Willis Haviland Carrier

Father of Air Conditioning

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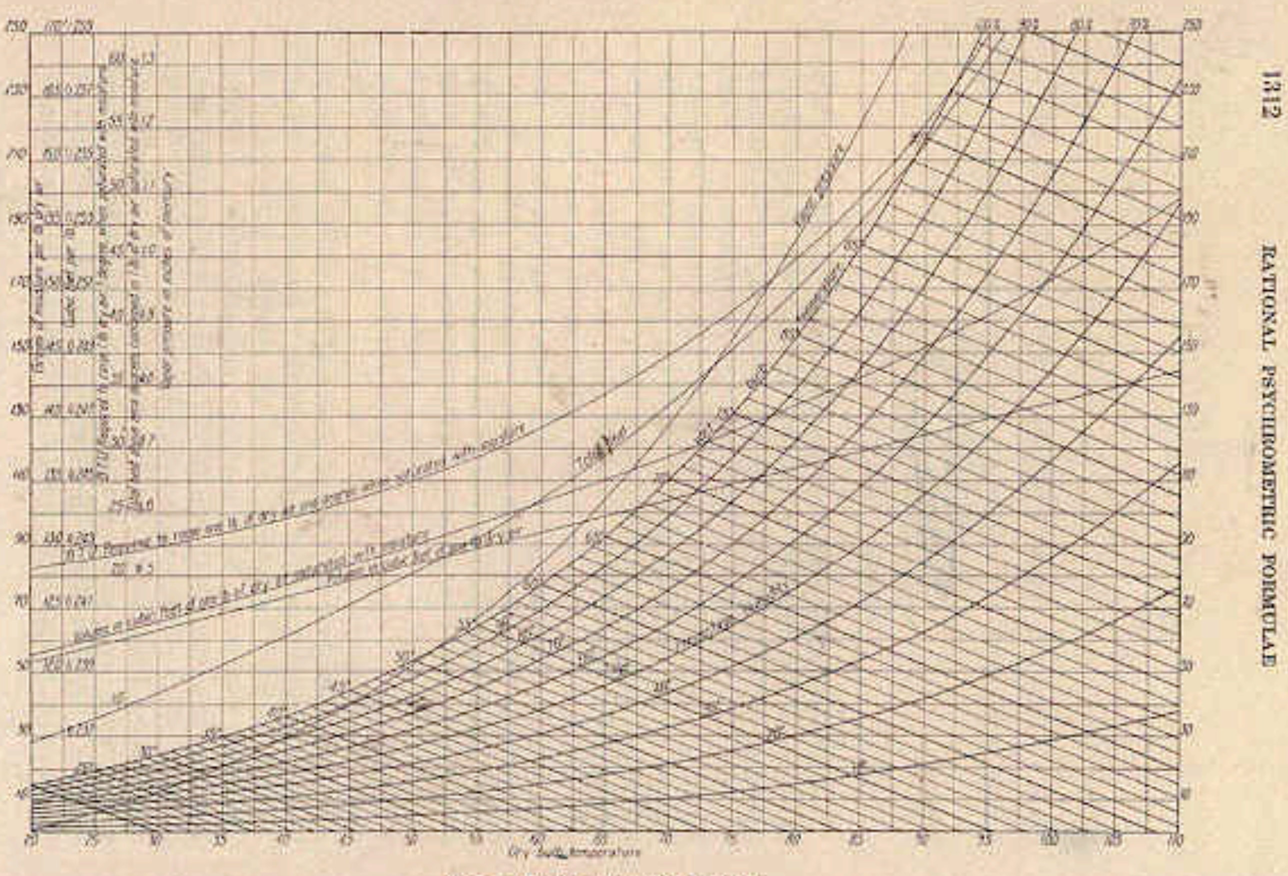

FIG. 1 PSYCHROMETRIC CHART

1312 RATIONAL PSYCHROMETRIC FORMULAE

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00468

RATIONAL PSYCHROMETRIC FORMULAE

THEIR RELATION TO THE PROBLEMS OF METEOROLOGY AND OF AIR CONDITIONING

By Willis H. Carrier

ABSTRACT OF PAPER

In many industries such as the manufacture of textiles, food products, high explosives, photographic films, tobacco, etc., regulation of the humidity of the atmosphere is of great importance. This paper deals with the subject of the artificial regulation of atmospheric moisture, technically known as air conditioning. It gives a theoretical discussion of the subject in which formulae are developed for the solution of problems. These formulae are based upon the most recently determined data and in order to establish a logical basis for the presentation of these data and the derivation of the formulae, the principles governing atmospheric moisture are reviewed and the present methods of determining atmospheric humidity are discussed.

Technical Paper 1: Rational Psychrometric Formulae, 1911
[The American Society of Mechanical Engineers]

00469 81/3
17

THE TEMPERATURES OF EVAPORATION OF WATER INTO AIR

AN EXPERIMENTAL DETERMINATION OF THE LAWS GOVERNING THE DEVIATION OF THE ACTUAL TEMPERATURE OF EVAPORATION FROM THE THEORETICAL

BY

W. H. CARRIER
MEM. A.S.M.E.

AND

DANIEL C. LINDSAY

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
29 WEST THIRTY-NINTH STREET, NEW YORK

Presented at the Annual Meeting of the Society, New York, December 1 to 4, 1924

The Society as a body is not responsible for the statements of facts or opinions advanced in papers or discussions (B2, Par. 3)

Technical Paper 2: The Temperatures of Evaporation of Water into Air, 1924 [American Society of Mechanical Engineers]

00465 13

Comparison of Thermodynamic Characteristics of Various Refrigerating Fluids

With Reference to Their Adaptability for Both Positive and Centrifugal Compression

W. H. CARRIER
and
R. W. WATERFILL,
Newark, N. J.

TECHNICAL
81/4
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Technical Paper 3: Comparison of Thermodynamic Characteristics of Various Refrigerating Fluid, 1924 [American Society of Refrigerating Engineers]

00453 81/5

1

Centrifugal Compression as Applied to Refrigeration

W. H. CARRIER
Newark, N. J.

Reprinted from February, 1926, number of REFRIGERATING ENGINEERING, *published by The American Society of Refrigerating Engineers, 35 Warren Street, New York, N. Y.*

The Society is not responsible for statements or opinions advanced in papers or discussions

Technical Paper 4: Centrifugal Compression as Applied to Refrigeration, 1926 [American Society of Refrigerating Engineers]

00456

4

Air Conditioning in the Printing and Lithographing Industry

By WILLIS H. CARRIER,[1] NEWARK, N. J., and ROBERT T. WILLIAMS,[2] NEW YORK, N. Y.

LIKE other key industries, the great printing and lithographing industry shows a distinct trend toward concentration. With this trend, and the consequent need for more careful technical control and greater standardization of product and process, has come an increased realization of the need for air conditioning in the printing and lithographing industry.

For 20 years or more air conditioning has played an important part in the textile industry, in the treatment and manufacture of tobacco products, in the production of high-grade confections, and in a long list of other industries dealing with materials that are affected adversely by seasonal and daily weather variations. The equipment therefore necessary automatically to create and control atmospheric conditions suitable to a given product or system has undergone long development and has entirely passed the experimental stage.

Even in the printing and lithographic industry, there are a number of important and progressive plants in the country that have had complete air-conditioning equipment for about 20 years. (See Fig. 1.) The wider use of air-conditioning equipment in the production of printed matter is therefore one of

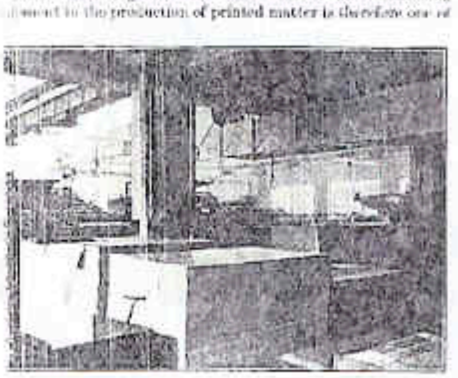

Fig. 1 Pressroom With Conditioning Ducts and Diffusers

the application of reliable and standard equipment to the particular needs of this industry.

The problem of air conditioning in printing and lithography resolves itself into reproducing in those parts of the plant where variations of humidity, temperature, cleanliness, and air circulation affect materials or processes, the natural atmospheric conditions that the trade has found by long experience give the best results. This involves the control of regain by such hygroscopic materials as paper and printers' rollers; the maintenance of a humidity sufficiently high to tend to prevent the formation of static electricity and sufficiently low to prevent "damped" rollers and paper; the maintenance of temperature at which ink has the required viscosity and flow and offers the right amount of "tack;" the elimination in so far as is economically practicable of floating dust, and the maintenance of suitable working conditions.

[1] President, Carrier Engineering Corp. Mem. A.S.M.E.
[2] Technical Engineer, Carrier Engineering Corp.

MOISTURE IN PAPER RELATED TO STRETCH AND SHRINKAGE

In so far as concerns the regain of moisture by paper, which is the most serious and obvious problem confronting the printer, this control is secured by maintaining throughout all parts of the plant where paper is used or stored a fixed relative humidity. Temperature has practically no effect upon paper, but its moisture content is a function of the relative humidity of the surrounding air, the amount varying for different grades of paper. (See Table 1.)

TABLE 1 EQUILIBRIUM MOISTURE CONTENT OF PAPERS UNDER VARIOUS CONDITIONS OF RELATIVE HUMIDITY

(From Bulletin No. 1, Lithographic Technical Foundation)

Kind of paper	Number of sheets	Relative humidity of atmosphere 35%	45%	55%	65%
Offset, %	18	4.04	5.08	6.06	7.00
Sized and super-calendered, %	9	3.58	4.13	5.30	6.17
Machine finished, %	1	3.48	4.30	5.52	6.24
Coated one side, %	10	3.30	4.45	5.37	6.27
Coated two sides, %	2	4.07	5.01	6.37	7.33
All kinds, %	40	3.91	4.79	5.75	6.71

(From Tests Made by C. D. Sadenwater, Cumberland Mills)

	Humidity 10%	20%	30%	40%	50%	60%	70%	80%	90%
Max. moisture, %	4.32	5.64	7.03	7.80	8.70	9.15	10.20	11.20	12.00
Min. moisture, %	2.00	2.30	3.42	4.72	5.26	5.85	6.32	7.22	8.27
Ave. moisture, %	2.87	4.12	5.07	5.82	6.38	7.31	8.09	9.63	10.38

This variation in the regain of paper with varying relative humidities exercises an important influence on printing and lithographic processes. The moisture content of paper affects its size. The amount of stretch or shrinkage varies with different stocks, but may be said to be from 0.214 to 0.55 per cent across the grain and from 0.056 to 0.25 per cent with the grain under a change in relative humidity of 35 to 65 per cent. When it is considered that the allowable variation in register in process presswork is rather under 0.02 in., or 0.045 per cent of a 44 by 64-in. sheet, it will be seen that certainly a variation of more than 5 per cent in the relative humidity of a pressroom will destroy register.

The center of a large pile of paper is under heavy pressure and is very nearly impenetrable. Even fire will not get to it. Moist air attacks the edges first, and the fibers swell. Not being able to stretch uniformly the stock stretches at the edges, which gives the sheet a curl or wave and makes it difficult or impossible to feed accurately. This also occurs when moist stock is piled in a dry atmosphere. The edges of paper will not curl or wave if the air is allowed to circulate uniformly over the whole surface of the individual sheets.

The moisture content of paper also seriously affects both its strength and printing quality, and these qualities are again in ratio to the relative humidity of the surrounding air.

Paper is ordinarily received from the mill with a moisture content of from 3 to 4 per cent, but inasmuch as this may be the equilibrium percentage corresponding to anywhere from 20 to 40 per cent relative humidity, depending upon the kind or make of paper, it is impossible to try to keep the atmosphere of the plant in equilibrium with the incoming stock. From every practical standpoint of operation and economy it is desirable to maintain a fixed relative humidity in the plant and to recondition the paper up to this point prior to running it on the presses.

PRINTERS' ROLLERS, HUMIDITY AND TEMPERATURE

Passing from paper to the other hygroscopic substances used by the printer there are the rollers and also the glues and pastes used in the bindery. Rollers, being made of glue and glycerin, are particularly sensitive to both moisture and temperature. Under fluctuating conditions they swell, shrink, and crack, the free glycerin sweats out, and they become distorted in shape. However, the rollers may be manufactured to function at any given

Technical Paper 5: Air Conditioning in the Printing and Lithographing Industry, 1929 [The American Society of Mechanical Engineers]

1929

00464

12

1

The Control of Humidity and Temperature as Applied to Manufacturing Processes and Human Comfort.

(Paper No. 324)

By Willis H. Carrier.[1]

The control of atmospheric conditions within an enclosure with reference to temperature, humidity, and cleanliness is termed "Air Conditioning."

The importance of this field of engineering has of late years become widely recognized, not only in engineering circles, but by the public at large. Perhaps this is best evidenced by the fact that the forthcoming edition of the Encyclopedia Britannica will contain a chapter devoted exclusively to air conditioning. Such chapters are already found in some of the leading engineering hand-books.

It has long been recognized that relative humidity is an important factor in the manufacture and processing of certain hygroscopic materials such as textiles. Since the normal relative humidity in textile factories is nearly always lower than that desired, various means have for many years been provided to increase the humidity by artificial means.

On the other hand, there are industries which require a definite and unvaried humidity so that at some periods the normal quantity of moisture in the air must be increased, and at other times lowered. Among such industries may be mentioned the manufacture of confectionery, the processing and weaving of artificial silk, and the printing and lithographing industry.

Other industries require not only a constant relative humidity, but also a fairly uniform temperature. An example of this is seen in the modern automatic wrapping machines, used for wrapping chewing gum, food products, confectionery, and machine made cigarettes, which require exact conditions of heat and moisture in order to function satisfactorily without frequent adjustments.

In the manufacturing and processing of most hygroscopic materials there is usually one or more stages in the process in which moisture has to be removed from the material. In all such products which are not in themselves soluble in water, this is usually accomplished by air drying.

In a very large portion of them, in order to avoid injury to the products which require temperature and humidity control, the rate of moisture removal must be controlled with accuracy in certain stages of the process, while at the end of the process of drying it may be extremely important to control with

1) Assisted by an Advisory Committee appointed by the American Society of Heating and Ventilating Engineers as follows:

Prof. A. C. Willard.	O. W. Armspach.	H. W. Ellis.
W. L. Fleisher.	H. P. Gant.	F. C. Houghten.
S. R. Lewis.	C. P. Yaglou.	L. A. Harding.
F. R. Still.		

Technical Paper 6: Control of Humidity and Temperature, 1929
[The American Society of Heating and Ventilating Engineers]

00455 3

A Review of Existing Psychrometric Data in Relation to Practical Engineering Problems

BY W. H. CARRIER,[1] NEWARK, N. J., AND C. O. MACKEY,[2] ITHACA, N. Y.

The authors review and correlate available psychrometric data, and discuss the application of these data to engineering problems. They analyze and correlate existing data with reference to deviations of observed wet-bulb temperatures from those of true adiabatic saturation. The paper also includes a tabulation of revised psychrometric values in accordance with the latest physical data with correction factors for all normal variations of barometric pressures. The authors make an analysis and give a demonstration of the proper method of employing the psychrometric heat function previously defined as the "total heat less the heat of the liquid," and afterward referred to in psychrometry as "total heat." For this function the authors offer the term "sigma function," to distinguish it from the enthalpy or true total heat which includes the heat of the liquid.

IN VIEW of the present wide employment of psychrometric data in various fields, and particularly in the field of air conditioning, and also in view of the fact that there have been numerous questions raised as to the limits of accuracy of existing data, it seems opportune to review and correlate, as far as possible, the past research in this field and to discuss the application of these data to engineering problems.

Objectives of Paper

First Objective. The analysis and correlation of existing data with reference to deviations of observed wet-bulb temperatures from those of true adiabatic saturation.

Second Objective. Presentation of a tabulation of revised psychrometric values in accordance with the latest physical data with correction factors for all normal variations of barometric pressures. The purpose of this is to permit the ready use of standard psychrometric data or charts for any other barometric pressure without involved calculations. The latter is a device that has long been needed and is of particular value in accurate calculation of test data.

Third Objective. An analysis and a demonstration of the proper method of employing the important and useful psychrometric heat function, previously defined by Carrier in 1911 (1),[3] as the "total heat less the heat of the liquid," and afterward referred to in psychrometry as "total heat." For this function will now be offered the term, the "sigma function" to distinguish it from the enthalpy or true total heat which includes the heat of the liquid.

Deviation of Observed Wet-Bulb Temperature From Temperature of Adiabatic Saturation

In the past 25 years, most of the engineering calculations involving humidity in air have been based on the psychrometric chart presented in 1911 by Carrier (1). The values given were based, not primarily, as many assume, on observed wet-bulb temperatures with a sling psychrometer, but on calculated values of adiabatic saturation. The paper (1) showed that experimentally the two values were in close agreement. However, test data presented in the original paper (1) in 1911 indicated two sources of deviation of the wet-bulb temperature from the temperature of adiabatic saturation. The first was the radiation factor which was indicated by the difference between the reading of an unshielded wet bulb and a wet bulb completely shielded from radiation, and the second was the difference between the reading of a radiation-shielded wet bulb and the observed temperature of adiabatic saturation, where the radiation-shielded wet bulb apparently gave the lower reading of the two. In view of the theory advanced, the latter variation was, however, thought at the time, to be due to an apparatus error.

Later observations conducted by Arnold (2) and by Dropkin (3) have shown the latter assumption to be incorrect and that it is not only possible, but in accordance with physical laws that the latter variation should exist. However, these two sources of deviation are in opposite directions tending to neutralize each other, and it has been proved that there is a definite air velocity where there is exact agreement between the wet bulb (not shielded from radiation) and the actual temperature of adiabatic saturation. Carrier's 1911 experiments (1) would indicate this velocity to be about 2000 fpm. Dropkin's test (3) would indicate it to be slightly over 1000 fpm. Arnold (2) would fix this velocity at about 500 fpm. Computations from his theory give a still lower value as shown in Appendix 1. The authors' present correlation would indicate it to be at an intermediate velocity

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[2] Professor of Heat-Power Engineering, Cornell University. Professor Mackey was graduated from Cornell in 1926 with the degree of M.E., and for the next two years served as instructor of experimental engineering at the University. He then was made assistant professor of heat-power engineering and three years later a full professor. He is the author of articles on psychrometric subjects for the American Society of Heating and Ventilating Engineers and the American Society of Refrigerating Engineers. He is a member of the scientific fraternities Sigma Xi and Tau Beta Pi.

Contributed by the Heat Transfer Committee of the Process Industries Division and presented at the Annual Meeting of The American Society of Mechanical Engineers, held in New York, N. Y., November 30 to December 4, 1936.

Discussion of this paper should be addressed to the Secretary, A.S.M.E., 29 West 39th Street, New York, N. Y., and will be accepted until February 10, 1937, for publication at a later date. Discussion received after the closing date will be returned.

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[3] Numbers in parentheses refer to the Bibliography at the end of the paper.

Technical Paper 7: A Review of Existing Psychrometric Data, 1936
[The American Society of Mechanical Engineers]

00454

2

PRO-58-2

The Contact-Mixture Analogy Applied to Heat Transfer With Mixtures of Air and Water Vapor

By W. H. CARRIER,[1] NEWARK, N. J.

The author derives and discusses the general contact-mixture formula for representing physical processes of heat transmission and fluid friction, and points out that the contact-mixture analogy serves directly and logically to correlate heat transfer with fluid friction. He compares the analogy with the conduction-viscosity theory and relates why the contact-mixture analogy explains all the phenomena connected with gas flow and heat transmission.

HERETOFORE in literature, it has been customary from the time of Reynolds to analyze heat transfer and resistance to flow of gases by using an analogy to the flow of viscous fluids. While this method can be made to give a fairly good correlation of the phenomena of heating and frictional resistance of gases it is not representative of the actual physical process, and it is not easily applied, for example, to condensing and evaporating of water vapor into air except by the application of another analogy. The author believes it to be quite in line with modern physical thought to state that there can be no such thing as shear in a gas and therefore there can be no true viscosity. Also, probably, there is no true conduction in a gas as in a solid but only diffusion of molecules continuously in motion.

Any gas is made up of molecules having different velocities, i.e., different temperatures. The energy of the molecule (i.e., the absolute temperature) varies directly as the square root of its molecular velocity. Therefore, the average temperature of a gas composed of molecules having different molecular velocities is the average of the square roots of their respective velocities. We do not know actually what occurs when a gas contacts with a surface at a different temperature. We do know, however, that molecules in contact with a hotter surface are heated, i.e., their molecular velocity is increased and these high-velocity molecules are diffused and are mixed with other molecules of the gas which have not been so contacted. Whether they retain their identity as high-velocity molecules (which is to be doubted) or whether they impart a portion of their surplus energy to the adjoining molecules, which do not contact the surface, is immaterial as far as any study on heat transmission is concerned. The average of the square roots of the velocity, i.e., the total energy is the same whether they retain their energy or whether they impart part of their increased energy to other molecules.

In the process of pure heat conduction in gases, there is no mechanical mixture or disturbance due to gravitational effect (convection) but only intermolecular diffusion, which depends upon the various permanent properties of the gas and its transient condition. The rate of heat diffusion, however, is found experimentally, to obey exactly the analogous laws of heat conduction, that is, it is directly proportional both to the distance and to the temperature difference between two boundaries. In a steady state of heat flow, there is a temperature gradient precisely as there is a temperature gradient in a solid, although in the first case, the temperature gradient is due solely to material transportation, while in the second case, it is due to the passage of heat from one molecule to another.

These rather obvious and elementary statements are made in the preface in order that there may be no misunderstanding of the basis on which the problem is approached.

When a gas is forced to pass over a surface at relatively high velocity, as for example, between plates or through a pipe, the main stream of air is turbulent above certain critical velocities. However, at all velocities there are two nonturbulent films. The first, which is probably ultramicroscopic or molecular in thickness, is necessarily a dense film of adsorbed gas having approximately the density of liquid or, as some physicists claim, even greater than that of the liquid. This would appear to be a rather permanent film. The second, is a film or zone in which there is a laminar flow as distinguished from a turbulent flow, i.e., all the particles are moving in parallel lines. There is no mechanical mixture within this film. Particles pass from the surface film through the laminar film only by diffusion and heat is conducted only by the process of diffusion, just as though there were no motion whatever within the film since the actual motion is at right angles to the effective path of molecular diffusion. In this film, warmed (contacted) particles pass outward by diffusion while cold (uncontacted) particles, and also previously contacted particles, diffuse inward from the outer surface of the laminar film to the surface film. There is no sharp demarcation between the laminar nonturbulent film and the outer turbulent body of air, but a gradual increase of turbulence. However, from the standpoint of analysis it is convenient to consider a line of sharp demarcation. The thickness of the adsorbed film does not change with the velocity. The thickness of the laminar film, however, varies directly with the velocity and at a somewhat lower rate, i.e., at a fractional power of the velocity.

There is a definite temperature gradient in this laminar film

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Technical Paper 8: The Contact-Mixture Analogy, 1936
[The American Society of Mechanical Engineers]

00455 3

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Technical Paper 9: A Review of Existing Psychrometric Data, 1936
[The American Society of Mechanical Engineers]

THE INVENTION OF

THE CENTRIFUGAL REFRIGERATING MACHINE

"PROPOSED" SCRIPT FOR A TAPE RECORDING

FOR THE SMITHSONIAN INSTITUTION

PLUS A COMPLETE HISTORICAL SKETCH

When the Smithsonian decided to display the compressor of the Original Centrifugal Machine, it requested a tape recording for the Archives. This type of description would institute a new practice, and consequently, there were no definite ideas about what it should be. To write the script was the original objective--but, as the story was developed by research and thought, it became increasingly evident that a complete coverage would be too long for an oral presentation.

There was entirely too much substance to the story for it to be left half told: The invention had projected a revolutionary development into the art of refrigeration; it had given a tremendous impetus to the development of air conditioning. The story had to depend too much upon memories that were fading rapidly with age; and it had to draw a clear distinction between the Centrifugal Compressor that would constitute the sole exhibit and an entirely new method of refrigeration in which the compressor was only one of numerous functional elements.

This led to a plan by which one document could be made to serve two purposes: One was to provide an abridged version for the oral presentation, and the other was to provide a complete and well-rounded Historical Sketch for the studious reader and the Archives.

The division between short and long could be shown by the style of typing. The short would be double-spaced in full-length lines; and the long would consist of the short plus all that was single-spaced and indented. With a little extra effort, good contunity could be maintained and the reader could be given a free choice according to time and interest.

The idea may have had some merit; but as research brought more and more facts to light, length got more and more out of hand. The upshot was a complete change of plan: An appropriate history would be written in the original short-long style, divided into chapters, and reinforced with some last minute illustrations--and the script for the tape could come later.

The author is not too happy about the length of the current edition (about 7500 words for the short, and 10,000 for the long); but he does feel that justice to the story has been reasonably well done.

Logan Lewis
March 1, 1962