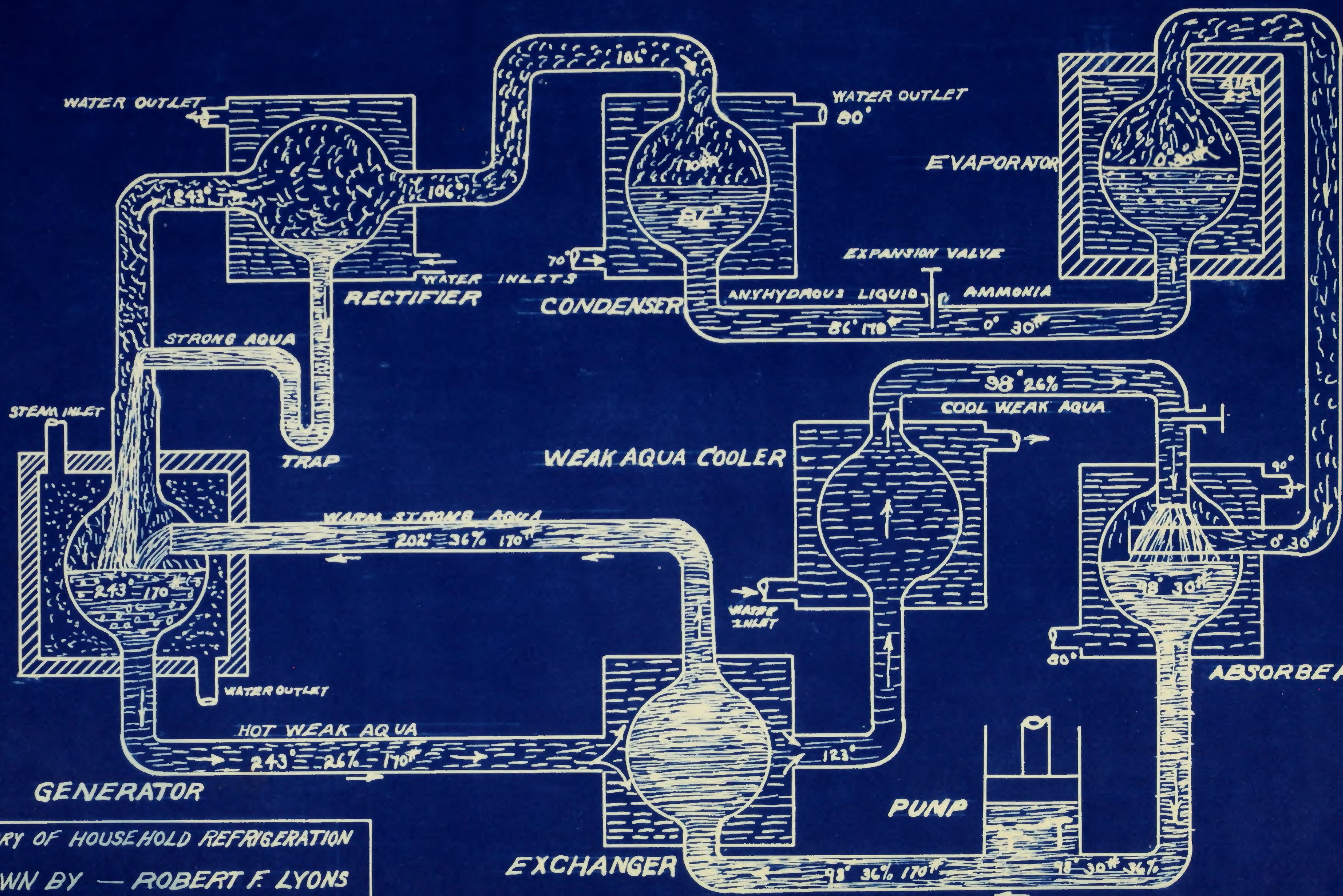
* Motz, William G. Principles of Refrigeration

erature difference between the water leaving the condenser and the temperature of the condensing ammonia in the saturated portion of the condenser.

The temperature of the evaporating fluid in the evaporator is determined by the temperature required in the box.

The temperature of the water or cooling medium available for cooling the absorber affects the conditions in the absorber. It is evident that the absorber must be supplied with some cooling medium since the changes of states such as condensation and absorption are accompanied by a liberation of heat. The pressure in the generator is determined by the condenser pressure which in turn depends on the condenser water temperature. Heat must be supplied to distill or dissociate the ammonia from the aqua in the generator. This heat is generally supplied by condensing steam, and the temperature of the steam must be a few degrees above the temperature of the aqua so that heat will flow into the aqua distilling off some ammonia vapor.

Assuming a condenser temperature of 70°F and a refrigeration temperature of 20°F the operation of the complete cycle may be noted (Figure 4). Beginning with the condenser, the following table shows the conditions of pressures and tempera-



THEORY OF HOUSEHOLD REFRIGERATION

DRAWN BY — ROBERT F. LYONS

PLATE IV THESIS-1934

FIG 4 DIAGRAM OF ABSORPTION SYSTEM

Re. 31

tures in the condenser as given in the Tables of the Bureau of Standards;*

I.	Water or air inlet temperature	70°F
2.	Water outlet temperature	80°F
3.	Difference between water outlet temp. and ammonia temp.	6°F
4.	Temp. of saturated ammonia	86°F
5.	Pressure of ammonia (lbs. abs.)	I70 # / sq. in.
6.	Temp. of liquid ammonia leaving the condenser	86°F

It will be noted in Figure 4 that liquid ammonia at 86°F and I70 # pressure flows to the expansion valve as in the compression system. The valve throttles the pressure to that required in the evaporator.

The conditions in the evaporator may be tabulated as follows.

Temp. of refrigerator	20°F
Temp. of boiling ammonia	0°F
Pressure of boiling ammonia	30 # abs.
Temp. of vapor leaving evaporator	0°F

Thus the expansion valve throttles the pressure from I70 # to 30 #; the throttled liquid passes into the evaporator, where it is evaporated by absorbing its latent heat from the refrigerator; it leaves the evaporator and

* Tables of Bureau of Standards - Ammonia
Department of Commerce Washington

passes to the absorber at 0° and 30 # pressure.

As the vapor passes into the absorber it mixes with the weak aqua ammonia and is readily absorbed due to the great affinity of water for the ammonia. The weak aqua ammonia absorbs all the ammonia that it can hold under the conditions and is then ready to be taken from the absorber thereby removing vapor from the evaporation.

The following tabulation indicates the conditions existing in the absorber assuming that the absorber is cooled by water from the condenser

Water inlet temperature	80°F
Water outlet temperature	90°F
Temperature difference	8°F
Temperature of aqua	98°F
Pressure in absorber	30# abs.
Concentration	36%
Temperature aqua leaving absorber	98°F

The strong aqua of 36% concentration at 98° and 30# pressure flows to the aqua pump, which discharges the strong aqua through the exchanger into the generator. The aqua pump in this system is operated by mechanical power. It is eliminated however in the new Electrolux machine as I will describe below.

The conditions in the generator are shown in the

following tabulation assuming that the weak aqua is 10% lower than the strong aqua and that the aqua in the generator is 20 below the temperature of the condensing steam in the generator heating coils:

Generator pressure	170# abs.
Concentration of strong aqua	36%
Difference of concentration	10%
Concentration of weak aqua	26%
Temperature of aqua	243°
Temperature difference	20°
Temperature of steam	263°
Pressure of steam	37# abs.
Temp. of vapors leaving generators	243°
Temp. of aqua (weak) leaving generator	243°

Thus the generator receives the 36% strong aqua from the absorber and distills off the ammonia until the solution contains only 26% ammonia. This hot weak aqua is returned to the absorber after passing through the exchanger and weak aqua cooler. A difference of about 8% to 10% will produce economical operation of the system under ordinary conditions.

It will be observed that the hot weak aqua from the generator and cool strong aqua from the absorber are led through the heat exchanger. The function of the exchanger is to allow the heats of the strong aqua and weak aqua to inter-

change, since the weak aqua must be cooled to the absorber temperature and the strong aqua must be heated nearly to the generator temperature. These liquids should flow through the exchanger in opposite directions for best results. The strong aqua may be assumed to be heated to its boiling point under the conditions but no evaporation is allowed to occur. The boiling temperature of 36% strong aqua at 170# from the tables is equal to 202 so that the aqua may be heated to 202 in passing through the exchanger.

In order to calculate the drop of temperature of the weak aqua in passing through the exchanger, it is necessary to know the relative weights of the strong and weak aqua per pound of ammonia carried from the evaporator to the condenser.

The following formula* indicates the amount of strong aqua to be pumped per pound of ammonia transferred

$$P_1 = \frac{1 - C_2}{C_1 - C_2}$$

P_1 = pounds of strong aqua

C_1 = concentration of strong aqua expressed as a decimal

C_2 = concentration of weak aqua expressed as a decimal

The pound of weak aqua P_2 pumped per lb. of ammonia transfered from the evaporator to the condenser, is equal to:

$$P_2 = P_1 - 1$$

For the case of 36% and 26% aqua, since 36% = 0.36 and 25%

* Refrigerating Data Book and Catalog: Am. Soc. of Ref. Eng.

= .25 the pounds may be calculated by substitution in the above formulae. From the calculation we find that 7.4# of strong aqua pass through the exchanger in one direction while 6.4# of weak aqua pass in the opposite direction. Assuming that there are no heat losses, or that the heat absorbed by the cool strong aqua is equal to the heat given up by the hot weak aqua, the temperature (t) of the weak aqua leaving the exchanger may be calculated as follows:

$$7.4\ (202 - 98) = 6.4\ (243 - t)$$

where t = temp. of weak aqua out of exchanger

thus t = 123

The heat absorbed by the strong aqua is equal to 7.4 (202 — 98) while that absorbed by the weak aqua is equal to 6.4 (243 — 123). The specific heat of the aqua may be taken as 1.0 B.t.u./ lb./ degree.

The conditions existing in the exchanger may be tabulated as follows;

Temp. of strong aqua at inlet —	98°
Temp. of strong aqua at outlet —	202°
Temp. of weak aqua at inlet —	243°
Temp. of weak aqua at outlet —	123°
Pressure of strong and weak aqua —	170# abs.

The weak aqua leaves the exchanger and passes

through the weak aqua cooler and then through the regulating valve to the absorber. In passing through the weak aqua cooler the aqua may be further cooled to 98°, the temperature of the aqua in the absorber. It is also evident that the flow of the weak aqua from the generator into the absorber must be regulated in some manner. This is generally accomplished by means of a float valve, which controls the height of the aqua in the absorber.

The ammonia and water vapor leaving the generator pass through the rectifier and then into the condenser. The function of the rectifier is to condense out the water vapor as much as possible so that only anhydrous ammonia vapor goes to the condenser. The rectifier may be cooled by water or some other means. The water vapor that is condensed out, of course, absorbs ammonia, making strong aqua, which must be trapped back to the generator. The temperatures of the vapor of the rectifier would be that of the vapors leaving the generator. Thus, the 106° and 170# pressure ammonia vapor passes to the condenser to be liquified.

It is evident the cycle is now complete and that the same anhydrous ammonia and the same aqua ammonia may be used over and over again.

Figure 4 illustrated in a diagrammatic way the principles of operation of the various important parts of the absorption refrigerating machine. Figure 5 is a diagram of

the new Electrolux Air Cooled refrigerator. This is the major absorption machine on the market. While it employs features that are new such as cooling the absorber with Methyl Chloride and using Hydrogen in the system, it is still in basic principles a typical absorption machine. As indicated in Figure 5* the operation of the machine as described in the paper by the manufactures is as follows.

"The Electrolux unit is charged with a small quantity of aqua ammonia (distilled water and ammonia) and hydrogen. The charge distributes itself naturally in the unit, the liquid seeking the lowest levels and the hydrogen filling the remaining space.

With the application of heat at the Generator (I), ammonia vapor is driven off from the strong solution (aqua ammonia) and together with small quantities of the strong solution is raised through the Pump Tube (2) to the Weak Liquid Stand Pipe (I6). Ammonia vapor with traces of water vapor is driven off in the Generator (I) leaving the aqua ammonia solution comparatively weak in ammonia (weak solution). The hot ammonia vapor passes from the Generator (I) through the Submerged Analyzer (3) High Temperature Rectifier (5) and Rectifier (6) where the small amount of water vapor entrained is condensed and drains to the Generator (I).

The hot ammonia vapor reaches the Lower Ammonia

* Electrolux Refrigeration Handbook; Servil Sales Inc.

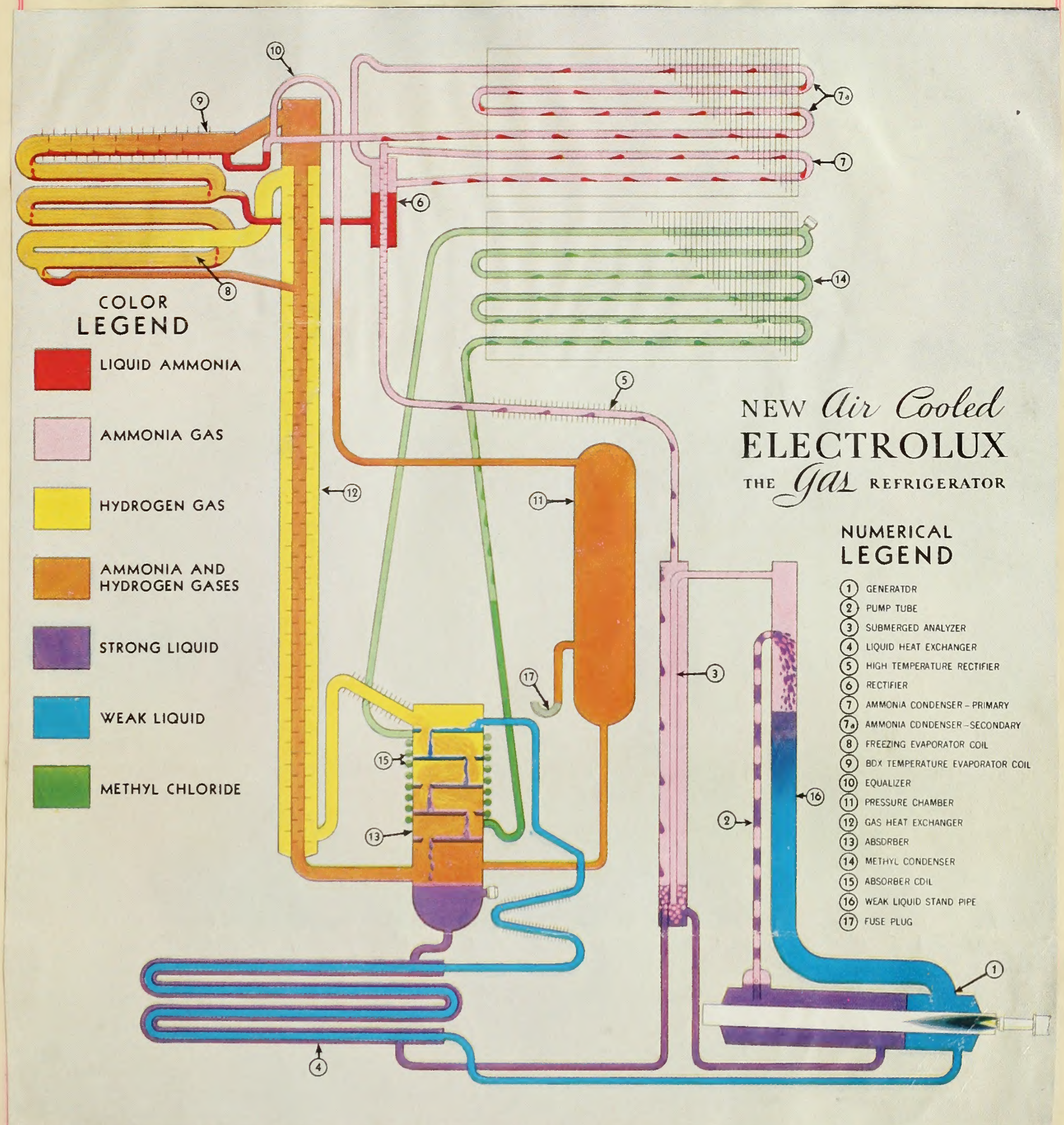


Figure 5

Pc 38

Condenser (7) where part of it is liquefied by cooling. The liquid ammonia maintains a level in the Rectifier (6) causing the liquid ammonia to flow into the Freezing Evaporator Coil (8). The remaining part of the ammonia vapor is liquefied in the Upper Ammonia Condenser (7A) and the resultant liquid flows to the Box Cooling Evaporator Coil (9). In the evaporator the ammonia liquid evaporates with the resulting absorption of heat.

In a cold room the greater part of the ammonia vapor liquefies in the Lower Ammonia Condenser (7) and is available for freezing cubes by evaporation in the Freezing Evaporator Coil (8). Since very little liquid flows to the Box Cooling Evaporator Coil (9) it is possible to obtain fast freezing without excessive cooling of the box.

As room temperature or refrigeration load demand increases the thermostat functions to increase the generator heat input and raises a greater amount of ammonia vapor to the condenser. This additional vapor is condensed in the Upper Ammonia Condenser (7A) and flows to the Box Cooling Evaporator Coil (9). This arrangement tends to maintain a more uniform box temperature with varying room temperature without the necessity of changing the temperature control setting.

An atmosphere of hydrogen, is continually sweeping the surface of liquid ammonia in the evaporator coils, keeps removing the ammonia vapor and causes continued evaporation.

The ammonia vapor thus formed in the evaporator mixes with hydrogen gas and the mixture is made to flow upward through the evaporator. This permits the location of the Box Cooling Evaporator Coil (9) in its most effective position; namely, at the top; and at the same time, the hydrogen gas which is saturated with ammonia passing upward from the Freezing Evaporator Coil (8) is enabled to pick up more ammonia at the higher temperature prevailing in the Box Cooling Evaporator Coil (9). Still another advantage results from the pre-cooling of the liquid ammonia coming from the Ammonia Condenser-Upper Part (7A) beforeit enters the Freezing Evaporator Coil (8). These features greatly increase the capacity of the unit.

In case all the ammonia vapor is not condensed in Upper Ammonia Condenser (7A) on account of high room temperature, the vapor passes through the Equalizer (IO) to the Pressure Chamber (II) which contains a quantity of reserve hydrogen. This results in displacement and transfer of reserve hydrogen into the Absorber (I3) thereby increasing the pressure in the system to the point where all the ammonia is liquefied in the Lower Ammonia Condenser (7) and Upper Ammonia Condenser (7A). When the room temperature becomes lower, the reserve hydrogen returns to the Pressure Chamber (II). This automatic pressure change permits very efficient operation of the unit under normal room temperature conditions as it is

not necessary to initially charge the unit with a high pressure to enable satisfactory operation under extreme conditions.

In the Gas Heat Exchanger (I2) cool heavy gas from the evaporator comes in thermal contact with warm light gas from the Absorber (I3) effecting a heat exchange and increasing the unit efficiency. The long column of heavy gas rich in ammonia in the center of the Gas Heat Exchanger (I2) readily overbalances the short column of heavy gas in the evaporator, thereby causing the desired upward flow in the evaporator.

A flow of weak solution being returned from the Generator (I) through the Liquid Heat Exchanger (4) contacts the ammonia and hydrogen gas mixture entering the Absorber (I3) and the ammonia is dissolved. The hydrogen returns to the evaporator.

The heat which is liberated by absorption of ammonia in the Absorber (I3) is carried away by the vaporization of a small quantity of methyl chloride in the Absorber Coil (I5). This vapor liquefies in the Methyl Chloride Condenser (I4) thereby dissipating the heat. The liquefied methyl chloride returns by gravity to the Absorber Coil (I5).

From the Absorber (I3) the strong solution is returned by gravity to the Generator (I), passing through the Liquid Heat Exchanger (4) where a heat transfer is accom-

plished because of the difference in temperature of the weak and strong solutions. After passing it then returns to the Generator (I) through bottom of submerged Analyzer (3) where part of the heat in the vapors leaving the Generator (I) is removed by serving the useful purpose of driving some ammonia from the strong solution. This results in a further increase in efficiency. Continued refrigeration is merely a repetition of this cycle."

CONCLUSION

CONCLUSION

The subject of Household Refrigeration is a broad one and with the one hundred odd makes of machines on the market it would be a great task to take each one separately and tell how one differed from the other. This is really not necessary for while they differ in small details the general principles are the same. I have described the major divisions, the compression system, and the absorption system. These two systems show the only theoretical differences. The other machines may differ in the refrigerant; in the type of compressor centrifugal or reciprocating; in the insulation, type and thickness; or in the system of cooling. These differences do not affect the theory involved.

Mechanical refrigeration is rapidly becoming one of our major industries, and with the improved methods of manufacture and improved refrigerants there will be more universal use of the mechanical refrigerators in the future.

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APPENDIX

TEST ON HOUSEHOLD UNIT

The following charts show the results of a test run on one of the standard makes of household refrigerators.

These photostatic charts show the hot room temperature which was maintained quite consistently at 110°F; the high side pressure which ranged between 145# and 155#; the low pressure side which varied from 2 to 18#; the inside cabinet temperatures which show the evaporator temperature from 12° to 16° F and the interior of the cabinet 40° to 46° F, as well as an electrical current recording chart showing wattage consumed and the off and on periods.

An interesting occurence shows on these charts. A line fuse burned out on the run (which was from 4:15 PM June 20 to 2 PM June 21, 1933) and was not immediately replaced. The fluctuations show in all charts. This is a very good indication of the performance of one of our standard household refrigerators.

(The photostatic prints appear only in the original copy and not in the carbon copy.)

CHARTS

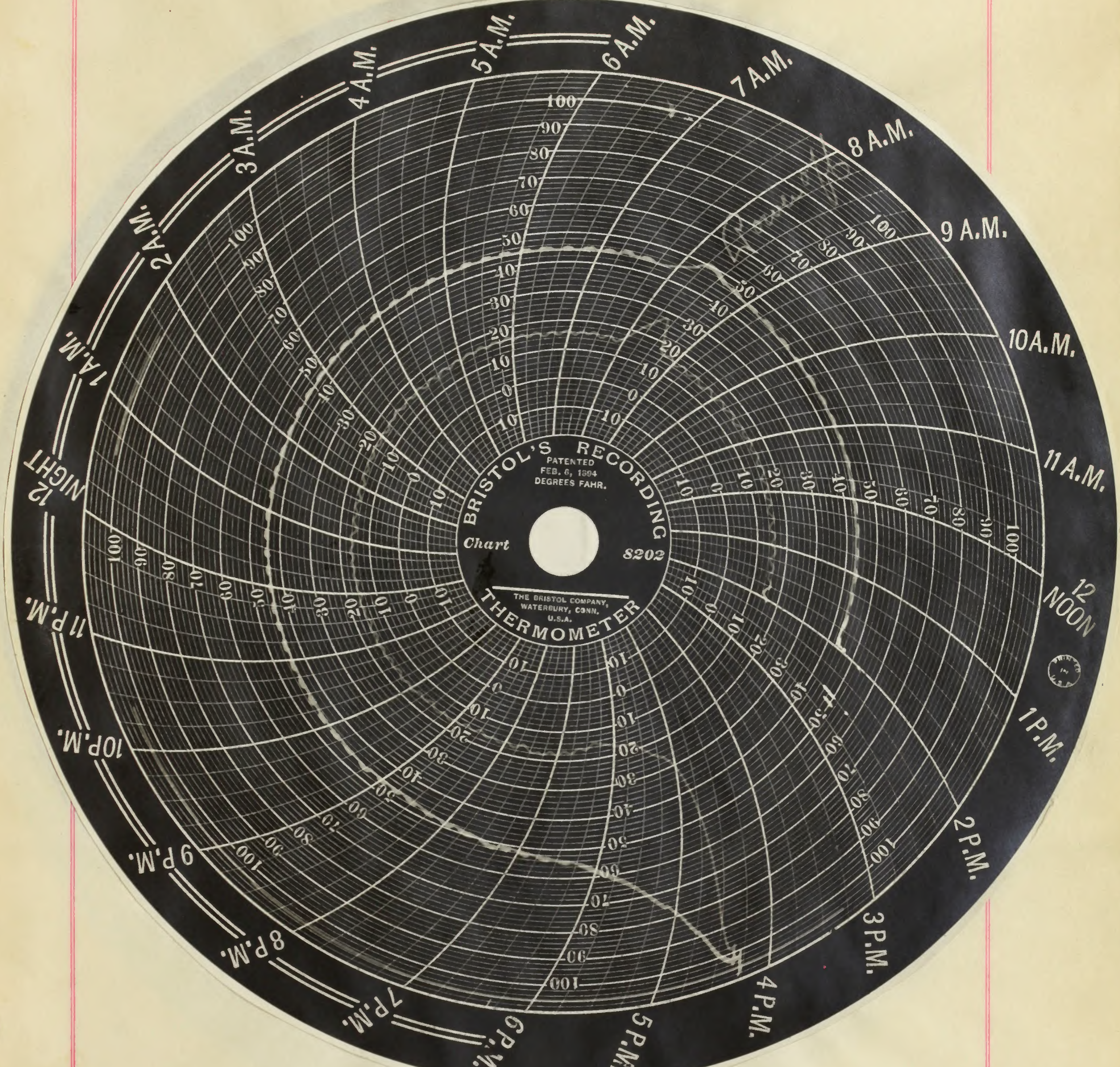
I. Low side pressure chart from 4:I5 PM June 20 to June 2I, I933.

2. Inside cabinet temperature chart.

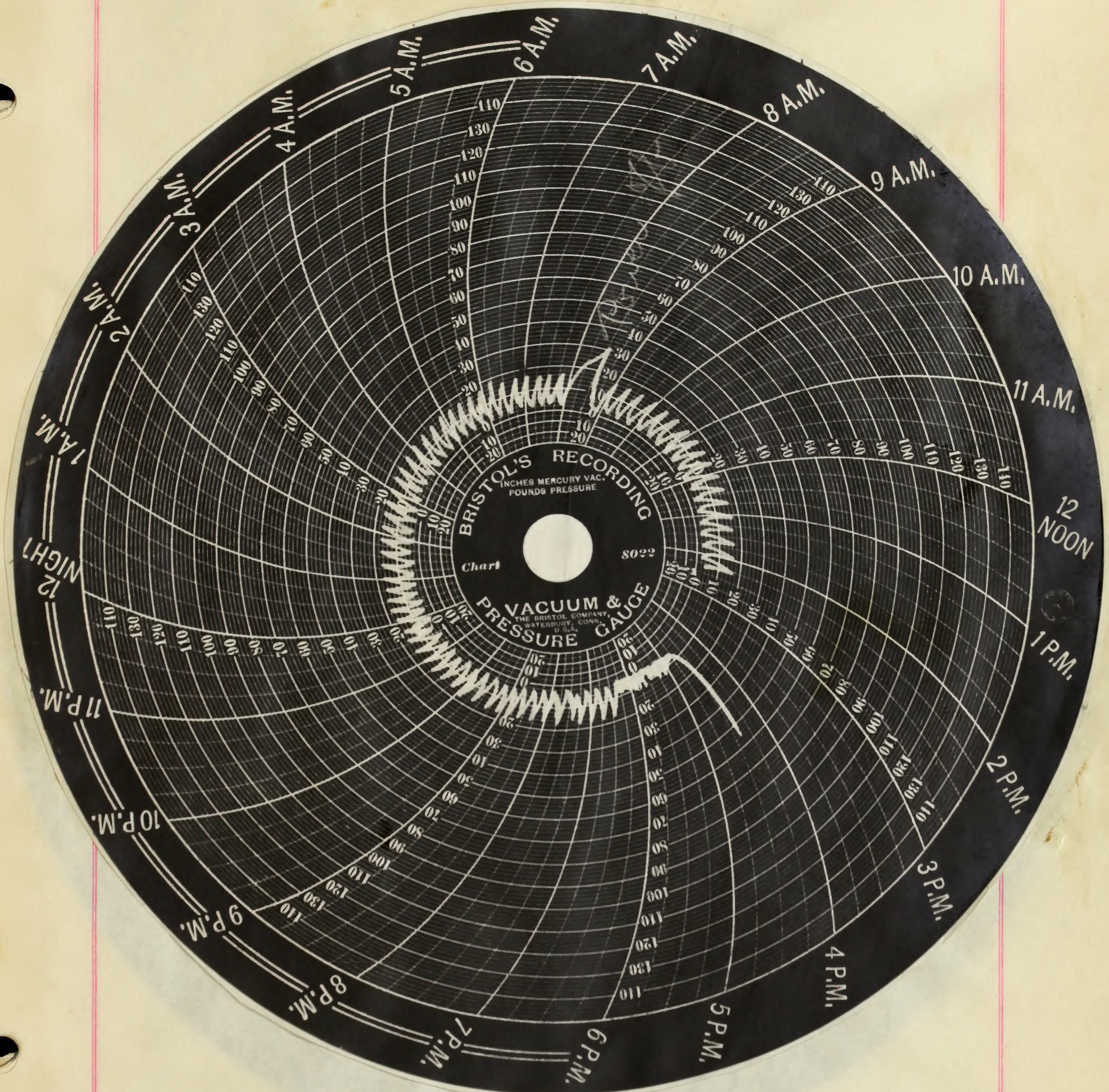
3. Room temperature chart.

4. High side pressure chart.

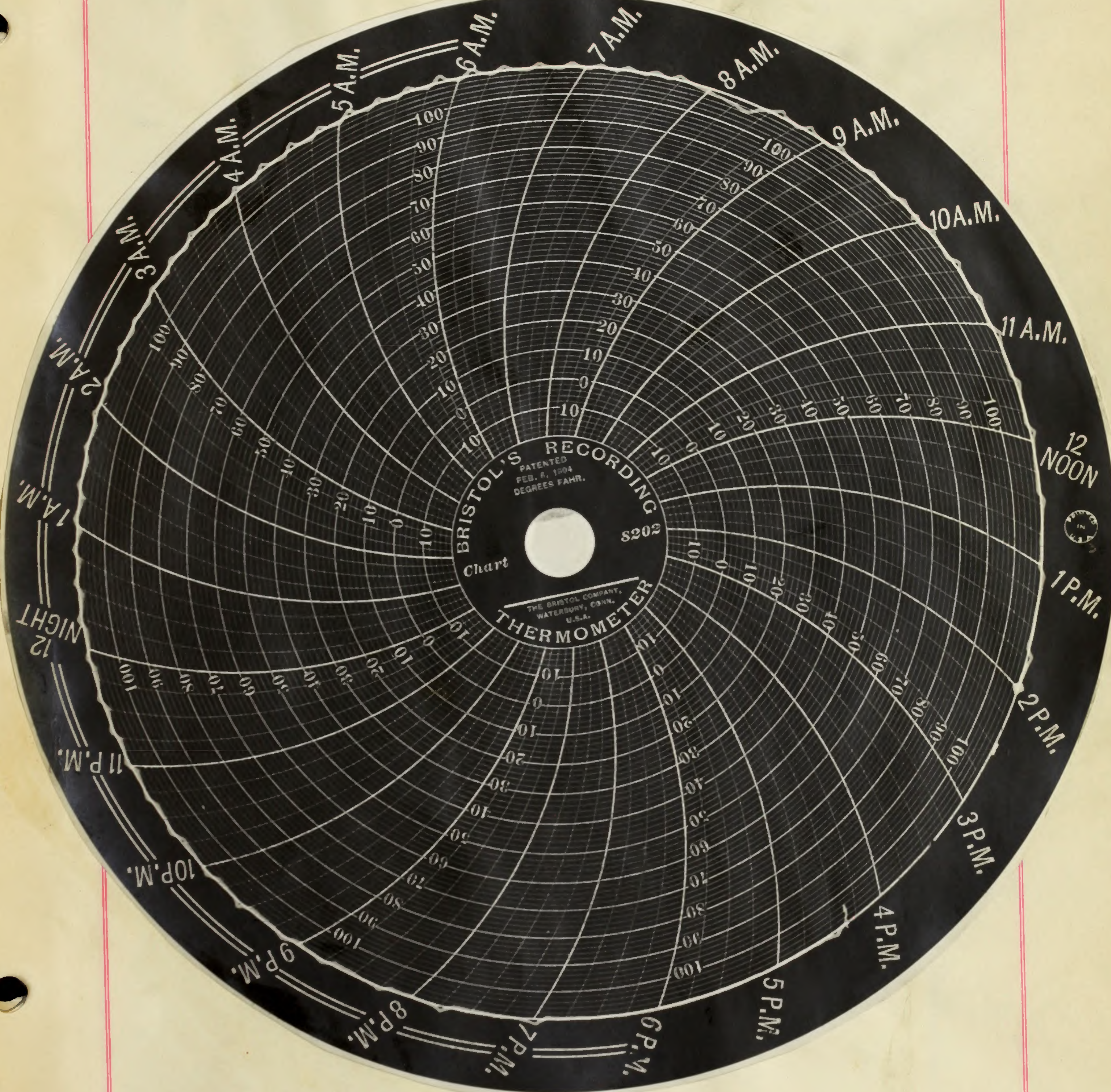
5. Recording Wattmeter Chart.



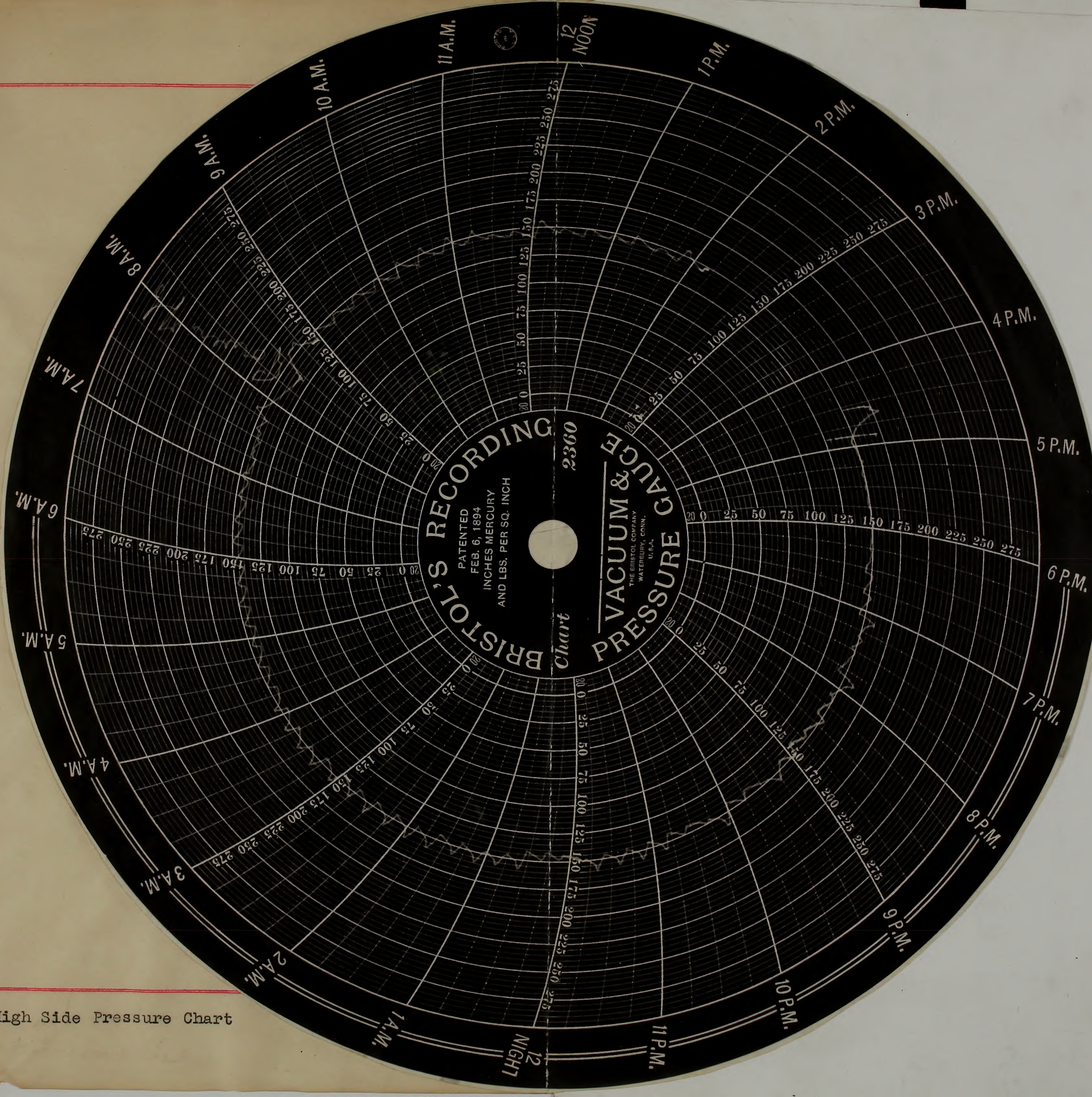
Inside Temperature Chart (Cabinet)



Low Pressure Chart



Room Temperature Chart



High Side Pressure Chart

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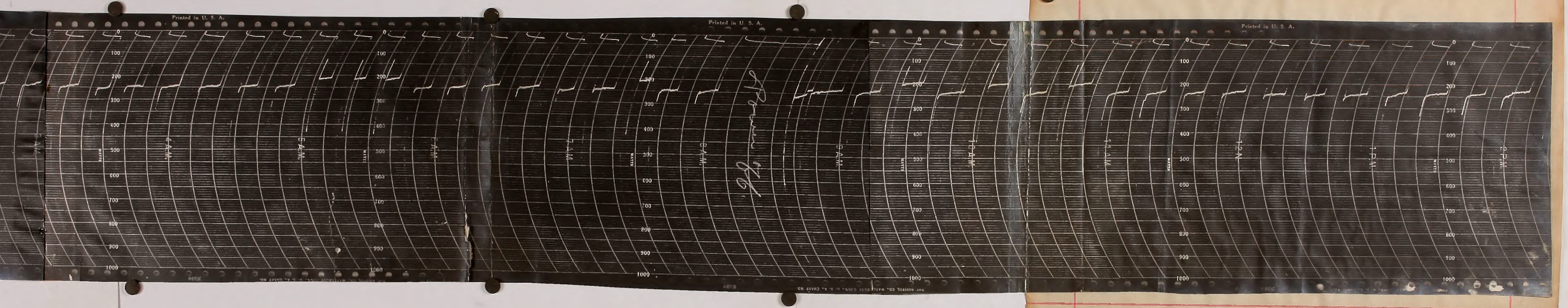
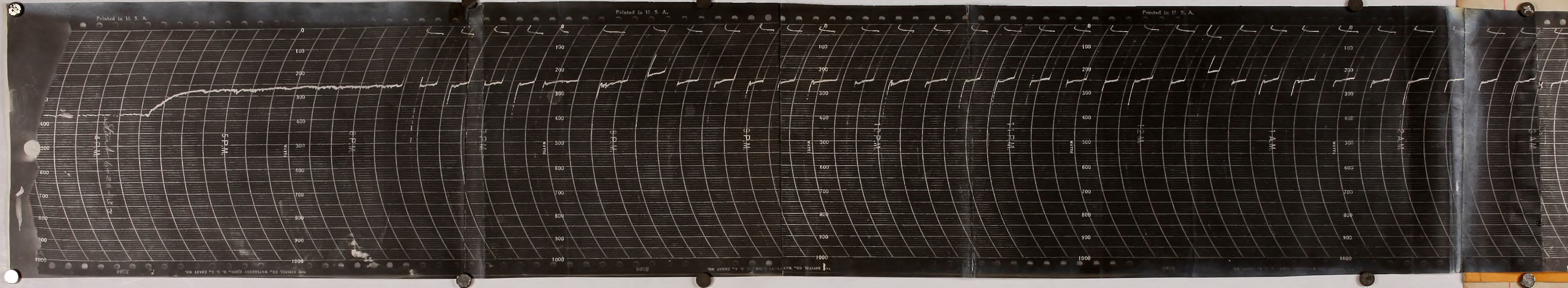


Recording Wattmeter Chart



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