NISTIR 7656

Thermal Analysis of Refrigeration Systems Used for Vaccine Storage

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ABSTRACT

Each year, billions of dollars of vaccines are stored in refrigerators at the facilities of a variety of medical providers. Many vaccines must be maintained in the range 2 °C to 8 °C to retain product potency. We have tested the performance of two types of household refrigerators to determine if these refrigerators are suitable to this task, and to identify proper storage and temperature monitoring methods. Nineteen calibrated Type T thermocouples, distributed through the refrigerator interior, served as reference thermometers. Attachment of thermocouples directly to vaccine vials gave accurate measurements of the vaccine temperature, which often differed from the air or interior wall temperatures during door openings or defrost cycles. A household, full-size freezerless refrigerator [capacity = 0.473 m^3 (16.7 cu. ft.)] proved fully adequate at maintaining vial temperatures within the desired 2 °C to 8 °C range, independent of how the refrigerator was loaded. Tests of intermittent and continuous door opening and of simulated power outages demonstrated the value of adding water bottles to the door as a thermal ballast. The performance of compact, dormitory-style refrigerators suffered from drift of the refrigerator set point, sensitivity to load density, and high temperature non-uniformity. These problems make the dormitory-style refrigerator [capacity = 0.077 m^3 (2.72 cu. ft.)] unsuitable for vaccine storage. We tested four electronic data loggers as a means of continuously logging refrigerator temperatures. Properly located, data loggers accurately monitored vial temperatures for extended periods.

1. INTRODUCTION

Each year, millions of dollars worth of vaccines are lost in the United States due to improper storage conditions. In order to maintain potency, many common vaccines must be kept refrigerated between 2 °C to 8 °C. When vaccines are exposed to temperatures above or below this range, their potency is reduced until they eventually become completely ineffective.

A number of factors influence whether vaccines stored in a refrigerator remain within the prescribed temperature range. Vaccine storage trays or boxes can obstruct refrigerator air flow, creating areas pockets of colder or warmer air. Vaccines stored in certain locations, such as near the refrigerator cooling unit, may be kept significantly colder than if placed in the main body of the refrigerator. Some factors may vary drastically between different refrigerator types (e.g. dorm style, freezerless, dual zone or pharmaceutical grade). Parameters such as temperature control stability, air circulation patterns, defrost cycles, and long-term drift of the temperature set point can play a major role in determining whether a refrigerator maintains suitable vaccine storage conditions. Because of this, simply setting a refrigerator to a temperature between 2 °C to 8 °C may not actually result in stored vaccines being kept within that temperature range.

Accurate monitoring of vaccine temperatures requires attention to the type of monitoring system used and its installation in the refrigerator. Different types of temperature monitoring systems can influence both the accuracy of the temperature measurement and the ease of use. Depending on the placement of a temperature monitoring device, as well as the time or frequency that its readings are recorded, the resulting temperature readings may or may not correspond to actual vaccine temperatures.

In this study, we explored a number of these factors in an attempt to determine which have the greatest impact on vaccine temperature. From this, we can make experimentally verifiable recommendations regarding the best and worst vaccine storage configurations and temperature monitoring setups. We used an array of calibrated thermocouples, mounted in multiple locations, as reference thermometers. An automated data-acquisition system measured the thermocouple temperatures continuously, for a wide variety of operating conditions. Attaching thermocouples directly to vaccine vials gave temperature measurements highly indicative of the actual vaccine temperatures.

We report measurements for two refrigerator styles: a) compact, "dormitory-style" refrigerator [capacity = 0.473 m^3 (16.7 cu. ft.)], and b) a household refrigerator [capacity = 0.077 m^3 (2.72 cu. ft.)] with no freezer unit. Our tests demonstrate that the dormitory-style refrigerator cannot reliably maintain vaccine temperatures in the range 2 °C to 8 °C. Weaknesses of the dormitory-style refrigerators include: poor long-term stability; sensitivity to loading conditions; and large temperature non-uniformities. The freezerless household refrigerator, on the other hand, can easily maintain vaccines at appropriate temperatures with only a few simple precautions.

A similar study exploring the suitability and performance of pharmaceutical grade refrigerators for vaccine storage was conducted by the Test Research Group for the Australian General Practice Network [1]. For further information on vaccine storage practices, including official storage guidelines from the Centers for Disease Control, consult references 2 - 5.

2. EXPERIMENTAL METHOD

Prior to this study, members of the NIST Thermometry Group visited seven Vaccines for Children (VFC) clinics in order to observe their vaccine storage practices. In our experimental trials, we attempted to replicate the range of vaccine storage conditions witnessed at VFC clinics.

This range included variations in loading density. For example, during influenza season, a large influx of patients could leave a clinic with dwindling vaccine supplies. At this time, their storage refrigerator would probably contain a low packing density. Other times, such as immediately following a large vaccine shipment, the same storage refrigerator might be filled to maximum storage capacity with boxes of vaccines. This would be considered a high density load. By testing a variety of low, medium, and high packing densities, we were able to quantify how this type of normal inventory fluctuation affects refrigerator performance.

We also experimented with different packaging styles. Many of the clinics surveyed used plastic trays or bins to organize and store their vaccine inventory. We also observed vaccines stored inside cardboard shipping boxes, as well as in their original light cardboard packaging. The Centers for Disease Control and Prevention (CDC) guidelines advise storing vaccines in plastic trays rather than uncontained on shelves or inside shipping boxes. However, during very busy times, clinic workers might temporarily store vaccines in their shipping containers until they can be organized into appropriate bins. As a result, we investigated whether these different packaging methods would affect the refrigerator's ability to maintain the proper vaccine storage

temperatures. In this study, we performed trials using three different packing styles: 1) vaccines stored exclusively in plastic trays; 2) vaccines stored inside various boxes, such as cardboard shipping boxes or their original thin cardboard packaging; and 3) vaccines stored in a mixture of plastic trays and cardboard boxes.

In our survey of VFC clinics, we noted multiple locations storing water bottles in refrigerator doors or in the main space of the refrigerator, a practice recommended by the Centers for Disease Control. This is because the additional thermal mass of the water bottles should act as a temperature ballast, lessening the impact of potential temperature fluctuation sources. To test the effectiveness of this practice, we performed some trials with water bottles filling the refrigerator door, and some trials without. The typical volume of water bottles used was equal to 3% to 5% of the total refrigerator capacity.

We performed a cycle of measurements on two different refrigerators (a compact, dormitory style and a full-size, single-door freezerless style) using permutations of the variables described above. Prior to the fist cycle of measurements, the refrigerators were adjusted to give a storage temperature of 4 °C. A complete listing of the different trials and order in which they were performed is contained in the measurement matrix (Table 1) shown below. After completing the trials with varying load densities, packing styles, and with/without water bottles, we performed some additional trials designed to simulate some of the different conditions that a VFC clinic might experience.

During the first cycle of trials, the refrigerator door was kept closed. However, in every day use, it is not possible to keep a refrigerator door closed at all times. The door must be opened briefly in order to add and remove vaccines for use. To mimic the opening and closing of the refrigerator door that occurs with normal use, we performed trials in which the door was opened at 15 minute intervals for 15 seconds at a time, over the course of at least 2 h. We carried out these measurement using at least two different packing schemes (one with water bottles and one without) for each refrigerator. We also recorded data with the refrigerator door left ajar for approximately 1 h, in order to observe what occurs if a clinic employee forgets to completely close the door.

Another non-idealized but common experience at VFC clinics is fluctuation in the storage room temperature. Poor HVAC control, inclement or seasonal weather changes, and planned or unplanned outages can all cause unexpected room temperature fluctuations. We wished to determine whether these types of changes affect a refrigerator's ability to maintain the required 2 °C to 8 °C temperature range. To do this, we recorded refrigerator temperature data while increasing the ambient room temperature by several degrees. As before, these trials were repeated for each refrigerator using at least two different packing schemes.

In the final set of trials, we observed what occurs to refrigerated vaccines stores in the event of a power outage. In these trials, the refrigerator was set up to run normally. After starting the measurement collection system, the refrigerator was unplugged and data collection continued overnight.

Table 1. Matrix of measurements performed for each refrigerator.

Trial	Load Density			Packing Style			Water Bottles	Measurement Parameters
	Low	Medium	High	Trays	Boxes	Mixed		
1	x			x				normal
2		x		x				normal
3		x		x			x	normal
4		x			x		x	normal
5		x		x			x	normal
6			x		x		x	normal
7	x					x	x	normal
8		x				x	x	normal
9			x			x	x	normal
10			x			x	x	increase room temp
11			x			x	x	periodic door opening
12			x			x	x	power off
13		x				x		normal
14		x				x		increase room temp
15		x				x		periodic door opening
16		x				x		power off
17	x			x				normal
18	x			x				periodic door opening

Note: During the dorm-style refrigerator tests, we moved 4 thermocouples from other locations to vials starting from 5th trial (in blue).

To determine the temperature distribution throughout the entire refrigerator space, we arranged 19 Teflon-insulated, Type T thermocouples in various regions in the refrigerator body. The thermocouples were attached to refrigerator walls or storage trays, hung in air, mounted inside of glycol-filled bottles, or most importantly, taped to actual vaccine vials. The most important feature of a refrigerator used for vaccine storage is its ability to maintain a vial temperature between 2 °C to 8 °C. Therefore, monitoring actual vial temperature in addition to other locations inside the refrigerator enabled us to effectively evaluate each refrigerator's performance. The installation pattern also allowed us to determine how well thermometers placed in different areas match the actual vaccine temperatures. This helped us produce useful guidelines for the best placement of refrigerator temperature monitoring devices.

The thermocouple reference junctions were maintained at 23 °C ±0.002 °C in an auxiliary stirred water bath. Prior to use, we calibrated each thermocouple at the melting point of ice (0 °C) by placing the thermocouple measuring junction in a Dewar flask containing crushed ice and distilled water. The flask itself rested inside the refrigerator under study. An automated, 6 ½ digit voltmeter monitored the voltage produced by each thermocouple.

In addition to the 19 thermocouples used to monitor temperature, we tested several different electronic temperature loggers throughout the course of this study. At present, VFC clinic workers are required to check a thermometer placed inside the refrigerator at certain intervals each day. Barring any inaccuracies inherent to the device or poor placement of the thermometer, this type of monitoring is still likely to be insufficient. Refrigerator temperature is not constant

over time, so a simple thermometer check once or twice a day will not give an accurate indication of whether the vaccines have remained within the designated temperature range.

Additionally, inexpensive electronic data loggers (e.g. self-contained temperature recording devices) may provide a useful alternative giving 24-hour-a-day monitoring of refrigerator temperature. To investigate the utility of data loggers, we placed three different data loggers inside the refrigerator throughout the study in order to compare their performance to that of the thermocouples. The placement of the thermocouples and data loggers was kept consistent for the duration of trials in each refrigerator. The thermometer installation patterns for each refrigerator are shown in Figs. 1 and 2 below.

Table 2 summarizes the equipment used for this study. Table 3 contains the uncertainties corresponding to the measurement devices and systems used.

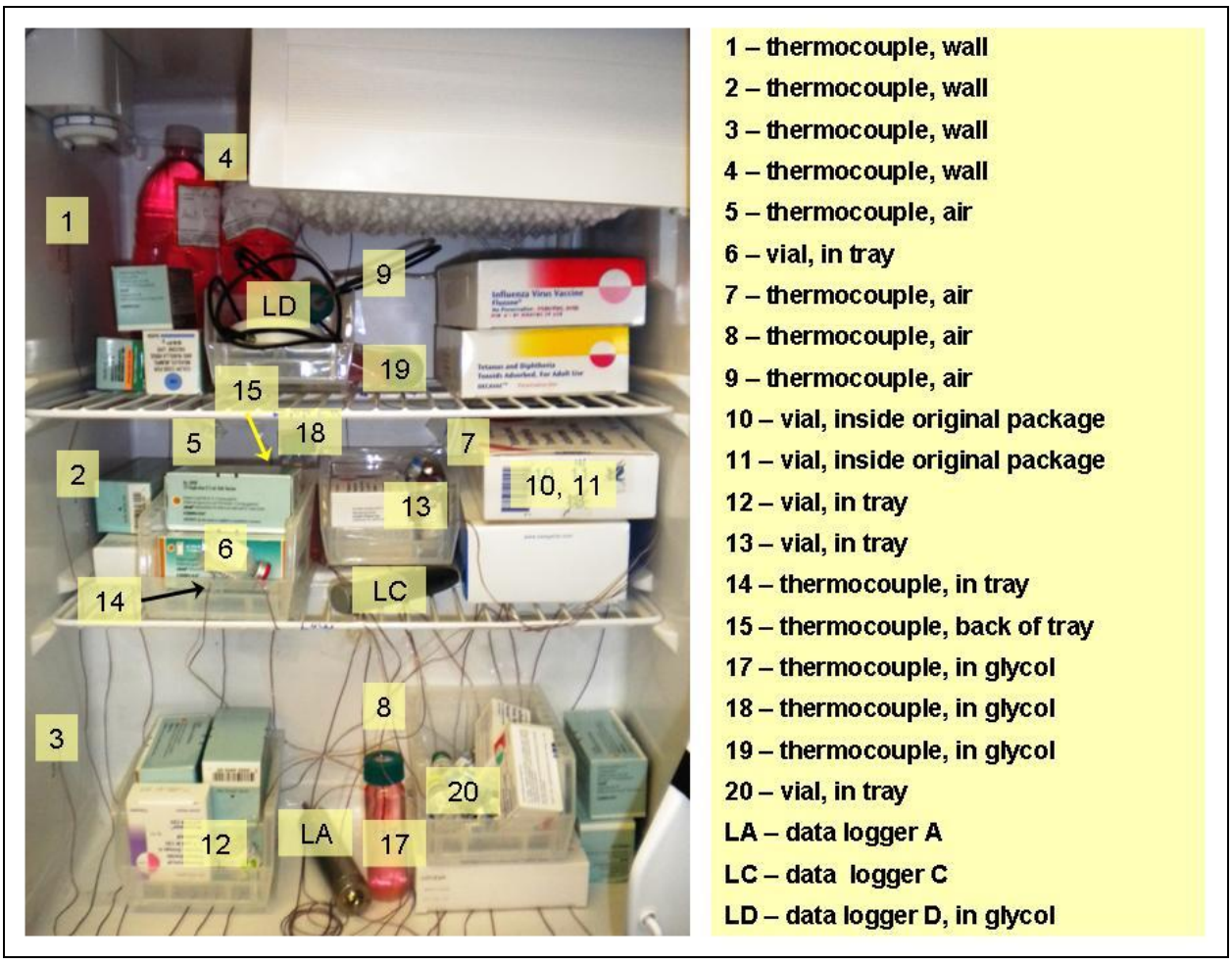


Fig. 1. Thermocouple and data logger installation pattern—dorm style refrigerator.

1 – thermocouple, wall
2 – thermocouple, wall
3 – thermocouple, wall
4 – thermocouple, wall
5 – thermocouple, air
6 – vial, inside box
7 – thermocouple, air
8 – thermocouple, air
9 – thermocouple, air
10 – vial, inside original package
11 – vial, inside original package
12 – vial, inside box
13 – vial, in tray
14 – thermocouple, in tray
15 – thermocouple, back of tray
17 – thermocouple, in glycol
18 – thermocouple, in glycol
19 – thermocouple, in glycol
20 – vial, on top of box
LA – data logger A
LC – data logger C
LD – data logger D, in glycol

Fig. 2. Thermocouple and data logger installation pattern—freezerless refrigerator.

Table 2. Equipment used for the present study.

Equipment name:	**Specifications:**
Dormitory-style refrigerator	▪ Compact refrigerator (120 V) ▪ Height: 0.665 m [26.1875 in.] ▪ Width: 0.479 m [18.875 in.] ▪ Depth: 0.486 m [19.125 in.] ▪ Capacity: 0.077 m^3 [2.7 cu. ft.] ▪ No forced convection
Freezerless refrigerator	▪ Automatic defrost single-door refrigerator (120 V) ▪ Height: 1.65 m [65.125 in.] ▪ Width: 0.813 m [32 in.] ▪ Depth: 0.676 m [26.625 in.] ▪ Capacity: 0.473 m^3 [16.7 cu. ft.] ▪ Forced convection of cooling air
Plastic trays	▪ Stacking plastic storage trays/ bins
19 thermocouples	▪ Type T (copper-constantan)

	▪ 0.5 mm diameter, 1.83 m length ▪ Teflon insulation ▪ Calibrated at 0 °C
Data logger A	▪ Rugged high-temperature logger ▪ Metal housing with integral 2.6 cm rigid probe ▪ Temperature range: –40 °C to +150 °C ▪ Temperature resolution: 0.05 °C ▪ Calibrated accuracy: ± 0.5 °C (from manufacturer) ▪ Memory: 32,767 readings ▪ Battery life: 1 year ▪ Body dimensions: 12.2 cm x 2.6 cm dia. ▪ Probe dimensions: 2.6 cm x 0.5 cm dia.
Data logger B	▪ Plastic housing with integral LCD display ▪ Temperature range: –35 °C to 80 °C ▪ Temperature resolution: 0.5 °C ▪ Accuracy: ± 0.5 °C (manufacturer rating) ▪ Memory: 16,328 readings ▪ Battery life: 1 year ▪ Nominal body dimensions: 12.6 cm x 2.4 cm max dia.
Data logger C	▪ Plastic-housing temperature and humidity Logger ▪ Temperature range: –35 °C to 80 °C ▪ Temperature resolution: 0.5 °C ▪ Accuracy: ± 0.3 °C (manufacturer rating) ▪ Memory: 16,328 readings ▪ Battery life: 1 year ▪ Nominal body dimensions: 10.2 cm x 2.3 cm max dia.
Data logger D	▪ Data logger with flexible temperature probes ▪ Temperature sensors in readout unit and in a flexible probes ▪ Temperature range (readout): –40 °C to 85 °C ▪ Temperature range (flexible probe): –15 °C to 105 °C ▪ Temperature resolution: 0.1 °C ▪ Accuracy: ± 0.5 °C (manufacturer rating) ▪ Memory: 2000 readings per channel ▪ Battery life: 2 years ▪ Nominal body dimensions: 7.6 cm x 7.5 cm x 2.3 cm
Thermocouple measurement system	▪ 6.5 digit multimeter with scanner

Table 3. Measurement Device Uncertainties

Device name:	**U(k=2), °C**
Thermocouple measurement system	0.12
Data logger A	0.58
Data logger B	1.41
Data logger C	0.67
Data logger D	0.59

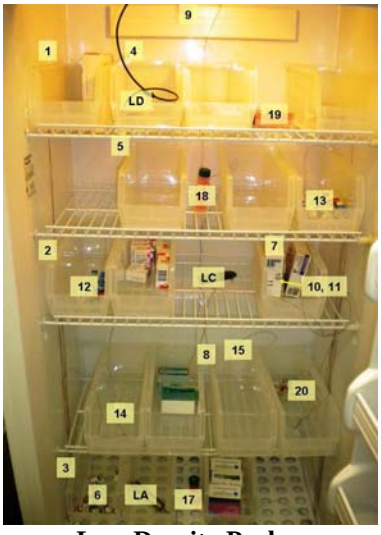
In general, each trial was started during the afternoon, and measurements recorded overnight and into the next morning. On average, we recorded 15 to 19 h of data for each trial, although some trials were continued over the course of several days. The only exception to this was the door opening trials, which only lasted 3 to 4 h. The thermocouple measurement system records readings once every 10 seconds. The individual data loggers can be set to various reading rates. In general, the loggers were set to record once every minute. However, during the door opening trials, we increased the reading rate to once every 10 to 42 seconds (depending on the capabilities of the logger). If we planned to record data for a very long time, such as over the course of a long weekend, the loggers were set to record data every 2 min. This was done to avoid running out of memory partway through the test.

3. INTERPRETATION OF RESULTS

3.1 Freezerless Refrigerator

3.1.1. Effect of loading density

In trials performed using this refrigerator model, vaccine storage density did not appear to have a major impact on the refrigerator's capability to maintain the desired temperature range. The photographs below (Fig. 3) show the various levels of packing density that were tested.



Low Density Pack

Medium Density Pack

High Density Pack

Fig. 3. Typical packing patterns.

Throughout the course of the study, average thermometer temperatures remained within approximately a 2 °C range regardless of whether the refrigerator load was low, medium, or high density. All of the thermometers maintained temperatures within the prescribed 2 °C to 8 °C range, with the exception of one thermometer (15) attached to the back of a storage tray (and thus not a good indicator of vial temperature), which read an average of 1.8 °C during one trial.

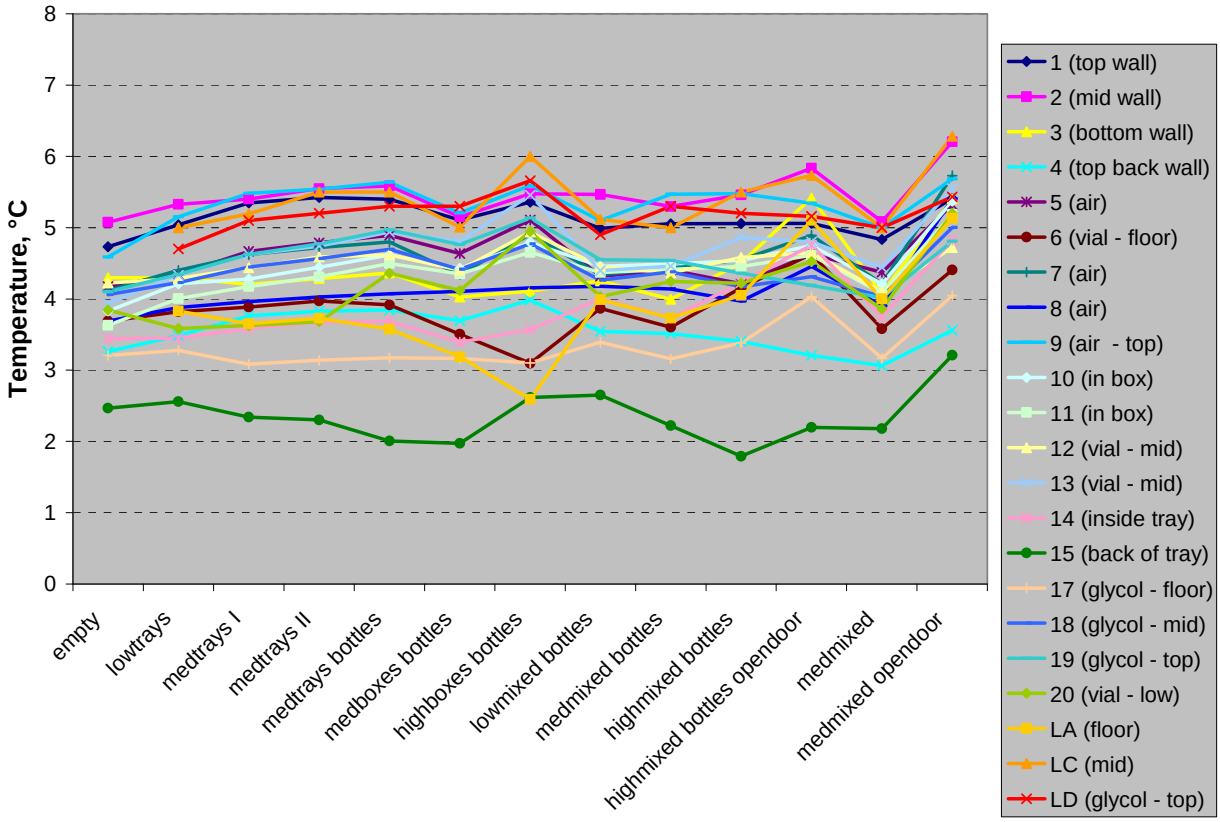


Fig. 4. Average temperature of freezerless refrigerator for all sensors, as a function of loading pattern. Labels on the abscissa correspond to entries in the measurement matrix of Table 1.

Figure 4 shows the average reading for each thermometer across all of the closed-door freezerless refrigerator trials, as well as the periodic door-opening trials. It is readily apparent that the main body of the refrigerator as well the vaccine vials themselves stayed within the prescribed temperature range, regardless of packing density variations. Considering a refrigerator used for everyday vaccine storage, the arrival of a large vaccine shipment or the onset of influenza season is likely to result in a sudden increase or decrease in the amount of material stored in the refrigerator. Because these types of load density variations do not greatly affect overall temperature stability, the freezerless refrigerator model appears to be suitable for normal vaccine storage.

3.1.2. Effect of packing style

As with the loading density variation, changing the vaccine packing style did not have a major impact on the overall refrigerator and vial temperature stability, whether plastic trays, cardboard boxes, or a combination of both were used to store the vaccines. (See Fig. 5.) While official guidelines for vaccine storage mandate that vials be stored in permanent trays or containers and organized by type, we observed other storage conditions during our visits to the VFC clinics. For example, a busy clinic with a sudden influx of vaccines might temporarily store vaccines inside their shipping boxes. The measurement results indicate that the freezerless refrigerator

model would be able to withstand this type of practice, continuing to preserve the prescribed vaccine storage temperature range regardless of packaging style.

Fig. 5. Various vaccine storage methods.

3.1.3. Effect of door opening and closing—normal use simulation

The results of the periodic door-opening trials also support the efficacy of the freezerless refrigerator model. Although thermometers attached to refrigerator walls and hanging in the air recorded temperatures above the allowed maximum temperature of 8 °C, all thermometers attached to vials remained within the desired range in spite of the repeated exposure to room temperature air.

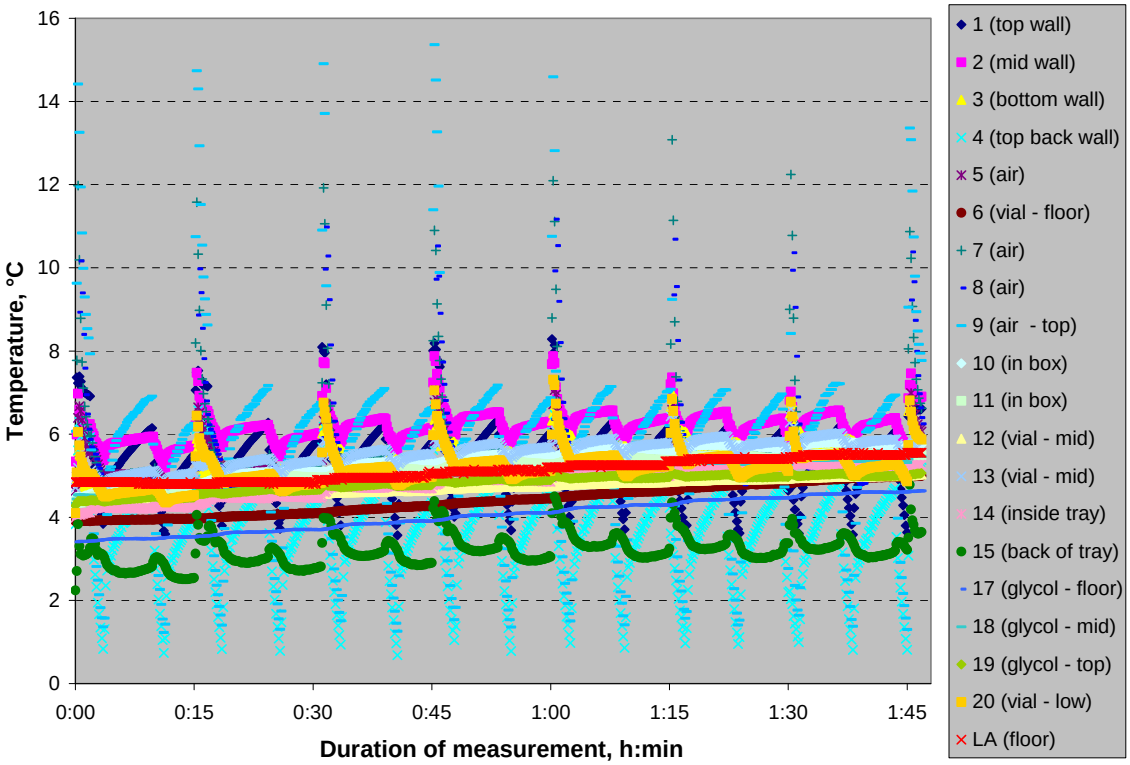


Fig. 6. Door opening trial for the freezerless refrigerator using a medium density mixed load with no water bottles.

As expected, the results shown in Fig. 6 above show a spike in temperature occurring each time the refrigerator door was opened. The majority of the thermometers recorded an overall higher average temperature during this trial than during the closed door test using the same packing scheme. Three thermometers, all of which were placed close to the refrigerator cooling unit, recorded a slightly lower temperature during the door opening trial. This is most likely due to the refrigerator pumping out additional cold air to compensate for the warm air introduced during door opening.

It is important to note that the thermometers attached to the refrigerator walls and hanging in the air were the only ones to show dramatic spikes exceeding the 8 °C limit. In contrast, the thermometers attached to vials, which recorded smaller temperature increases in response to the door opening, remained within the prescribed temperature range of 2 °C to 8 °C for the duration of the test, as shown in Fig. 7 below.

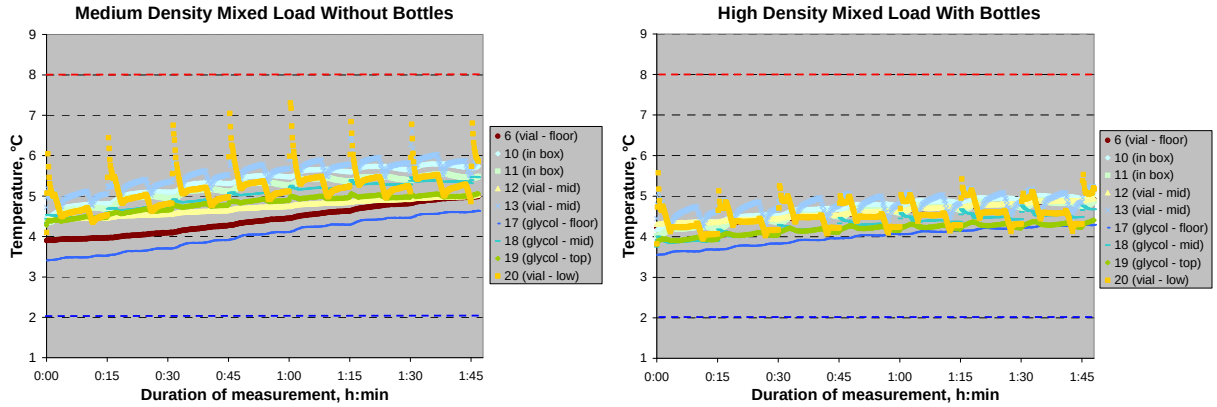


Fig. 7. Door-opening trials for the freezerless refrigerator using two different loading configurations, with and without water bottles. Only thermocouples monitoring vial temperatures are shown.

Fig. 7 compares the data recorded during the medium density, mixed loading scheme without water bottles trial to that of the high density mixed scheme with water bottles trial. The data from the second trial (with bottles) shows similar, but slightly smaller temperature fluctuations. While it is difficult to determine whether the water bottles made a difference during the closed door tests, the data from the two door-opening trials—with and without water bottles—supports the assertion that bottles stored in a refrigerator door help to reduce temperature fluctuations.

To further evaluate the water bottles' effectiveness as a temperature stabilizer, we compared the temperature increase of the thermometers across the two separate trials. In general, the average temperature recorded during the door opening test was higher, except in the case of a few thermometers near the cooling unit, as discussed previously. As always, the most important features to examine are the temperature increases of the actual vials. Table 4 below shows the different door opening temperature changes for the two trials, with and without water bottles. In this case, the temperature change is defined as the difference between the average temperature recorded during the closed door trial and the average temperature from the door-opening trial with the same loading configuration.

Table 4. Temperature changes during door-opening tests (all values in degrees Celsius).

Sensor Name/Location	High Density Mixed With Bottles	Medium Density Mixed No Bottles
1 (top wall)	0.00	0.57
2 (mid wall)	0.37	1.12
3 (bottom wall)	0.91	1.32
4 (top back wall)	-0.20	0.50
5 (air)	0.42	0.95
6 (vial - floor)	**0.48**	**0.83**
7 (air)	0.34	1.52
8 (air)	0.49	1.51
9 (air - top)	-0.13	0.69
10 (in box)	**0.21**	**1.16**
11 (in box)	**0.16**	**1.11**
12 (vial - mid)	**0.07**	**0.62**
13 (vial - mid)	**-0.06**	**1.11**
14 (inside tray)	0.53	1.07
15 (back of tray)	0.41	1.03
17 (glycol - floor)	0.65	0.88
18 (glycol - mid)	0.14	0.97
19 (glycol - top)	-0.17	0.79
20 (vial - low)	**0.30**	**1.34**
MT (floor)	1.05	1.13
SU (mid)	0.23	1.28
TD (glycol - top)	-0.04	0.43

The vial data is highlighted in boldface colored font. All of the thermometers recorded a smaller temperature increase when water bottles were used in the door. Without water bottles, the periodic door opening resulted in an increase of 0.2 °C to 1.2 °C higher than that with water bottles. While this is not a huge effect, it is enough to recommend widespread use of water bottles as a ballast in vaccine storage refrigerator doors. In particular, if a refrigerator's average temperature happened to be operating on the higher side of the prescribed range, an extra degree of protection against temperature fluctuation due to normal door opening could be the difference between a viable vaccine and a ruined vaccine.

The effect of the water bottles was even more dramatic during the test in which the refrigerator door was left cracked open for 1 h, to simulate an employee forgetting to completely close the door. Table 5 below shows the amount of time it took once the door was opened for each of the vials to exceed the allowed maximum temperature of 8 °C.

Table 5. Time after opening door until vial temperature exceeded 8 °C.

Name and Location	High Density Mixed With Bottles (minutes)	Medium Density Mixed No Bottles (minutes)
vial 20 (on top of box)	3	1
vial 13 (in tray)	12	2
vial 10 (inside original packaging)	20	9
vial 11 (inside original packaging)	25	9
vial 6 (inside cardboard box)	32	17
vial 12 (inside cardboard box)	46	49

The window of time before the vaccines exceeded the allowed temperature was significantly longer when the water bottles were in place. Depending on how the vaccines are stored, water bottle ballast can provide an extra 2 min to 15 min of leeway before vaccines are subjected to out-of-range temperatures. Storing the vaccines inside their original packaging or in a cardboard box provides a further layer of protection from the warm outside air.

3.1.4. Effect of Increasing Room Temperature

Although vaccine storage refrigerators should be kept in a fairly well temperature controlled room, considerable ambient temperature fluctuations may result from planned HVAC outages at night or weekends, or from unplanned circumstances such as an AC outage or poor thermostat control. To determine whether these fluctuations impact the freezerless refrigerator's ability to maintain its set point temperature, we performed three trials in which the room temperature was increased 3 °C to 5 °C above the ambient operating temperature of 21 °C to 22 °C.

Data logger D has a thermometer included in the main readout unit as well as an additional probe attached via cable. This probe was inserted into a glycol-filled bottle kept inside the refrigerator throughout all of the trials, while the readout unit was kept outside of the refrigerator, in a tray taped to the refrigerator door. In this way, we were able to simultaneously measure both the internal refrigerator temperature and the external ambient temperature using the same device. By plotting the relationship between internal refrigerator and ambient temperature, we can determine the effect an increase in room temperature can have on vaccine storage conditions.

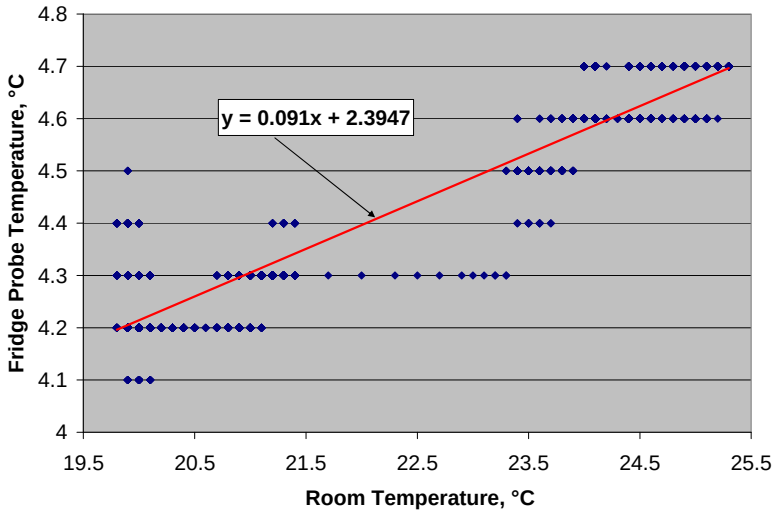


Fig. 8. Refrigerator temperature versus ambient temperature

Figure 8 shows the results of one of the increased room temperature trials. This data was recorded over a period of 7.5 days. Each day, the room temperature control was increased by approximately 1 °C, allowing for adequate stabilization time of both the ambient and corresponding refrigerator temperatures. We also performed two shorter trials, in which the room temperature control was set to increase by either 3 °C or 5 °C, and the ambient and refrigerator sensors were monitored overnight. The data from the shorter trials was similar to that of the trial shown above.

From Fig. 8, it appears that the ambient temperature and the corresponding internal refrigerator temperature are directly related. As the room temperature rises, so does the temperature of the vaccines stored inside the refrigerator. Extenuating factors, such as refrigerator load density, timing of a cooling cycle, and initial refrigerator temperature, are likely to complicate this equation beyond a simple linear relationship. However, it is helpful to examine a linear fit applied to the data to determine whether any generalizations can be made.

Although the relationship between exterior and interior refrigerator temperature is inherently complex, we can extract simple and important observations from our brief investigation into this phenomenon. A linear fit applied to each of the data sets results in a slope of ~ 0.1 °C. This means that each time the room temperature rises one degree, we can expect the internal refrigerator temperature to increase approximately one-tenth of a degree. For the refrigerator temperature to rise a full degree, the room temperature would need to increase by 10 °C.

As such, while room temperature fluctuations of 1 °C to 2 °C are not likely to cause significant danger to refrigerated vaccine storages, it is clear that some circumstances could cause a serious issue. For example, an air-conditioning outage during the summer time may result in a room heating up very quickly. During an actual AC outage, the ambient temperature may rise much higher than in our tests. If this type of event occurred on a weekend or another time when employees are not present to diagnose the problem, there is a strong possibility of internal refrigerator temperatures varying outside of acceptable vaccine conditions.

3.1.5. Effect of a Power Outage

To observe what occurs following a power outage, we performed two trials in which the closed refrigerator was unplugged and monitored overnight. During these trials, the room temperature was stable to within 1 °C. In both trials, all of the thermometers recorded a fairly steep increase in temperature that slowed down slightly over time. All of the thermometers, including those attached to vaccine vials, exceeded the allowed maximum temperature in 5 h for the medium density (no bottles) trial, and in 9 h in the high density with bottles trial. Figure 9 below shows the temperature readings of all of the thermometers during one of the power off trials. The sudden drop in temperature following the peak corresponds to the point at which the refrigerator was plugged back in.

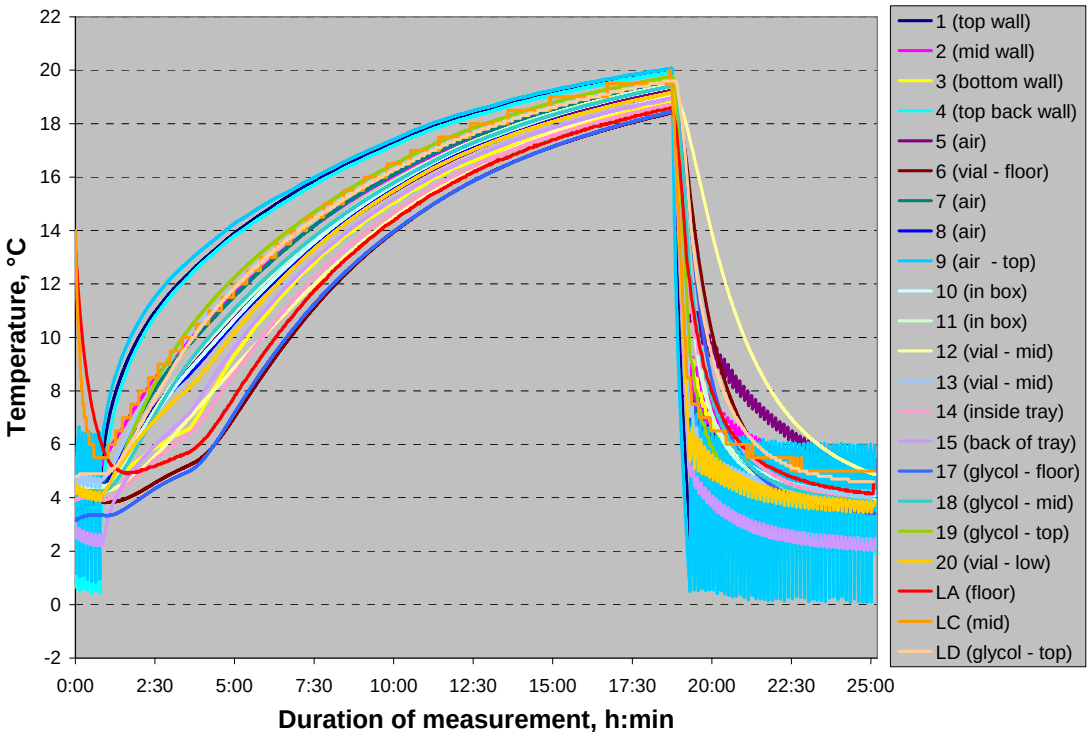


Fig. 9. Thermometer response during a power-outage event.

The next graph (Fig. 10) shows the data collected starting from the time that the refrigerator was unplugged, at 14:15. The dashed red line indicates the 8 °C upper limit, and the blue dashed line shows the 2 °C minimum.

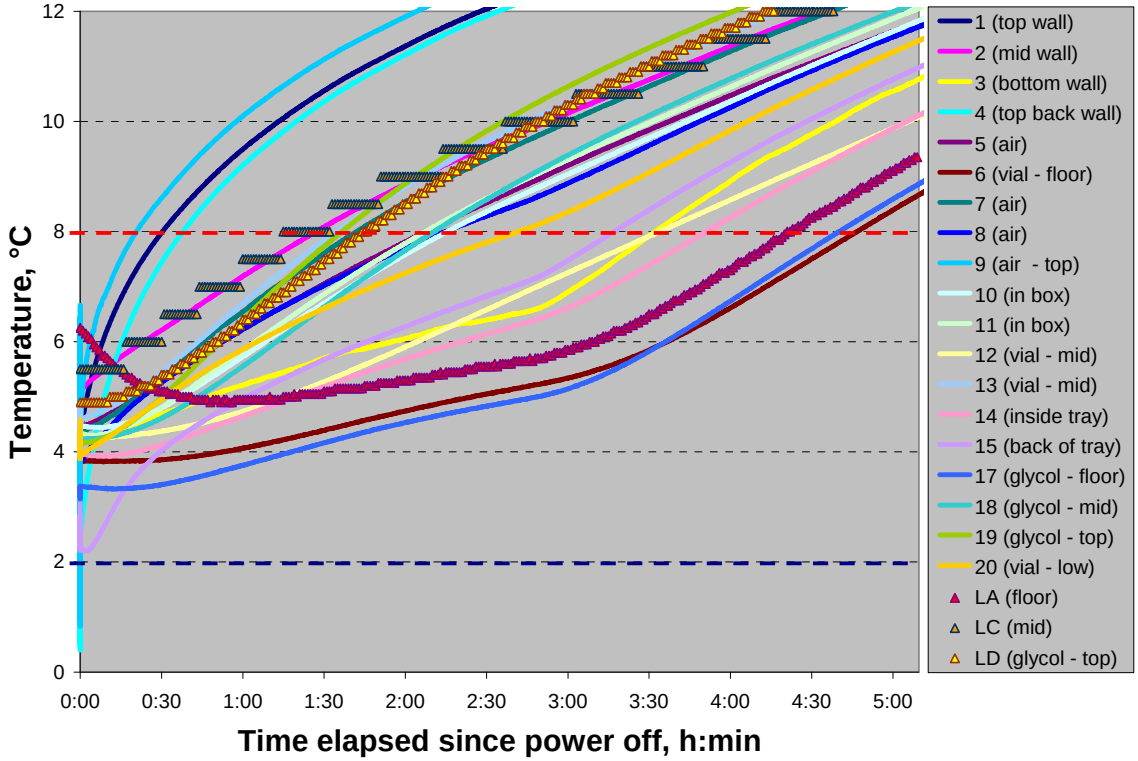


Fig. 10. Expanded view of thermometer response during a power-outage event.

To determine the required response time to preserve vaccine viability during a power outage situation, we examined the amount of time elapsed from the point that the refrigerator was unplugged until the thermometers attached to vials exceeded 8 °C. This information is reported in Table 6 below.

Table 6. Time after power-off until vial temperature exceeded 8 °C.

Name and Location	High Density Mixed With Bottles (hrs:mins)	Medium Density Mixed No Bottles (hrs:mins)
vial 13 (in tray on upper shelf)	1:55	1:35
vial 11 (inside original packaging, middle shelf)	3:05	2:07
vial 10 (inside original packaging, middle shelf)	3:22	2:15
vial 20 (on top of box, mid-lower shelf)	4:16	2:42
vial 12 (inside cardboard box, middle shelf)	4:34	3:34
vial 6 (inside cardboard box, floor level)	8:37	4:47

We drew several conclusions from this data. The vials that exceeded the maximum temperature the most quickly were those that were not contained in boxes or packaging and were stored in the upper region of the refrigerator. This occurs for two obvious reasons. With the power off, the fans do not circulate air throughout the cavity, so the warmer air rises to the top of the refrigerator. Hence, vials stored in the top portion of the refrigerator are exposed to warmer air than those stored in the bottom. The vials contained in their original packaging or in cardboard boxes fared better than their "exposed" counterparts because of the additional layer of thermal insulation. In order to heat up a vial inside a container, thermal energy first must be conducted

through layers of cardboard. As such, to preserve vaccine efficacy in the event of a power outage, it is best to keep more sensitive medicines stored inside boxes and away from the upper region of the refrigerator.

Table 6 shows the effect of storage method and location on the amount of time elapsed before vaccines exceeded the maximum temperature limit. Depending on the location and storage container for a particular vaccine, workers have between 1.5 h and 4.5 h before the vaccines warm above 8 °C to get the power restored or to move the vaccines to a new location. During the first trial, a vial stored inside a box on the floor maintained temperature for over 8 h. In spite of this, storing vaccines on the refrigerator floor is not recommended because the floor tends to be colder than the bulk of the refrigerator, and thus may keep vaccines below the allowed minimum temperature of 2 °C (more critical than that of the allowed maximum temperature of 8 °C) during normal operation.

The results of these trials further support the efficacy of using water bottles as a temperature ballast. Including water bottles in the refrigerator door provided an extra 20 min to 3 h 50 min before the vials exceeded the temperature limit, depending on their location.

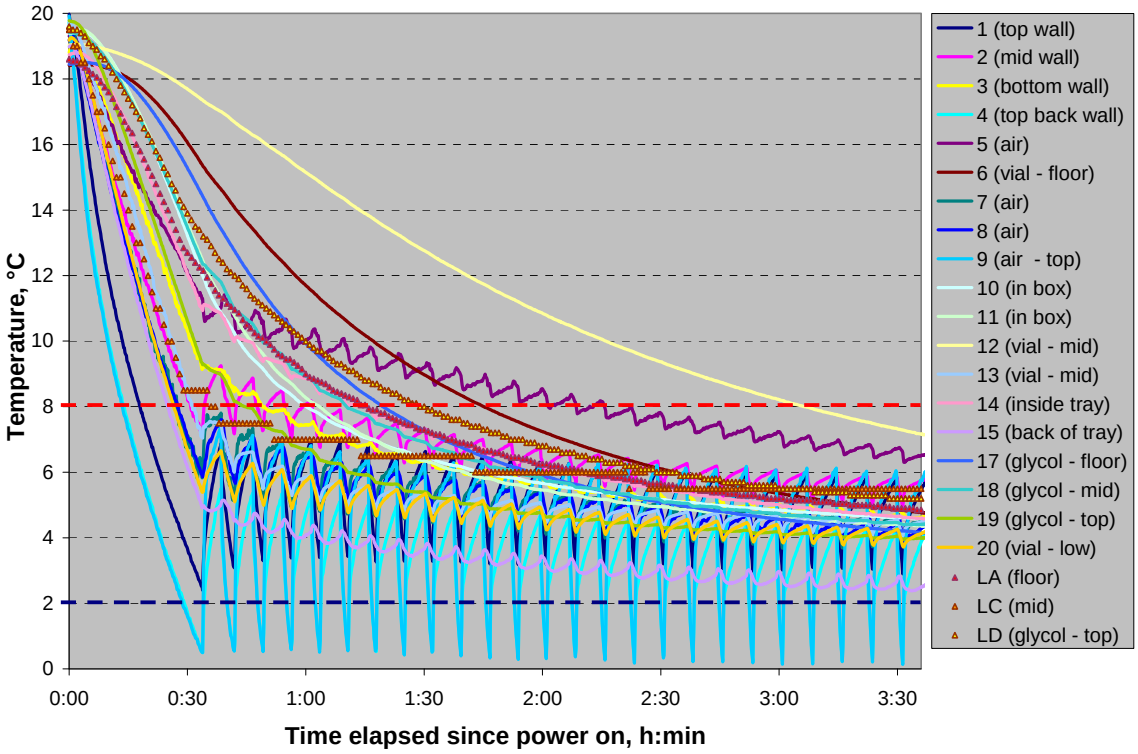


Fig. 11. Recovery after restoration of power for a freezerless refrigerator.

In order to observe the time required for the refrigerator to return to equilibrium following a power outage, we continued recording data after the refrigerator was powered. Obviously, the length of the power outage and the resulting maximum temperature attained will affect the length of time required to get the refrigerator back down to its original baseline.

During the high density mixed load (including water bottles) trial, the refrigerator was left unplugged for a total of 15 h 31 min. During the medium density mixed load trial, the total power off time was 17 h 59 min. Because of this, the refrigerator reached a different maximum temperature in each trial, so the effect of loading density and water bottles on power outage recovery time cannot be evaluated based on these trials. The main point to note from the above data is that vials open to main refrigerator air flow returned to the specified temperature range the most quickly, while those contained in a thermally insulating package, such as a cardboard box, took the longest to recover to an allowed temperature. In both trials, the freezerless refrigerator took at least 6 h to completely re-equilibrate from ambient following the simulated power outage.

3.1.6. General Stability of Vial Temperature and Suitability of Freezerless Refrigerator Model for Maintenance of Vaccine Storage Conditions

The freezerless refrigerator model's performance appears suitable for vaccine storage. Vaccine vial temperatures remained within the specified 2 °C to 8 °C range throughout all of the packing variation trials, as well as during the 15 second door opening trials. Drift of the refrigerator control thermometer appears to be negligible.

3.1.7. Best and Worst Locations for Vial Storage

Throughout the course of the closed-door freezerless refrigerator trials, vaccine vials remained within the desired temperature range regardless of their location in the refrigerator. However, based on the results of the door opening and power-off trials, it appears that some storage methods and locations within the refrigerator may be better for vaccine storage than others. In general, vials stored inside cardboard shipping boxes or in their original cardboard packaging experienced the least temperature disruption during normal, periodic door-opening operation. Storage in plastic trays also provided suitable thermal insulation. The vials that recorded the largest temperature fluctuations were kept open to the air and placed directly on refrigerator shelves or on top of boxes, close to the front of the refrigerator. This comes as no surprise, since this type of storage method provides very little thermal insulation from the surge of warm, ambient air that enters the refrigerator each time the door is opened.

During the simulated power outage trials, the vials placed in the bottom portion of the refrigerator were the last to exceed the allowed maximum temperature. Again, storage inside cardboard boxes provided the greatest level of thermal insulation, followed by storage inside the original (thinner) cardboard packaging. During normal operation, fans inside the refrigerator distribute warmer and cooler air to maintain a fairly uniform temperature distribution throughout the interior space. Once a power outage begins, pockets of warmer and cooler air begin to separate, as the cooler air settles around the floor of the refrigerator and the warm air rises towards the top. As a result, vials kept on the upper shelves and not contained in boxes experienced the fastest temperature increases.

3.1.8. Best and Worst Methods of Monitoring Vial Temperature

In this study, we used several different temperature sensing devices in various locations throughout the refrigerator in order to determine the best way to monitor actual vial temperature. While attaching a thermocouple thermometer to a vial is a very accurate way to determine vaccine temperature, this is not a feasible strategy for clinics or storage facilitities. To determine the suitability of different vial temperature monitoring schemes, that is, the best and worst locations and monitoring devices for this purpose, we can compare the temperature readings of the vial-attached thermocouples to the readings of the other thermometers.

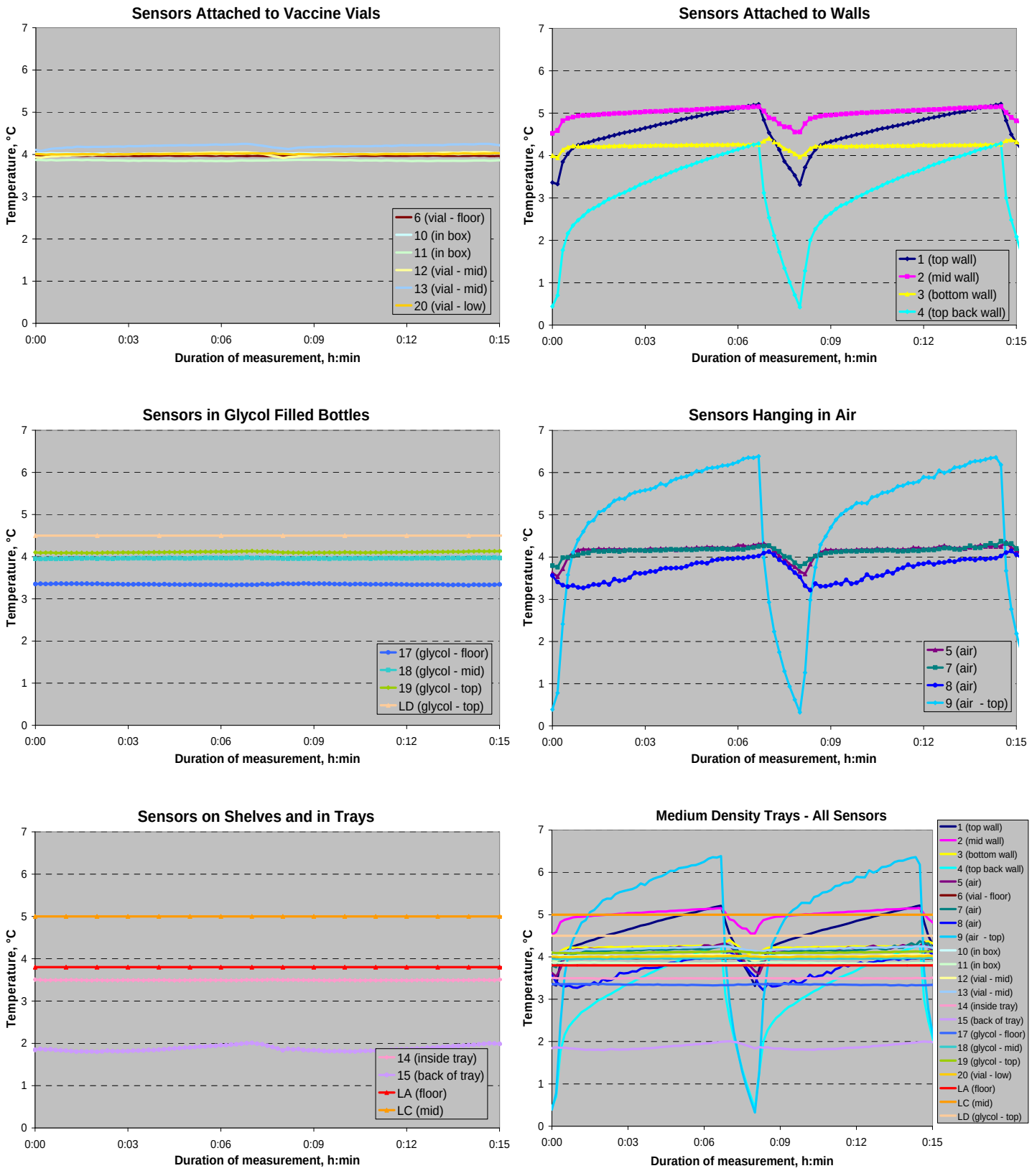


Fig. 12. Response of sensors with different mounting methods.

The graphs in Fig. 12 show a 15 minute period of data collected during the trial with a medium density packing of trays, with water bottles. This section of data is representative of the standard operating mode of the refrigerator observed throughout the course of our study. The first five graphs each contain data for thermometers placed in different types of locations (see Fig. 2 for thermometer locations). In this case the thermometers are classified by their location inside the refrigerator, whether they are attached to a vaccine vial, a wall, kept inside a glycol filled bottle, hanging in the air, or placed on a shelf or in a tray. The sixth graph shows the same data excerpt, but contains the readings for all of the thermometers. Using these graphs, we can determine which thermometer locations and types gave readings that most closely matched the actual vial temperatures.

Best Locations for Temperature Sensors

- The thermocouples contained inside glycol filled bottles and placed in the central or upper portion of the refrigerator matched the vaccine temperatures closely (18, 19). During the door-opening and power-off trials, these thermometers displayed temperature increases similar in magnitude and rate to those recorded by the vial thermometers.
- Data logger D (LD), with its probe contained in a glycol filled bottle placed in the upper region of the refrigerator, also matched the vial thermometer data fairly well. In general, the Data logger D gave temperature readings 0.5 °C to 1 °C higher than the bulk of the vial thermometers. However, this logger was placed one refrigerator shelf higher than the vials, so this discrepancy may be related to location rather than logger performance.
- As a general rule, the closer the thermometer is placed to the actual location where vaccines are stored, the closer its readings will be to actual vaccine temperatures.

Mediocre Locations for Temperature Sensors

- Thermometers placed on main refrigerator shelves, in the air, or inside of a tray *in the areas where vaccines were stored* produced data reasonably similar to that of the vial thermometers most of the time (5, 7, 8, 14, LC).
- However, the thermocouple attached to a tray (14) read consistently colder values than the vial thermometers.
- The thermometers hanging in the air space close to the vials gave readings that were fairly representative of vial temperature during the closed door testing, but showed much greater sensitivity to door opening and power outages than the vial thermometers. If we were to rely upon one of these thermometers for vaccine temperature monitoring, we would likely experience multiple “false alarms” that the temperature had exceeded 8 °C.
- In addition to the sensitivity issue noted above, data logger C (LC) recorded temperatures an average of 1 °C higher than the vial temperatures. Since LC was placed on the same shelf as several vials, this is most likely a result of the logger’s resolution, which is much lower than that of the thermocouples, or an issue with its calibration. Even so, as long as the refrigerator is kept in the middle of the 2 °C to 8 °C range, logger LC placed near the vials could be sufficient for vaccine temperature monitoring.

Unacceptable Locations for Temperature Sensors

- Placing a thermometer on the floor of the refrigerator will result in readings colder than the actual vial temperatures. Thermocouple 17, inside a glycol filled bottle, should have been able to closely match vial thermometers due to its similarity to a vial (liquid inside a glass bottle) and high temperature resolution. However, it consistently recorded temperatures almost a degree colder than the vials.
- Data logger A (LA) also suffered from being placed on the floor. For the most part, temperature fluctuations recorded by data logger A had the same magnitude as those experienced by the vials. However, the logger readings were consistently cooler than the vials. Data logger A should be tested further using a more centralized placement in the refrigerator. Under this condition, it is likely provide very accurate monitoring of vial temperature.
- Thermometers attached to upper refrigerator walls or anywhere in the top airspace of the refrigerator performed extremely poorly (1, 2, 4, 9). These thermometers were subject to dramatic fluctuations in response to normal refrigerator temperature control and defrost cycles as well as during our simulation trials. Thermometers placed in this area are right next to the cooling unit, so they pick up a major temperature change each time the refrigerator starts or stops pumping out cold air.
- Refrigerator walls generally should not be used as an indicator of main cavity temperature. The thermometer attached to the back of a tray (15) did not perform well either, possibly due to its close proximity to the wall.

3.1.9. Defrost Cycle Issues

Throughout the course of the freezerless refrigerator measurements, we noted the occurrence of periodic temperature spikes due to the refrigerator's defrost cycle. These temperature spikes generally appeared once every 2 to 3 days. As evidenced by the graph below (Fig. 13), which shows a standard freezerless refrigerator model defrost cycle, vaccine vial temperatures were not greatly affected by these periodic temperature increases. During this particular cycle, none of the vial-attached thermometers recorded temperatures above the 8 °C temperature limit. Occasionally, the temperature spike would be larger, and some of the vials would briefly exceed 8 °C. In this case, the time that the vials were out of the allowed temperature range was generally between 5 min and 15 min.

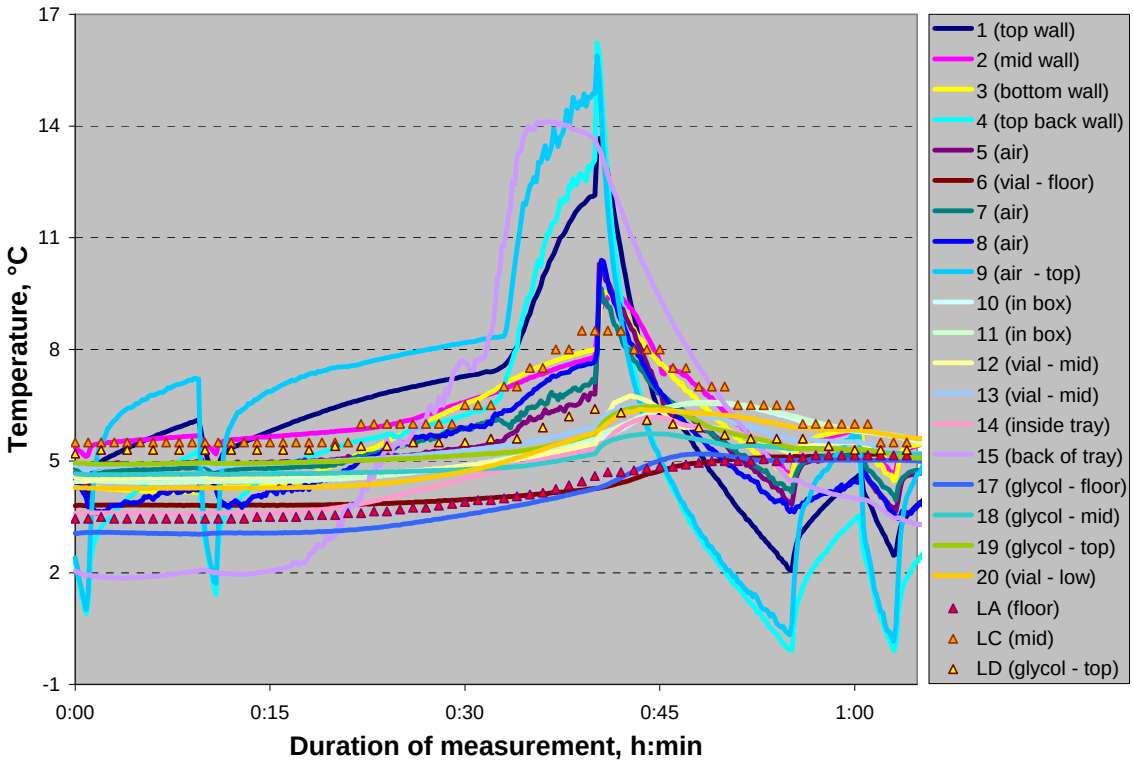


Fig. 13. Temperature spike due to a defrost cycle.

However, depending on the placement of thermometers used to monitor vaccine temperatures, the incidence of a defrost cycle could cause a VFC worker to incorrectly surmise that vaccine temperatures strayed outside of both the allowed maximum and minimum temperature bounds. Referring again to the graph, some of the thermometers attached to walls or hanging in the air recorded quite dramatic temperature spikes followed by a significant drop well below the 2 °C limit. If one of these thermometers were used to ascertain vial temperatures, then employees may improperly adjust the refrigerator set-point temperature and dispose of vaccines needlessly. As a result, care must be taken in determining the best placement for temperature monitoring devices in order to most accurately determine vial temperature during events such as refrigerator defrost cycles.

3.2. Dormitory Style Refrigerator

3.2.1. Effect of loading density

In trials performed using the dorm-style refrigerator, vaccine storage density (see Fig. 14) had a noticeable effect on the refrigerator's ability to maintain consistent and uniform vaccine storage temperatures.

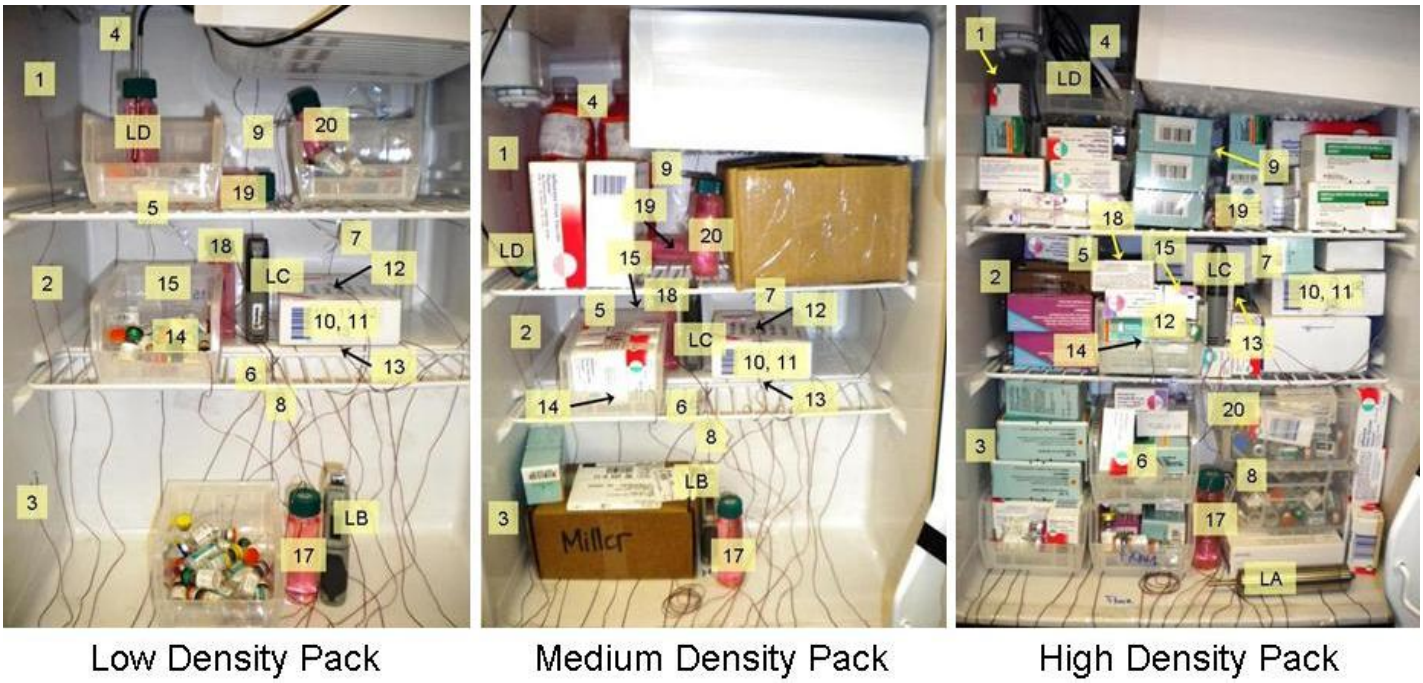


Fig. 14. Three packing densities tested with the dormitory style refrigerator.

In particular, higher density packing increased the range of location-specific temperature variation. This is reflected in the Fig. 15 below, as the vertical spread of the data is larger for the trials with a high density loading scheme than in the lower density trials. Since the dormitory-style refrigerator does not have a fan system, a high packing density most likely limits air flow, creating "pockets" of hot and cold air.

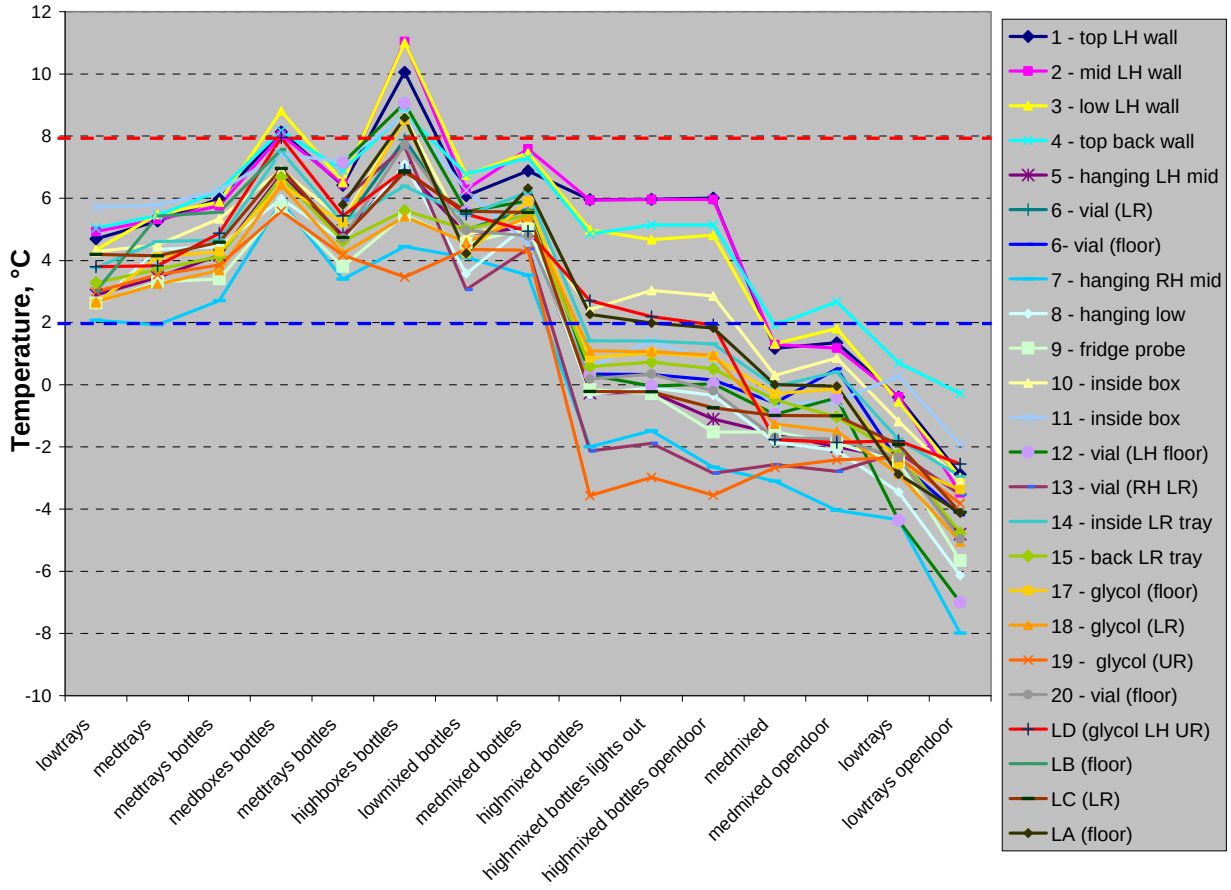


Fig. 15. Average temperature of dormitory-style refrigerator for all sensors, as a function of loading pattern. Labels on the abscissa correspond to entries in the measurement matrix of Table 1.

After 15 days of the total 42 day duration of the measurements on this refrigerator, the refrigerator ceased to maintain the required 2 °C to 8 °C temperature. In Fig. 15 above, starting from the 9th trial (high density mixed, with bottles), the majority of the thermometers recorded average temperatures below the allowable minimum temperature of 2 °C. The control settings of the refrigerator were left unchanged throughout the duration of the study, so these results are indicative of a problem with the refrigerator model's temperature control—the set point appears to drift over time. The dorm-style refrigerator does not appear capable of maintaining the narrow temperature range required for any reasonable length of time, nor does it maintain a consistent temperature profile thorough the interior of the refrigerator. Such a lack of temperature control will require periodic adjustment to the set-point temperature in an effort to maintain the required 2 °C to 8 °C temperature range; this will result in both unacceptable thermal excursions and a decrease in operational efficiency. These observations alone demonstrate that the dormitory-style refrigerator model is not suited to vaccine storage.

The lack of air circulating fans makes the formation of cold and warm air pockets extremely likely, especially in the case of high density loading patterns. Because the dormitory-style

refrigerator is small to begin with, it is likely to be over-stuffed at times, rendering it even more unreliable. As a result, based on the results of our study, we do not recommend that the dormitory-style refrigerator be used for vaccine storage under any circumstance.

3.2.2. Effect of packing style

The magnitude of overall set point drift and unpredictable temperature fluctuations was so large that any effect caused by the different packing styles (trays, boxes or a mix of both, as shown in Fig. 16) was indeterminable.

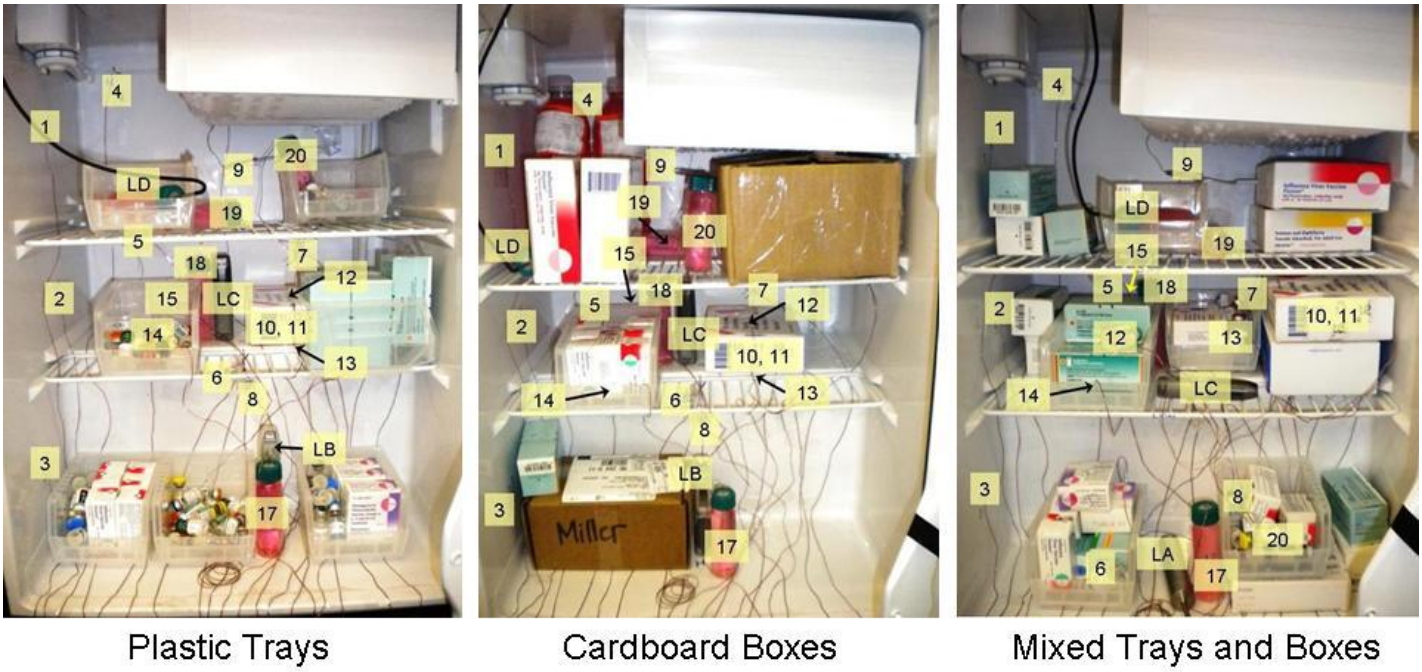


Fig. 16. Packing styles tested with the dormitory-style refrigerator.

3.2.3. Effect of door opening and closing—normal use simulation

Prior to the start of the door opening and closing trials, the majority of the thermometers (including all of those attached to vials) recorded temperatures well below the allowed minimum, to as low as –5.16 °C (recorded by vial 12 at the start of the low density trays run). Since the dorm-style refrigerator was unable to perform to the specified requirements even under idealized, closed door operation, its performance during periodic door opening and closing is a somewhat moot point. We note, however, that the majority of the thermometers actually recorded an overall average temperature decrease in response to the door opening.

Figure 17 below shows the temperature data from a door-opening trial in which a high density mixed (with bottles) packing scheme was used. As seen in the graph, many of the thermometers recorded a brief temperature spike each time the door was opened. As expected, the most dramatic temperature increases were recorded by the thermometers hanging in the air.

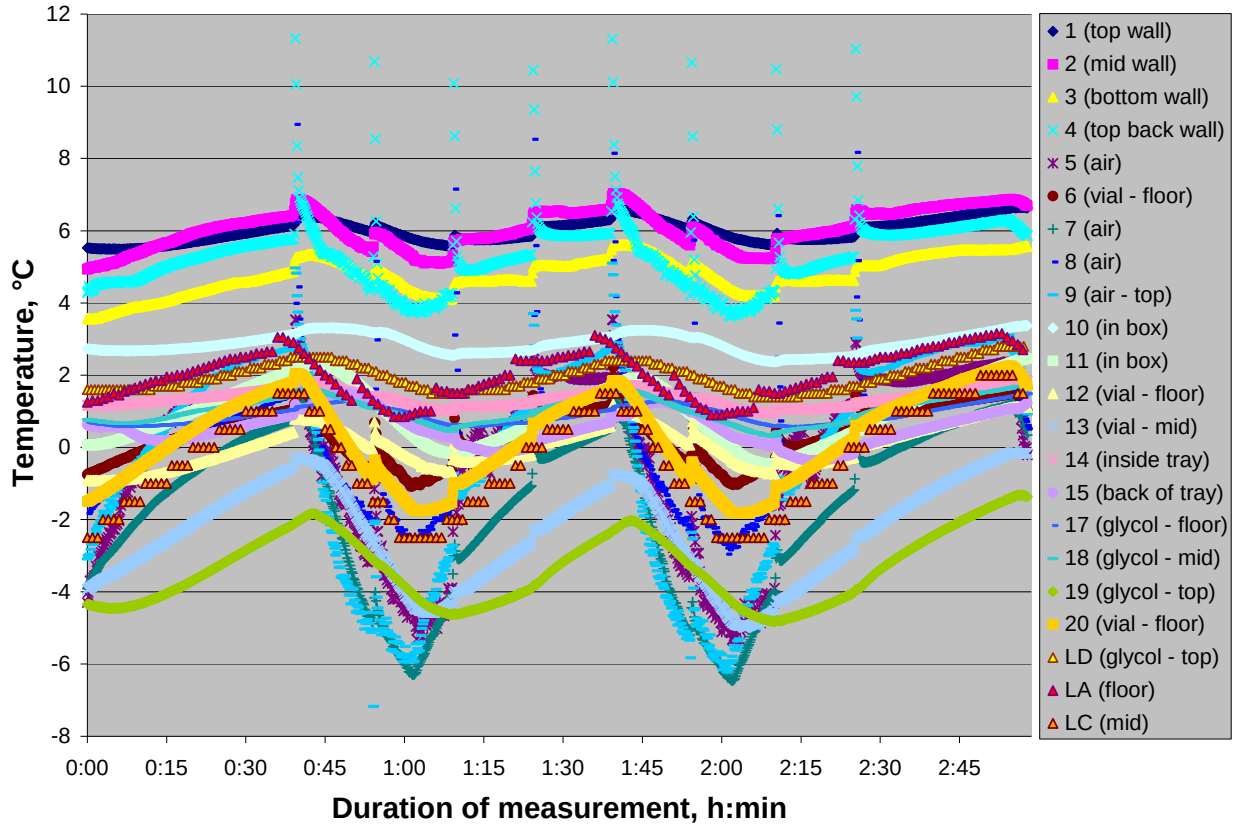


Fig. 17. Door-opening trial for the dormitory-style refrigerator.

In spite of the brief temperature spikes caused by periodically opening the door, the majority of the thermometers actually recorded an overall average temperature decrease in response to the door opening. This was probably caused by the refrigerator cooling unit working harder to counterbalance the influx of warmer ambient air. During the last door-opening trial, in which a low-density packing scheme was used, all of the thermometers showed a marked average temperature decrease, recording average temperatures between 0.74 °C to 3.19 °C lower than during the closed-door trial with the same packing scheme. In this case, even if the refrigerator set point was within the specified range at the start of the trial, the temperature decrease associated with door opening could have easily caused the vaccine temperatures to drop below the allowed minimum by the end of the trial. This adds to the evidence that dormitory-style refrigerators are not acceptable for vaccine storage.

Only one door-ajar trial (without use of bottles) was performed on the dormitory-style refrigerator, so no comment can be made regarding the bottles' efficacy in this case. At the time the refrigerator was opened, all of the thermometers read temperatures much lower than the allowed minimum (vial thermometers ranged from –2.8 °C to –8.1 °C). Even so, all of the vial temperatures exceeded the 8 °C maximum before the door was closed again, as shown in the Table 7 below.

Table 7. Time after opening the door until vial temperatures exceeded 8 °C.

Name and Location	Low Density Trays No Bottles
vial 20 (open to air, floor level)	18 mins
vial 12 (open to air, on top of box on middle shelf)	26 mins
vial 13 (open to air, in tray on middle shelf)	29 mins
vial 11 (inside original packing, middle shelf)	31 mins
vial 10 (inside original packing, middle shelf)	33 mins
vial 6 (open to air, in tray on floor level)	37 mins

The refrigerator door was closed after being left ajar 1 h 15 min; the vials took approximately 3 h 20 min to return to their steady-state temperature.

3.2.4. Effect of Increasing Room Temperature

The increasing room temperature trials for the dormitory-style refrigerator were performed in the same manner as with the freezerless model. As before, an increase in ambient temperature was positively correlated with increasing refrigerator temperature. Fig. 18 below shows a plot of internal refrigerator temperature versus ambient, as recorded by the two data logger D probes. The graph shows the data from the high-density mixed-packing (with bottles) trial; the other trial, with a medium-density mixed load, produced similar results. In this case, we can use a linear fit to approximate the relationship between internal refrigerator and ambient temperatures.

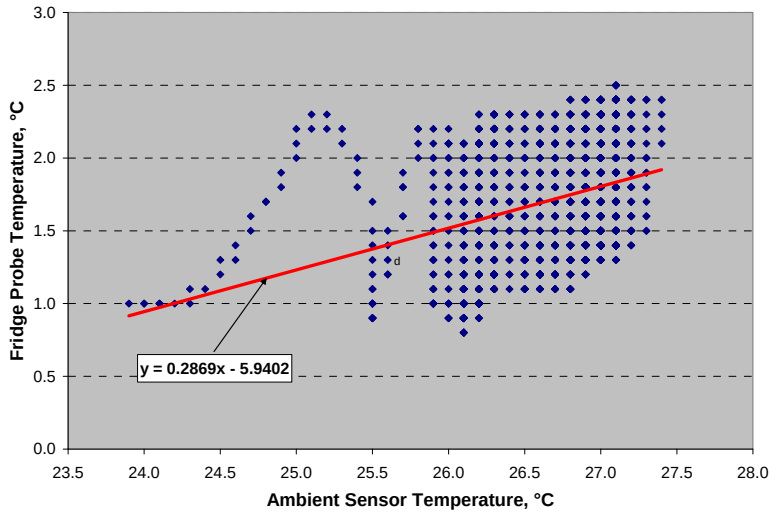


Fig. 18. Refrigerator temperature versus ambient temperature.

The slope of the linear fit applied to the above data is ~ 0.3 °C/°C. A similar graph for the medium-density load trial produced a slope of ~0.3 °C/°C. This means that for every 1 °C increase in room temperature, the internal refrigerator temperature rises by approximately 0.3 °C. This is almost triple the effect observed in the freezerless refrigerator trials. Clearly, the dorm-style refrigerator is much more susceptible to even minor room temperature fluctuations than the freezerless model. An ambient temperature increase of only 3 °C could cause the interior

temperature of the dorm-style refrigerator to rise by 1 °C. This is of significant concern when stored vaccines must be kept within a 2 °C to 8 °C temperature range. The results of the increasing room temperature trials further demonstrate the deficiencies of this particular refrigerator model as a vaccine storage unit.

3.2.5. Effect of a Power Outage

We performed two power-outage simulation trials using the dormitory-style refrigerator, in which the closed refrigerator was unplugged and monitored overnight. In both trials, most of the thermometers recorded initial temperatures well outside of the allowed range before the refrigerator was even powered off. In the first trial, a high-density mixed (with bottles) load, 14 of the 22 thermometers, including all but one of the vial-attached thermometers, had initial temperature readings below 2 °C. For example, the reference thermocouple (#18, in a glycol bottle in the middle of the refrigerator) read 1.1 °C at the start of the test. In the second trial, a medium-density mixed (no bottles) load, all of the thermometers had initial temperatures well below 2 °C. In this case, the same reference thermocouple had a starting temperature of –1.22 °C.

The internal refrigerator rose fairly quickly after the initial shut off of power, and then gradually leveled off at ambient room temperature. The following two graphs (Fig. 19 and 20) show the initial temperature rise for each trial, from the time that the refrigerator was unplugged until all of the thermometer readings exceeded the 8 °C limit, shown on the graphs as a red dashed line. The blue dashed line indicates the 2 °C lower limit.

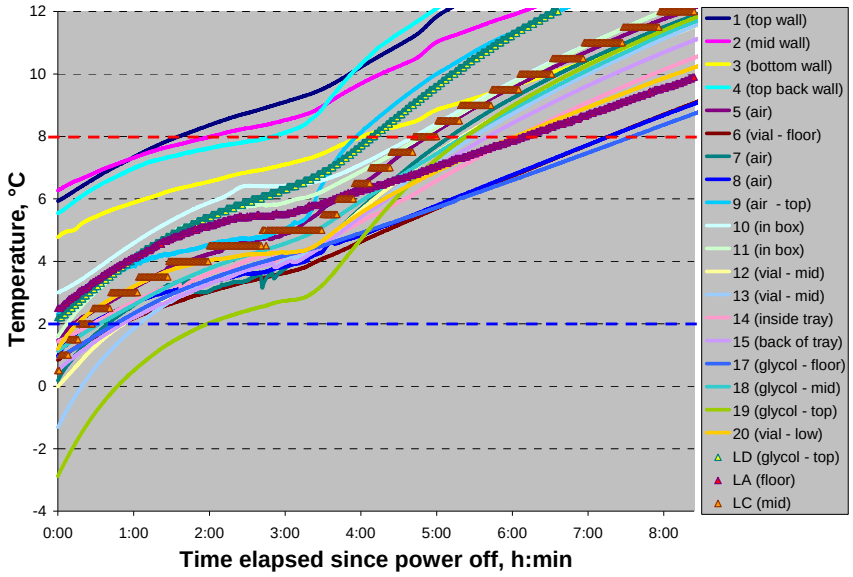


Fig. 19. Expanded view of thermometer response during a power-outage event for a high-density loading with bottles.

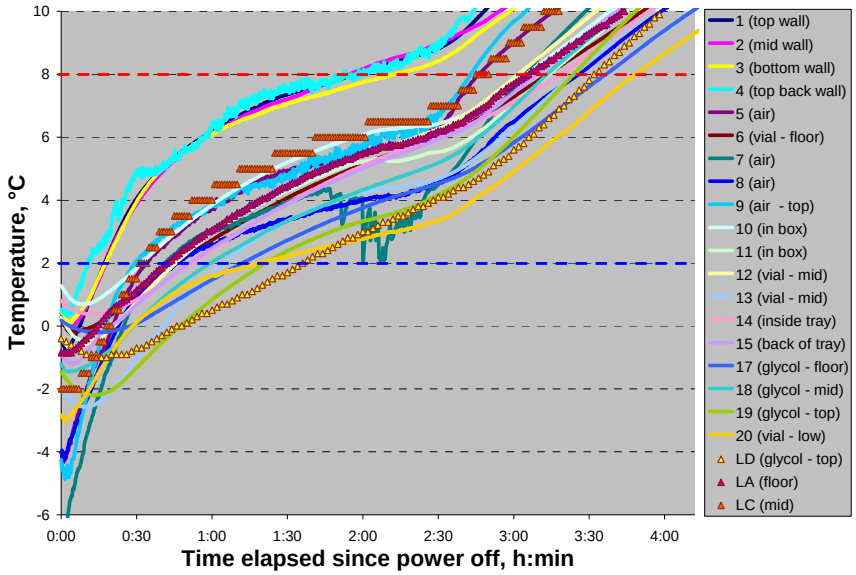


Fig. 20. Expanded view of thermometer response during a power-outage event for medium-density loading without bottles.

The dormitory-style refrigerator has already repeatedly proved itself to be unsuitable for vaccine storage, even under idealized, closed door unadjusted operation. As a result, attempting to protect vaccines stored in a dormitory-style refrigerator during a power outage is problematic. Even so, we can make some interesting observations on the length of time elapsed from the start of the outage until the vaccine vials exceeded the upper temperature limit. This information is summarized in the Table 8 below.

Table 8. Time after power outage until vial temperature exceeded 8 °C.

Name and Location	High Density Mixed With Bottles (hrs:mins)	Medium Density Mixed No Bottles (hrs:mins)
vial 10 (inside original packing, middle shelf)	4:42	3:05
vial 11 (inside original packaging, middle shelf)	4:47	3:14
vial 12 (open to air, on top of box on middle shelf)	5:20	3:02
vial 13 (open to air, in tray on middle shelf)	5:30	3:24
vial 20 (open to air, floor level)	6:02	3:48
vial 6 (open to air, in tray on floor level)	7:16	3:13

It is immediately obvious that the refrigerator exceeded the 8 °C temperature limit much more quickly during the second trial (with a medium-density, mixed load and no water bottles) than during the first (high-density load, with bottles). (See Fig. 21.) This occurred despite the fact that the median starting temperature was approximately 4 °C colder than that of the second trial. This is further proof of the effectiveness of water bottles stored in the refrigerator door in resisting temperature change.

High Density Load, with Bottles Medium Density Load, No Bottles

Fig. 21. Refrigerator loading at different densities and with and without water bottles.

3.2.6. General Stability of Vial Temperature and Suitability of Dormitory-Style Refrigerator Model for Maintenance of Vaccine Storage Conditions

Throughout the tests using the dormitory-style refrigerator, vial temperatures rarely remained within the specified range. During the first two trials (low and medium density trays), thermometers 10 and 11 remained within 2 °C to 8 °C temperature range. However, both of these thermometers were attached to vials inside the same original package, so this cannot be taken as representative of vials stored throughout the refrigerator space. Prior to the fifth trial (medium-density trays with bottles), additional thermometers were attached to vials spread out around the refrigerator. From this point on in the study, during every single trial, at least one or more monitored vial strayed outside the allowed temperature range. From these results, it is clear that the dormitory-style refrigerator can not be relied on to maintain vaccine storage temperatures, regardless of the packing density or storage containers used.

3.2.7. Best and Worst Locations for Vial Storage

The dormitory-style refrigerator's performance was consistently unacceptable, regardless of vaccine storage location within the refrigerator. As a result, it is not possible to recommend a "good" storage area. Anywhere on or near the floor, or near to the cooling and freezer unit in the top right corner appear gave particularly unstable results. However, since the refrigerator space is quite small, and lacks any type of air circulation system, virtually any storage spot will be relatively close to one of these "bad areas." Because of this, the dormitory-style refrigerator is NOT recommended for vaccine storage under any circumstance.

4. DATA LOGGER EVALUATION

Throughout the course of trials performed on both refrigerators, we tested the performance of several electronic temperature loggers along with the thermocouples. The data loggers tested,

labeled LA, LB, LC, and LD, are described in Table 2. We wished to evaluate the data loggers' effectiveness at monitoring vial temperature.

At present, many VFC clinics use digital display, analog, or liquid in glass thermometers to monitor the temperature of their vaccine storage refrigerators. They are only required to check and record the temperature readings of these thermometers twice each working day. Based on the results of our study, a number of factors, including the frequency of refrigerator door opening, refrigerator defrost cycles, room temperature increases, and power outages, could cause an employee to obtain a false representation of the actual refrigerator and/or vial temperature based on this methodology. For example, an overnight power or AC outage could cause the refrigerator and corresponding vaccine temperatures to rise outside of the viable range. If the outage is corrected before the next morning, the refrigerator may return to its cooled equilibrium state by the time employees come to work and check their temperature monitoring devices. In this case, they would fail to detect that the vaccine vials exceeded the allowed temperature range overnight, rendering them potentially unusable. This type of situation could pose a serious danger to clinic patients, since they could be unknowingly administered an ineffective vaccine.

In the same light, other conditions could cause employees to record a "false positive" temperature, and discard vaccines unnecessarily. Depending on a thermometer's accuracy, its placement inside the refrigerator, and the time that it is checked, its reading may or may not correspond to actual vaccine vial temperature. Some thermometers are more sensitive to temperature fluctuations than the fluid-filled vaccine vials, which have a larger thermal mass. If an employee happened to read one of these thermometers during the refrigerator's standard defrost cycle, which produces a brief air-temperature spike, he or she might determine that the vaccines had exceeded the allowed temperature limit. In our experiments, we found that the actual vial temperatures were not greatly affected by the defrost cycle, but that some of the other thermometers indicated significant temperature increases. Because of these issues, we believe it is necessary for vaccine storage refrigerators to have in place continuous data loggers to obtain truly representative, reliable readings of actual vaccine temperatures.

In addition to providing continuous temperature data, the widespread use of data loggers in VFC clinics would reduce the overall workload involved in refrigerator temperature monitoring. At present, VFC workers must manually record refrigerator temperature two times a day. The VFC coordinator is then responsible for reviewing hand-written temperature logs to determine if any lapses occurred. Electronic data loggers connect to a computer via USB and can quickly download data through easy-to-use software interfaces. Logger data for multiple days are automatically summarized into spreadsheets and graphs in a manner of minutes, relieving the VFC coordinator of all data entry and analysis work. As a result, we believe that the use of data loggers for vaccine temperature monitoring would not only improve the reliability this process, but also make it significantly more efficient.

Since the data from the dormitory-style refrigerator tests showed dramatic temperature fluctuations and a large location-specific temperature spread due to the poor performance of the refrigerator, we will only consider data from the freezerless refrigerator trials in our evaluation of the data loggers. While some of the data loggers performed better than others, all of the loggers gave temperature readings within their specified resolution (0.5 °C or 1 °C) of the readings from

the vial-attached thermometers during the majority of the freezerless refrigerator trials. During the door opening trials, the data loggers showed very small temperature increases in response to the door opening, similar to the vials themselves.

When the freezerless refrigerator underwent a defrost cycle, we observed that data logger D and data logger A logger readings matched those of nearby vial thermometers. Data logger C showed a larger temperature spike than any of the vials, exceeding the 8 °C limit. This may have been due to its placement directly on a shelf rather than inside a box or a tray, or may have simply been a function of the sensitivity of the device.

In the power outage simulation trials, all of the data loggers exceeded the 8 °C maximum 30 min to 2 h 30 min before the vials placed nearest to them exceeded the limit. The largest discrepancies were associated with the vials stored inside of cardboard boxes, which took the longest to warm up to room temperature following the start of the power outage. In general, if the data loggers are stored in the same fashion as the vaccine vials, whether in trays or inside cardboard boxes, and in the same part of the refrigerator, they will most likely give readings within their resolution (0.5 °C or 1 °C) of the actual vial temperatures. In the case of a power outage, unless the problem can be remedied very quickly, the vaccines are likely to become unusable. As a result, the function of the data loggers in this case is more to demonstrate the occurrence of an outage rather than to predict the exact temperatures of the vials at a given time.

While the data logger A readings appeared to be fairly representative of nearby vial temperatures throughout the various trials, we noticed that the logger took a very long time to equilibrate to refrigerator temperatures after it was removed to room temperature air during the data downloading process. Because of data logger A's heavy-duty metal structure, it has a large thermal mass and takes a significant amount of time to equilibrate to the surrounding air temperature. In our trials, the cool-down time for data logger A was as much as 3 or 4 h. During this time period, the logger is not very useful as a vial temperature monitoring device. Data logger C, which had a lighter plastic exterior, still required approximately an hour of equilibration time once it was taken from room temperature and placed inside the refrigerator.

Data logger D, which has a temperature sensor inside the main unit as well as an external probe attached via cable, eliminates the need to wait for thermal equilibrium after replacing a room temperature logger back into a refrigerator. In our tests, the external probe was inserted into a glycol filled bottle placed inside the refrigerator, while the main device unit was kept outside of the refrigerator. To collect data from the logger, we simply detached the main unit from the cable, leaving the external probe inside the refrigerator. The main unit was then connected to the USB data collection cradle in order to download the logger readings. This allowed us to keep the external probe at refrigerator temperatures throughout the study, eliminating the need to wait for device equilibration following each course of data collection. The data logger D design has an additional advantage in that main unit of the device, if kept outside of the refrigerator, can be used to simultaneously monitor room temperature. The detachable-probe data logger design is the most user-friendly and for convenience displays the internal refrigerator temperature and external room temperature outside of the refrigerator.

Overall, the data loggers' performance seems to be sufficient for monitoring vaccine temperatures. The most important factor for temperature monitoring accuracy is the placement of the device inside the refrigerator. Just as vaccines should not be stored on the refrigerator floor, neither should the data loggers used to monitor vaccine temperatures. This is because the floor tends to be much cooler than the rest of the refrigerator's interior. During our testing, data logger A was placed on the refrigerator floor, and as a result, it tended to record temperatures 0.5 °C to 1 °C cooler than the thermometers attached to vaccines stored in the center of the refrigerator. A configuration like that of data logger D, in which an external temperature probe was kept inside of a glycol-filled bottle, is likely to give the most representative picture of the actual vaccine vial temperatures. Regardless of the type of data logger chosen, it should be stored in the same manner as the vaccines in order obtain the most accurate readings. Simply placing a data logger directly on a refrigerator shelf is not likely to give an accurate representation of vial temperatures. If the vaccine vials are stored inside trays or boxes, the data loggers should be stored in the same way.

5. SUMMARY

Table 9 below summarizes the results obtained in this study.

Table 9. Comparison of refrigerator performance in response to tested criteria.

COMPARISON OF REFRIGERATOR PERFORMANCE IN RESPONSE TO TESTED CRITERIA		
Criteria	**Freezerless Refrigerator**	**Dorm-Style Refrigerator**
Loading density	▪ No impact on performance	▪ Noticeable impact on performance due to lack of air circulation ▪ High-density loading patterns increased location-specific temperature variation
Packing style (Trays, Boxes or Mixed)	▪ No impact on performance	▪ Indeterminable
Opening/ closing refrigerator door	▪ Vial temperatures showed small increases in response to door opening, but remained in 2 °C to 8 °C range throughout trial ▪ Thermometers in air / attached to walls exceeded 8 °C ▪ Keeping water bottles in door reduced temperature change. Without use of bottles, temperature increase up to 1.2 °C higher	▪ Most thermometers recorded brief increases in response to door opening, but showed overall temperature decrease ▪ If drifting refrigerator set point had been corrected prior to start of trial, vial temperatures still may have dropped below allowable range
Door left ajar	▪ All vial temperatures exceeded 8 °C within 1 min to 49 min, depending on location and storage method ▪ Vials stored inside boxes or original packaging stayed within allowed range up to 48 min longer than uncontained vial ▪ Use of water bottle ballast provided an extra 2 min to 15 min before vaccines exceeded limit	▪ All vial temperatures exceeded 8 °C within 18 min to 37 min, depending on location and storage method
Increasing room temperature	▪ Room and refrigerator temperature directly related ▪ For every 1 °C increase in room temperature, refrigerator temperature rises approximately 0.1 °C ▪ Small room temperature fluctuations will not greatly impact refrigerator performance	▪ Room and refrigerator temperature directly related ▪ For every 1 °C increase in room temperature, refrigerator temperature rises approximately 0.3 °C ▪ Small room temperature fluctuations pose a greater threat to vaccines stored in this refrigerator

Criteria	Freezerless Refrigerator	Dorm-Style Refrigerator
Power outage	▪ Depending on vial location and storage container, it takes 1.5 to 4.5 h for vials to exceed 8 °C after power off ▪ Water bottle ballast provided an extra 20 min to 3 h 50 min before vaccines exceeded limit ▪ Vials stored in boxes or original packaging, stored away from the upper region of refrigerator had slowest temperature increase ▪ Requires at least 6 h to fully re-equilibrate following an outage	▪ Power outages exacerbate already poor refrigerator temperature control ▪ Water bottles provided significant thermal insulation—in trial with water bottles included, vials took an extra 1 hr 40 min to 4 h 14 min to exceed 8 °C, even though initial temperature was 4 °C colder during no bottles trial
General stability of vial temperature	▪ Good ▪ Vaccine vials remained within specified temperature range during regular operation, regardless of packing density or type	▪ Extremely poor ▪ Vaccine vials were rarely kept between 2 °C to 8 °C ▪ In nearly every trial, one or more monitored vials strayed outside of this range
Refrigerator temperature control drift	▪ Negligible	▪ Severe temperature control drift ▪ Within 2 weeks of use, median temperature drifted ~ 4 °C lower than original set point ▪ Would require constant adjustment to maintain specified range
Defrost cycle	▪ Defrost cycle runs every 2-3 days ▪ Vials occasionally exceeded 8 °C for less than 15 min ▪ Thermometers placed in air / near walls recorded dramatic temperature spike followed by a drop below 2 °C	▪ No defrost cycle ▪ Refrigerator interior quickly becomes encased in frost and ice

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