

A STUDY OF THE EFFECT OF AIR VELOCITY
AND TEMPERATURE ON GROUND BEEF

Thesis for the Degree of M. A.
MICHIGAN STATE UNIVERSITY
John B. Lough, Jr.

1958



A STUDY OF THE EFFECT OF AIR VELOCITY
AND TEMPERATURE ON GROUND BEEF

by

John B. Lough, Jr.

A Thesis

Submitted to the College of Business and Public
Service, Michigan State University
in partial fulfillment of the
requirements for the
degree of

MASTER OF ARTS

School of Hotel, Restaurant and
Institutional Management

1958

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
Problem	4
Statement of the problem	5
Delimitations	5
Hypotheses	6
Definitions of terms	6
Review of Literature on Heat Transfer	8
Methods of heat transfer	8
Insulating layer	9
Newton's law of cooling and heating	11
Boltzman's fourth power law	11
Organization of the Remainder of the Thesis	14
II. FACTORS AFFECTING THE RATE OF DEFROSTING	15
Composition of the Specimen	16
The Size and Shape of the Specimen	17
Temperature of the Air Around the Specimen	19
Velocity of the Air Past the Specimen	19
Amount of Surface Dehydration of the Specimen	20
Relative Humidity of the Air Surrounding the Specimen	21
Initial Temperature of the Specimen	23
Final Defrosted Temperature of the Specimen	24

CHAPTER	PAGE
Placement of the Thermocouple	24
Summary	24
III. APPARATUS AND METHODOLOGY	25
The Wind Tunnel	25
Computing Air Velocity in the Test Chamber . .	31
Number of Replications of Each Test	38
Testing Procedure	39
Summary	40
IV. DATA AND DISCUSSION OF RESULTS	41
Defrosting at 71 Degrees Fahrenheit	43
Time-temperature relationship	43
Typical defrosting curves	43
The rates of defrosting for all specimens	
defrosted at 71 degrees Fahrenheit	47
Number of minutes needed to defrost	
specimens at 71 degrees Fahrenheit	50
Defrosting at 81 Degrees Fahrenheit	53
Typical defrosting curves	53
The rates of defrosting for all specimens	
defrosted at 81 degrees Fahrenheit	56
Number of minutes needed to defrost	
specimens at 81 degrees Fahrenheit	60
Comparing Rates of Defrosting at 71 Degrees	
Fahrenheit to the Rates of Defrosting at	
81 Degrees Fahrenheit	63

CHAPTER	PAGE
Optimum Air Velocity	67
Moisture Loss During Defrosting	67
Summary	77
V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS . . .	78
Summary	78
Conclusions	80
Recommendations	81
SELECTED BIBLIOGRAPHY	83

LIST OF TABLES

TABLE	PAGE
I. Air Velocities in Wind Tunnel	33
II. Rates of Defrosting at Various Air Velocities in an Air Temperature of 71 Degrees Fahrenheit	48
III. Average Rates of Defrosting at 71 Degrees Fahrenheit and Rate Differentials Between Sequential Air Velocities	49
IV. Average Defrosting Times at 71 Degrees Fahrenheit and Time Differential Between Sequential Air Velocities	52
V. Rates of Defrosting at Various Air Velocities in an Air Temperature of 81 Degrees Fahrenheit	57
VI. Average Rates of Defrosting at 81 Degrees Fahrenheit and Rate Differentials Between Sequential Air Velocities	59
VII. Average Defrosting Times at 81 Degrees Fahrenheit and Time Differentials Between Sequential Air Velocities	62
VIII. Comparing the Rates of Defrosting at Two Defrosting Temperatures	65
IX. Comparing the Defrosting Times at Two Defrosting Temperatures	69

TABLES

PAGE

X.	Average Moisture Change During Defrosting at Various Air Velocities with an Air Temperature of 71 Degrees Fahrenheit	72
XI.	Average Moisture Change During Defrosting at Various Air Velocities with an Air Temperature of 81 Degrees Fahrenheit	73

LIST OF FIGURES

FIGURE	PAGE
1. Dispersing of the Stagnant Layer by Increased Air Velocity	12
2. Sealright Container With Lid and Meat Specimen. .	18
3. Test Chamber Showing Hygrometer and Meat Specimen	22
4. Diagram of Wind Tunnel	27
5. Motor, Fan Box and Shutter	29
6. Air Velocity Meter in Plexiglass Pipe	30
7. Bunsen Burner Arrangement for Temperature Control	34
8. Ice Bin Arrangement for Temperature Control . . .	35
9. Brown Electronik Recorder	36
10. Complete Wind Tunnel System in Operation	37
11. Representative Time-Temperature Graph, Defrosting at 71 Degrees Fahrenheit	46
12. Representative Time-Temperature Graph, Defrosting at 31 Degrees Fahrenheit	55
13. Rates of Defrosting	68
14. Average Defrosting Time	70
15. Per Cent Moisture Change When Defrosting at 71 Degrees Fahrenheit	75
16. Per Cent Moisture Change When Defrosting at 81 Degrees Fahrenheit	76

ACKNOWLEDGMENTS

Although the bibliography indicates many of the sources of information, such a device cannot do justice to all those persons who have been instrumental in guiding the thought that went into this project.

The author wishes to express his sincere thanks to Dr. J. Leon Newcomer for his inspirational supervision and continued ready help in this investigation. He also wishes to thank Doctors R. D. Wilson, and S. E. Thompson for their suggestions and cooperation throughout this endeavor.

The writer expresses his appreciation to Professor L. J. Bratzler of the Department of Animal Husbandry for his guidance and for making equipment and facilities available for this study.

CHAPTER I

INTRODUCTION

Through the years many methods have been used to preserve meats. A few of the preservation methods used are drying, canning, irradiating, freezing and freeze-drying.

Canned and canned irradiated meats are cooked, and thereby are limited in the number of ways they can be prepared for the table. Flavor changes may also take place in the canning process, more than in the freezing process, which may make meats prepared in this manner somewhat less acceptable.

Dried meats go through physical changes which affect their ability to be reconstituted to their original volume. Also, with air-dried meats there is extensive protein denaturation, the texture is tough and dry, the color is darker, the odor and flavor are frequently¹ abnormal.

Freeze-dried meats have a higher acceptability than² the conventionally air-dried meats, but the process is expensive. The cost is sixteen to twenty-four cents per

¹
H. Wang and others, "A Histological and Histochemical Study of Beef Dehydration, IV, Characteristics of Muscle Tissue Dehydration by Freeze-Drying Techniques," Food Research, 19:543-545, June, 1954.

²
Ibid.

pound of water removed compared to two to seven cents per pound of water removed by the air-dried method. This makes it impractical unless a reduction in weight is necessary for shipping, or because there is a lack of refrigerated storage space.³

Of the above mentioned preserving methods, freezing is probably the most widely used and most practical today. For centuries cooks have been aware of the significance of chilling meat to preserve it, but only for the past twenty years have they been aware of the tremendous potentialities in freezing meat. The nutritive value of properly frozen meat is nearly equal to that of fresh meat. Frozen meats have substantially the same mineral, protein and vitamin content.⁴

One disadvantage of frozen meats is that more heat is needed to bring them to the final state of doneness. The transfer of heat may be accomplished by a variety of methods. The item can be defrosted slowly in a refrigerator at approximately 40 degrees Fahrenheit. The slow defrost method is used with the thought that slow defrosting gives the meat fibers a chance to absorb some of the

³ Tischer, R. G., Brockmann, M. C., "Freeze-Drying Ups Quality of Q. M. Quick-Serve Rations", Food Engineering, 30:110-112, January, 1958.

⁴ "Freezing Foods", The Wise Encyclopedia of Cookery, (New York: Wm. H. Wise and Co., Inc., 1954), p. 489.

drip that comes from the thawed meat. The absorption of drip depends more on the temperature at which the meat was frozen rather than the rate of defrosting.⁵

Meat may be defrosted by more rapid means such as exposure to air at room temperature (approximately 72 degrees Fahrenheit) or temperature higher than room temperature, as in a warming oven. Meat is sometimes thawed in water since it conducts heat more rapidly than air. Cuts defrosted in water may gain weight and the natural meat juices become diluted.⁶ Defrosting ground beef, with its many cut surfaces, in water would provide an excellent opportunity for water to dilute the natural meat juices, washing away much of the flavor and nutritive value.

Another rapid method of defrosting is to cook the meat directly from the frozen state by such methods as roasting, braising, frying or broiling.

One of the methods of defrosting at temperatures below those which would cook the meat is by the use of forced convection of air within a satisfactory temperature range.

⁵ Lowe, Belle, Experimental Cookery. (fourth edition: New York: John Wiley & Sons, Inc., 1955), p. 105.

⁶ Ibid., p. 103.

THE PROBLEM

It is probable that commercial meat freezing began in New Zealand for the purpose of keeping mutton in good condition during transportation to England. As long ago as 1891 New Zealand shipped 2,153,000 mutton carcasses.

Today there are 21 million cu. ft. of storage space in meat packing plants in the United States plus many more million cubic feet of storage space for frozen vegetables, fruits, and prepared foods.⁷ Defrosting of the millions of pounds of frozen foods is an important process.

Quick freezing of meat is done by several methods today. The product can be frozen by direct immersion in a refrigerating medium, by indirect contact with a refrigerant by placing the product on a metal surface cooled by refrigerating media, and also by freezing in a blast of cold air. The old method of air freezing has been improved by rapidly circulating the air, which brought this method out of the slow freezing class into the quick freezing class. There are numerous types of airblast freezers operating with air velocities ranging all the way from 100 feet per minute up to 3500 feet per minute.

⁷ Donald K. Tressler, Clifford F. Evers, The Freezing Preservation of Foods, (Westport, Conn.: The AVI Publishing Company, 1957), p. 88.

Air blast or forced convection freezing is probably⁸ the most common method used today. However, little work has been completed on the use of forced convection for defrosting meat. This study has been done in an effort to investigate the defrosting of meat by forced convection.

Statement of the problem. The purpose of this study was to determine the rate of defrosting of ground beef at varying air velocities and temperatures. The objectives of the study were threefold: (1) to determine the effect of different air velocities at constant temperatures on the rate of defrosting ground beef; (2) to determine the effect of varying air temperatures at a constant air velocity on the rate of defrosting ground beef; (3) to determine an optimum air velocity, within the air velocities studied, if the rate of defrosting is found to be influenced by air velocity.

Delimitations. The scope of this study was limited to fourteen defrosting tests and at least two replications of each test. The meat specimens used for defrosting were one pound ground beef specimens having a uniform composition of 60.6 per cent moisture, 13.8 per cent fat, and 25.6 per cent muscle fiber and connective tissue. The

⁸

Ibid., p. 121.

specimens were defrosted in still air and six air velocities from 100 f.p.m. to 600 f.p.m. by 100 f.p.m. increments and two air temperatures of 71 to 72 degrees Fahrenheit and 81 to 82 degrees Fahrenheit.

Any conclusions drawn from this work would be valid only when applied to defrosting the same kind of meat under the same conditions, although implications can be made of the rate of temperature change applied to other types of meat and frozen products.

Hypotheses. Three hypotheses were the basis for making this study: (1) that forced convection does increase the rate of defrosting frozen ground beef; (2) that higher temperatures of the air surrounding the meat increase the rate of defrosting; (3) that an optimum air velocity exists within the air velocities studied.

Definitions of terms. To clarify terms in order that there will be no misunderstanding, these terms will be used as follows throughout this study:

Defrost. To raise the temperature above the frozen point. In this work the word defrost is used to mean the changing of temperature in the meat specimen from +2.0 degrees Fahrenheit to +34.0 degrees Fahrenheit.

Rate of defrost. In this study the rate of defrost is the temperature change per unit of time having the dimensions of degrees Fahrenheit per minute.

Still air. The term "still air" applies to a condition surrounding the specimen where the air currents occurring are by natural convection and not due to forced convection.

Thermocouple. A thermocouple is a device consisting of two dissimilar metals joined at one end and the other ends connected to a millivolt meter. The millivolt meter indicates a change in voltage generated within the circuit when the joined ends are subjected to different temperatures. The millivolt meter is calibrated in temperature.

Defrosting meat. Water changes from the solid state to the liquid state at 32 degrees Fahrenheit. The water in beef contains dissolved minerals and salts which lower the freezing point to about 28 degrees Fahrenheit.

To defrost meat, heat must be transferred to the meat to raise the temperature above 28 degrees Fahrenheit in order to change the state of the water in meat from the solid to the liquid state.

⁹
Statement by Lymon J. Bratzler, Professor of Animal Husbandry, Michigan State University, interview.

REVIEW OF LITERATURE ON HEAT TRANSFER

The preliminary search of literature revealed no studies having a direct relation to the rates of defrosting meats. Defrosting of meats involves a transfer of heat from the material surrounding the meat to the meat. The inclusion of a review of heat transfer is important to any study on defrosting of meat.

Methods of heat transfer. Heat energy may be transferred by conduction, convection, and by radiation. They are defined as follows:

Conduction is the transfer of heat from one particle of matter to another, the particles being fixed in position relative to each other.

Convection is the transfer of heat from one part of fluid to another by the mixing of the warmer particle of the fluid with the cooler. Motion in the fluid caused by difference in density within the fluid is called natural convection. If the motion of the fluid is caused by some mechanical means such as a stirrer, pump, or fan, it is called forced convection.

Radiation is the transfer of heat from one body to another as a result of the bodies emitting and absorbing a form of energy called radiant energy.¹⁰

10

H. J. Stoevers, Applied Heat Transmission, (New York: McGraw-Hill Book Company, Inc., 1941), p. 39.

The defrosting of frozen meat to the point where it is workable is a matter of transferring heat to the meat from the surrounding medium.

Heat transfer takes time and energy. It has been shown that heat transfer by convection will take place at an increased rate if the heating fluid is put in motion around the object by a fan or pump.¹¹

Insulating layer. Brown and Marco report that much of the resistance to heat transfer by convection is caused by an insulating layer of air through which heat must pass. Their explanation is:

From the work of investigators in the fields both of fluid flow and of heat transfer, the concept has developed that when a fluid flows over a surface, as in the case where air is flowing along a wall (whether in streamline or in turbulent flow) a stagnant film adheres to the surface and acts as a heat insulator. Experiments in recent years have shown the actual existence of such a film, although it is found to be not entirely stagnant. In fact where the main fluid stream is moving at a velocity in the range of turbulent flow, the film itself may be divided into two layers: the first composed of particles completely without motion adhering to the surface and particles creeping along in streamline flow with increasing velocity as the distance from the surface is increased; and the second layer, much thicker than the first, being a transition zone composed of eddy currents moving at a higher velocity although not so swiftly as the main portion of the fluid stream. The boundary between these two layers is not sharply defined.

¹¹

Ibid., p. 1.

No attempt is ordinarily made to measure the thickness of the film, which may be immeasurably thin or several hundredths of an inch in thickness, but in the study of heat transfer it may be visualized as a barrier to the flow of heat, a barrier that adheres to the surface but is partially wiped off and accordingly reduced in effectiveness as the velocity of the fluid is increased.

In the process of heat transfer by convection, heat is transferred really by conduction through the stagnant portion of the film and is then transferred to the moving particles and carried away by convection currents into the main portion of the fluid stream.¹²

Another explanation of the effect of the insulating layer given by Henderson and Perry is as follows:

Much of the resistance to heat transfer by convection is found in the layer of fluid, in laminar flow without mixing, moving adjacent to the surface. Heat is transferred through this layer only by conduction. The surface conductance can be thought of as the conductance of a layer, having the conductivity of the fluid. The conductance can be increased by reducing the thickness of the laminar layer by more vigorous agitation, more active thermal circulation, or by operation at higher Reynolds-number values.¹³

Figure 1 shows in diagram form the laminar or stagnant layer of air at the surface of a solid.

12

Aubrey I. Brown, Salvatore M. Marco, Introduction to Heat Transfer, (New York: McGraw-Hill Book Company, Inc., 1951), pp. 83-84.

13

S. M. Henderson, R. L. Perry, Agricultural Process Engineering, (New York: John Wiley and Sons, Inc., 1955), p. 225.

Newton's law of cooling and heating. Newton's law of cooling and heating states that the rate of heat transfer is directly proportional to the difference in temperature between the two substances.¹⁴ Figure 1 shows how moving air, by dispersing much of the stagnant layer and bringing the warm air close to the specimen, increases¹⁵ the temperature difference between the two substances.

Since heat is transferred by radiation and conduction as well as by convection, these two items were considered in planning the study.

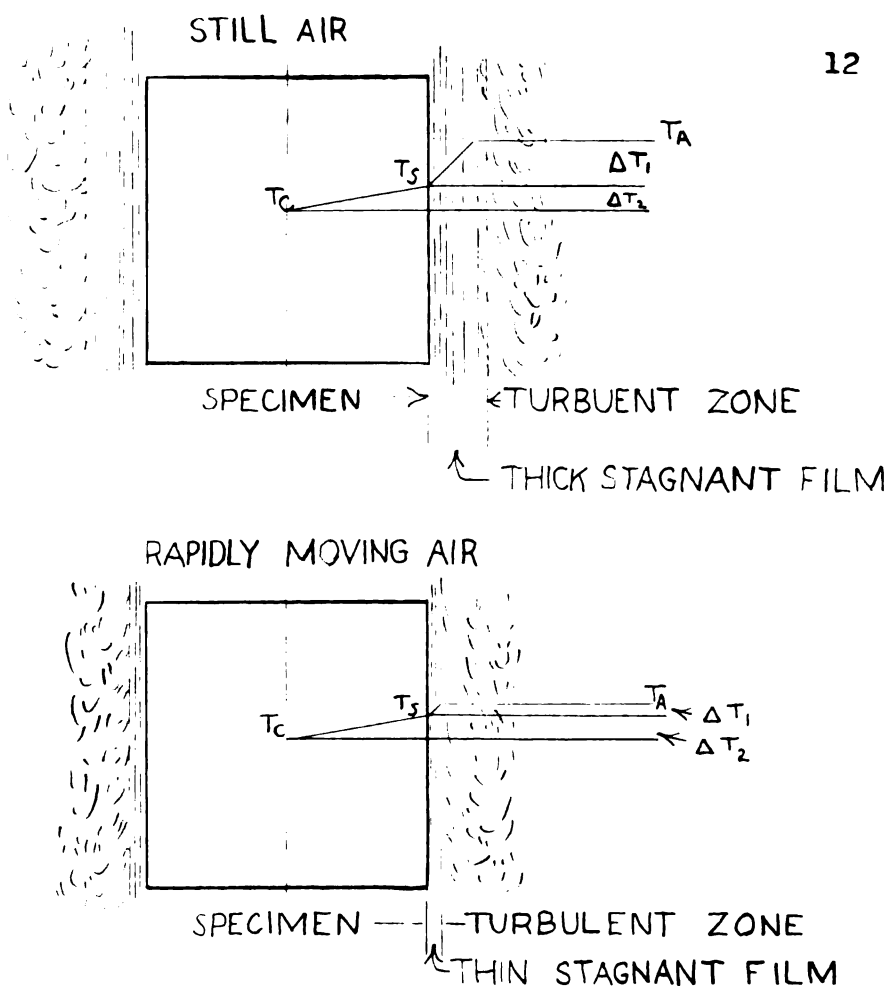
Boltzman's fourth-power law. This law states that the heat transfer rate by radiation is a function of the difference between the fourth power of the source temperature (in degrees Kelvin) and the fourth power of the temperature of the absorber (in degrees Kelvin).¹⁶ At the low temperatures encountered in this work, the effects of radiation are negligible and need not be considered.¹⁷

¹⁴ Archie G. Worthing, David Halliday, Heat, (New York: John Wiley and Sons, Inc., 1948), p. 442-43.

¹⁵ Henderson and Perry, loc. cit.

¹⁶ Worthing and Halliday, op. cit., pp. 438-39.

¹⁷ Statement by Dr. J. Leon Newcomer, Director, Food Service Industry Research Center Laboratory, Michigan State University, personal interview.



T_A = TEMPERATURE OF THE AIR

T_S = TEMPERATURE AT SPECIMEN'S SURFACE

T_C = TEMPERATURE AT SPECIMEN'S CENTER

$\Delta T_1 = (T_A - T_S)$ = DIFFERENCE BETWEEN AIR TEMPERATURE AND SURFACE TEMPERATURE

$\Delta T_2 = (T_S - T_C)$ = DIFFERENCE BETWEEN SURFACE TEMPERATURE AND CENTER TEMPERATURE

$\frac{dH}{dt}$ = CHANGE IN HEAT TRANSFER WITH RESPECT TO TIME

$$\frac{dH}{dt} = T_S - T_C$$

$(T_S - T_C) \text{ MOVING AIR} > (T_S - T_C) \text{ STILL AIR}$

$\therefore \frac{dH}{dt} \text{ FOR MOVING AIR} > \frac{dH}{dt} \text{ FOR STILL AIR}$

FIGURE 1 18

THE AIR CONDITIONS SURROUNDING A MEAT SPECIMEN UNDER STILL AIR AND FORCED CONVECTION CONDITIONS

The experimental equipment was designed to minimize direct contact between the meat specimen and the bodies at higher temperatures. Therefore, heat transfer by conduction can be safely ignored.

In consideration of these precautions the principal mode of heat transfer between the air and the test specimens was limited to convection.

ORGANIZATION OF THE REMAINDER OF THE THESIS

Chapter I has introduced the problem and stated the delimitations of the study. A review of literature as it pertains to defrosting meat by forced convection is also contained in the first chapter.

The remainder of the thesis has been arranged into four parts. Chapter II has been devoted to a review of the factors that influence the rate of heat transfer when defrosting meat by forced convection. Chapter III deals with the apparatus used in defrosting the meat specimens and the methodology of conducting the tests. Chapter IV is a presentation and discussion of the results of the defrosting tests. The final chapter contains a summary of the entire study, conclusions drawn from the author's investigations, and his recommendations.

CHAPTER II

FACTORS AFFECTING THE RATE OF DEFROSTING GROUND BEEF

Ground beef was used in this study because it was reasonably priced, readily available, it was possible to get a uniform specimen, and because it is a product that is widely used.

Ground beef is usually defrosted completely before cooking is started because it frequently has other ingredients mixed with it to form a finished product such as meat loaf or meat balls. The meat must be completely defrosted so that a uniform mixture with the other ingredients may be obtained. Defrosting at temperatures above 150 degrees Fahrenheit would probably cook the surface before the center of the meat became soft enough to mix with the other ingredients. Therefore a rapid method of defrosting at relatively low temperatures is necessary.

The study was concerned with studying the effect of different air velocities at given temperatures on the rate of defrosting meats. Other factors also influence the rate of defrosting. It therefore becomes necessary to establish conditions whereby all factors except air velocity and air temperature could be maintained constant.

The rate of defrosting was assumed to be influenced by eight variables: (1) composition of the specimen; (2) size and shape of the specimen; (3) temperature of the air around the specimen; (4) velocity of the air past the specimen; (5) amount of surface dehydration of the specimen; (6) relative humidity in the air surrounding the specimen; (7) initial temperature of the specimen; and (8) final defrosted temperature of the specimen.

Composition of the specimen. A study of the effect of fat and moisture on the freezing of beef revealed that beef with a high percentage of water and a low percentage of fat required more time to freeze than beef with a lower percentage of moisture and a higher percentage of fat. Since it is the water that changes state from liquid to solid when meat is frozen, it is assumed that more time is needed to change the state of a larger amount of water¹⁹ when all other conditions are constant.

Freezing of meat involves the transfer of heat from the meat to the surroundings of the meat. It was assumed that the rate of defrosting might also be influenced by the composition of the specimen. To obviate this possibility, ground sirloin butt having a uniform composition of 60.6

Q. H. Tucker, "The Effect of Fat and Moisture on the Freezing of Beef" (unpublished Master's thesis, Michigan State University, East Lansing, 1943).

per cent moisture, 13.8 per cent fat, and 25.6 per cent muscle fiber and connective tissue was used.

The size and shape of the specimen. The rate of defrosting involves a time-temperature relationship. More time would be required for a specified amount of heat to penetrate to the center of a larger specimen than for a smaller one. Therefore it was necessary to adopt a constant size and shape for all specimens.

Too small a specimen would lead to a short defrosting time which might cause time measuring errors. If the specimens are large, an unnecessarily long time is required to obtain data. Furthermore, it would have been unnecessarily wasteful to use a very large specimen of meat.

Preliminary experiments indicated that a size that met the above requirements satisfactorily was a cylinder approximately three and one half inches long by three and one half inches in diameter. A one pint, cylindrical, fiber ice cream container was found to have these dimensions. Each container held one pound of ground beef. Figure 2 shows a container and meat specimen.

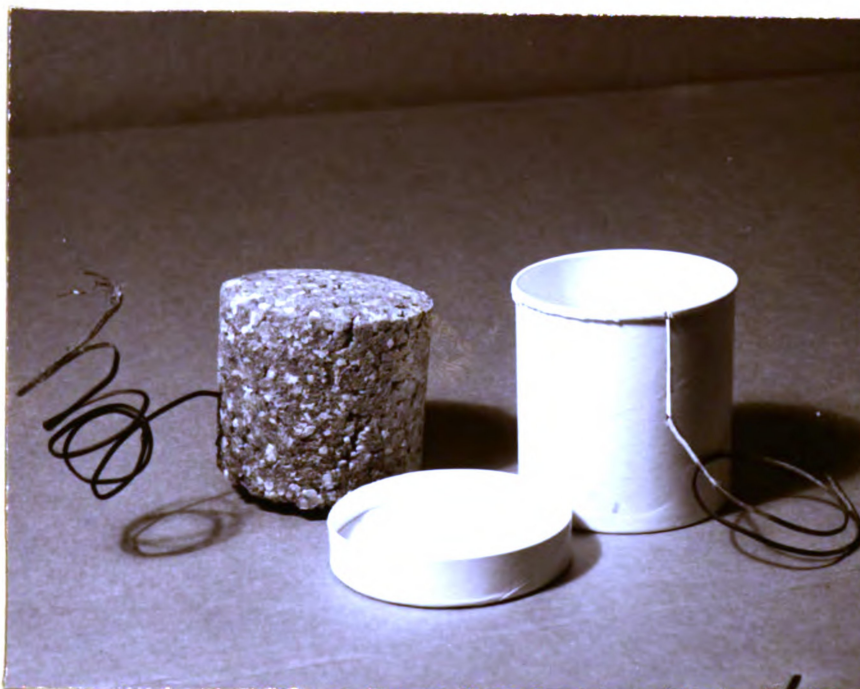


FIGURE 2
CONTAINER, COVER, AND MEAT SPECIMEN
WITH THERMOCOUPLE EMBEDDED

Temperature of the air around the specimen.

Newton's law of cooling and heating states that the rate of heat transfer is directly proportional to the difference²⁰ in the temperature of the two substances. If air temperatures were not held constant the change in rate of heat transfer would not be due to a change in the air velocity alone.

In this study, the air temperatures were controlled between 71 and 72 degrees Fahrenheit and between 81 and 82 degrees Fahrenheit.

Velocity of the air past the specimen. A basic engineering principle states that the main resistance to heat transfer is found in a relatively stagnant laminar layer and an adjacent turbulent zone at the fluid solid interface. As the velocity of the heating fluid is increased the more it disperses this laminar layer. When this laminar or insulating layer of air is reduced in thickness, the temperature difference between the specimen²¹ and the main body of heating fluid becomes greater. This greater difference in temperature between the two

²⁰

Archie G. Worthing, David Halliday, Heat, (New York: John Wiley and Sons, Inc., 1948), p. 442-43.

²¹

S. M. Henderson, R. L. Perry, Agricultural Process Engineering, (New York: John Wiley and Sons, Inc., 1955), p. 225.

substances provides for a greater rate of heat transfer as explained by Newton's law of cooling and heating.

Before collecting data, preliminary tests using still air, and tests at 100, 300, 500, 700, and 900 feet per minute were made to determine the air velocities at which to work.

Air velocities above 600 feet per minute continued to give an increase in rate of defrosting, but the increase became less and less with each increment in air velocity. It was decided to limit the study to air velocities from still air to 600 feet per minute, since this was the range where the greatest difference in defrosting time took place.

Amount of surface dehydration of the specimen. The dry muscle fibers on the surface of a sample form an insulating layer and impede the transfer of heat from the air to interior of the meat specimen. It was assumed that the degree of surface moisture might influence the rate of heat transfer.

The procurement schedule for the meat used in these tests was arranged so that it would not remain in frozen storage more than twenty days and thereby limit the amount of surface dehydration because of a long storage period.

Another feature of the fiber containers was that they were plastic lined and formed a more air proof

container than plain cardboard. It was assumed that the plastic lined containers helped to reduce the amount of surface dehydration.

Relative humidity of the air surrounding the specimen. It was suspected before any tests were run that relative humidity would affect the rate of defrosting. An attempt was made to control the relative humidity of the air within the test chamber by placing an open vessel of water in the test chamber. This was ineffective since even in the presence of the water, relative humidity varied between eighteen and one hundred per cent.

The relative humidity in the test chamber was indicated by a hygrometer as is shown in Figure 3. The relative humidity was recorded and a rank correlation run by the Spearman coefficient of correlation.²² There was a positive correlation of .178 when defrosting at 71 to 72 degrees Fahrenheit, and a positive correlation of .429 at 81 to 82 degrees Fahrenheit.

It appears from these two positive correlations, even though slight, that meat might tend to defrost faster at higher relative humidities.

22

H. C. Fryer, Elements of Statistics (New York: John Wiley and Sons, Inc., 1954), pp. 226-27.

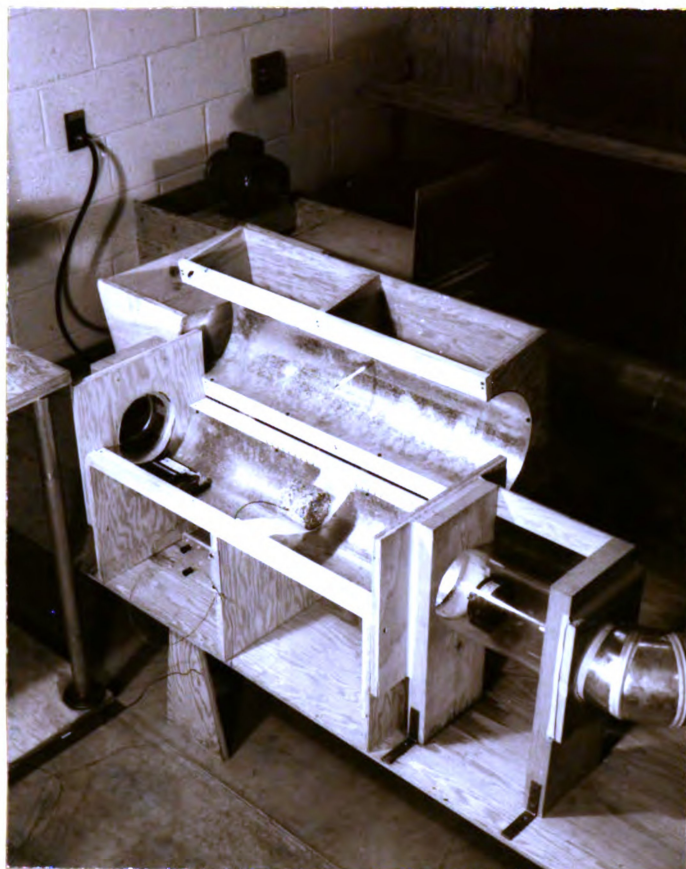


FIGURE 3
TEST CHAMBER SHOWING HYGROMETER
AND MEAT SPECIMEN

Spearman's coefficient of correlation is arrived at by the formula $r_s = 1 - \frac{6\sum(D^2)}{n(n^2-1)}$. The rates of defrosting at a given air velocity were given ranks. One for the fastest rate, two for the next fastest and so on. The relative humidities for the corresponding rates of defrosting were ranked in the same manner. One for the highest relative humidity for a given temperature and air velocity.

D = the difference between these two ranks.

n = the number of times that particular test was performed.

Initial temperature of the specimen. Referring again to Newton's law of cooling and heating, the rate of heat transfer is directly proportional to the difference in temperature of the two substances.²³ This being the case, it was necessary to start each test with the same difference in temperatures. The temperature in the defrosting chamber was established before each test and held within one degree Fahrenheit above that temperature throughout the test.

The meat specimens were kept in a freezer at minus three degrees Fahrenheit. Timing of the defrosting period was started when the center temperature of the sample reached plus two degrees Fahrenheit.

Final defrosted temperature of the specimen. The specimens in all tests were considered defrosted when the center reached a plus 34 degrees Fahrenheit. This temperature gave a margin of six degrees above the 28 degrees Fahrenheit where meat is normally considered defrosted.

Placement of the thermocouple. The distance from the surface of the specimen to the position of the thermocouple junction was critical. The accuracy of this experiment depended upon the accurate determination of the geometric center of the specimen. To accomplish this, the mold was half filled with ground beef, the thermocouple placed through a slot in the side of the container and centered according to a template. Ground beef was then placed gently over the thermocouple until the one pound desired weight was reached. The meat was tamped lightly to press out any entrapped air.

Summary. Chapter II discusses eight variables assumed to influence the rate of defrosting meat. They are: (1) composition of the specimen; (2) size and shape of the specimen; (3) temperature of the air around the specimen; (4) velocity of the air past the specimen; (5) amount of surface dehydration of the specimen; (6) relative humidity of the air surrounding the specimen; (7) initial temperature of the specimen; and, (8) final defrosted temperature

of the specimen. It was brought out that controls were put on these factors so that they would be held as constant as possible allowing only air velocity and air temperature to be varied.

Also mentioned in Chapter II was the necessity for accurate placement of the thermocouple at the center of the specimen to help insure precise recording of the center temperature during defrosting.

CHAPTER III

APPARATUS AND METHODOLOGY

Chapter III is a discussion of two phases of the development of this study. They are: (1) description of the wind tunnel, and (2) discussion of the methodology.

The eight factors discussed in Chapter II made it necessary to construct apparatus that would hold these variables constant. To do this a wind tunnel was designed to provide controlled air velocity and air temperature so that the meat specimens could be defrosted at a constant temperature with a variety of air velocities and at a constant air velocity at two different air temperatures.

It was necessary to compute the air velocity in the test chamber. The method for doing this is also shown in Chapter III.

A discussion of the testing procedure used in collecting the data is presented in this chapter.

The wind tunnel. A wind tunnel was designed to provide independently controlled air temperatures and air velocities. The system consisted of a blower, defrosting chamber, air velocity meter, air heating and cooling devices, assembled into a closed wind tunnel arrangement. A diagram is shown in Figure 4.

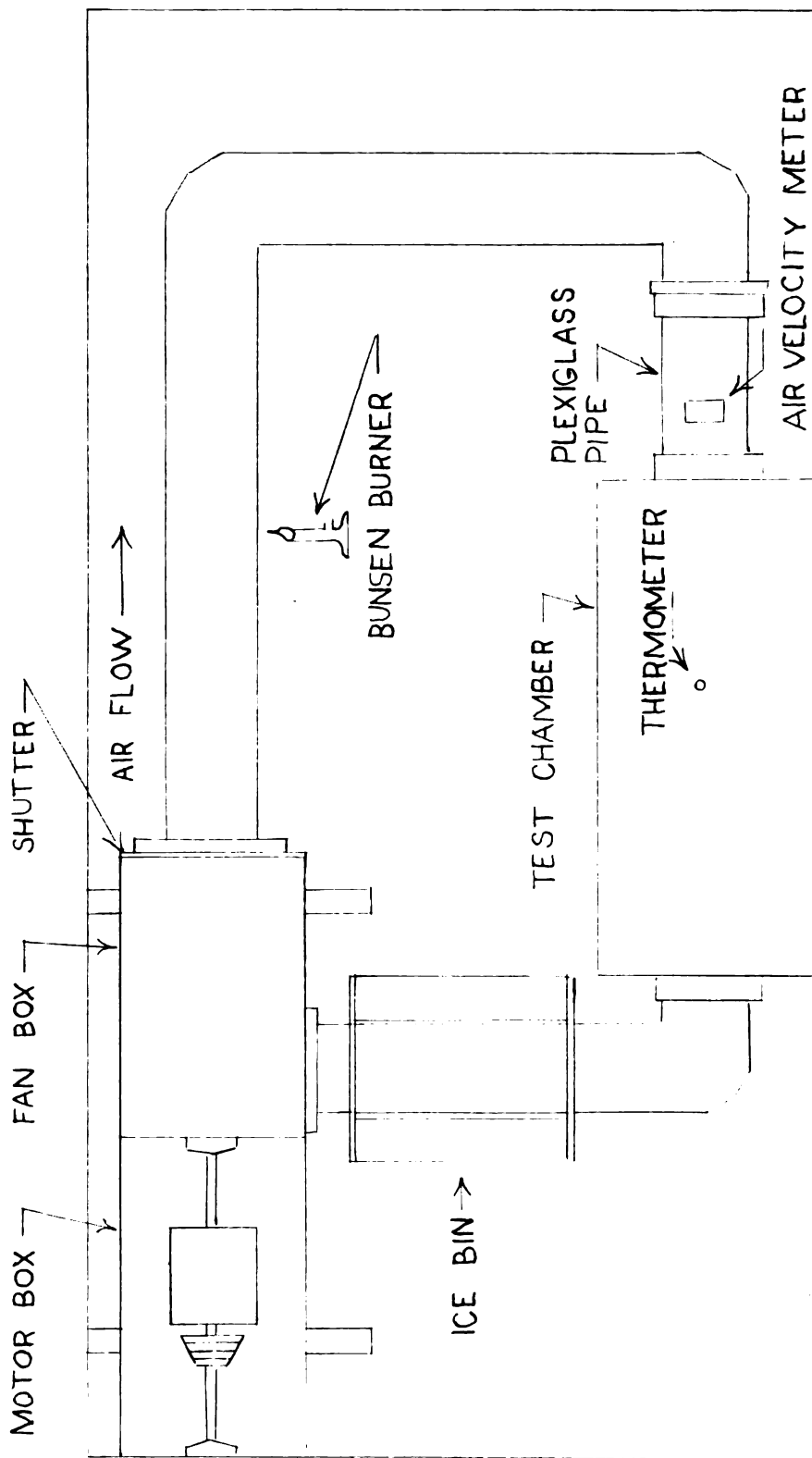


FIGURE 4
 DIAGRAM OF WIND TUNNEL

Air was circulated through the system by a 10" aluminum fan driven by a one half horsepower, 1725 revolutions per minute electric motor. A four step pulley on the motor shaft with steps of 2", 3", 4-1/8" and 5" drove another four step pulley on the fan shaft with steps of 2", 2-3/4", 3-1/2" and 4", and gave a variety of air velocities up to 900 feet per minute in the defrosting chamber. Air velocities were further controlled by means of a shutter in front of the fan.

Figure 5 shows the motor and fan box with the shutter. The fan box was 12" x 12" x 18". Air is circulated through the ducts, meter tube, and test chamber by the electric motor driven fan.

The air velocity was indicated by a FloRight air velocity meter, model MRF, installed in a 12" length of 5-1/2" diameter Plexiglass pipe. Figure 6 shows the air velocity meter installed in the Plexiglass pipe.

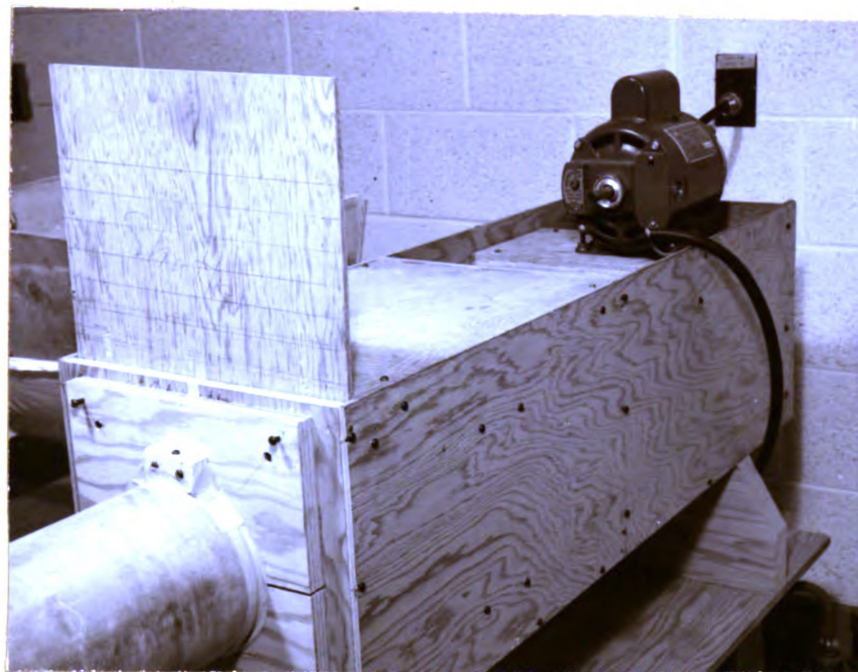


FIGURE 5
MOTOR, FAN BOX AND SHUTTER



FIGURE 6
AIR VELOCITY METER IN PLEXIGLASS PIPE

The test chamber consisted of a conduit 10" in diameter and 30.5" long, cut lengthwise and hinged at the back for easy access to the test specimen. Figure 3, page 22, shows the test chamber open with a specimen in place.

Computing air velocity in test chamber. Since the diameter of the test chamber was greater than the Plexiglass pipe, it was necessary to determine mathematically the air velocity around the specimen in the test chamber. A constant of 2.9008 was multiplied by the desired test chamber air velocity to determine what the reading should be on the air velocity meter. The constant was determined by the following method.

Calculation to determine air velocity.

Area A = 5-1/2" diameter meter pipe = 23.7583 sq. in.

Area B = 10" diameter test chamber = 78.5400 sq. in.

Area C = 3-1/2" diameter test specimen = 9.6212 sq. in.

Area D = Area of annular ring around test specimen.

Area D = B - C = 68.9188 sq. in.

Velocity E = velocity in meter pipe in feet per minute.

Velocity F = velocity in annular ring in feet per minute.

Velocity F = velocity E $\times \frac{D}{A}$

Velocity F (feet per minute) =

$$\text{velocity E (feet per minute)} \times \frac{68.9188 \text{ sq. in.}}{23.7593 \text{ sq. in.}}$$

Velocity F (feet per minute) =

$$\text{velocity E (feet per minute)} \times 2.9008$$

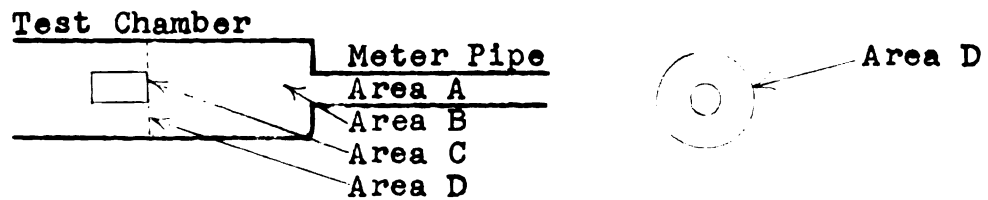


TABLE I
AIR VELOCITIES IN WIND TUNNEL

Velocity F	Velocity E
0 feet per minute	
100	$\times 2.9008 = 290.08$
200	530.16
300	870.24
400	1160.32
500	1450.40
600	1740.48
700	2030.56
800	2320.64
900	2610.72

Temperature control. The temperature in the test chamber was indicated by a thermometer. The temperature of the air in the conduits was reduced by putting ice in bins on the conduits. The temperature was increased by heating the conduits with a Bunsen burner. The Bunsen burner and an ice bin are shown in Figures 7 and 8 respectively.

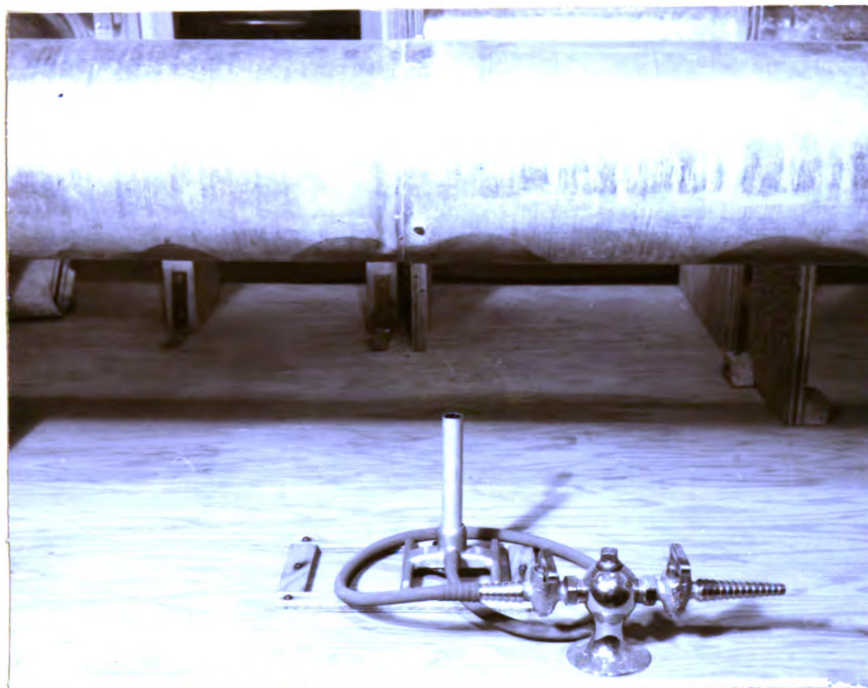


FIGURE 7
BUNSEN BURNER ARRANGEMENT FOR
AIR TEMPERATURE CONTROL



FIGURE 8
ICE BIN ARRANGEMENT FOR
AIR TEMPERATURE CONTROL

The temperature at the center of the specimen was recorded on a six lead Brown Elektronik Recorder model number 153 x 62P6-x-16 shown in Figure 9.



FIGURE 9
BROWN ELEKTRONIK RECORDER

The wind tunnel system with recorder is shown, as it appeared in operation, in Figure 10.

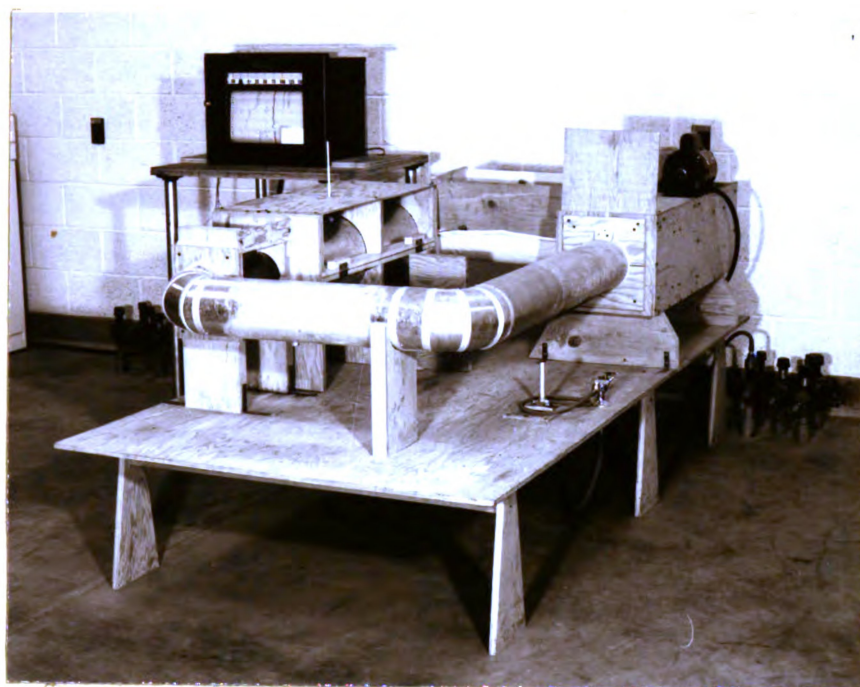


FIGURE 10
COMPLETE WIND TUNNEL SYSTEM
IN OPERATION

Number of replications of each test. The proper number of replications for a given case depends on the desired accuracy of the results, the uniformity of the material under study, and the precision of the technique²³ of observation.

An electric clock with a sweep second hand readable to within one quarter minute was used to time each defrosting period.

The temperature recorder was checked periodically with a slush ice mixture known to be 32 degrees Fahrenheit to give assurance that it was functioning properly.

The desired air velocity was established in the wind tunnel before each test. The air velocity meter was observed periodically to make sure that the air velocity remained constant.

The desired air temperature was also established in the test chamber prior to running a test. A thermometer in the test chamber indicated the air temperature and was observed frequently in order to maintain a constant temperature within the desired one degree limit.

It was decided that two replications of each test would give the desired degree of accuracy. In some instances the difference in rate of defrosting caused some

²³

E. Bright Wilson, Jr., An Introduction to Scientific Research, (New York: McGraw-Hill Book Company, Inc., 1952), p. 46.

question as to the accuracy of the results, and in these instances further replications were run until the doubt about the results was eliminated. The testing at 400 feet per minute in air of 81 to 82 degrees Fahrenheit is an example of this.

Testing procedure. Before making a test, the proper air temperature and air velocity were established in the defrosting chamber. A ground beef specimen was then placed on a cheese cloth sling in the defrosting chamber and the specimen's thermocouple connected to the recording potentiometer. The time was noted when the temperature at the center of the specimen arrived at +2.0 degrees Fahrenheit. One complete defrosting test was recorded for each set of defrosting conditions. For the replications of a given test, the starting time was recorded and periodic checks taken during the defrosting period. The recorder was allowed to run continuously when the center temperature approached +34 degrees Fahrenheit so the ending time could be recorded accurately when the specimen reached +34 degrees Fahrenheit.

The shortest time in which the defrosting was done was 2.61 hours and the longest was 4.65 hours.

Complete time-temperature graphs, which appear in Figure 11 for tests at 71 to 72 degrees Fahrenheit and Figure 12 for the tests at 81 to 82 degrees Fahrenheit,

show the characteristic defrosting curve for defrosting the one pound specimens at the selected air velocities.

Summary. Chapter III contains a description of the wind tunnel which was designed to control the factors which affect the rate of defrosting the ground beef specimens.

It was necessary to compute the air velocity for the test chamber from the air flow meter reading in a Plexiglass pipe of smaller diameter than the test chamber. A constant of 2.9008 was determined and the desired test chamber air velocity was multiplied by the constant to determine the proper reading on the meter.

The testing procedure is explained at the end of Chapter III.

CHAPTER IV

DATA AND DISCUSSION OF RESULTS

The last section of Chapter III contained a description of the testing apparatus and the procedure for making the tests and recording the data. The data collected were in terms of a rate of defrosting in order that it could be easily determined whether higher air velocities do cause an increase in the rate of defrosting. The data are now presented and analyzed in an effort to determine whether the defrosting rate is effected by moving air.

The two defrosting temperature ranges, as mentioned before, were from 71 to 72 degrees Fahrenheit and from 81 to 82 degrees Fahrenheit, and will be referred to in this chapter as defrosting at 71 degrees Fahrenheit and 81 degrees Fahrenheit.

The data presented in the first part of this chapter show the time-temperature relationship at the center of the specimen during defrosting at 71 degrees Fahrenheit for still air and air velocities of 100 to 600 feet per minute by 100 feet per minute increments. The defrosting rates of all tests and replications are presented in Table II. The arithmetic averages of the defrosting rates for the tests and replications for a given set of conditions were computed to give the information needed to determine

whether higher air velocities increase the rate of defrosting. Besides defrosting rates the data was also gathered in terms of total time required to defrost a specimen. The average defrosting times are presented in Table IV which includes a column showing the decrease in defrosting time at a given air velocity from the preceding air velocity.

The data gathered during the 81 degree Fahrenheit tests and replications are presented and analyzed in the same manner as the 71 degree data. First the time-temperature relationship at the center of the specimen during defrosting is presented, then the rate of defrosting for all tests and replications, the average rates of defrosting, and the average defrosting times in minutes.

To determine whether an excessive amount of moisture would be lost by forced convection defrosting a record was kept of the moisture lost during the defrosting of the specimens. The relationship between moisture loss and air velocity during defrosting is presented at the end of this chapter.

DEFROSTING AT 71 DEGREES FAHRENHEIT

Time-temperature relationship. The time-temperature relationship at the center of a defrosting meat specimen produces an S-shaped curve when plotted on a graph. This S-shaped curve is due to the additional heat needed to change ice to water, and can be explained by the following: The temperature of ice below 32 degrees Fahrenheit freezing temperature, when placed where the surrounding temperature is above freezing temperature, tends to rise fairly rapidly to the point where the ice changes to the liquid state. The temperature change rate slows during the time the change of state is taking place and then speeds up after the liquid state is reached.²⁴ The change of state of the water in beef occurs between 25 and 28 degrees Fahrenheit, depending upon the salts present in the meat, and it is between 25 and 28 degrees Fahrenheit where a slightly flatter spot in the temperature rise curve occurs.

Typical defrosting curves. Figure 11 shows in graphic form the temperature rise rate of one pound ground beef specimens defrosted at 71 degrees Fahrenheit. Temperature in degrees Fahrenheit from 0 to +34.0 is shown shown on the vertical axis. Time in minutes from 0 to 280

²⁴

Harvey E. White, Modern College Physics, (New York: D. Van Nostrand Company, Inc., 1953), pp. 275, 276.

is shown on the horizontal axis. Seven air velocities from still air to 600 feet per minute by 100 feet per minute increments are plotted.

These curves are presented here to show typical defrosting curves for one pound ground beef specimens defrosted at the air velocities used in these tests. The defrosting curves also show the increase in defrosting rate when defrosting in moving air when compared with defrosting in still air. These curves are specifically for ground beef defrosted under the conditions of this study, but defrosting curves for all meats are similar.

Complete curves are plotted for specimens defrosting in still air and at an air velocity of 600 f.p.m. Partial curves are plotted for air velocities from 100 f.p.m. to 500 f.p.m. and from the 170 minute time lapse point to the time when the specimen temperature is 34 degrees Fahrenheit. The five curves as plotted on the graph were between the still air test curve and the 600 f.p.m. test curve. At the time lapse point of 170 minutes the still air curve and the 600 f.p.m. curve were separated by only three degrees, and to plot all the curves in this space would be confusing.

The right hand curve labeled "S" represents thirty temperature readings of the specimen taken at ten minute intervals in still air. A smooth curve was drawn from the start of the test at +2 degrees Fahrenheit to the +34 degrees Fahrenheit point using the intermediate points as

guides. The time-temperature relationship for defrosting in still air at air temperature of 71 degrees Fahrenheit is shown by the curve labeled "S".

The curve labeled "6" at the left was constructed by plotting 20 temperature readings at ten minute intervals from +2 to +34 degrees Fahrenheit. At +34 degrees Fahrenheit the ground beef was thoroughly thawed and uniformly workable.

Curves "S" and "6" do not go through all points which were used to determine the lines. Undetermined irregularities in the specimen or defrosting procedure probably prevented some of the points from falling on a smooth curve, and would perhaps be eliminated by additional replications.

Analysis of the data indicates that the ground beef specimen defrosted in still air took 279.43 minutes to defrost. The largest decrease in defrosting time in still air conditions was 49.18 minutes which occurred with air velocity of 100 f.p.m. Defrosting with air velocities of 200 and 300 f.p.m. gave decreases of 18.25 minutes and 16.38 minutes respectively, which were the second and third largest decreases in defrosting time.

The time differentials between the 400, 500, and 600 f.p.m. tests were much less than the time differentials between the still air, 100, 200, 300 and 400 f.p.m. tests.

38 -
37 -
36 -
35 -
34 -
33 -
32 -
31 -
30 -
29 -
28 -
27 -
26 -
25 -
24 -
23 -
22 -
21 -
20 -
19 -
18 -
17 -
16 -
15 -
14 -
13 -
12 -
11 -
10 -
9 -
8 -
7 -
6 -
5 -
4 -
3 -
2 -
1 -
0 -
-1 -
-2 -
-3 -
-4 -
-5 -
-6 -
-7 -
-8 -
-9 -
-10 -
-11 -
-12 -
-13 -
-14 -
-15 -
-16 -
-17 -
-18 -
-19 -
-20 -
-21 -
-22 -
-23 -
-24 -
-25 -
-26 -
-27 -
-28 -
-29 -
-30 -
-31 -
-32 -
-33 -
-34 -
-35 -
-36 -
-37 -
-38 -
-39 -
-40 -
-41 -
-42 -
-43 -
-44 -
-45 -
-46 -
-47 -
-48 -
-49 -
-50 -
-51 -
-52 -
-53 -
-54 -
-55 -
-56 -
-57 -
-58 -
-59 -
-60 -
-61 -
-62 -
-63 -
-64 -
-65 -
-66 -
-67 -
-68 -
-69 -
-70 -
-71 -
-72 -
-73 -
-74 -
-75 -
-76 -
-77 -
-78 -
-79 -
-80 -
-81 -
-82 -
-83 -
-84 -
-85 -
-86 -
-87 -
-88 -
-89 -
-90 -
-91 -
-92 -
-93 -
-94 -
-95 -
-96 -
-97 -
-98 -
-99 -
-100 -

Temperature (degrees Fahrenheit)

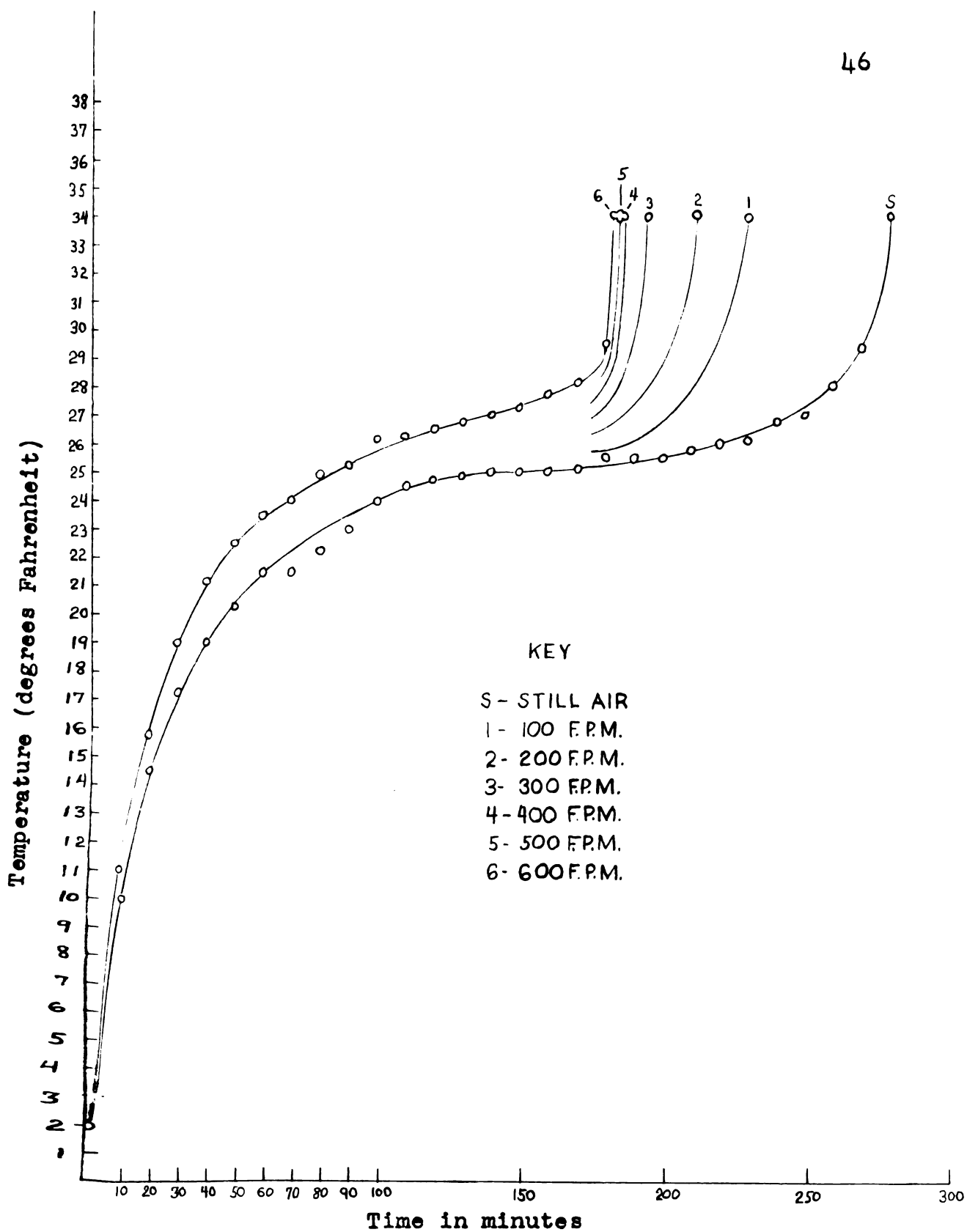


FIGURE 11
 REPRESENTATIVE TIME-TEMPERATURE GRAPH WITH DEFROSTING
 TEMPERATURE 71 DEGREES FAHRENHEIT

The shapes of all the curves were similar. There was a rapid temperature rise to 23 degrees Fahrenheit where the temperature rise rate slowed due to the change of state of the water in the meat. After all the ice melted at 28 degrees Fahrenheit the temperature rise rate increased again.

The rates of defrosting for all specimens at 71 degrees Fahrenheit. The defrosting rates for all specimens at 71 degrees Fahrenheit are recorded in Table II. One defrosting test was made at each air velocity, and at least two replications of each test were made. For some tests more replications were made to verify the results already obtained. It is apparent in Table II that the defrosting rate increased when done under conditions of higher air velocity. The increase in defrosting rate becomes more noticeable when the arithmetic averages of the tests for each selected air velocity are determined.

The arithmetic averages of the defrosting tests at selected air velocities are shown in Table III. The average rate of defrosting for the replications under still air conditions was 0.1146 degrees Fahrenheit per minute. The average rate of defrosting all replications in an air velocity of 100 f.p.m. was 0.1356 degrees Fahrenheit per minute. The rate of defrosting increased 0.0210 degrees Fahrenheit per minute at an air velocity of 100 f.p.m.

TABLE II
RATES OF DEFROSTING AT VARIOUS AIR VELOCITIES
IN AN AIR TEMPERATURE OF
71 DEGREES FAHRENHEIT

Air Velocity f.p.m.	Rates of Defrosting			
	Test	Replication 1	Replication 2	Replication 3
Still air	0.1103	0.1171	0.1168	0.1140
100	0.1242	0.1353	0.1250	0.1502
200	0.1530	0.1438	0.1538	0.1538
300	0.1620	0.1711	0.1693	0.1553
400	0.1675	0.1735	0.1688	0.1758
500	0.1675	0.1720	0.1775	
600	0.1680	0.1839	0.1833	0.1798
				0.1495

TABLE III

AVERAGE RATES OF DEFROSTING AT 71 DEGREES FAHRENHEIT
AND RATE DIFFERENTIALS BETWEEN
SEQUENTIAL AIR VELOCITIES

Air Velocity f.p.m.	Average Rate of Defrosting (°F/min.)	Rate Differential from Previous Rate of Defrosting
Still air	0.1146	
100	0.1356	0.0210
200	0.1511	0.0155
300	0.1644	0.0133
400	0.1714	0.0070
500	0.1723	0.0009
600	0.1787	0.0029
Total differential		0.0606 °F/min.

compared to still air conditions. The increase of 0.0210 degrees Fahrenheit per minute in defrosting rate obtained by increasing the flow of air from still air conditions to 100 f.p.m. was the largest differential occurring between any two tests. The second largest differential in defrosting rate occurred when the air velocity of 100 f.p.m. was increased to 200 f.p.m. The average rate of defrosting at 200 f.p.m. was 0.1511 degrees Fahrenheit per minute. When compared with the preceding air velocity, the rate of defrosting at 200 f.p.m. was 0.0155 degrees Fahrenheit per minute faster. The defrosting rates continue to increase at a diminishing degree until the rate for defrosting under air velocity of 600 f.p.m. conditions was reached. The defrosting rate under maximum air velocity conditions of 600 f.p.m. was 0.1787 degrees Fahrenheit per minute. The total increase in rate of defrosting specimens under still air conditions compared to those defrosted in an air velocity of 600 f.p.m. was 0.0606 degrees Fahrenheit per minute.

Number of minutes needed to defrost specimens. By changing the defrosting rates from degrees Fahrenheit per minute to the number of minutes necessary to change the temperature of the ground beef specimen from +2 degrees Fahrenheit to +34 degrees Fahrenheit, the results can be presented in a form which is perhaps more readily

understood. Table IV shows the average number of minutes necessary to defrost the ground beef specimens under the seven selected air velocities in an air temperature of 71 degrees Fahrenheit. The average defrosting time for all specimens defrosted in still air was 279.43 minutes. The average defrosting time for all specimens defrosted in an air velocity of 100 f.p.m. was 230.25 minutes. The decrease of 49.13 minutes in defrosting time between still air tests and 100 f.p.m. tests is the largest time decrease between any two tests. The average defrosting time for all specimens defrosted under air velocity conditions of 200 f.p.m. was 212.0 minutes, which is 18.25 minutes faster than defrosting at the previous air velocity and the second largest time differential between two tests. The defrosting times continued to diminish at a decreasing rate. The average defrosting time at 600 f.p.m., the highest air velocity used, was 183.40 minutes. Defrosting at 600 f.p.m. took an average of 96.03 minutes less than did defrosting in still air.

In summary the data presented in this section shows that the rate of defrosting was increased when the meat specimens were defrosted in higher air velocities. The rate differentials between the defrosting tests at various air velocities were as follows: (1) the largest rate differential was between the still air tests and the

TABLE IV
AVERAGE DEFROSTING TIMES AT 71 DEGREES FAHRENHEIT
AND TIME DIFFERENTIAL BETWEEN
SEQUENTIAL AIR VELOCITIES

Air Velocity f.p.m.	Average Defrosting Time in Minutes	Differential in Minutes From Previous Defrosting Time
Still air	279.43	
100	230.25	49.18
200	212.00	18.25
300	195.12	16.88
400	186.62	8.50
500	185.75	0.87
600	183.40	2.35
Total differential		96.03

100 f.p.m. tests, (2) the second largest rate differential was between the 100 f.p.m. tests and the 200 f.p.m. tests, (3) the rate differentials between tests continued to decrease as air velocities were increased.

DEFROSTING AT 81 DEGREES FAHRENHEIT

The data from the defrosting tests done at 81 degrees Fahrenheit was recorded in the same manner as the data from the 71 degree Fahrenheit tests. The typical defrosting curves are presented followed by the rates of defrosting for all specimens tested. The arithmetic averages of all the tests under like conditions follow the rates for all tests and show how much the rate of defrosting is increased for a specific air velocity. The average rates of defrosting were converted to minutes and this is shown following the average rates.

Typical defrosting curve. Figure 12 shows in graphic form the temperature rise rate for the samples defrosted at various air velocities in a chamber where the air is 81 degrees Fahrenheit.

Temperature in degrees Fahrenheit from 0 to +35.0 is charted on the vertical axis. Time in minutes from 0 to 220 is charted on the horizontal axis. Representative defrosting curves for defrosting in still air and in air moving at a velocity of 600 f.p.m. were plotted

according to temperature readings recorded at 10 minute intervals.

Partial (or incomplete) curves for the air velocities from 100 f.p.m. to 500 f.p.m. were drawn from the 140 minute reading to the end of the defrosting period. The portions of the curves at readings less than 140 minutes lapse time would have been plotted between the still air curve and the 600 f.p.m. curve. Since the temperature range at the 140 minute mark was only 1.75 degrees Fahrenheit, only partial curves of the five air velocities were plotted to make the graph more legible.

Temperature rise in the specimen defrosted in still air was fairly rapid to 23 degrees Fahrenheit per minute. From the 23 degree temperature to the 28 degree temperature, the rate of temperature rise was slower, and from 28 degrees up to 34 degrees Fahrenheit, the rate of temperature rise once again increased. Twenty-two temperature readings taken at ten minute intervals were recorded to provide the data for plotting the time-temperature curve for the specimen defrosted in still air. The total time required for the specimen to defrost in 81 degrees Fahrenheit in still air was 202.62 minutes.

Seventeen temperature readings from +2 to +34 degrees Fahrenheit at ten minute intervals produced the data needed to plot the curve for the specimen defrosted in an air velocity of 600 f.p.m. The curve labeled "6"

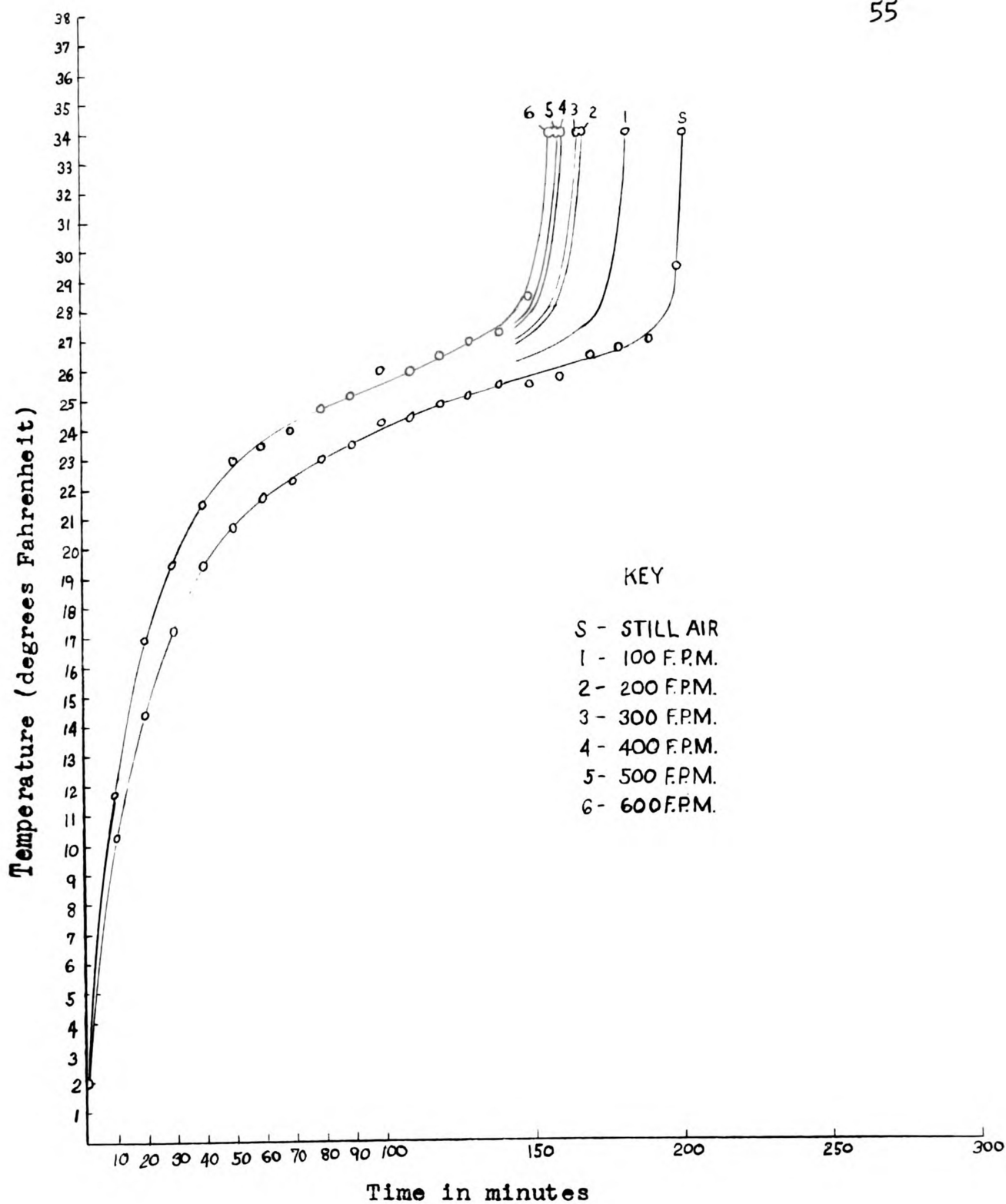


FIGURE 12
 REPRESENTATIVE TIME-TEMPERATURE GRAPH WITH DEFROSTING
 TEMPERATURE 81 DEGREES FAHRENHEIT

indicates a rapid temperature rise rate to 23 degrees Fahrenheit, a slower temperature rise rate to 28 degrees Fahrenheit, and above 28 degrees Fahrenheit the temperature rise rate once again increases. The total time required to defrost a specimen in air moving at a velocity of 600 f.p.m. at an air temperature of 81 degrees Fahrenheit was 157.66 minutes.

An analysis of the data reveals that the largest decrease in defrosting time, 19.22 minutes, occurred when the air velocity was increased from still air conditions to an air velocity of 100 f.p.m. The second largest decrease in defrosting time occurred with the air velocity of 200 f.p.m. This decrease from the time needed to defrost at 100 f.p.m. was 13.57 minutes. The decrease in defrosting times do not continue in regular progression from the 200 f.p.m. test to the 600 f.p.m. test. However, it is believed that a regular progression would have occurred if more replications had been made.

The rates of defrosting for all specimens at 81 degrees Fahrenheit. The data from the original tests at 81 degrees Fahrenheit and all replications of those tests appear in the form of defrosting rates in Table V. The data in Table IV show that the original test and at least two replications were made for all air velocities. In still air three replications were made, and in an air

TABLE V
RATES OF DEFROSTING AT VARIOUS AIR VELOCITIES
IN AN AIR TEMPERATURE OF
81 DEGREES FAHRENHEIT

Air Velocity f.p.m.	Rates of Defrosting						
	Test	Repli- cation 1	Repli- cation 2	Repli- cation 3	Repli- cation 4	Repli- cation 5	Repli- cation 6
Still air	0.1553	0.1544	0.1600	0.1623			
100	0.1793	0.1647	0.1802				
200	0.1910	0.1945	0.1802				
300	0.1882	0.1930	0.1863				
400	0.2025	0.2006	0.2119	0.2077	0.1772	0.1910	0.1954
500	0.2140	0.1981	0.1855				
600	0.2077	0.2031	0.1981				

velocity of 400 f.p.m., six replications were made. The number of replications run at the various velocities were increased when unknown variables caused part of the test results to be inaccurate.

An analysis of the data presented in Table V indicated a general increase in the rate of defrosting when the tests were run at a higher air velocity.

The arithmetic average rates of defrosting of the tests and replications done at the same air velocities appear in Table VI. Here it can be seen clearly that the rate of defrosting does increase when the specimen is defrosted in air moving at a higher velocity. The average rate of defrosting for the specimens defrosted in still air was 0.1580 degrees Fahrenheit per minute. The average rate of defrosting for the specimens defrosted in the maximum air velocity of 600 f.p.m. was 0.2029 degrees Fahrenheit per minute. The difference between the rate of defrosting in still air and the rate of defrosting at the maximum air velocity of 600 f.p.m., in an air temperature of 81 degrees Fahrenheit, was 0.0449 degrees Fahrenheit per minute.

A comparison of the rates of defrosting at the selected air velocities with the preceding rate indicates that the largest increase in rate of defrosting occurred between still air conditions and an air velocity of 100 f.p.m. The increase in rate of defrosting at an air

TABLE VI
AVERAGE RATES OF DEFROSTING AT 81 DEGREES FAHRENHEIT
AND RATE DIFFERENTIALS BETWEEN
SEQUENTIAL AIR VELOCITIES

Air Velocity f.p.m.	Average Rate of Defrosting °F/min.	Rate Differential From Previous Rate of Defrosting
Still air	0.1580	
100	0.1747	0.0167
200	0.1852	0.0105
300	0.1892	0.0040
400	0.1980	0.0088
500	0.1993	0.0013
600	0.2029	0.0036
Total differential		0.0449 °F/min.

velocity of 100 f.p.m. was 0.0167 degrees Fahrenheit per minute faster than defrosting in still air.

Defrosting in air velocity of 200 f.p.m. gave an increase in rate of defrosting of 0.0105 degrees Fahrenheit per minute over the rate for defrosting in an air velocity of 100 f.p.m. The difference between the 100 f.p.m. rate and the 200 f.p.m. rate was the second largest rate increase in the 81 degree Fahrenheit tests.

The data obtained in the 200 f.p.m. tests and subsequent tests to a maximum velocity of 600 f.p.m. show that the rate of defrosting continues to increase, but by smaller increments and not in regular progression. More replications of the tests, if run, possibly would have indicated a regular progression in the increase in rates of defrosting.

Number of minutes needed to defrost specimens at 81 degrees Fahrenheit. The rates of defrosting presented in Table V were converted to average defrosting times in minutes. The average defrosting times appearing in Table VI are to the right of the column which indicated the air velocity, and the decrease in defrosting time from the preceding air velocity appear at the right of the average defrosting times.

The average defrosting time for the specimens defrosted in still air at an air temperature of 81 degrees

Fahrenheit was 202.62 minutes. The average defrosting time for the specimens defrosted in an air velocity of 600 f.p.m. was 157.66. The decrease in defrosting time between still air and an air velocity of 600 f.p.m. was 44.96 minutes, as can be seen in Table VII.

The data in Table VII also show that the largest difference in defrosting time occurred in the test specimens defrosted in an air velocity of 100 f.p.m. compared to the still air tests. The average difference was 19.22 minutes. The second largest difference in defrosting time came with an air velocity of 200 f.p.m. compared with the defrosting time for tests at 100 f.p.m. The difference between 100 f.p.m. and 200 f.p.m. air velocity tests was 13.57 minutes.

The decrease in defrosting times beyond the 200 f.p.m. tests do not follow a regular progression.

The data collected when defrosting ground beef specimens in air of 81 degrees Fahrenheit per minute at selected air velocities show that the defrosting rate increases when defrosted under higher air velocity conditions.

An analysis of the data also shows that the rate differentials between the defrosting tests at various air velocities were as follows: (1) the largest rate differential was between the still air tests and the 100 f.p.m.

TABLE VII

AVERAGE DEFROSTING TIMES AT 81 DEGREES FAHRENHEIT
AND TIME DIFFERENTIALS BETWEEN
SEQUENTIAL AIR VELOCITIES

Air Velocity f.p.m.	Average Defrosting Time in Minutes	Differential in Minutes from Previous Defrosting Time
Still air	202.62	
100	183.40	19.22
200	169.83	13.57
300	169.15	0.67
400	162.03	7.13
500	161.16	0.87
600	157.66	3.50
Total decrease		44.96 minutes

tests, (2) the second largest rate differential was between the 100 f.p.m. tests and the 200 f.p.m. tests, (3) the rate differentials between tests continued to decrease as air velocities were increased.

COMPARING RATES OF DEFROSTING AT 71 DEGREES FAHRENHEIT TO THE RATES OF DEFROSTING AT 81 DEGREES FAHRENHEIT

Before the defrosting tests were run it was thought that the effects of moving air past a defrosting specimen would probably be the same at different air temperatures. In order to determine whether the effects of moving air were the same, two defrosting temperatures were used. For comparison purposes, graphs and tables will present both the rates of defrosting in degrees Fahrenheit change per minute and number of minutes required for a 32 degree Fahrenheit temperature change. The data from the two defrosting temperatures are compared to see if the effects of moving air are the same.

The defrosting curve when defrosting at either 71 degrees Fahrenheit or at 81 degrees Fahrenheit conforms to the same general shape. A rapid rise in the curve occurs to 23 degrees Fahrenheit, then a slower rise in the curve to 34 degrees Fahrenheit. The most noticeable difference in the two curves is that at higher temperatures the specimens defrosted in a shorter period of time than did

the specimens defrosted at the corresponding air velocity at the lower temperature.

A noticeable similarity between the two defrosting temperatures is that the largest and next largest differentials in defrosting times come between the 100 f.p.m. tests and 200 f.p.m. tests respectively. The data supporting this statement are presented in Tables IV and VII.

Table VIII shows the average rates of defrosting for all air velocities at the two selected temperatures as also seen in Tables III and VI. The fourth column shows the difference in defrosting times when air temperature was increased from 71 degrees Fahrenheit to 81 degrees Fahrenheit. The difference in rate of defrosting due to increased temperature of 10 degrees Fahrenheit in still air was 0.0434 degrees Fahrenheit per minute. The difference in rate of defrosting at 100 f.p.m. was 0.0391 degrees Fahrenheit per minute. The difference in rate of defrosting at 200 f.p.m. was 0.341 degrees Fahrenheit per minute. From the 300 f.p.m. tests through the 600 f.p.m. tests, the difference between the high and low temperature rates of defrosting varied from 0.0242 to 0.0270 degrees Fahrenheit per minute. The higher temperature always produced the higher rate of defrosting which was expected to happen when defrosting was done at higher temperatures.

TABLE VIII

COMPARING THE RATES OF DEFROSTING
AT TWO DEFROSTING TEMPERATURES

Air Velocity f.p.m.	Average Rate of Defrosting		Difference in Rates of Defrosting Between Two Temperature Ranges
	71 degrees Fahrenheit	81 degrees Fahrenheit	
Still air	0.1146	0.1580	0.0434
100	0.1356	0.1747	0.0391
200	0.1511	0.1852	0.0341
300	0.1644	0.1992	0.0248
400	0.1714	0.1980	0.0266
500	0.1723	0.1993	0.0270
600	0.1787	0.2029	0.0242

The graph in Figure 13 shows the defrosting rates for the two air temperatures plotted as curves. The vertical axis on this graph is assigned temperature change values per minute from 0.090 to 0.210 degrees Fahrenheit per minute. The horizontal axis is used to show air velocity in feet per minute.

Curve A represents the defrosting rates at 71 degrees Fahrenheit for the various air velocities and Curve B represents the defrosting rates at 81 degrees Fahrenheit for the various air velocities.

It can be seen that the curves are converging slightly from the still air tests to the 300 f.p.m. tests, and from the 300 f.p.m. to 600 f.p.m. the curves run almost an equal distance apart. By changing the rates of defrosting to time in minutes, it is easy to see that by raising the temperature ten degrees Fahrenheit and holding the air velocity constant defrosting can be accomplished in 24.5 minutes less at 600 f.p.m. to 76.8 minutes less when the defrosting is done in still air.

Figure 14 is the information in Table IX plotted in graphic form. Time in minutes appears on the vertical axis and air velocity in feet per minute appears on the horizontal axis. Curve A represents the tests defrosted at 71 degrees Fahrenheit, and is the upper curve because all tests at this temperature took longer to defrost than did

the tests at 81 degrees Fahrenheit and the corresponding air velocity. The 81 degree Fahrenheit tests appear in Curve B.

Curves A and B converge slightly from the still air tests to the tests at 300 f.p.m. From 300 f.p.m. to 600 f.p.m. the curves run almost parallel.

OPTIMUM AIR VELOCITY

By observation of the two curves in Figure 13 it can be seen that the rate of defrosting increases a greater amount for a given increase in air velocity below 350 or 400 f.p.m. air velocity than it does above this range of air velocity. It appears from this graph that an optimum air velocity could be placed between 350 and 400 f.p.m.

MOISTURE LOSS DURING DEFROSTING

Moisture loss in defrosted meats is an important consideration to a food service operator, and a method of defrosting which increases moisture loss would be difficult to justify. All specimens were weighed before and after defrosting to determine the percentage of moisture lost during defrosting. The difference in weight of the specimens was considered to be a change in the amount of moisture in the specimen.

25

It was learned in a discussion with Mildred Jones, Dept. of Foods and Nutrition, Michigan State University, that weight loss in a piece of meat not altered mechanically is considered to be moisture loss.

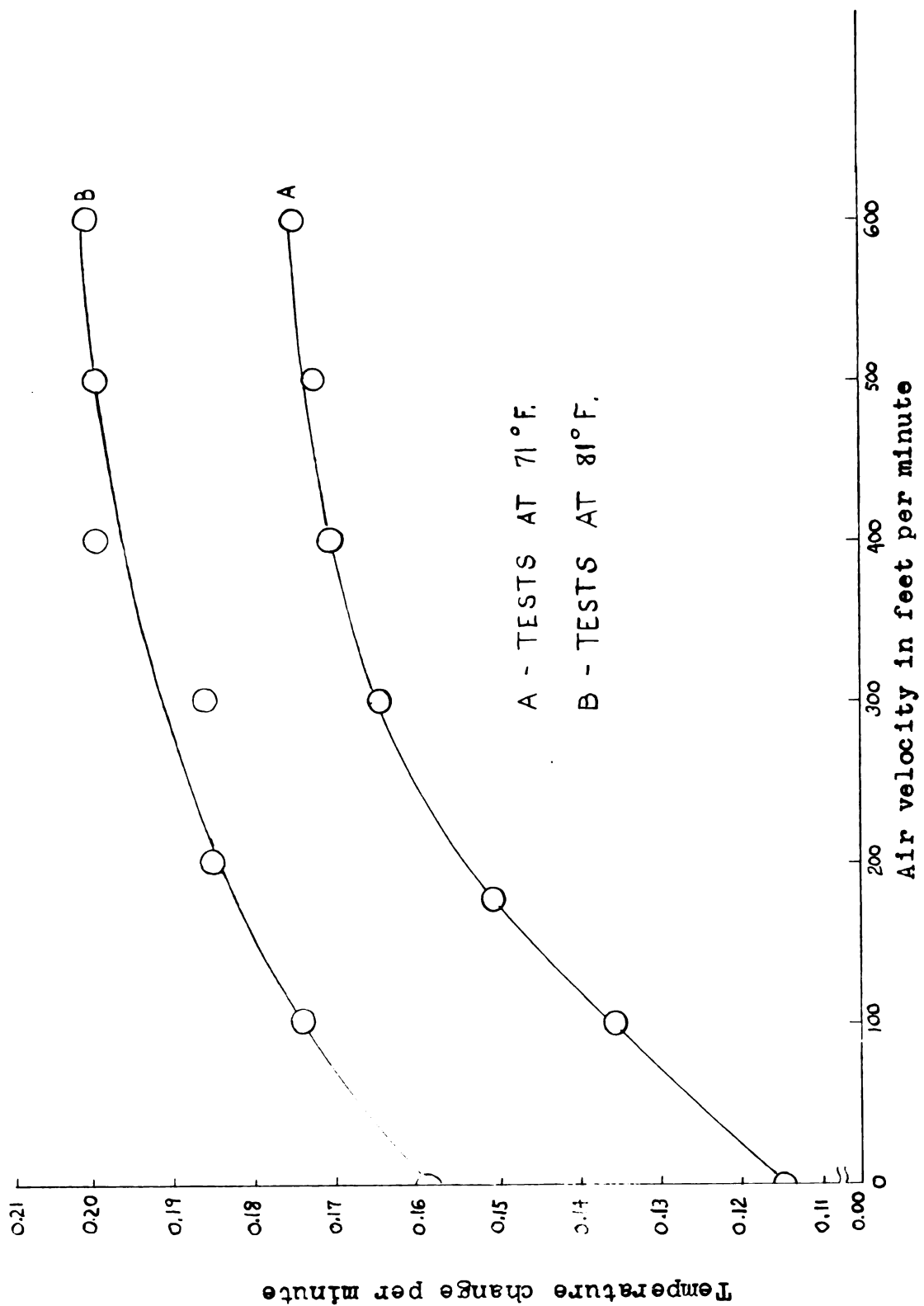
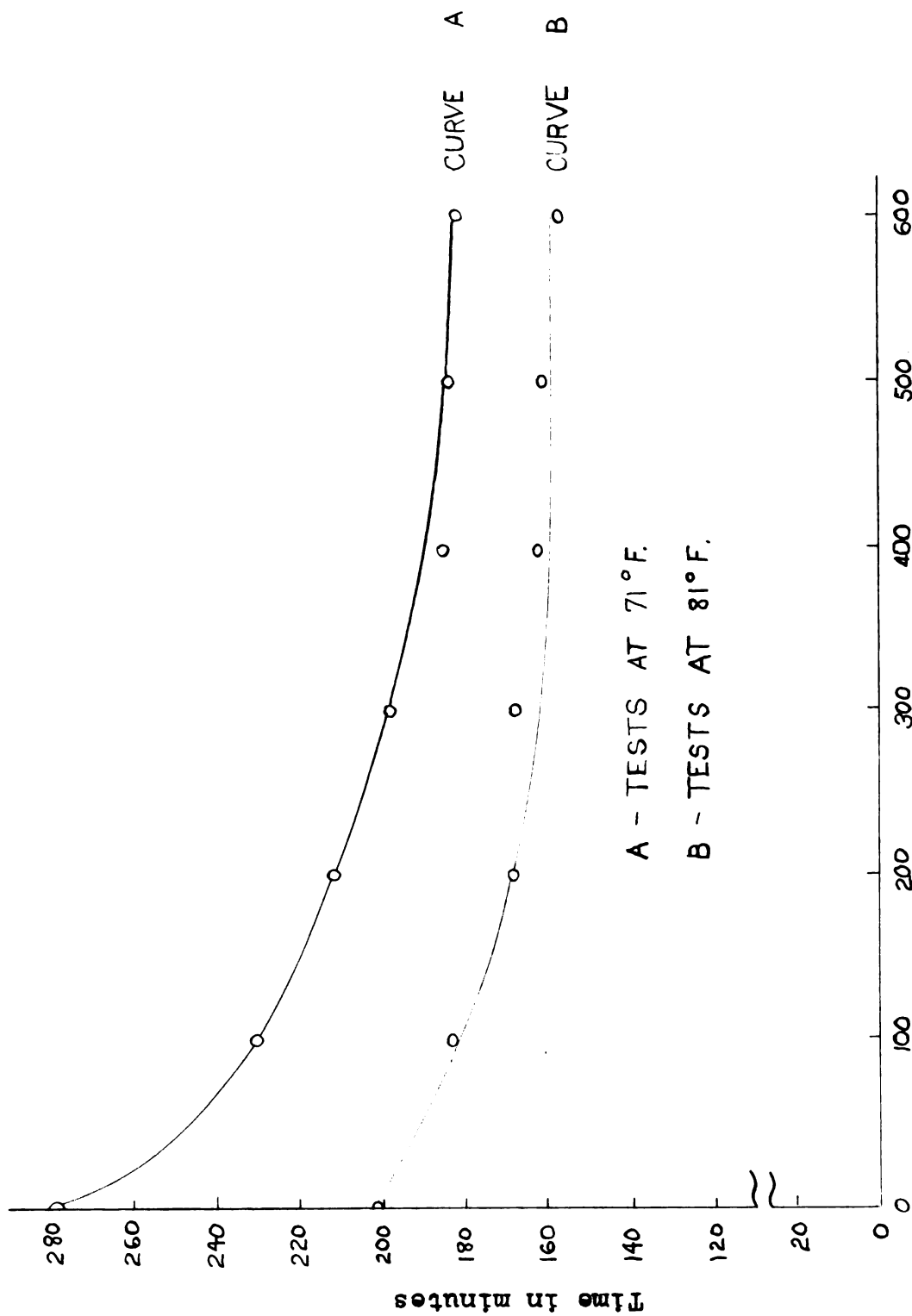


FIGURE 13

RATES OF DEFROSTING

TABLE IX
COMPARING THE DEFROSTING TIMES AT THE
TWO DEFROSTING TEMPERATURES

Air Velocity f.p.m.	Average Defrosting Time		Difference in Minutes Between 71°F and 81°F Tests
	Average Defrosting Time in Minutes 71° F	Average Defrosting Time in Minutes 81° F	
Still air	279.43	202.62	76.81
100	230.25	183.40	46.85
200	212.00	169.83	42.85
300	195.12	169.15	25.97
400	186.62	162.03	24.59
500	185.75	161.16	24.59
600	183.40	157.66	25.74



A - TESTS AT 71°F.

B - TESTS AT 81°F.

Average defrosting times

FIGURE 14

AVERAGE DEFROSTING TIMES

A variation in moisture loss from test to test occurred perhaps because the relative humidity in the test chamber was not constant. However, the data collected did show a trend toward greater moisture loss with increased air velocities. The trend was apparent when defrosting both at 71 and 81 degrees Fahrenheit.

Percentage of moisture loss for all specimens defrosted at 71 degrees is shown in Table X. Two of the specimens defrosted in still air gained slightly under one per cent moisture, but all other specimens lost moisture. The far right hand column of Table X shows the average per cent moisture loss for the specimens defrosted at the various air velocities. The average moisture loss when defrosting in still air at 71 degrees Fahrenheit was 0.0025 per cent which was the lowest per cent moisture loss for any 71 degree Fahrenheit test. The highest average moisture loss for all of the tests at 71 degrees Fahrenheit and 600 f.p.m. was 3.3225 per cent.

Table XI shows the per cent of moisture loss from all specimens defrosted at 81 degrees Fahrenheit. In Table XI as in Table X, the far right hand column shows the average per cent moisture loss for the specimens defrosted at the various air velocities.

TABLE X
AVERAGE MOISTURE CHANGE DURING DEFROSTING AT VARIOUS AIR VELOCITIES
AIR TEMPERATURE 71 DEGREES FAHRENHEIT

Air Velocity f.p.m.	Per Cent Moisture Change			Average Moisture Change Per Cent
	Test	Repli- cation 1	Repli- cation 2	Repli- cation 3
Still air	0.79	0.79	+0.78	+0.79
100	0.80	1.59	0.00	0.44
200	1.59	0.80	1.59	0.00
300	3.94	1.59	3.18	1.57
400	1.62	1.52	1.57	
500	3.93	3.97	1.59	0.56
600	4.70	1.95	3.51	3.13
				-0.0025
				-0.775
				-0.995
				-2.57
				-1.57
				-2.54
				-3.32

TABLE XI
AVERAGE MOISTURE CHANGE DURING DEFROSTING AT VARIOUS AIR VELOCITIES
AIR TEMPERATURE 81 DEGREES FAHRENHEIT

Air Velocity f.p.m.	Test	Per Cent Moisture Change						Average Moisture Change Per Cent
		Repli- cation 1	Repli- cation 2	Repli- cation 3	Repli- cation 4	Repli- cation 5	Repli- cation 6	
Still air	0.00	+0.7	0.00	+1.64				+0.585
100	0.44	0.00	1.57					-0.670
200	1.18	2.34	2.38					-1.96
300	3.19	1.59	3.19					-2.65
400	2.4	3.18	3.18	3.18	3.19	4.73	2.39	-3.18
500	3.19	4.73	4.73					-4.22
600	4.0	4.8	3.97					-4.26

The average moisture change when defrosting in still air at 81 degrees Fahrenheit was 0.583 per cent increase. Moisture was lost when defrosting at all other air velocities. The largest loss of 4.26 per cent moisture was for the specimens defrosted at 600 f.p.m.

The moisture losses are presented graphically in Figure 15 for the 71 degree Fahrenheit tests, and Figure 16 for the 81 degree Fahrenheit tests. On both graphs the per cent of moisture change is shown on the vertical axis and air velocity in feet per minute is shown on the horizontal axis. A trend line drawn on each graph presents the relationship of moisture change percentages plotted against air velocity. The trend is toward more moisture loss at higher air velocities and more moisture loss when defrosting is done at 81 degrees Fahrenheit than when the defrosting is done at 71 degrees Fahrenheit. The moisture loss curve in Figure 16 starts to level off at about 500 f.p.m. where the moisture loss curve in Figure 15 continues nearly straight for its full length. More testing at air velocities above 600 f.p.m. would be needed to establish whether the moisture loss curve does start to level off at the higher air velocities, or if it would continue straight.

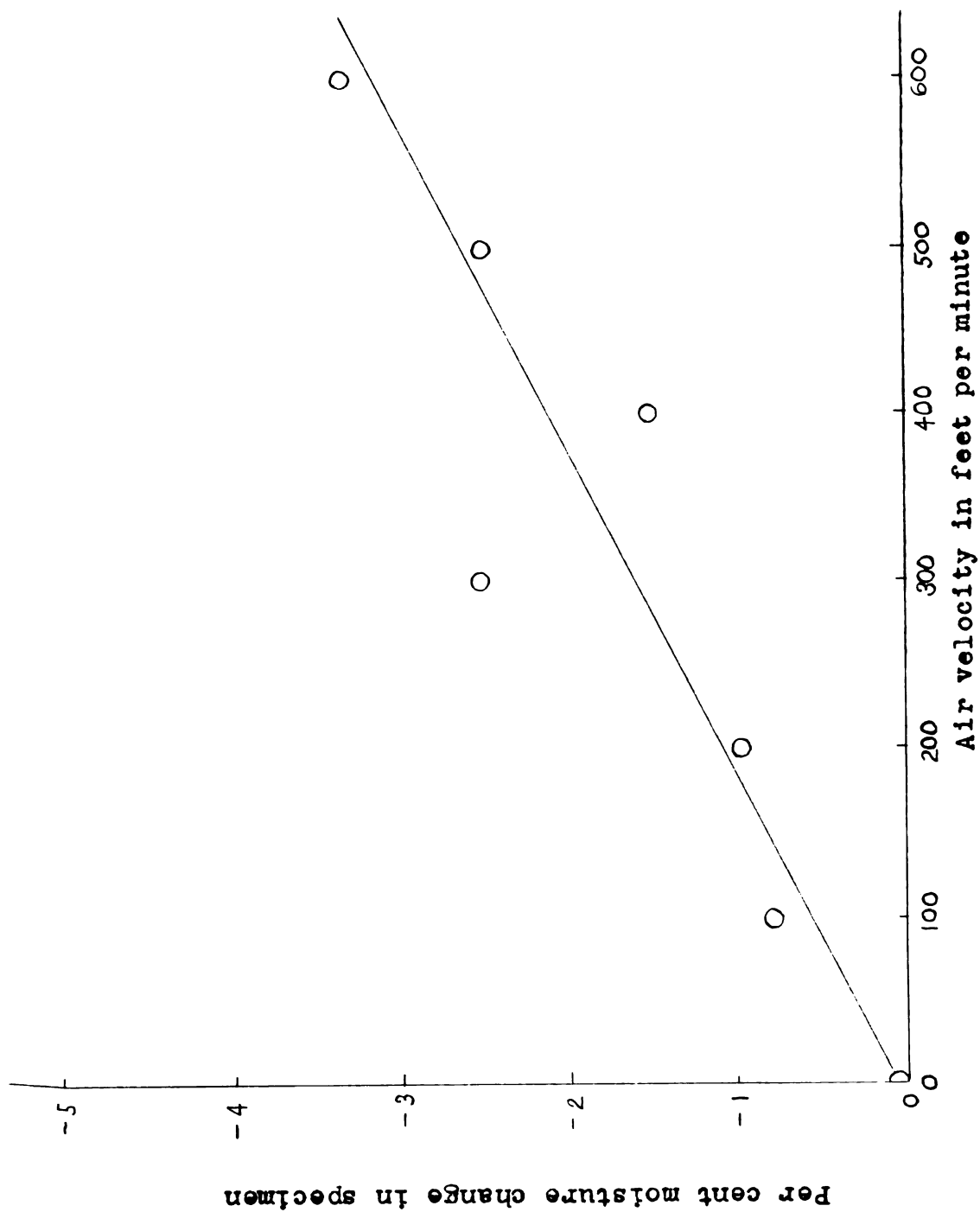


FIGURE 15
PER CENT MOISTURE LOSS WHEN DEFROSTING
AT 71 DEGREES FAHRENHEIT

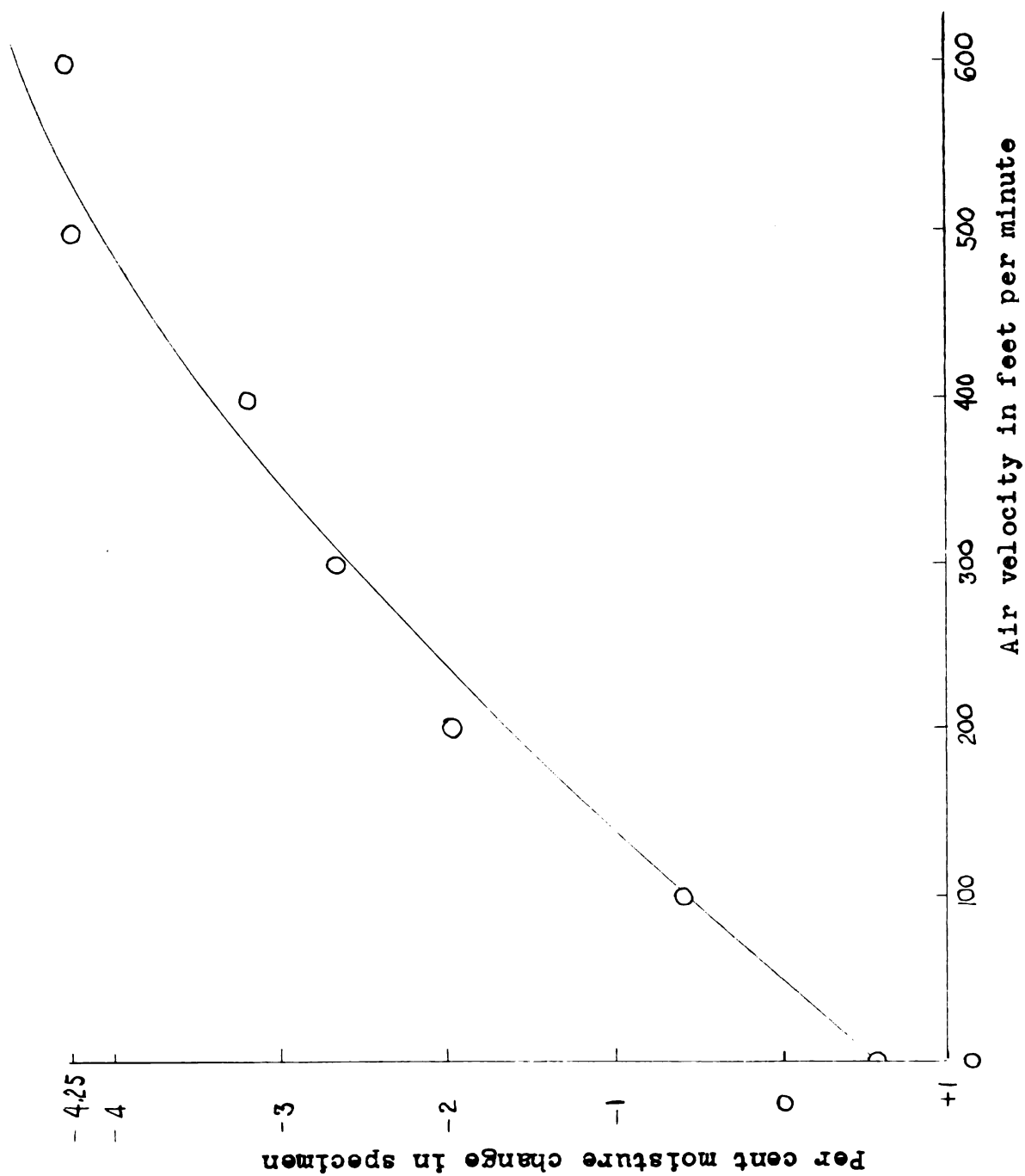


FIGURE 16

PER CENT MOISTURE LOSS WHEN DEFROSTING
AT 81 DEGREES FAHRENHEIT

SUMMARY

The influence of forced convection on the rate of defrosting ground beef has been analyzed in this chapter by averaging the rates of defrosting of all replications at given air velocities and temperatures, and it was determined that at both 71 and 81 degrees Fahrenheit the rate of defrosting was increased by defrosting at a higher air velocity. It was also determined that the rate of defrosting was increased when the ground beef specimens were defrosted at 81 degrees Fahrenheit from the rate of defrosting obtained when defrosting at 71 degrees Fahrenheit.

An optimum air velocity was determined by observation of the rate of defrosting curves plotted on a graph. The optimum air velocity was placed between 350 and 400 f.p.m.

Chapter IV concluded with an analysis of the moisture loss at the two defrosting temperatures and seven air velocities. Moisture loss was found to be greater at higher temperatures and higher air velocities.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

The purpose of this study was to determine the effect of air velocity on the rate of defrosting ground beef. The purpose was broken down into three objectives: (1) to determine the effect of different air velocities at a given temperature on the rate of defrosting ground beef; (2) to determine the effect of a different air temperature at a given air velocity on the rate of defrosting ground beef; (3) to determine an optimum air velocity, within the air velocities studied, if the rate of defrosting is found to be influenced by air velocity.

Chapter II contained a review of background literature covering the three methods of heat transfer, conduction, convection and radiation, and also references giving information about the insulating layer of air surrounding a solid and forming a barrier to heat transfer.

A search made for literature about defrosting meat revealed little information on the subject.

Chapter II also discussed the factors which affect the rate of defrosting meat. The factors are: (1) composition of the specimen; (2) size and shape of the specimen; (3) temperature of the air surrounding the specimen;

(4) velocity of the air past the specimen; (5) amount of surface dehydration of the specimen; (6) relative humidity of the air surrounding the specimen; (7) initial temperature of the specimen; and (8) final defrosted temperature of the specimen.

The testing apparatus and methodology of collecting data discussed in Chapter III were designed to hold the factors affecting the rate of defrosting as constant as possible.

In Chapter IV representative defrosting curves were presented to show the time-temperature relationship during the defrosting of a ground beef specimen at the selected air velocities.

The defrosting data were presented in two ways: (1) as rates of defrosting having the dimensions of degrees Fahrenheit change per minute, and (2) defrosting time in minutes that it took the temperature at the center of the specimen to go from +2 degrees Fahrenheit to +34 degrees Fahrenheit.

The data gathered at the two defrosting temperatures of 71 and 81 degrees Fahrenheit were compared to determine the effects of the different air temperatures at the same air velocities on the rate of defrosting ground beef.

A record was kept of the moisture loss from the meat specimens during defrosting at the different temperatures

and air velocities to help determine the practicality of defrosting by the forced convection method at 71 and 81 degrees Fahrenheit.

CONCLUSIONS

A study of the defrosting rates of one pound ground beef specimens at selected air velocities and air temperatures has borne out the hypotheses used in making this study. The conclusions derived from this study are:

1. The first hypothesis, that forced convection does increase the rate of defrosting frozen ground beef, was found to be true. The largest differential in rate of defrosting between any two sequential air velocities, using velocities varying from still air to 600 f.p.m. by 100 f.p.m. increments, was found between the velocities of still air and 100 f.p.m. The second largest rate differential was found between 100 and 200 f.p.m. air velocities. The rate differentials continued to diminish as air velocities were increased, but not in regular progression.

2. The second hypothesis, that higher temperatures of the air surrounding the meat increases the rate of defrosting, was also found to be true.

3. The third hypothesis was to determine an optimum air velocity within the air velocities studied. An optimum air velocity might be placed by observation between 350 to 400 f.p.m. Air velocities above 400 f.p.m. produced a

slower rate of rise in the rate of defrosting than did the air velocities up to this general air velocity level.

It was not a primary purpose of this study to determine the percentage of moisture lost from the ground beef specimens during defrosting. However the specimens were weighed before and after defrosting and a record was kept of this information.

It appears from the data gathered that both higher air velocity and higher air temperatures tend to increase the moisture loss from the defrosting specimen.

RECOMMENDATIONS

While the defrosting tests were being conducted, several additional tests were conceived which might yield valuable information on the defrosting of frozen meats.

Some work was done with the data from these tests to determine whether or not relative humidity influenced the rate of defrosting. However, the information was very limited so no valid conclusions could be drawn. The limited data indicate that increased relative humidity increases the rate of defrosting. It is recommended that a study be designed to obtain more information on the effect of relative humidity on the rate of defrosting.

Recent developments in plastic packaging indicate the possibility of defrosting packaged meat as fast or faster than uncovered meat without the loss of moisture

which accompanies the defrosting of uncovered meats under forced convection conditions. It is recommended that defrosting tests be designed to determine the rate of defrosting plastic wrapped meats.

The conclusions reached in this study apply only to the conditions used in these tests. It is recommended that further tests be conducted using temperatures higher than 81 degrees Fahrenheit, but below cooking temperatures, and below 71 degrees Fahrenheit, but not below the normal refrigerator storage temperature for meat of 38 degrees Fahrenheit. Also tests of air velocities above the 600 f.p.m. maximum used in these tests would contribute to defrosting information.

It is recommended that a study be made on the feasibility of developing a forced convection defrosting device for commercial use. There is also the possibility of adapting existing equipment, such as forced convection ovens or a refrigerator with an additional air circulating system, for the purpose of defrosting in shorter periods of time than is possible by defrosting in still air.

One aspect of defrosting at temperatures above 40 or 45 degrees Fahrenheit is that of bacteria growth in the meat. No attempt was made to measure the bacteria growth in these tests and it is, therefore, recommended that similar tests be conducted with the purpose of determining whether or not the meat becomes dangerously contaminated.

SELECTED BIBLIOGRAPHY

A. BOOKS

- Brown, A. I., and S. M. Marco. Introduction to Heat Transfer. New York: McGraw-Hill Book Company, Inc., 1951. 267 pp.
- Henderson, S. M., and R. L. Perry. Agricultural Process Engineering. New York: John Wiley and Sons, Inc., 1955. 402 pp.
- Lowe, Belle. Experimental Cookery. Fourth edition. New York: John Wiley and Sons, Inc., 1955. 573 pp.
- Stoever, H. J. Applied Heat Transmission. New York: McGraw-Hill Book Company, Inc., 1941. 226 pp.
- Tressler, Donald K., and Clifford T. Evers. Fresh Foods. Vol. I of The Freezing Preservation of Foods. Westport: The AVI Publishing Company, 1957. 1214 pp.
- White, Harvey E., Modern College Physics. Second edition. New York: D. Van Nostrand Company, Inc., 1953. 823 pp.
- Wilson, E. Bright, Jr., An Introduction to Scientific Research. New York: McGraw-Hill Book Company, Inc., 1952. 375 pp.
- Worthing, A. G., and D. Halliday. Heat. New York: John Wiley and Sons, Inc., 1948. 522 pp.

B. AGRICULTURAL EXPERIMENT STATION REPORTS

- Cone, J. F., Mary L. Dodds, N. B. Guerrant, J. G. Heck, Jean H. Sabry, J. E. Nicholas, M. D. Shaw, and R. Q. Thompson. "Effects of Thawing and Refreezing on the Quality of Certain Frozen Foods", Bulletin 614, Pennsylvania State University, (November, 1956), 22 pp.
- Fenton, F., I. T. Flight, D. S. Robson, K. C. Beamer, and J. S. How. "Study of Three Cuts of Lower and Higher Grade Beef, Unfrozen and Frozen, Using Two Methods of Thawing and Two Methods of Braising", Cornell University Agricultural Experiment Station Memoir 341, (March, 1956), 67 pp.

C. PERIODICAL LITERATURE

- Averbach, E., H. Wang, N. Maynard, D. M. Doty, and H. R. Kraybill. "A Hystological and Hystochemical Study of Beef Dehydration V. Some Factors Influencing the Rehydration Level of Frozen Dried Muscle Tissue," Food Research, XIX (March, 1954), pp. 557-63.
- Deinker, C. F., and O. G. Hankins. "Rates of Freezing and Thawing Meats," Food Technology, III (December, 1953), pp. 53-8.
- Paul P., and A. M. Child. "Effect of Freezing and Thawing Beef Muscle Upon Press Fluid Losses and Tenderness," Food Research, II (July, 1937), pp. 339-47.
- Tappel, A. L., R. Martin, E. Plocher. "Freeze-dried Meats V. Preparation Properties and Storage Stability of Precooked Freeze-Dried Meats, Poultry and Seafood," Food Technology, II (November, 1957), pp. 599-603.
- Tischer, R. G., M. C. Brockman. "Freeze-Drying Ups Quality of Q. M. Quick-Service Rations," Food Engineering, XXX (January, 1958), pp. 110-12.
- Wang, H. E. Averbach, V. Bates, D. M. Doty, and H. R. Kraybill. "A Hystological and Hystochemical Study of Beef Dehydration IV. Characteristics of Muscle Tissue Dehydrated by Freeze-Drying Techniques," Food Research, XIX. (March, 1954), p. 543-45.
- Wierlicki, E., L. E. Kunkle, And F. E. Deatherage, "Changes In The Water Holding Capacity and Cationic Shifts During the Heating and Freezing and Thawing as Revealed by a Simple Centrifugal Method Measuring Shrinkage," Food Technology, II (February, 1951), pp. 69-73.
- Wierlicki, E., V. R. Cahill, and F. E. Deatherage, "Effects of Added Sodium Chloride, Potassium Chloride, Calcium Chloride, Magnesium Chloride and Citric Acid on Meat Shrinkage at 70°C and of Added Sodium Chloride on Drip Losses After Freezing and Thawing," Food Technology, II (February, 1957), pp. 74-76.

D. UNPUBLISHED MATERIAL

- Tucker, H. Q. "The Effect of Fat and Moisture on the Freezing of Beef." Unpublished Masters thesis, Michigan State University, East Lansing, Michigan, 1953.

ROOM USE ONLY

ROOM USE ONLY

MICHIGAN STATE UNIVERSITY LIBRARIES



3 1293 03062 2066