



INVESTIGATING AIR MOVEMENT INSIDE OF PACKAGES
TO DETERMINE IF IT IS A SIGNIFICANT FACTOR
WHEN TESTING PERMEABILITY RATES OF PACKAGES

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THESIS



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ABSTRACT

INVESTIGATING AIR MOVEMENT INSIDE OF PACKAGES TO DETERMINE IF IT IS A SIGNIFICANT FACTOR WHEN TESTING PERMEABILITY RATES OF PACKAGES

By

William Davis Loveland

Air movement over the inside surfaces of packages would increase the Moisture Vapor Transmission Rate through the walls of the package. To date, no research has been performed to make accurate measurements to determine if air movement inside of packages exists. This research was performed to determine if air movement inside of packages exists, to record the velocities of the air movements found, and to map the direction of flow. The results of this research will be useful to those in the packaging industry interested in calculating the Moisture Vapor Transmission Rate of packages.

The packages used for testing were various types of commercial packages readily available on the retail shelf. The test conditions to which these packages were subjected are: static conditions, air movement over outside surfaces, temperature differential, and vibration. Both empty packages and packages containing product were tested.

The instrumentation used is capable of measuring air velocities as low as 0.28 feet per minute. Using this instrumentation, no air movement could be detected in any of the packages tested under the static condition. Also no air movement could be detected in the packages tested

under the condition of air movement across their outside surfaces. Packages tested under temperature differential did have measurable air movement inside them. Velocities of over 3 feet per minute were measured inside of some of the packages tested. The air movement measured was turbulent and nondirectional. This made it impossible to draw maps of the direction of flow. Readings were also recorded for air movements inside of packages subjected to various frequencies of vibration. It is not possible to determine from this research whether these readings were caused by air movement produced inside the package by vibration.

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BY

William Davis Loveland

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INTRODUCTION

The performance of a package on the retail shelf and in storage is directly related to the permeability rate of the package. It has been proven that the flow rate of sweep gas over the surface of a barrier material has an effect on the permeability rate through the material.¹ As the flow rate of the sweep gas increases from zero, the permeability through the material increases. It has also been shown that a flow over the surface of both sides of a material will further increase its permeability rate.

Air flow over the outside surfaces of packages sitting on retail store shelves is known to exist and measurements of the velocities of these flows have been made.² Up to this time, however, there has been nothing but conjecture about whether or not there is flow over the inside surfaces of packages. It was suspected that some type of flow did exist inside of packages. Jerry Angst, in a report submitted to Dr. Hugh E. Lockhart at Michigan State University in August, 1967, stated that he had detected air movement inside of packages. Mr. James B. Shields, Instrument Sales Division, Hastings-Raydist Incorporated, Hampton, Virginia, reported in a telephone conversation with the author, August, 1968, that his company had experienced air movement inside of closed paperboard containers. He could not provide information as

to the type and caliper of paperboard or to the size of the containers. They had not experimented further to determine why this phenomenon was detected. They attributed the air movement to the porosity of the paperboard and to heat which might radiate through the paperboard material. The research performed for this thesis is to detect and accurately measure any air movements which might be present inside of packages.

The instrumentation used in this research to measure air movements is capable of detecting air flow as low as 0.28 feet per minute. The velocity of air movements can be measured with an accuracy of approximately $\pm$ 0.161 feet per minute. Directional readings are taken for all air movements detected in order to make mappings of the movements and to determine the air-flow pattern inside of the packages tested.

Several different types of commercial packages, varying in style and material composition, are tested. Packages are tested both containing product and with the product removed. All of the packages tested were tested under the same four conditions. These conditions consisted of:

1. Static Condition (Package undisturbed and protected from the other three test conditions)
2. Temperature Differential (Bottom of package heated to a temperature 10°F hotter than the top)
3. Outside Air Movement (Air movement across the outside surfaces of the package, up to 100 feet per minute)
4. Vibration (Package vibrated through a frequency range of 1 cps to 10,000 cps, 0.25 inch amplitude)

The aim of this thesis is to survey an area of packaging which has become of concern to the packaging industry recently

and for which no technical data has been reported. Its scope is limited to a small portion of the packages commercially available on the retail shelf today. The data gathered is technically accurate enough to be useful to those concerned about this area of packaging.

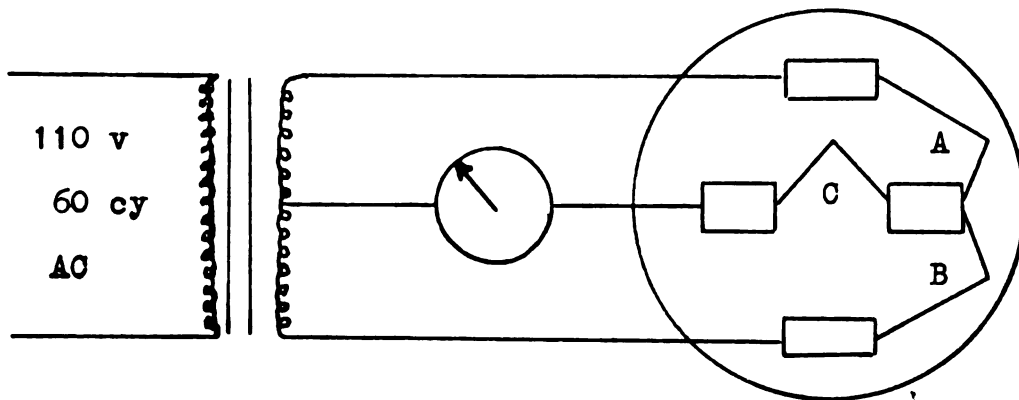
The value of this thesis lies in that its results can be used as a documented guide, by those in the packaging industry interested in whole package testing, to determine whether or not their testing systems should include provisions for sweeping gas over the inside of packages. It also establishes the range of velocities which might be present inside of packages and the type of flow which would be found.

INSTRUMENTATION

The instrumentation used for recording measurements of air movements is centered around the Hastings Air Meter, Model AB-12. The Hastings Air Meter has a direction sensing air velocity probe (S-22A), which works on a compensated heated thermopile principle. A low voltage AC bridge circuit has two noble metal thermocouples as sensing elements. Thermocouples A & B are heated by alternating current. Any change in air flow past the probe causes a change in temperature of these thermocouples. This results in a change in the DC voltage output from the thermocouples. This voltage change is monitored by a millivoltmeter connected to the circuit.

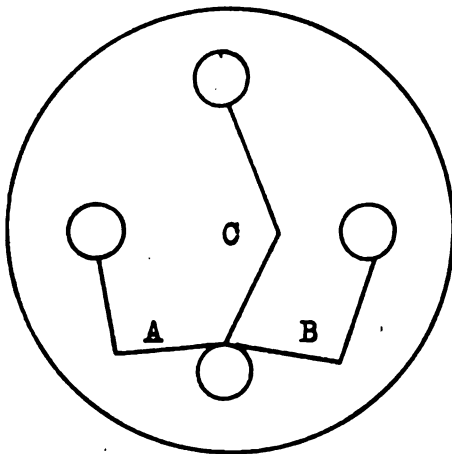
A third thermocouple (C) is in the same circuit as the DC millivoltmeter. This couple is the same size as those in the AC circuit, but it is unheated. It is the function of this thermocouple to compensate for ambient temperature changes. A change in ambient temperature develops voltage deviations in all of the thermocouples; but the transient effects in the heated and unheated elements are equal and opposite, thus compensating for changes in ambient temperature. A diagram of the Hastings Air Meter and the directional probe are shown in Figure 1.

Schematic



Meter Probe

Top



Front

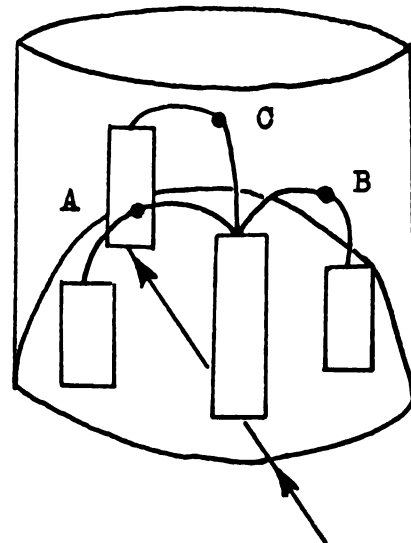


Figure 1 Diagram Of Hastings Air Meter Principle

The millivoltmeter, which monitors the change in DC voltage produced by the thermocouples, is calibrated to show air velocity in feet per minute. A DC voltage of 2.0 millivolts will cause a full scale deflection of the meter. At full scale deflection, the meter reading is 0.0 feet per minute indicating no air movement past the probe. In other words, the velocity reading is in inverse proportion to the voltage across the meter. As the voltage across the meter decreases, the velocity reading increases. This is not however, strictly a linear relationship. A potentiometer located in the meter circuit allows the meter to be accurately adjusted to a zero position.

The air velocities of most interest to this research are between 0.0 feet per minute and 2.0 feet per minute. This is represented by a voltage range of only 0.13 millivolts on the meter scale. This means that we are working with only 6.5% of the full scale. In order to more accurately record the readings in this small range of the scale, the scale is expanded.

The Keithley Instruments, Model 660, Guarded DC Differential Voltmeter, is connected across the meter circuit in order to expand this area of the scale and make the readings more accurate. This meter is capable of accurately recording voltages to ± 0.002 millivolts. The Hastings Air Meter is only capable of an accuracy of ± 0.027 millivolts. When recording air velocities from 0.00 feet per minute to 2.00 feet per minute, this sensitivity would mean an accuracy of

96.3% for the Differential Voltmeter as compared to an accuracy of only 50.0% for the Hastings Air Meter.

The power supply used with the Hastings Air meter was three 4FH Burgess 3 volt batteries connected in series. This supplied the 9 volts needed to operate the meter. The original system, which this replaced, was four $1\frac{1}{2}$ volt size C batteries connected in series. The original system could not supply a constant voltage to the meter for more than a few seconds. This caused inaccuracies in the air velocity readings.

In order to detect any sharp voltage drops in the system due to electrical shortcircuits or malfunctions, the system was continuously monitored by a digital voltmeter. The Digitec, Model 200 A, Digital DC Voltmeter, manufactured by the United Systems Corporation, was connected across the leads from the power supply to the Hastings Air Meter. This controlled inaccuracies in the recorded velocity readings due to voltage drops unrelated to those caused by air movement.

Another piece of equipment that was found to be necessary for accurate readings is a holding device for the meter probe. The probe is very sensitive to even slight changes in its horizontal position or in its rotational angle. A change in either one of these orientations would cause it to produce different and inaccurate voltage readings. The probe holding device is designed to make sure that the probe remains in the same orientation when it is moved from one test condition to another.

CALIBRATION

The National Bureau of Standards does not recognize a standard test procedure or test equipment for measuring air velocities below 60 feet per minute. The Hastings Air Meter was calibrated by Hastings-Raydist Inc. using their own method of calibration. This method was not obtainable for use in this research nor was information available on the relationship between voltage output of the thermocouples and air velocity for readings below 2.00 feet per minute.³ A method for this calibration below 2.00 feet per minute was therefore devised specifically for use in this research.

Equipment

The main piece of equipment made for this calibration is an extruded glass tube 1.01 inches in diameter. The tube is designed to channel a flow of air past the meter probe and then into a measured area of the tube where the volume of the flow is measured. Figure 2 shows a diagram of the calibration tube. Nitrogen gas at 10 psi is fed into one end of the glass tube from a pressurized tank. As the nitrogen enters the tube, a 1½ inch thick section of steel wool in the tube disperses the nitrogen flow so that it will become turbulent.

Turbulent flow is necessary because it causes a much more uniform distribution of velocity over the cross sectional

area of the tube than is caused by viscous flow. It also follows an entirely different law of resistance. In viscous flow, a uniform velocity is never obtained. The velocity at the center of the tube is approximately 20 percent greater than the mean velocity in the tube. This is because of the retarding effect on the velocity by the walls of the tube. As the flow becomes more turbulent, the velocity becomes more uniform throughout the cross section of the tube.⁴ The more uniform the flow becomes in the tube, the less critical the placement of the meter probe in the tube becomes. The flow is also made turbulent because turbulent flow is the type of flow that is expected to be encountered inside the packages.

At a point 18 inches further down the tube from the steel wool is the insertion point for the meter probe. This is accomplished through a hole blown in the side of the tube. A stem is connected to the tube 6 inches further down from this insertion point. This stem admits soap bubbles into the tube. These bubbles are used in the calibration process. Next comes the metering section of the tube where the volume of flow through the tube is measured.

Along with this flow tube is a simple bubble-making apparatus which produces soap bubbles which are used in the calibration process. The bubble-making apparatus is a hose connected to an air supply. A tube with a bulb containing liquid soap at one end is inserted into the hose. The soap is forced into the hose by squeezing the bulb. The air

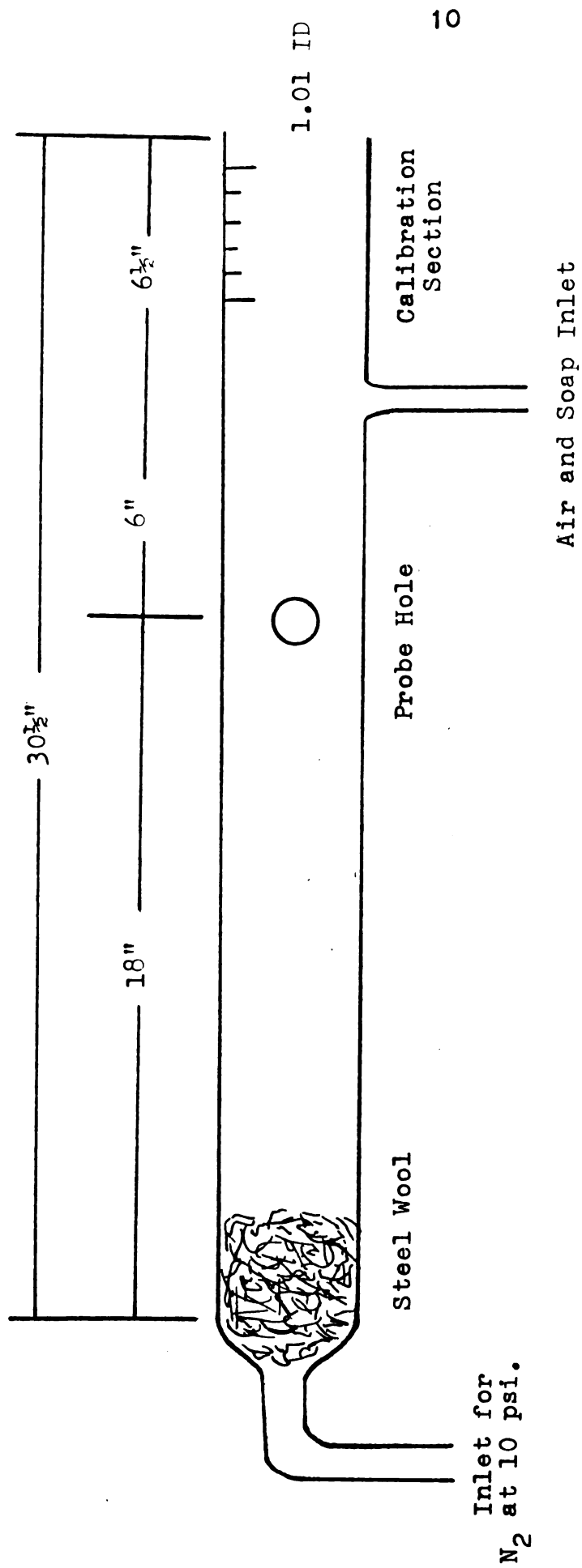


Figure 2 Diagram of Glass Calibration Tube

flowing in the hose forces the soap up into the calibration tube. As it enters the tube, it forms a bubble across the cross section of the tube. A clamp is then placed on the hose sealing off the air supply. The nitrogen flow then pushes the bubble into the metering section of the tube. The passage of the bubble through this section is timed in order to calculate the volume flow of the nitrogen. The calibration equipment is shown in Figure 3 and Figure 4.

It is not possible to produce only a single bubble at a time inside the flow tube. The design of the equipment is such that it creates a situation where two or more bubbles are always produced at a time. It was found, however, through repeated experimentation that this situation did not affect the speed of the bubble through the calibration section of the tube. It was found that as long as the bubbles in the tube are not multiple bubbles, joined together or foam and there is no soap residue on the walls of the tube, it does not matter how many bubbles there are in the tube at the time of calibration. Results are reproduceable with from 1 to 6 bubbles being in the tube at a time. The readings taken for calibration purposes are not made with more than 3 bubbles in the tube at a time.

It is found necessary to tilt the tube on an angle of 5° from the nitrogen inlet downward toward the open end. This is necessary to let the excess soap solution in the tube drain out the end. If this solution remains in the bottom of the tube, its attraction to the calibration bubble will greatly

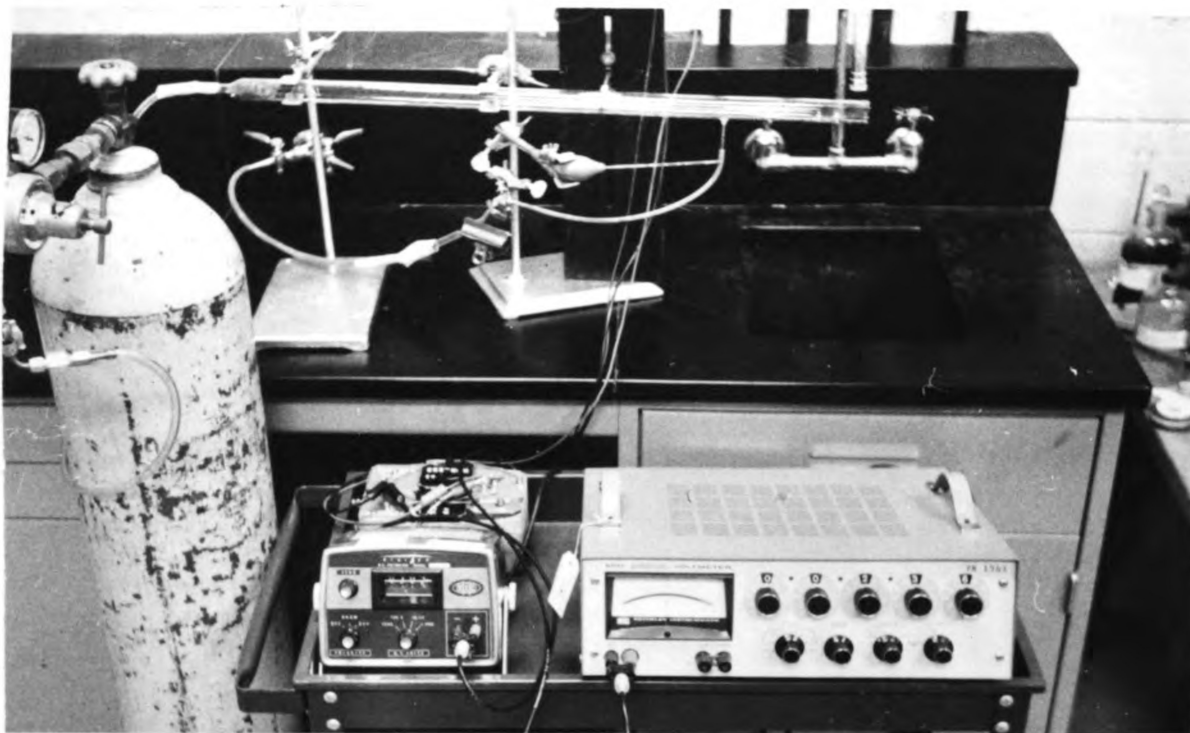


Figure 3. Calibration equipment.

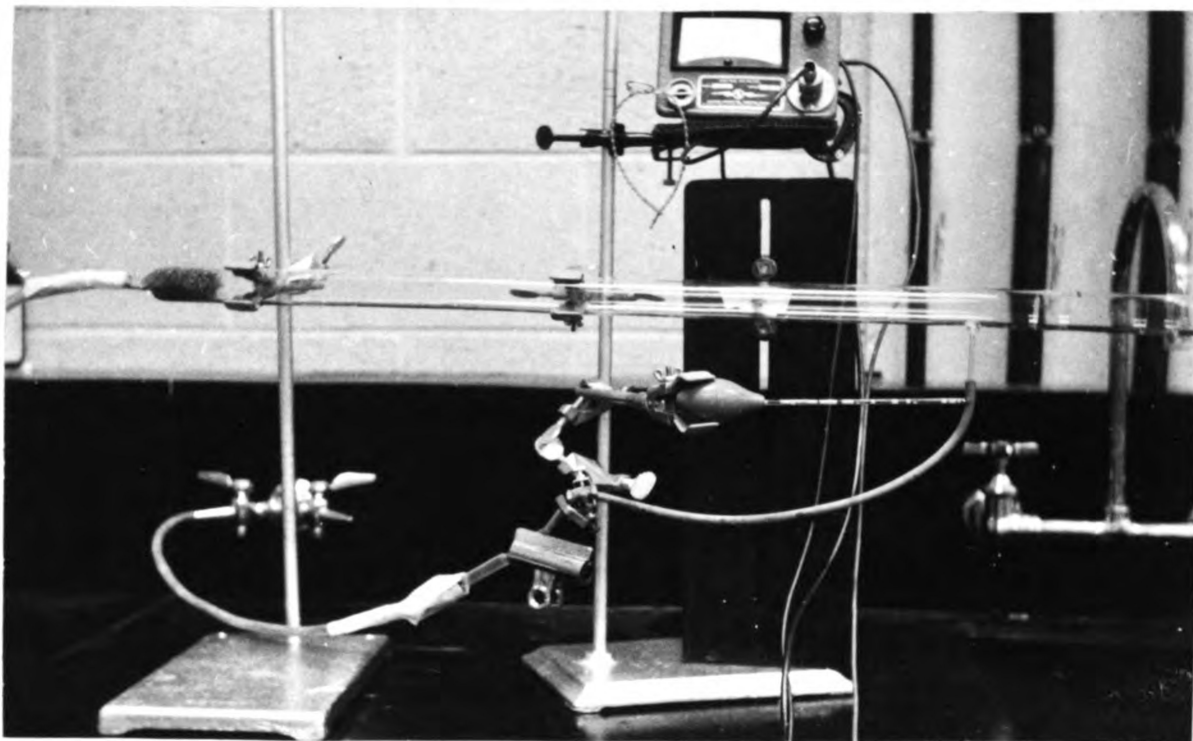


Figure 4. Bubble making apparatus.

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affect the speed of its passage through the tube.

Calibration Procedure

The mean velocity of a fluid mass flow in a pipe is equal to its mean speed or the mean distance it travels, per unit of time, relative to the pipe wall. The mass of fluid flowing per unit of time is the same at any two points in the fluid stream provided that the flow is steady.⁵ Using these assumptions as laws for fluid flow in the glass calibration tube, the following formula is used to calculate the mean velocity of flow in the tube.

$$U = \frac{G}{Aw}$$

where: A = transverse area of pipe (sq. ft.)

U = mean velocity of fluid (ft. per sec.)

w = specific weight of fluid (lb. per cu. ft.)

G = weight (mass) rate of flow (lb. per sec.)

If the fluid is compressible, the density will vary throughout the flow in direct proportion to the drop in pressure due to friction, assuming that the flow is isothermal. The laws relating to fluid flow in pipes are dependent upon the physical and mechanical properties of the fluid such as viscosity, density, pressure or head, and velocity. They are also dependent upon the nature of the fluid itself; that is, to what degree the fluid is compressible and on the size and roughness of the pipe used. In order to include all of the variables that affect the flow of a gas in a pipe, a more complicated formula such as the Chezy formula should be used.⁶

$$V = C \sqrt{R_H F / L}$$

where: V = linear velocity (ft. per sec.)

C = friction factor

R_H = hydraulic radius (ft.)

F = friction loss (ft.-lb. mass of fluid passing)

L = duct length (ft.)

However, when a compressible fluid is flowing under low pressure, the pressure drop is usually so slight as to make the change in specific weight negligible. Also, since there is no way of calculating the friction loss in the tube, which should be very small, the simpler equation for finding the velocity in the tube is used.

The calibration procedure is first to produce a bubble across the cross section of the glass tube. The air supply and nitrogen supply are then both sealed off so there is no flow. The differential voltmeter is then nulled against the voltage being produced by the thermocouples. The valve on the nitrogen tank is then partially opened causing flow in the tube. The bubble is pushed by the flow of nitrogen and is timed as it passes through the metering section in the tube. The metering section is 3.78 inches long. Since the diameter of the tube is 1.01 inches, the volume of the metering section is 0.00175 cu. ft. The volume rate of flow is calculated by dividing the volume of the metering section (0.00175 cu. ft.) by the time it takes the bubble to cover the metered distance. The mass rate of flow is then calculated

by multiplying this value by the specific gravity of nitrogen (0.0782 lb/cu. ft.). The mean velocity is calculated by using the formula.

This procedure is repeated, opening the valve on the nitrogen tank different amounts each time. This is done until many readings for voltage, read off the meter, and calculated velocities are obtained for velocities between 0 feet per minute and 3 feet per minute. The values of voltage (in volts) vs. velocity (in feet per minute) are then plotted on a calibration graph.

Calibration Graph

In order to translate the voltage readings from the Hastings Air Meter into velocity of the air movement past the probe, the relationship between the two variables has to be determined. This is done by first plotting the values of voltage vs. velocity, obtained in the calibration procedure, on a graph. A regression line is then drawn by finding the line of best fit through the points. A measure of how accurately the voltage predicts the velocity is then calculated.

A useful measure of the accuracy of prediction is obtained by calculating the standard deviation of the errors of prediction. It is then assumed that the positive errors corresponding to points above the regression line cancel the negative errors corresponding to points below the regression line. The sizes of all the errors are obtained by subtracting the regression line value of y , denoted by y_1' , from the observed value of y , denoted by y_1 . The size of the errors

is therefore denoted by $(y_i - y_i')$. It is then possible to calculate the standard error of estimate.

$$\text{Standard Error of Estimate } s_e = \sqrt{\frac{\sum_{i=1}^n (y_i - y_i')^2}{n - 2}}$$

Assuming that the values of $(y_i - y_i')$ are independently and normally distributed with zero means and the same standard deviation, then s_e is an estimate of the standard deviation. The normal distribution assumption enables approximate probability statements about the errors of prediction to be made. It can be stated that approximately 95 percent of the errors of prediction will be less than $1.96s_e$ in magnitude.⁷

$$s_e = \frac{0.5277}{78}$$

$$s_e = 0.00677$$

$$1.96s_e = 0.133$$

Approximately 95 percent of the errors of prediction will be less than 0.133. This means that by using the voltage from the Hastings Air Meter and using the calibration curve, the velocity of the air movement can be determined with an accuracy of ± 0.133 feet per minute. The calibration curve is shown in figure 5.

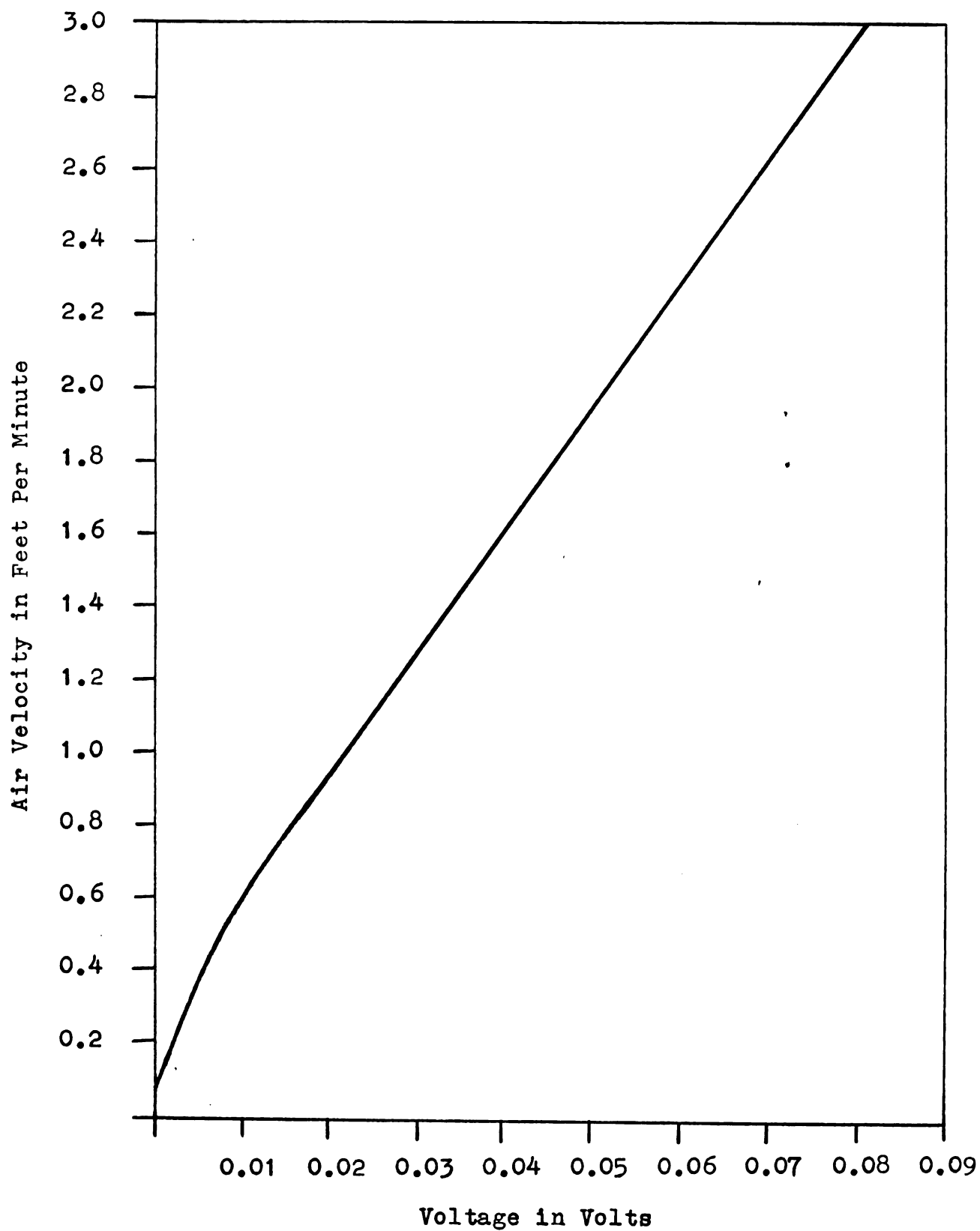


Figure 5 Calibration Graph

TESTING PROCEDURE

In order that the results of this research can be reproduced and that all the conditions of the research can be controlled, a standard testing procedure is established. Every package is tested using this procedure. All of the conditions set forth in the testing procedure are not deviated from in recording any of the test results.

Standard Package

Since it cannot be assured that the air meter will remain in calibration over an extended length of time, it is necessary to recalibrate it before each reading is taken. In order to establish a standard condition in which the air meter can be adjusted to zero feet per minute, a package is built in which no known factors can cause air movement. This "standard package" is a plywood container 7" x 7" x 7". The inside of the container is lined with 2" thick styrofoam for insulation against heat conduction through the plywood which could cause convection currents inside the container. The outside of the standard package is overwrapped with aluminum foil to reflect infra-red radiation and further act as insulation from outside conditions.

In order to make sure that there is no air movement inside of the standard package, the air meter probe is

inserted into the package and the package tested under varying environmental conditions. No variation in the meter reading under any of the test conditions is considered an indication that no air movement is present and that the standard package can be used to establish a condition in which there is no air movement.

Nulling the Meter

Before each reading is taken, the probe is inserted into the standard package and the voltage nulled on the differential voltmeter. This establishes a voltage reference that can be designated a velocity of 0.00 feet per minute.

In testing the packages the scale on the differential voltmeter has to be changed from 0.010 mv full scale to 0.100 mv full scale in order to protect the meter from overloading. This condition occurs when the probe is removed from the standard package and exposed to high velocities in the outside environment before it is inserted into the test package. The scale is then changed back to 0.010 mv full scale in order to take the test readings. An overloading of the meter will cause a static charge in the meter which will cause large inaccuracies in the test readings. Every time the meter scale is changed to a higher scale range and back again more than once, the meter has to be nulled. Also if the meter is overloaded, the differential voltmeter should be allowed to stand for about an hour to dissipate the charge before any further readings are taken. The meter should again be nulled before taking readings.

Static Condition

Each package is tested under four conditions. The first condition, the static condition, is used as a control condition; and the other three are conditions which are likely to be encountered during normal storage and retail shelf periods.

For the purpose of this research, a static condition is defined as an environment free from temperature differentials, air circulation, or vibration. In order to obtain this condition, the test package is placed in an enclosed area free from air currents and vibration. The atmosphere inside the enclosure is maintained at 77°F and 5% relative humidity. The package is stabilized in this environment for a period of at least 5 minutes before it is tested.

Environmental Air Movement

A second test condition under which the packages are tested is an induced air flow over the outside surfaces of the package. In order to create this condition, a test chamber is built in which regulated air flows can be created. The test chamber is a rectangular tunnel 24 inches long by 14 inches wide by 17 inches high. An 8 inch in diameter fan blade is mounted at one end of the tunnel to create air flow through the tunnel. The speed of the fan is changed by regulating the voltage to the fan motor by the use of a powerstat. In order to regulate the air velocities over the surface of the packages to specific known amounts, the air velocities over the surface of the packages are correlated

to the voltage supplied to the fan by the powerstat. This is accomplished by recording the powerstat voltage and then measuring the air velocity over the surface of the package by using the Hastings Air Meter. In order to make sure that changes in line voltage do not affect the speed of the fan and consequently the air velocities produced, the line voltage to the powerstat is monitored by a vacuum tube voltmeter.

All of the packages are tested at a distance of 13 inches from the fan blade. At this distance the system is capable of producing air velocities up to 100 feet per minute. The air flow created by the fan is very turbulent and simulates very well the turbulent air flow that is encountered by a package on the retail store shelf.

Temperature Differential

The third test condition is that of a temperature differential between the top and bottom of the test package. The differential is established at 10°F . After taking several measurements of temperature differentials between the shelves of retail super markets it is felt that a 10°F differential is the maximum differential experienced by the large majority of packages under display conditions. The average package will only experience a 2°F to 3°F temperature differential. There is no way of measuring differentials which might be experienced under warehousing conditions. It is felt, however, that a 10°F differential will adequately represent severe conditions.



Figure 6. Controlled airflow test chamber.



Figure 7. Testing under conditions of induced airflow.

To establish this condition, the bottom of the test package is heated with a controlled temperature hotplate. Thermometers attached to the bottom and the top of the package measure the temperature differential. Uniformity in the test condition is established by stabilizing all the test packages at the same temperature before heating. The heating process progresses at the same rate for all of the packages by always having the regulated hotplate set at the same temperature and positioning it always at the same distance from the package. Testing under this condition is shown in figure 8.

Vibration

The fourth condition under which the packages are tested is subjecting them to different frequencies of vibration. The packages are vibrated through a frequency range of 1 cycle per second to 10 kilocycles per second. The amplitude of the vibrations is set at 0.25 inches. The reason this value is selected is because it is the lowest amplitude at which significant air movements can be detected.

The instrumentation used to create this condition is a Ling Shaker. The Ling Shaker is connected to a Hewlett Packard Signal Generator through an amplifier system. The frequency of the Ling Shaker is adjusted by setting the frequency output of the Signal Generator. The amplitude of the vibration is determined by adjusting the amplifier system. The package to be tested is secured to a platform connected to the Ling Shaker. The vibration instrumentation is shown in Figure 9.



Figure 8. Testing under conditions of temperature differential.

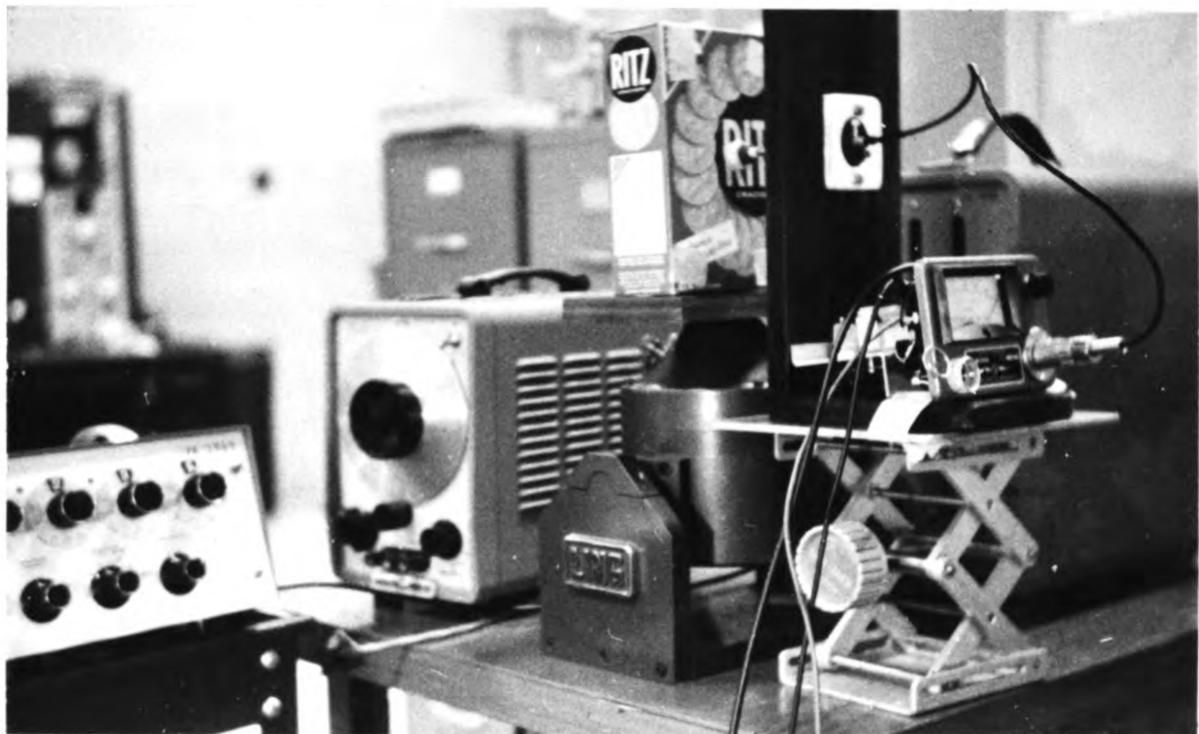


Figure 9. Testing under conditions of vibration.

Taking Readings

Readings of the air movement inside of the test package are made by first nulling the meter inside the "standard package" and then inserting the air velocity probe inside the test package. Any detectable air movement is read as a change in voltage reading on the differential voltmeter.

The probe is nulled by inserting it into the insulated package and allowing it to remain undisturbed for one minute. This gives any air movement, created by the insertion of the probe into the package, time to settle down below a detectable level. After the meter is nulled, the probe is allowed to remain inside the package another minute to make certain that there is no drift in the meter reading caused by unsettled air.

The meter scale on the differential voltmeter is then changed from 0.01 mv full scale to 0.10 mv full scale to guard the meter against overload caused by large voltage readings which will occur when the probe is removed and exposed to the relatively large air velocities in the outside environment. The probe is then inserted into the test package and is allowed to remain undisturbed for one minute while disturbed air is allowed to decrease to a negligible level. The meter scale is then changed back to 0.01 mv full scale. The test package is then subjected to one of the four conditions described and the voltage reading taken.

Finally the meter scale is again changed to 0.10 mv and the probe removed from the test package. It is inserted

into the standard; and after a minute wait, the scale is changed to 0.01 and a reading is taken. Any change between this voltage reading and the first voltage reading taken in the standard is considered as meter drift. This value is subtracted from the voltage readings taken in the test package in order to arrive at a more accurate test reading.

Recording Readings

All air movement detected inside the test packages is recorded in feet per minute. Since only 4 of the 220 readings taken are above 3.00 feet per minute these values are not plotted on the calibration graph. The symbol (**) is used to record these values. The probe used with the Hastings Air Meter to measure air movement is a directional probe. All air movement which is flowing in the opposite direction to that which the probe is measuring gives negative readings. The probe is only calibrated in its positive direction, therefore, no quantitative values are recorded for negative readings. There velocities are recorded using the symbol (neg).

Testing Full Packages

In order to test packages containing product, the thermocouples in the probe had to be protected from the product. If any of the product touches the hot thermocouples it burns onto the thermocouple and the probe can no longer be used. In order to avoid contact between the product and the probe, No. 16 wire screen is formed into a cylindrical tube 1 inch in diameter and placed into the full package. The screen forms a tunnel into which the probe is inserted.

Reflectivity

The air meter is very sensitive to any change in the temperature of the thermocouples. These temperature changes could be caused by means other than air movement past the thermocouples. The extraneous variables of the difference in heat reflectivity or absorption of the inner wrap or surface of a package could cause superficial air velocity readings. This variable is investigated in order to determine whether or not a difference in package inner wraps or surfaces should be included as a factor in taking test data.

Two extremes in package linings are tested. The test packages are two folding carton cake mix boxes $7\frac{1}{2}" \times 5\frac{1}{2}" \times 1\frac{1}{2}"$. One carton is lined with aluminum foil and the other carton's interior is painted with black paint. Both packages are tested under the same static conditions. The results show that there is no difference between readings taken in these packages. Different package liners or surfaces can therefore be excluded as a testing variable needed to be considered in this research.

Test Packages

An effort is made to test a good cross section of the packages commercially available on the retail shelf. The packages tested are chosen because it is thought that they represent, in size and configuration, the more widely used commercial packages. Some packages are tested with the product in them, and some are tested with the product removed. It is desirable to test the same type of package with and without product, but in some cases this cannot be done for fear that the product will damage the probe. Therefore, only the packages containing large particle products are tested with the product in the package. Table 1 shows the packages tested and a description of each.

TABLE 1
LISTING OF THE PACKAGES TESTED

PRODUCT	TYPE OF PACKAGE	DIMENSIONS
Quaker Puffed Wheat	Folding Carton	7½" X 2¼" X 10"
Lipton Tea Bags	Folding Carton	5½" X 4¾" X 2½"
Quaker Oats	Paperboard Tube	Dia. 4" Ht. 7¼"
Quaker Oats	Paperboard Tube	Dia. 5¼" Ht. 9¼"
Ritz Crackers	Folding Carton	6½" X 3¼" X 9"
Ritz Crackers	Folding Carton	5½" X 1½" X 7¾"
Lay's Potato Chips	Bag	7" X 4" X 15"
Johnson Baby Powder	Plastic Bottle	2½" X 2½" X 6½"

Testing Pattern

The aim of this research is to detect, measure, and map air movements found inside closed packages. In order to be able to map air flows discovered, testing patterns for the packages have to be devised. The testing patterns enable all the packages to be investigated to the same degree and establish standard reference points from which to base air mappings.

All rectangular packages are tested at the four corners and in their geometric center. In addition, a few of the rectangular packages are tested across the width of the package in order to establish a depth dimension to the mappings. Cylindrical packages, bags, and plastic can are tested in three positions vertically down the center of the package. Each of the probe insertion points on the package is given a number. The numbers start with 1 at the left uppermost point on the package and continue sequentially from left to right across the width of the package. For those packages where a depth dimension is tested, the numbering continues from left to right across the width of the package. The probe used in taking the readings is a directional probe. This allows not only the air velocity at each insertion point to be taken but also the direction of the air movement at the point can be determined. The probe is rotated through 360° in each insertion point. Readings are taken at intervals of 90° apart allowing readings in four directions. Each of the four directions is given a letter designation. The letter

A is used for the direction perpendicularly upward from the bottom of the package. The letter B designates the direction 90° clockwise from A (to the right of the package). At an angle of 180° from A (downward) is direction C and direction D is 270° from A (to the left).

TESTING RESULTS

Static Conditions

As defined in the Testing Procedures section of this thesis, a static condition is an environment free from temperature differential, air circulation, or vibration. These stimuli, which might produce air movement inside the package, are removed. The condition is used as a control condition for the other three variables. If air movement is detected inside the test package under this condition, it is known that other variables besides the ones being removed are responsible. If no air movement is noticed under this condition but is noticed later under one of the variable conditions under study, it can be predicted with a high degree of certainty that this variable condition is responsible for the movement.

The results of the test performed under the static condition show that there is no detectable air movement in any of the packages tested. The results show an air velocity reading of 0.00 feet per minute for all the packages tested. The indication holds constant whether the packages contain product or are empty and for all of the probe insertion points independent of probe orientation. The accuracy of these results is subject to the ability of the instrumentation to detect air movement. Therefore, these

results are accurate to 0.28 feet per minute. Below this value, the instrumentation is incapable of recording air movement. The readings recorded under this condition are shown in Table 2.

TABLE 2

TEST RESULTS FOR PACKAGES TESTED UNDER STATIC CONDITIONS
77° FAHRENHEIT 59% RELATIVE HUMIDITY

PACKAGE	AIR VELOCITY (fpm)
QUAKER PUFFED WHEAT (5 oz) (Empty)	0.00
LIPTON TEA BAGS (3½ oz) (Empty)	0.00
QUAKER OATS (18 oz) (Empty)	0.00
QUAKER OATS (42 oz) (Empty)	0.00
RITZ CRACKERS (8 oz) (Empty)	0.00
RITZ CRACKERS (8 oz) (Full)	0.00
RITZ CRACKERS (16 oz) (Empty)	0.00
RITZ CRACKERS (16 oz) (Full)	0.00
LAY'S POTATO CHIPS (4½ oz) (Empty)	0.00
LAY'S POTATO CHIPS (4½ oz) (Full)	0.00
JOHNSON BABY POWDER (9 oz) (Empty)	0.00

Outside Air Movement

Any measurable air movement over the outside surfaces of the package is defined as the condition of outside air movement. As described under Testing Procedures, the air velocity over the outside of the packages is varied from 0 feet per minute to 100 feet per minute.

The test results show that air velocities between 0 feet per minute and 100 feet per minute over the outside surfaces of the test packages did not create any detectable air movement inside the packages. A constant reading of 0.00 feet per minute is recorded for all of the test packages under all surface velocities in the 0-100 feet per minute range. The results did not vary for full or empty packages nor did it vary for any change in probe insertion position or probe orientation. Again, the accuracy of these results is subject to the ability of the instrumentation to detect air movement. Therefore, these results are accurate to 0.28 feet per minute. Below this value, the instrumentation is incapable of recording air movement. The test results obtained under this condition are shown in Table 3.

Temperature Differential

As defined under Testing Procedure, a condition of temperature differential is established when there is a 10°F difference in temperature between the top and the bottom of the test package. This condition is established by heating the bottom of the package.

TABLE 3

TEST RESULTS FOR PACKAGES TESTED UNDER CONDITIONS OF OUTSIDE
AIR MOVEMENT OF 0-100 FEET PER MINUTE

PACKAGE	AIR VELOCITY (fpm)
QUAKER PUFFED WHEAT (5 oz) (Empty)	0.00
LIPTON TEA BAGS (3 $\frac{1}{4}$ oz) (Empty)	0.00
QUAKER OATS (18 oz) (Empty)	0.00
QUAKER OATS (42 oz) (Empty)	0.00
RITZ CRACKERS (8 oz) (Empty)	0.00
RITZ CRACKERS (8 oz) (Full)	0.00
RITZ CRACKERS (16 oz) (Empty)	0.00
RITZ CRACKERS (16 oz) (Full)	0.00
LAY'S POTATO CHIPS (4 $\frac{1}{2}$ oz) (Empty)	0.00
LAY'S POTATO CHIPS (4 $\frac{1}{2}$ oz) (Full)	0.00
JOHNSON BABY POWDER (9 oz) (Empty)	0.00

Table 4 shows the wide range of air velocities that are produced inside the test packages under this condition. The velocities produced are mainly between 0 feet per minute and 3 feet per minute with only 4 of the 220 readings taken exceeding 3 feet per minute. Having a product in the package greatly reduced the velocity of the air movements in the package. The highest velocity recorded in a package containing product is 0.90 feet per minute. On the average, higher velocities are recorded in the larger packages than in the smaller packages, but they are not extremely higher. In some cases the velocities in the smaller packages exceeded the velocities in the larger packages.

An attempt is made to map the air movements inside the packages. The arrows in Figures 10 through 20 in the Appendix of this thesis show the direction of the air movement at the insertion points of the packages tested. The direction of the arrows is determined by calculating the vector sum of the air velocities at the insertion points. The length of the arrows, however, do not indicate the magnitude of the vector.

It can be seen from the Figures that the directions shown by the arrows, for any of the packages, do not have any definite pattern to them. It is therefore impossible to determine a general pattern of air movement inside the package and make mappings of the movements. A probable reason for lack of any regularity is that the air movements are very turbulent and discontinuous. There is no overall directionality throughout the package.

TABLE 4

TEST RESULTS FOR PACKAGES TESTED UNDER CONDITIONS OF
TEMPERATURE GRADIENT

PACKAGE		AIR VELOCITY (fpm)			
		(A)	(B)	(C)	(D)
QUAKER PUFFED WHEAT (5 oz, empty)	1	neg	neg	1.26	1.26
	2	neg	neg	.90	.20
	3	neg	1.60	2.28	1.26
	4	neg	2.28	2.76	neg
	5	neg	neg	.90	.72
LIPTON TEA BAGS (3 3/4 oz, empty)	1	2.92	1.60	1.96	neg
	2	neg	.90	1.08	neg
	3	neg	1.32	.56	1.26
	4	1.82	2.12	1.00	1.78
	5	neg	.72	.90	1.60
QUAKER OATS (18 oz) (empty)	1	2.28	.84	1.26	.90
	2	neg	1.60	.90	.56
	3	neg	neg	1.08	1.08
QUAKER OATS (42 oz) (empty)	1	**	1.26	.70	1.96
	2	**	1.26	1.42	1.60
	3	neg	1.96	1.42	1.26
RITZ CRACKERS (8 oz) (empty)	1	neg	neg	1.42	1.68
	2	neg	1.60	1.32	.38
	3	neg	1.12	1.00	.76
	4	neg	neg	1.36	**
	5	neg	1.16	1.12	1.47
	6	neg	neg	1.42	1.68
	7	.90	.49	.44	.56
RITZ CRACKERS (8 oz) (full)	1	.40	.26	.14	.00
	2	.44	.20	.12	.40
	3	.28	.00	.00	.00
	4	.26	.06	.48	.90
	5	.12	.46	.72	.69
	6	.87	.44	.48	neg
	7	.40	.34	.13	.00

** These velocities are higher than the range covered by the calibration graph. (3 feet per minute.)

neg Air movement opposite to the direction of the probe.

TABLE 4 (continued)

PACKAGE		AIR VELOCITY (fpm)			
		(A)	(B)	(C)	(D)
RITZ CRACKERS (16 oz) (empty)	1	neg	1.36	1.46	.66
	2	**	2.60	1.43	neg
	3	1.60	neg	.90	2.28
	4	neg	1.26	1.26	2.92
	5	neg	neg	2.60	2.08
	6	neg	2.76	1.88	.73
	7	neg	.84	.76	2.60
	8	neg	1.26	1.46	1.08
RITZ CRACKERS (16 oz) (full)	1	.40	.48	.70	.52
	2	.26	.48	.26	.00
	3	.06	.00	.32	.26
	4	.00	.90	.26	.46
	5	neg	neg	.48	neg
	6	.49	.06	.06	.20
	7	.06	.00	.06	.20
	8	.06	.00	.20	.20
LAY'S POTATO CHIPS (4½ oz, empty)	1	1.95	1.00	.69	neg
	2	neg	2.92	1.18	neg
	3	1.25	neg	1.60	1.43
LAY'S POTATO CHIPS (4½ oz, full)	1	.00	.00	.00	.00
	2	.00	neg	.20	neg
	3	neg	.26	.00	.76
JOHNSON BABY POWDER (9 oz, empty)	1	neg	.12	.26	neg
	2	.62	.84	.72	neg
	3	neg	neg	1.60	1.95

Vibration

The vibration to which the packages are subjected has an amplitude of 0.25 inch and is varied through a frequency range of 1 cycle per second to 10 kilocycles per second. Table 5 gives the maximum amplitude of the air velocities recorded inside the packages and at what vibration frequencies they occurred.

Every package is found to have what might be called a resonant frequency at which the magnitude of its vibration increases. The maximum air velocity is always recorded at this point. Each type and size of package had a different resonant frequency. The resonant frequency for full packages is generally higher than for the empty packages. The largest air velocity recorded under this condition is 2.64 feet per minute.

TABLE 5
TEST RESULTS FOR PACKAGES TESTED IN VIBRATION

PACKAGE	FREQUENCY	AIR VELOCITY (fpm)
QUAKER PUFFED WHEAT (5 oz) (Empty)	21 cps	1.66
LIPTON TEA BAGS (3 $\frac{1}{4}$) (Empty)	19 cps	0.98
QUAKER OATS (18 oz) (Empty)	26 cps	1.32
QUAKER OATS (42 oz) (Empty)	13 cps	1.04
RITZ CRACKERS (8 oz) (Empty)	43 cps	1.12
RITZ CRACKERS (8 oz) (Full)	43 cps	2.39
RITZ CRACKERS (16 oz) (Full)	26 cps	2.60
RITZ CRACKERS (16 oz) (Full)	30 cps	2.64
LAY'S POTATO CHIPS (4 $\frac{1}{2}$ oz) (Empty)	11 cps	1.32
LAY'S POTATO CHIPS (4 $\frac{1}{2}$ oz) (Full)	14 cps	0.84
JOHNSON BABY POWDER (9 oz) (Empty)	12 cps	1.88

DISCUSSION OF RESULTS

The static test condition is used as a control condition. It is an environment in which the other three variable conditions under test have been removed. Finding no air movement in the test packages under this condition does not make it correct to conclude that the three variable conditions that are being tested are the only possible conditions that could cause air movement inside the packages. In removing the three test conditions, outside air movement, temperature differential, and vibration from the static control condition, other conditions may have also been inadvertently removed. These other conditions may also have some affect on air movement inside of a package during storage and display periods. The significance of finding no air movement under the static condition lies in the fact that it indicates that when testing the packages, each test condition is able to be isolated. It can therefore be assumed that no other variable will intervene in the testing. The results that are recorded are directly related to the test variable.

The test data shows that no air movement is measured inside any of the packages under the condition of outside air movement over the package surfaces. The test condition of up to 100 feet per minute over the outside surfaces of the packages is much more severe than that which

would be encountered by a package under normal display conditions. The maximum velocity that is normally experienced by a package under normal display conditions is approximately 50 feet per minute.⁸ These results then indicate that air movement over the outside surfaces of a package does not produce air movement inside of the package. This is only valid in conditions where the surface velocities on the outside of the package do not exceed 100 feet per minute.

Under the condition of 10°F temperature differential, it is possible to produce air velocities inside of a package. These velocities can exceed 3 feet per minute inside of empty packages but do not reach over a maximum of 0.90 feet per minute inside of packages that contain a product. Since it is possible to produce air movement inside of test packages under a condition of temperature differential, it is logical to assume that air movements are also produced inside of commercial packages subjected to this same condition.

Only the condition of 10°F temperature differential is tested in this research. Other degrees of temperature differential are not examined. Further research would be needed to correlate temperature differentials normally experienced by a package in storage and display with air velocities produced inside of the package.

It is impossible to map the direction of the air movement produced inside of the test packages. No pattern of flow is evident inside of any of the packages tested. The best explanation for this condition is that the air movement

produced is turbulent, discontinuous, and nondirectional.

Air velocities are recorded under the condition of vibration, but these velocity readings should not be considered very significant for two reasons. First, the amplitude of the vibration has to be 0.25 inch before movement is detected. This amplitude is larger than what would normally be experienced by a package for the frequencies recorded. Second, and most important, it cannot be determined whether or not these readings are produced by air movement produced by the vibrations or by the vibration of the probe itself. Evidence points to the vibration of the probe as causing the readings.

Significance

The significance of the results of this research is that it is a guide, to those in the packaging industry who are interested in determining the permeability rate of fabricated packages, for determining what conditions they must include in their package testing systems. It has been proven that flow over the surface of a packaging material will increase the permeability rate through the material. It had not been determined up to this time what flow rates, if any, and patterns of flow are experienced inside of a package.

The results of this research show that under conditions which would be experienced in air conditioned warehouses and stores no air movement could be detected inside of any of the several different types of commercial packages tested. The equipment used for this research is sensitive

to air movements as small as 0.28 feet per minute.

This statement is therefore accurate for velocities above 0.28 feet per minute.

The results also show that air movement can be produced inside of packages that are subjected to temperature differential. The air movement produced inside of these packages is turbulent, discontinuous, and nondirectional.

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A P P E N D I X

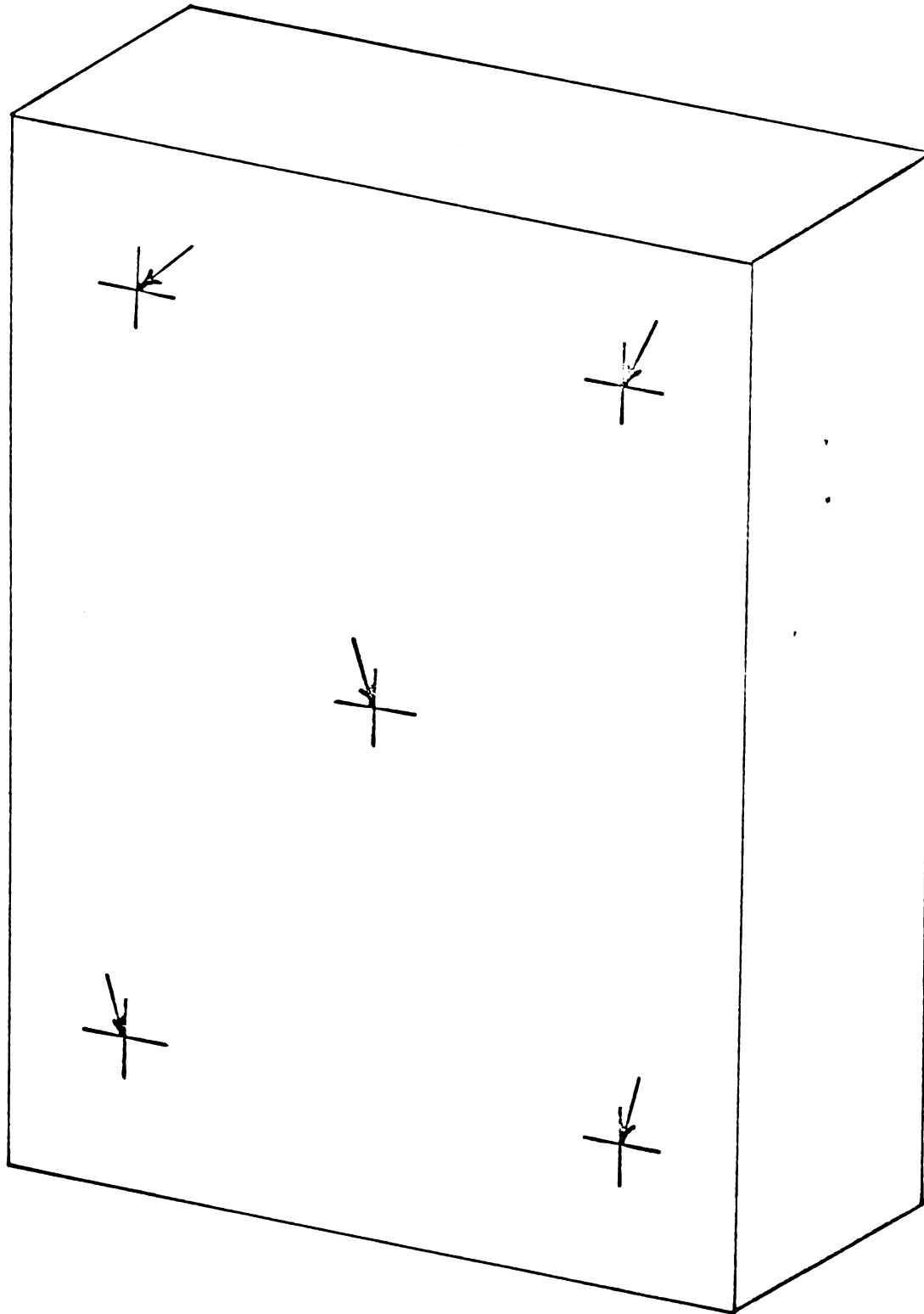


Figure 10

Quaker Puffed Wheat Package
Diagram of Air Movement Under Conditions
Of 10°F Temperature Differential

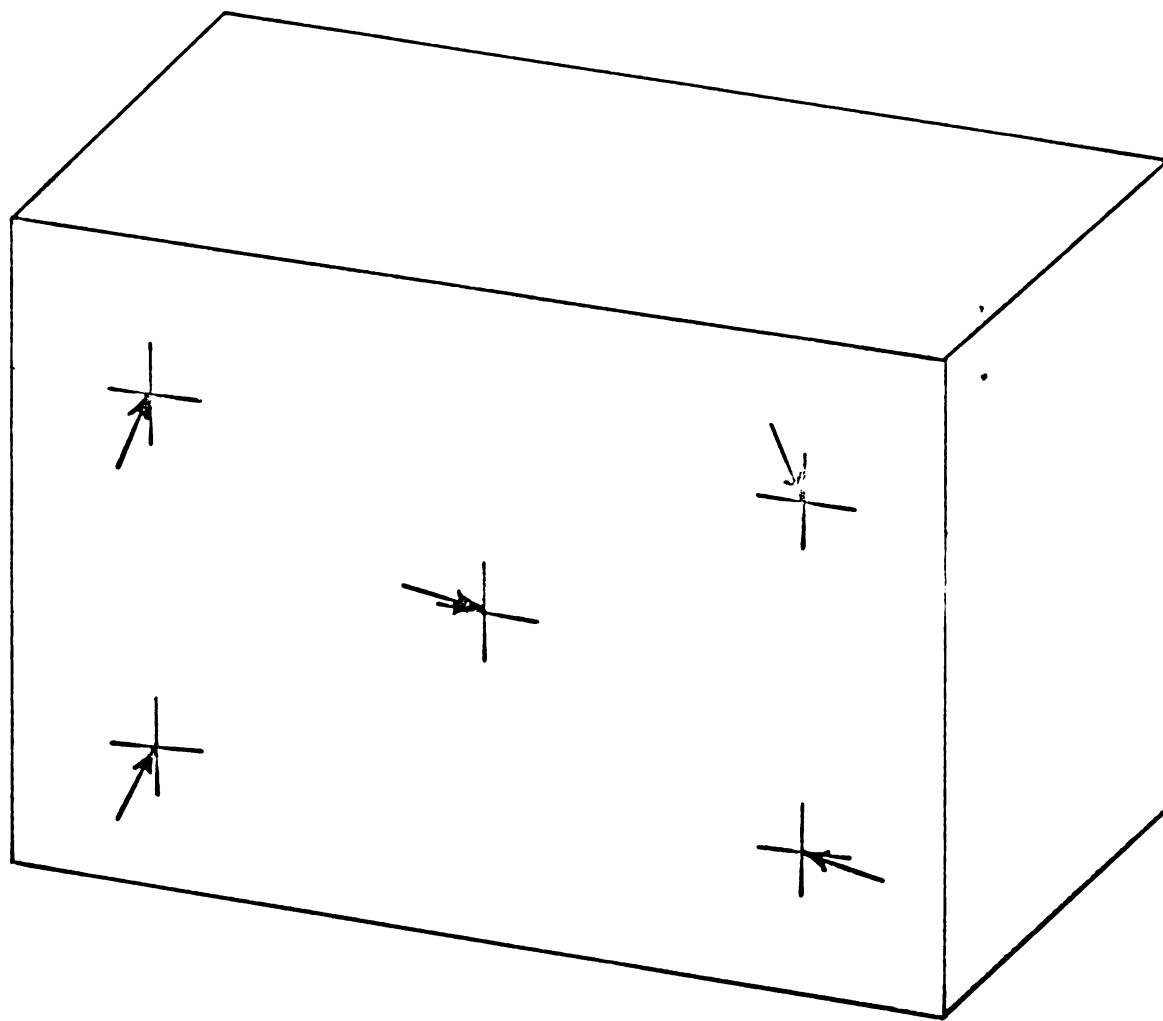


Figure 11

Lipton Tea Bags Package
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

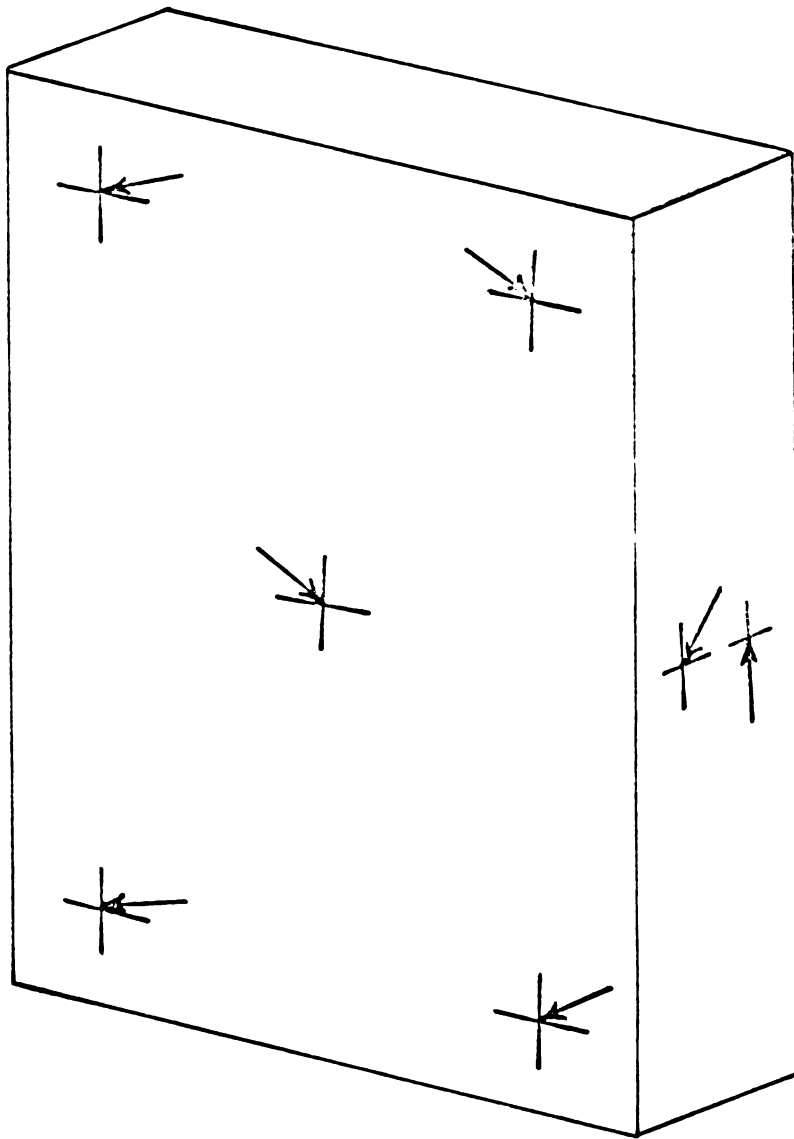


Figure 12

8 oz. Ritz Crackers Package (Empty)
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

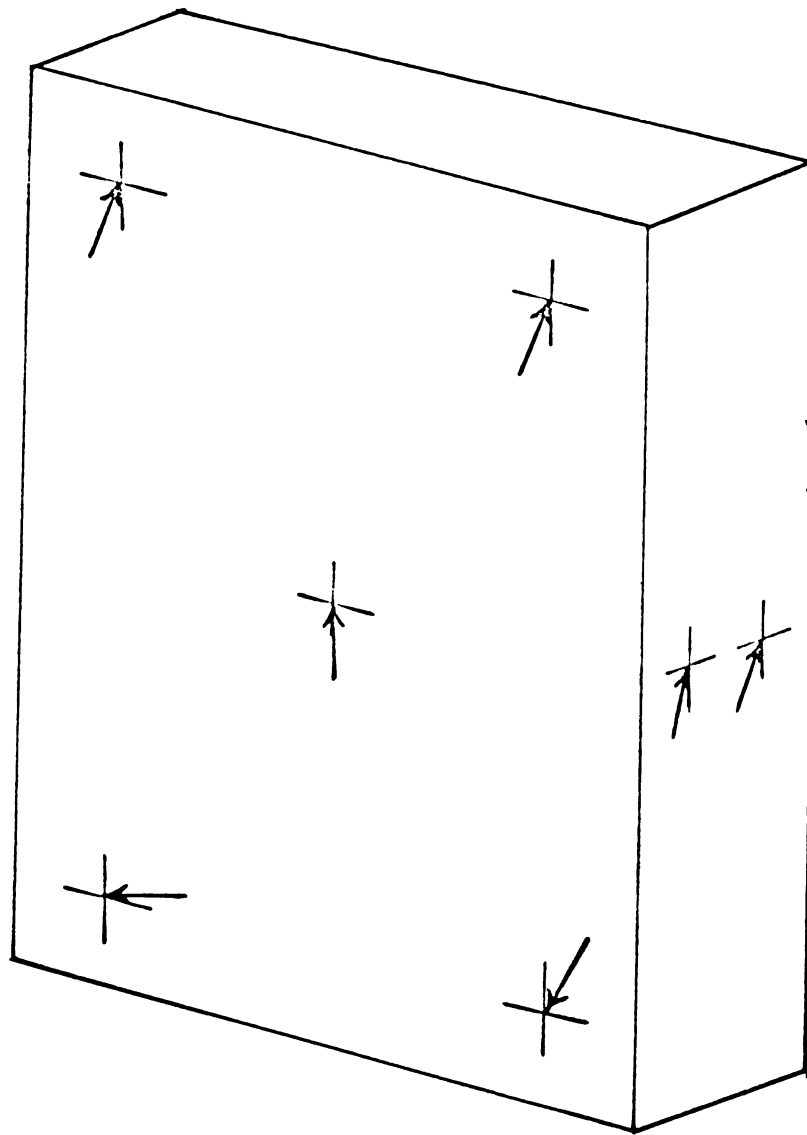


Figure 13

8 oz. Ritz Crackers Package (Full)
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

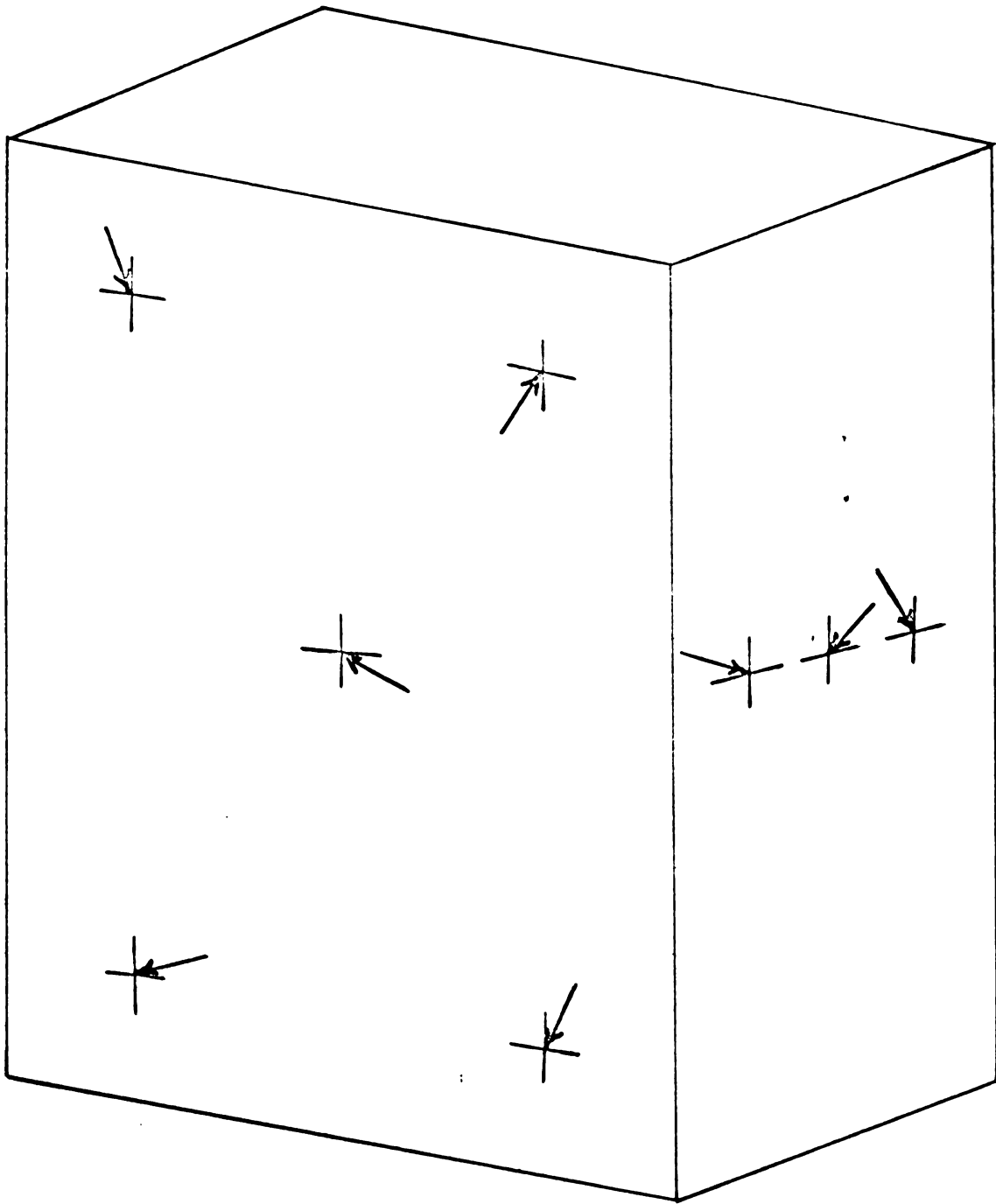


Figure 14

16 oz. Ritz Crackers Package (Empty)
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

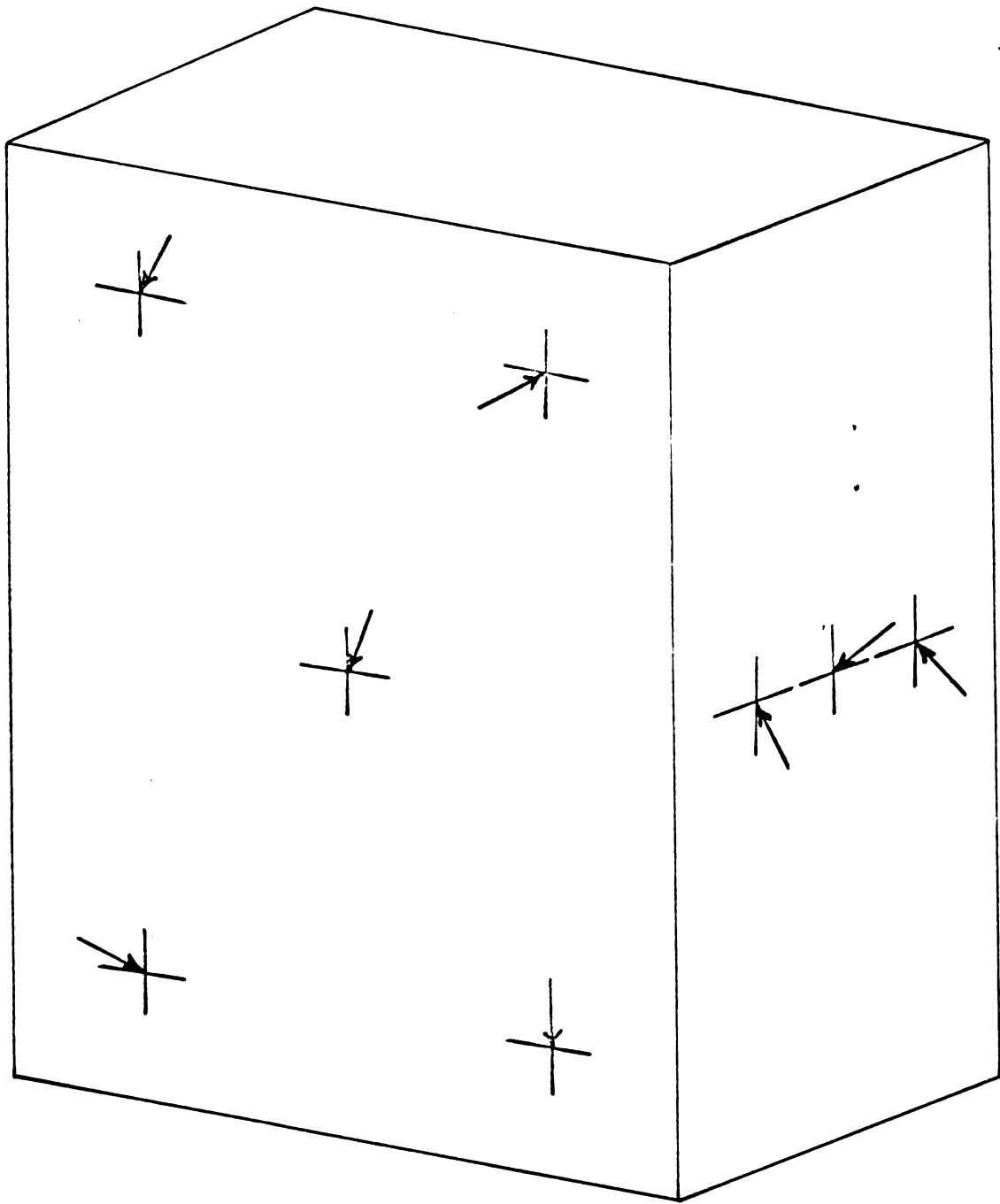


Figure 15

16 oz. Ritz Crackers Package (Full)
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

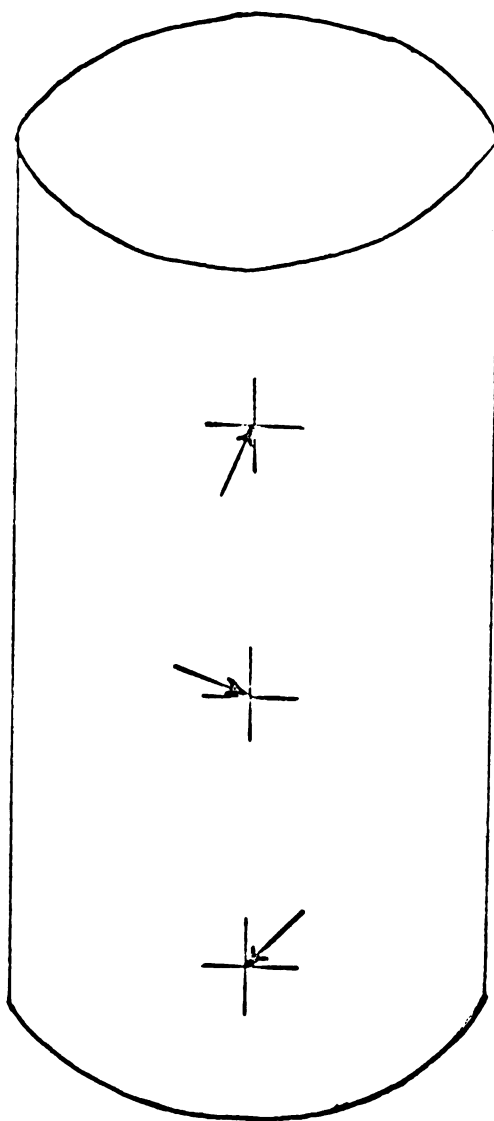


Figure 16

18 oz. Quaker Oats Package
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

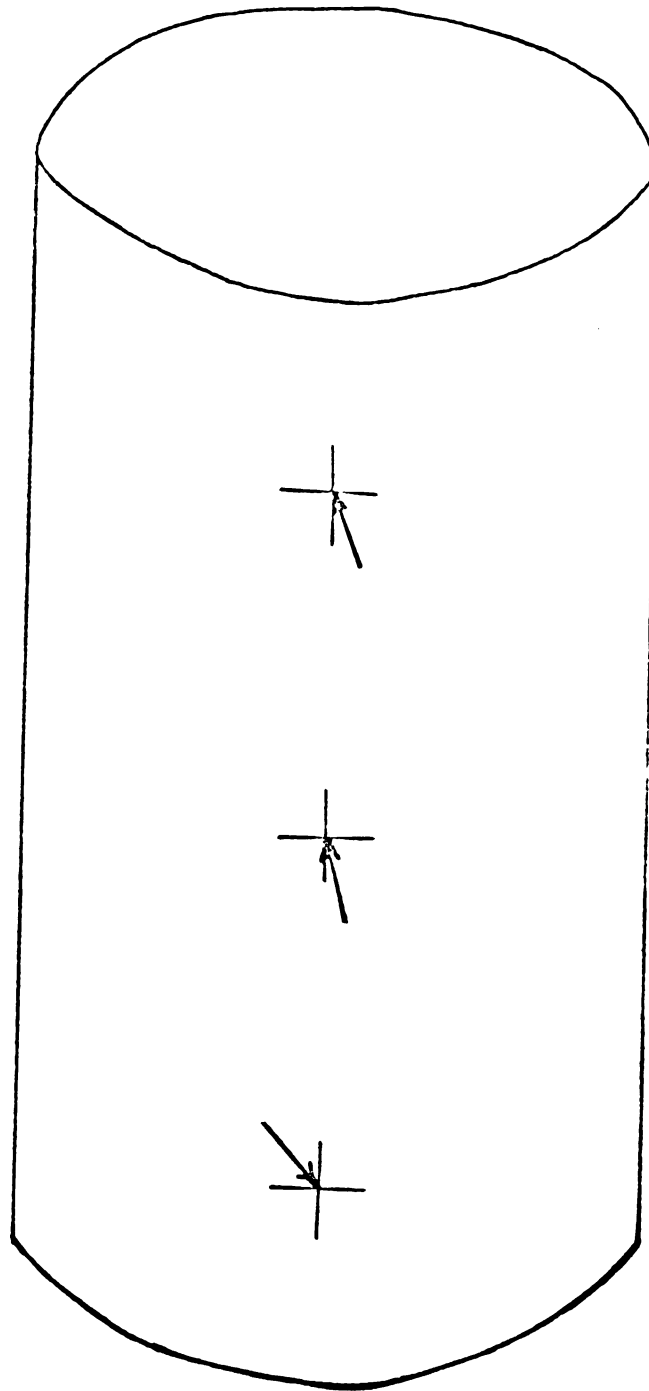


Figure 17

42 oz. Quaker Oats Package
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

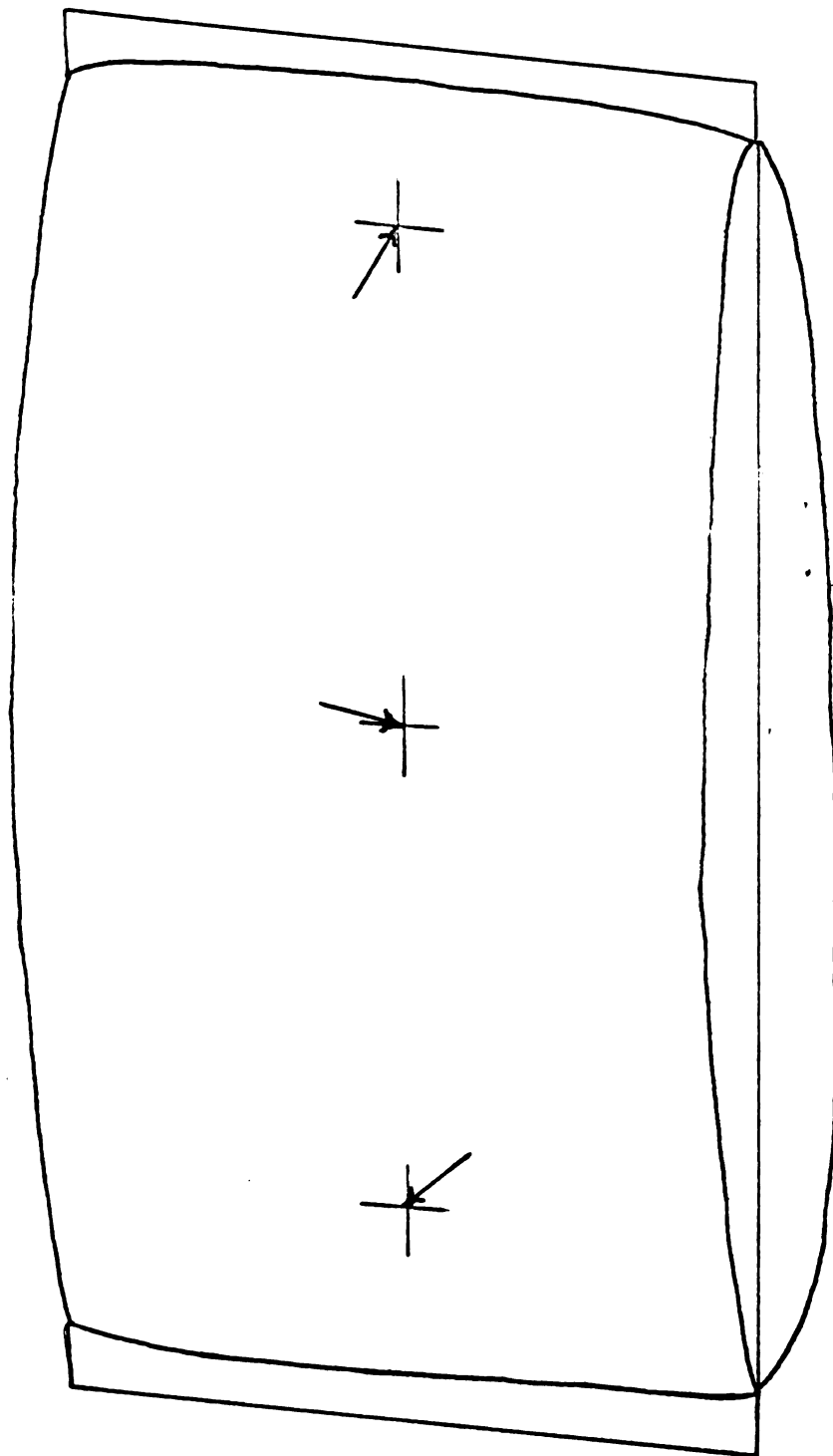


Figure 18

Lay's Potato Chips Package (Empty)
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

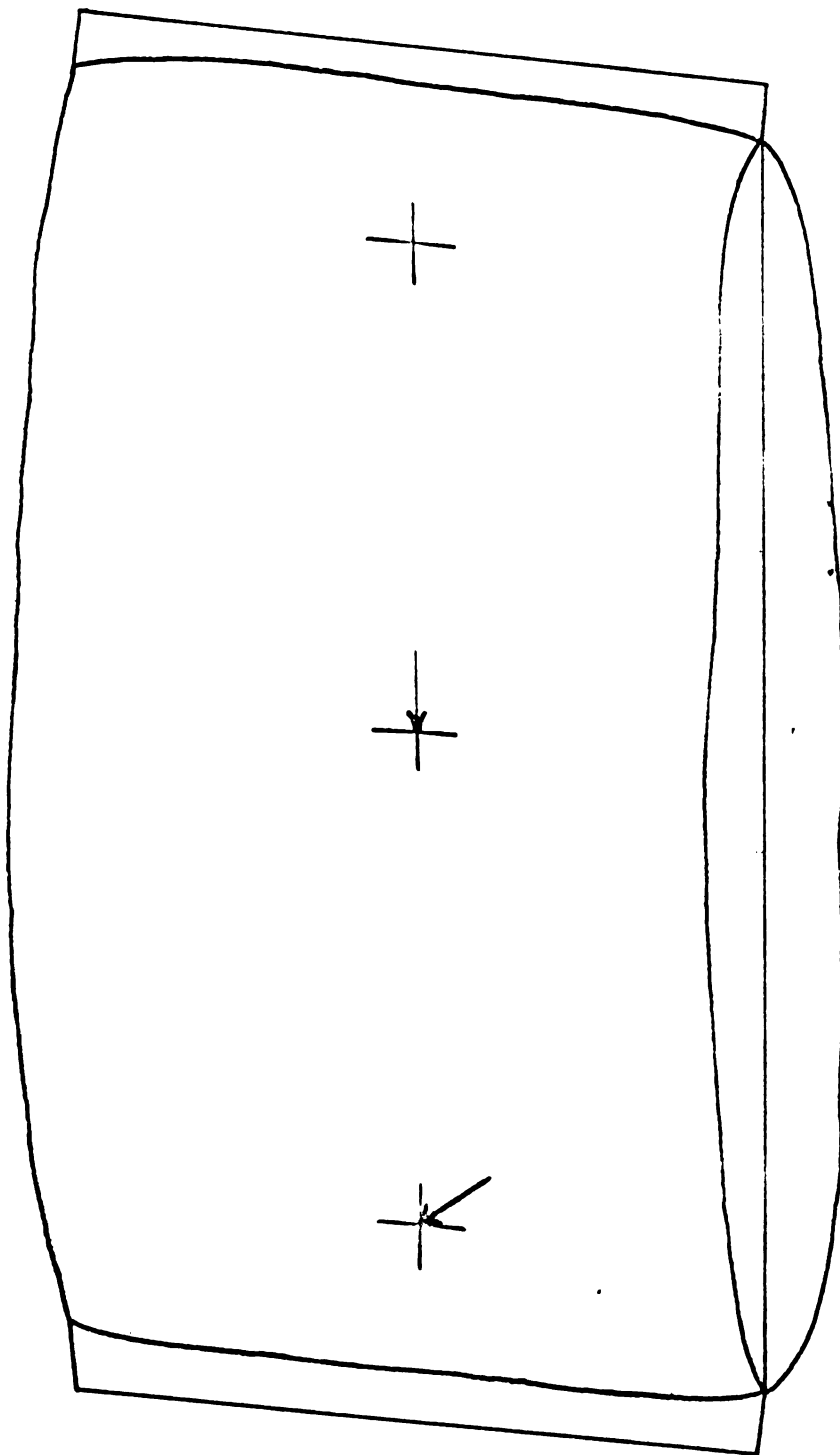


Figure 19

Lay's Potato Chips Package (Full)
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

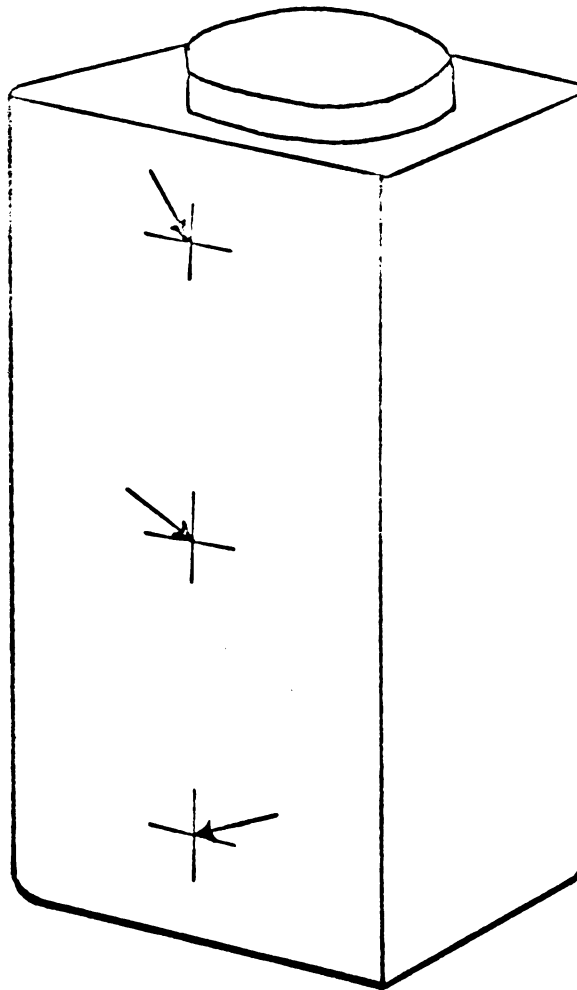


Figure 20

Johnson Baby Powder Package
Diagram Of Air Movement Under Conditions
Of 10°F Temperature Differential

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