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Item Type	event;event
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Download date	2025-04-24 23:45:27
Link to Item	https://hdl.handle.net/20.500.14394/30115

The Effects of Door Opening and Food Placement on Food Temperature within the Refrigerator when Power is Lost during a Disaster

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Food is an essential part of our lives. Its consumption is required by humans in order to survive and to have energy to perform daily tasks. Thus it is very important that the food, in both its cooked and raw forms, is prepared in a clean hygienic environment, stored at regulated temperatures and made of quality ingredients. Maintaining an appropriate temperature is one of the most important factors to food safety.

Incidences of foodborne illness have been steadily increasing over the years. Various causes include cross contamination, unhygienic practices, low quality raw materials, improper handling and storage of food (Centers for Disease Control and Prevention, January 2001). According to the Centers for Disease Control and Prevention (CDC), 1991 one of the leading causes of foodborne illnesses today is the temperature at which food is stored. The CDC estimated that foodborne diseases cause nearly 76 million illnesses, 325,000 hospitalizations and nearly 5,000 deaths in the United States each year.

Since storing foods at refrigerated temperatures is important it is essential to know the correct temperatures at which food needs to be stored. According to U.S. Food and Drug Administration (FDA, 2009) guidelines, the temperature danger zone is between 41°F (5°C) and 135°F (57°C). The United States Department of Agriculture (USDA, 2009) recognizes a different temperature danger zone which is slightly more conservative than the FDA's: 40°F (4°C) to 140°F (60°C). The FDA is responsible for writing the Model Food Code upon which most State base health codes for foodservice operations; therefore the FDA's temperature danger zone was used for this study. Keeping food at the proper temperature during normal operation is relatively straightforward. However, when an operation loses power, the task of maintaining refrigerated temperatures is not so simple. This study explores different ways to protect cold food in the case of a power outage.

Refrigeration and its Impact of Food Safety and Quality

Refrigeration is the process of removal of heat from a body or a material, which is done by placing the warm material or food next to a cold material. When this is done there is migration of heat from the warm material to the cold material until they both have the same temperature (Avery, 1991).

The key to maximizing the length of a product's shelf life is to maintain optimal temperature and humidity. Refrigerators maintain optimal conditions through heat

removal (temperature reduction), air circulation and humidity control (Katsigris & Thomas, 2009). Air circulation helps ensure uniform temperature and humidity for all food being stored. If temperature and humidity are not properly controlled then the food will start to deteriorate and spoil; once this process initiates it cannot be stopped or reversed (Katsigris & Thomas, 2009).

Temperature is the most important factor in the safe storage of cold foods. Bacteria grow most rapidly in the range of temperatures between 41°F (5°C) and 135°F (57°C). This is called the "Temperature Danger Zone" and it is within this range that some bacteria almost double in number in as little as 20 minutes (FDA, 2006). When the power goes off, if the refrigerator temperature remains below 41°F (5°C) the food will remain safe. However, maintaining temperatures below 41°F (5°C), can be very difficult when the power goes off.

Although some organisms can grow at low temperatures, their growth rate is greatly reduced at temperatures below 41°F (5°C). Food stored at 50°F (10°C) will spoil four times faster than food stored at 41°F (5°C) which will spoil two times faster than food which is stored at 32°F (0°C) (Banwart, 1981). An example of bacteria that can grow at refrigerated temperatures is *Listeria*. While *Listeria can* grow at temperatures near 32°F (0°C), it grows much faster at temperatures of 41°F (5°C) and above (FDA, 2009). *E. coli O157:H7*, *Campylobacter*, and *Salmonella* are other examples of pathogenic bacteria which grow between 41°F (5°C) and 135°F (57°C) (CDC, 2001).

Disaster Management

Countries around the world are facing a growing number of both natural and man-made disasters (Telford & Cosgrave, 2006). In such an event, the government and its various supporting agencies should be prepared to ensure a safe food supply to people affected during and after such crises. In the United States, various federal government agencies like the CDC, FDA, USDA and Federal Emergency Management Agency (FEMA) are tackling this problem. During both natural disasters and man-made crises one of the first things that may happen is a loss of electricity. When this happens safe food storage becomes a challenge. Disasters may also impact relief organization's ability to supply victims with new food supplies.

Disasters are not the only challenges the world is facing, today the scenario around us is changing, countries having the biggest and the strongest economies are experiencing deep economic and financial crises. In such circumstances, it is important to maximize the use of all resources, including food. If there is a power loss, people may not be able to dispose of potentially unsafe food and buy new because of their limited resources. Eating potentially unsafe food is not an acceptable alternative; when people are laid off they may have lost their health care coverage and may not be able to afford medical attention.

If the power goes out regularly or if it goes out during an emergency or a disaster what should the people living in such areas do? How long will food stored in refrigerators be safe to eat after the power is lost? Are there any ways to prolong the time before the food temperature reaches the "Temperature Danger Zone" and becomes unsafe to

consume? According to the FDA (2007) guidelines "when power goes out a refrigerator can keep food cold only for four hours if the doors of the refrigerator are not opened". If the power is out for more than four hours the food in it cannot be consumed. All this leads to the question of what can be done to prolong the time it takes food in a refrigerator that has lost power from entering into the "Danger Zone" and becoming potentially unsafe to consume. It is that question, which led to this study on the effect of different variables on the temperature within a refrigerator when power is lost. To fully understand which variables will impact the temperature, a review of the science behind the heat transfer is needed.

Heat Transfer

Determining the actual heat lost from the cabinet by calculating the different conduction and convection components independently is extremely difficult. A more practical approach is to determine the overall heat transfer coefficient (U). U can be determined experimentally by tracking the rate of heat loss through the cabinet for known inside and outside temperatures. Once U is known then the rate of heat transfer can be estimate based on the temperature of the room and the temperature of the food, using the following equation:

$$q = UA\Delta T$$

Where q is the rate of heat flow

U is the overall heat transfer coefficient

A is the surface area of the cabinet

ΔT is the temperature difference between the inside and outside air temperatures

The rate at which heat moves depends on the driving force ΔT and the resistance. The area (A) and overall heat transfer coefficient (U) can be combined to represent the resistance to heat flow (UA). The greater the driving force the faster heat moves into the refrigerator. The greater the resistance the slower heat moves. The amount of heat gain by food impacts the rate of temperature change based on the heat capacity and mass of the food. The equation governing temperature change is as follows:

Heat gained/lost = mass * heat capacity * (start temperature - finish temperature)

The purpose of this study was to determine how long food could be safely stored inside a refrigerator during a power outage. One condition that is likely to occur is the stratification of temperature within the cabinet. Hot air rises and cool air stays at the bottom so when the power would go out it was assumed that the food in the top shelves of the refrigerator would gain temperature more rapidly than the food at the bottom shelf, hence the first hypothesis states that containers of water on the bottom shelf will maintain temperature longer than containers on the top and middle shelf.

The next hypothesis relates to the construction of the cabinet. The door is the thinnest of all the “walls” of a refrigerator. In addition the door gasket is likely to allow additional heat to enter the refrigerator. Since more heat is entering through and around the door, food articles placed near the door are likely to increase in temperature faster than those at the back of the cabinet. The second hypothesis states that the containers of water placed in the back of the refrigerator will maintain temperature longer than the containers in the front.

The larger the mass of an object the more energy is required to raise its temperature. This principle leads to the third hypothesis: full-gallon containers of water will maintain temperatures longer than the half-gallon containers.

When the door of the refrigerator is opened, cold air rushes out and hot air moves in to replace it. This led to the first of the next two hypotheses, which state that opening the refrigerator door will cause the water temperature to rise faster. The refrigerator used in this study had a top and bottom door with a single compartment: Hypotheses five states that opening either door of the refrigerator will cause the temperature of the front containers to rise faster than that of the back containers. Whether the top or bottom door is opened will also likely impact conditions inside the refrigerator. When the bottom door is opened hot air rushes in and the cool air rushes out and the hot air rises. This may displace the air faster resulting in greater heat gain by the cabinet. If the top door is opened, the cold air in the bottom of the refrigerator may not be impacted. Therefore, the next hypotheses states: opening the bottom door will have a greater impact on the total heat gain than opening of the top door of the refrigerator. This leads to the next two hypotheses: opening the top door of the refrigerator will have a greater impact on the top containers and opening the bottom door of the refrigerator will have a greater impact on the bottom containers. Finally, if a barrier to reduce air flow is added over the door openings the water should hold temperature longer. The last hypothesis states that adding curtains will reduce the heat gain when the refrigerator doors are opened. The null hypotheses to be tested are as follows:

H₁₀: temperatures of the gallon containers on all three shelves in the refrigerator will remain the same.

H₂₀: the gallon containers placed in the back and front of the shelves in the refrigerator will maintain temperature for the same amount of time.

H₃₀: both the full and half gallon containers will maintain temperature for the same amount of time.

H₄₀: opening either refrigerator door will not cause the temperature to rise in the containers.

H₅₀: opening either door of the refrigerator will not cause the temperature of either the front or the back containers to rise faster than the other.

H₆₀: opening the top door of the refrigerator will have the same impact on all the containers.

H₇₀: opening the bottom door of the refrigerator will have the same impact on all the containers.

H₈₀: opening the bottom door will have a same impact on the total heat gain as opening the top door of the refrigerator.

H₉₀: adding curtains in refrigerators will not reduce heat gain when the refrigerator doors are opened.

Methodology

The purpose of this study was to determine the impact of the placement of food, the volume of food and the opening of the refrigerator on the temperature of the food stored in a refrigerator that has lost power. The variables used were: volume, position and door openings. Six containers filled with water were used to simulate food: three half-gallon milk containers and three full-gallon milk containers. Six positions were identified in the refrigerator for placement of the gallons: top shelf front and back, middle shelf front and back and bottom shelf front and back. The containers were placed in the center in the front and back of all the shelves. Five different door treatments were applied: no door opening, top door opening, bottom door opening, top door opening with curtains and bottom door opening with curtains.

Material used for the Experiment

The experiment was conducted in a commercial kitchen at Purdue University, with a commercial two-door refrigerator manufactured by Traulsen, model number RHT132WUT. Water was selected as the medium of study since it is readily available, low on cost, has a known uniform heat capacity and was expected to have a relatively homogenous temperature throughout its volume. Half-gallon and full-gallon containers were used to evaluate the effect of volume on temperature gain. A Pico technology TC-08 serial thermocouple data logger was used to measure the temperature changes in the water. The TC-08 serial data logger has 8 ports, which allowed eight possible temperatures to be recorded simultaneously. It measures temperatures from -454°F (-270°C) to 360°F (+182°C), plus or minus 2°C. Air temperature was measured using humidity and temperature USB data loggers. These data logger can record temperatures from -104°F (-40°C) to +158°F (+70°C), plus or minus 2°C and can store up to 32,000 temperature and humidity readings combined.

Setup

The serial TC-08 was attached to a computer by a serial cord. Eight extension probes were connected to the TC-08. The extension wires were used to connect the probes in the refrigerator to the TC-08. The wires were run between the frame and the refrigerator door seals. The extensions wires were thin enough so that their impact on the door seals was expected to be negligible. Six temperature-recording probes were inserted in the tops of the containers, one per container. Holes were made on top of the caps of these containers just large enough to allow the passage of a temperature probe. The two remaining ports on the TC-08 data logger were used to record the surface temperature of one of the half and one of the full gallon containers.

Two of the three USB probes were placed in the refrigerator, one on the top shelf and the other on the bottom shelf. The third USB air probe was kept outside the refrigerator to record the air temperature. The sample rate was set to one minute.

Two configurations for the containers in the refrigerator were used: regular and flip. In the regular position the half-gallon containers were placed in the front of the full-gallon containers on each shelf. In the flip position the full-gallon containers were placed in the front of the half-gallon containers on each shelf. The rotation in position of container was done to see what difference volume made in terms of rise in temperatures and opening of doors.

Data collection procedures

The full- and half-gallon containers were filled with one half and one gallon of water respectively. The top and bottom USB air temperature probes were activated and placed inside the refrigerator, one on the top shelf and one on the bottom shelf. The outside USB was also activated and the surface temperature probes were also attached to the two containers as described earlier, the remaining temperature probes were inserted, one in each of the six containers. Next the containers were placed inside the refrigerator. The TC-08 data logger was activated using its software on the computer. This set up was left overnight so that the air and water temperatures stabilized. The stabilized air temperatures inside the cabinet ranged from 26°F (-3°C) to 32°F (0°C). The water temperatures ranged from 32°F (0°C) to 35°F (2°C).

Test Descriptions

There were 6 treatments, tested during this experiment.

No door Opening

The setup procedure described earlier was followed for each round of tests conducted, including tests with the containers in the flip position. The power to the refrigerator was turned off and the Pico data logger began recording temperatures. During this period no one was allowed to switch on the refrigerator or open the refrigerator door. This test was repeated, the results combined and a graphical representation of the temperatures was prepared. After each test the refrigerator was switched on so that the water and air temperatures could restabilize before the next test.

Top door opening

The refrigerator was set up with the containers in the regular position. To test the impact, the top door of the refrigerator was held open 10 seconds at 15 minute intervals. The door was opened to a 90° angle every time. A stopwatch was used to time the opening of the door and the 15 opening cycle. The door was opened manually every time. In all 300 readings were collected. This test was also repeated twice. The positions of the containers were flipped and the test was repeated.

Bottom door opening

The same set up and test specifications were repeated for the Bottom door opening test, as was for the top door opening, the only difference being that here the bottom door of the refrigerator was opened instead of the top door.

Top door opening with curtains

Plastic curtains were hung inside the refrigerator in the top door area. They were attached using two plastic hooks with duct tape at the back. The hooks were stuck on the either side of the door on the inner walls of the refrigerator. A shower curtain bought from a local store was used. It was trimmed to a size slightly larger than the actual door and was attached and hung between the two hooks in the interior of the refrigerator with the help thin nylon rope. Three slits were made in the plastic curtain for access to the interiors of the top part of the refrigerator. The top door with the curtains was opened after every fifteen minutes for ten seconds at a 90° angle and the temperature was measured over a period of 300 readings. The above test was repeated with the containers in the flipped position.

Bottom door opening with curtains

This experiment was set up and run the same way as the previous one, with the exception that the set up was done for the opening of the bottom door of the refrigerator. The entire test was repeated with the containers in the flipped position.

Calculation of Heat Loss

Calculating Q value and UA value

To determine the impact of the different treatments, the heat gained by the refrigerator and containers was calculated based on the heat transfer equation given in table below. The resistance term (UA) was determined experimentally during the tests with the doors closed.

The first step to determining UA was to calculate the heat gained by the water at one-minute intervals for 300 minutes. The heat gained by the water was calculated based on the thermal capacity of the water, mass of the water and the change in its temperature. The thermal capacity of water used was 4.2kJ/kg*K. Once the Q value was found, the formula $UA=Q/\Delta T$ was used to find UA. Here ΔT was the room temperature minus the air temperature inside the refrigerator. With UA it is then possible to predict temperature changes for the water and evaluate the different treatments.

Statistics

Once all data were collected, initial analyses were performed using Microsoft excel 2003 spreadsheets. The single dependent variable, change in temperature, was regressed against the independent variables using multiple regressions.

The independent variables were the position of the containers: top, middle or bottom shelves, the volume of the containers: half- or full-gallon containers, the position of the containers in each shelf: front or back, the outside air temperature, the previous

temperature of the container and the average temperature of the remaining containers. STATA was the statistical package used to analyze the data and run the regression.

Results

Below are the hypothesis listed with the results discussed-

H₁₀: temperatures of the gallon containers on all three shelves in the refrigerator will remain the same.

It was seen that during all the 5 tests that there was significant difference between the temperatures of the containers placed in the top, middle and bottom shelf with a significance of 0.000. The coefficients represent the temperature difference based on the vertical position in the refrigerator. The coefficient for the top shelf was 0.048°C greater than the bottom shelf while the coefficient for the middle gallon was 0.019°C greater than that of the containers in the bottom shelf (see Table 1). The coefficients represent the temperature difference based on the vertical position in the refrigerator. The temperature of the containers on the top shelf increased an average 0.048°C over those on the bottom shelf each minute of the test. So after 60 minutes the containers on the top shelf will be 2.9°C warmer than those on the bottom. Based on the coefficients the containers on the bottom shelf maintain temperature the longest. The first null hypothesis, the temperatures of the containers on all three shelves in the refrigerator will remain the same, could be rejected for this treatment.

Table.1 Regression output for the door closed treatment

Temperature	Coefficient (In °C)	Standard Error (In °C)	P-Value
Top shelf	0.0484	0.0029	0.000
Middle shelf	0.0195	0.0022	0.000
Front of shelf	0.0129	0.0018	0.000
Full-gallon containers	-0.041	0.0024	0.000
Outside air temperature	0.0025	0.0029	0.039
Previous temperature	0.9475	0.0025	0.000
Average temperature of remaining containers	0.055	0.0025	0.000
Constant	-0.061	0.0694	0.381

H₂₀: the gallon containers placed in the back and front of the shelves in the refrigerator will maintain temperature for the same amount of time.

The coefficient of containers in front was greater than that of the containers at the back by 0.0129°C with had a significance of 0.000 (see Table 1). Thus the temperature of the containers in the front increased an average of 0.0129°C over those at the back each minute of the test. So after 60 minutes the containers in the front of the shelf will be 0.774°C warmer than those at the back. Thus there is evidence to reject the second hypothesis, which states that the containers in the back and front will maintain safe temperatures for the same amount of time.

H₃₀: both the full- and half-gallon containers will maintain temperature for the same amount of time.

The size of the container was significant with a p-value of 0.000. The regression output indicated that the full-gallon containers maintained temperature for a longer period of time than half-gallon containers. The half-gallon containers had an average temperature increase of 0.015°C over the full-gallon containers each minute of the test. Thus rejecting the third hypothesis.

H₄₀: opening either refrigerator door will not cause the temperature to rise in the containers.

The readings were analyzed using regression. The regression output showed that there were significant differences between the temperatures of the top, middle and bottom containers. The coefficient of the containers on the top shelf was 0.024 greater than that of the bottom shelf with a significance of 0.000. The coefficient of the containers in the middle shelf was 0.004 greater than that of the containers on the bottom shelf with a significance of 0.010. Thus showing significant rise in the temperatures of the containers in the refrigerator when the refrigerator door was opened, thus rejecting the fourth null hypothesis.

H₅₀: opening either door of the refrigerator will not cause the temperature of either the front or the back containers to rise faster than the other.

The output showed that the containers in the front had a higher temperature than the containers in the back, but the difference in the temperature is not statistically significant as it had a p-value of 0.191. Therefore, the fifth hypothesis, which states that opening either door of the refrigerator, will not cause the temperature of neither the front nor the back gallon containers to rise faster than the other could not be rejected for this treatment.

H₆₀: opening the top door of the refrigerator will have the same impact on all the containers.

The temperature of the containers on the top shelf increased an average 0.024°C over those on the bottom shelf each minute of the test. So after 60 minutes the containers

on the top shelf will be 1.4°C warmer than those on the bottom. The sixth hypothesis, which states that opening of the top door will have the same impact on all containers, was rejected for this treatment.

H_{7o}: opening the bottom door of the refrigerator will have the same impact on all the containers.

The regression output showed that there was significant difference between the temperatures of the top and bottom shelf containers. The top shelf variable had a coefficient of 0.023°C when compared to the bottom shelf; the significance level was 0.000. The containers on the middle shelf also had a temperature, which was statistically different than those on the bottom shelf. The coefficient was 0.005°C with a significance of 0.000. As with previous treatments, the vertical position inside the refrigerator impacted the water temperature. The temperature of the containers on the top shelf increased an average 0.023°C over those on the bottom shelf each minute of the test. So after 60 minutes the containers on the top shelf will be 1.38°C warmer than those on the bottom. The seventh hypothesis, which states that opening of the bottom door will have the same impact on all the containers, was also rejected for this treatment.

H_{8o}: opening the bottom door will have a same impact on the total heat gain as opening the top door of the refrigerator.

To compare the effect of the different treatments, an effective UA was calculated for each treatment. The effective UA is the effective resistance to heat entering the refrigerator and ultimately the food. Given similar driving forces and temperature difference between the room and the refrigerator, UA gives a good measure of the impact of each treatment on the heat absorbed by the water and ultimately its temperature change. The five treatments were no door opening, top door and bottom door opening and top and bottom door with curtains. The UA values were calculated after every 15 minutes over a period of five hours. The reported UA for each treatment was the average for that five-hour period.

The analyses of the data found no significant difference between the UA's of all the four treatments involving door openings. In other words there was not any significant difference in the amount of heat gained by the full- and half-gallon containers during the opening and closing of the door with or without curtains and regardless of which door is opened. There is not enough statistical evidence to prove that opening of the bottom door has a greater impact on the total heat gain than opening the top door of the refrigerator. The eighth hypothesis which states that opening the bottom door will have a same impact on the total heat gain as opening the top door of the refrigerator could not be rejected.

Table 2 - Comparison of UA's for the five treatments

Type of Treatment	Mean UA value	Mean Standard Deviation
No door opening	0.0150 _a	0.0050
Top door opening	0.0180 _b	0.0030
Bottom door opening	0.0183 _b	0.0035
Top door opening with curtains	0.0172 _b	0.0039
Bottom door opening with curtains	0.0186 _b	0.0034

H₀: adding curtains in refrigerators will not reduce heat gain when the refrigerator doors are opened.

There is no significant difference in the heat gained with or without curtains in the refrigerator, as represented by the mean UAs shown in Table 2. Since there was no significant differences, the ninth null hypothesis cannot be rejected.

Conclusions

It was seen consistently during the analysis of the data that the bottom full-gallon containers maintained temperature for the longest period of time. From this study's result, if the starting temperature in a refrigerator was 3°C, the temperature of the food in the top shelf would become 5.9°C, which would be 2.9°C warmer than the food kept on the bottom shelf in the first 60 minutes of a power failure. From a practical stand point this means that the temperature in the top of the refrigerator would already be in the danger zone within the first hour. So it would be advisable and prudent to store fruits on the top shelves of a refrigerator during a crisis. This also reaffirmed the fact that the cold air would be always at the bottom of the refrigerator and hence it would be the coldest part in the refrigerator; hence, the best place to store meats would be the bottom shelf of the refrigerator.

The full-gallon containers maintained temperature the longest. If the temperature of the refrigerator was 3°C and the power went off, after 60 minutes the temperature of the half-gallon container in the refrigerator would reach 5.46°C, which is 2.46°C warmer than the full-gallon container. This in turn means that the half-gallon containers would be

in the danger zone within one hour. This indicates that the volume of food placed in the refrigerator is a very important component in determining the temperature of the food when the power is lost.

The opening of either door of the refrigerator resulted in the half-gallon and full-gallon containers on the top shelf increasing in temperature the fastest. This shows that no matter which door of the refrigerator was opened the top part of the refrigerator was the warmest part. This is logical since the hot air inside the cabinet rose. Since the temperature rose on the top shelf more quickly when the doors were opened, this makes it even more critical to place items requiring lower temperatures on the bottom shelf.

The curtain, which was put inside near the door of the refrigerator, it did not prevent temperature loss. This was the case when the curtains were placed either at the top or bottom door of the refrigerator. This shows that something more than a curtain is needed to prevent the hot air from getting into the refrigerator and the cold air from rushing out of the refrigerator when the doors are opened.

Implications and applications

The results from this study provide several implications, which are useful to the food service industry as well as to consumers. During emergencies large quantities and bigger containers of food should be stored together as they gain heat and gain temperature at a much slower rate than if they were stored in small containers.

The FDA states that food is safe in a refrigerator when the power goes out after a period of four hours without opening the door. But when this study was conducted the water gallons at the back in the bottom of refrigerator had a temperature of around 3°C (37°F) after five hours and still it was not in the temperature danger zone of which starts at (41°F), and may be it could take an hour for that gallon container to reach the temperature zone which mean that instead of 4 hours you now have 6 hours until the food goes into the danger zone. But we need to further investigate this with different food products like salads, semi solids to see what the difference in the temperatures is.

One thing that an operator can do to prepare for a power failure is to combine portions when possible to create the largest most compact thermal mass. In doing so, the rate of temperature increase for the item can be reduced. As much as possible one should avoid storing food in the top shelves of the refrigerator in the front, as this is where there will be the maximum temperature increase. If it is possible to prepare before a crisis hits, the refrigerator should be arranged so that once the power has gone off, the refrigerator door should be kept closed as the refrigerator will gain heat and increase in temperature as much as 42 percent fast than if the door is not opened.

The curtains in the refrigerator did not make a significant impact in preventing temperature increase. The addition of curtains may even cause several problems. One potential problem might be the risk of the curtains getting dirty and becoming unsanitary in which case they might cause more damage than good. Results from this study suggest that storing most of the foods in the bottom and back of a refrigerator during an emergency is the best position as it will be the coldest part.