ABSTRACT

Title of Document:	IMPROVING COLD CHAIN TECHNOLOGIES THROUGH THE USE OF PHASE CHANGE MATERIAL
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Vaccine-preventable diseases are responsible for about 25% of the 10 million deaths occurring annually for children under five years of age. The World Health Organization's Expanded Programmes on Immunization succeed in providing standardized guidelines for vaccine storage and distribution, but often fail to accommodate the unique infrastructure between and within countries. In order to better regulate the temperature of vaccines as they travel through countries, we have selected and characterized an appropriate phase change material (PCM) that will resist temperature fluctuations outside of a range of 2-8 °C, based on appropriate thermophysical properties. Additionally, we have integrated the selected PCM within a geometrically and thermally optimized cold box, maintaining long-term stabilization of temperatures within a range of 2-8 °C. In meeting these objectives, we have demonstrated the feasibility of a technological solution that may be readily implemented in the existing vaccine distribution supply chain, or that holds potential to be the centerpiece for new, more efficient vaccine distribution strategies.

FIXING REFRIGERATION EFFICIENCY TO SUSTAIN HEALTH

By

Team FRESH at UMD

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Dedication

The cold chain is only as strong as its weakest link.

We dedicate this research to reaching the goal of universal vaccination.

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List of Abbreviations

BCG: Bacillus Calmette-Guérin

CAD: Computer Aided Design

CDC: Centers for Disease Control and Prevention

DSC: Differential Scanning Calorimeter

DT: Diphtheria and Tetanus Toxoids

DTP: Diptheria-tetanus-pertussis

EPI: Expanded Programme on Immunization

FEA: Finite Element Analysis

GAVI: Global Alliance for Vaccines and Immunisation

GIVS: Global Immunization Vision Strategy

HepB: Hepatitis B

Hib: Haemophilius Influenza Type B

ILR: Ice-lined refrigerator

IPPI: Intensive Pulse Polio Immunization

KEPI: Kenya Expanded Programme on Immunisation

LMIC: Low and Middle-Income Countries

MDR-TB: Multiple Drug Resistant Tuberculosis

MVA –A: Merck Vaccine Network – Africa

OCC: Out of the cold chain

OPV: Oral Polio Vaccine

PCM: Phase Change Material

PEPFAR: (U.S.) President's Emergency Plan for AIDS Relief

RFID: Radio Frequency Identification

SCP: Specific Cooling Power

TT: Tetanus Toxoid

UNICEF: United Nations Children's Fund

USAID: U.S. Agency for International Development

VVM: Vaccine Vial Monitor

WHO: World Health Organization

YF: Yellow Fever

Chapter 1: Introduction

Research Objectives

Today, vaccine-preventable diseases are responsible for about 25% of the 10 million deaths occurring annually for children under five years of age (WHO & UNICEF). The World Health Organization's (WHO) Expanded Programmes on Immunization (EPI) succeed in providing standardized guidelines for vaccine storage and distribution, but often fail to accommodate the unique infrastructure between and within countries. In the current vaccine supply chain, the "cold chain," passive temperature stabilization relies on insulated vaccine carriers storing ice packs, or cold boxes, but poor design often renders vaccines impotent due to freeze damage (T. Wirkas, Toikilik, S., Miller, N., Morgan, C., & Clements, C.J., 2007).

In order to better regulate the temperature and preserve a greater percentage of vaccines as they are shipped through lower-middle income countries (LMICs), significant improvements are required in our fundamental understanding of passive refrigeration technology – ways of cooling cargo without an active power source – and the integration of such knowledge into design strategies for more efficient passive temperature stabilization.

Towards this end, we propose the following specific objectives:

Objective 1: *To survey problems in the existing cold chain including technical and human errors to develop a clear set of design criteria for our project and for the benefit of other researchers.*

Objective 2: *To select and comprehensively characterize an appropriate phase change material (PCM) that will resist temperature fluctuations outside of a range of 2-8 °C, based on appropriate thermophysical properties.*

Objective 3: *To examine the influence of PCM geometry and organization on temperature stabilization by theoretically and experimentally incorporating the selected PCM within a cold box in a variety of configurations and evaluating temperature stability.*

Objective 4: *To use the data generated in objectives 2 and 3 to create an effective thermally-optimized prototype cold box that meets the design criteria from objective 1.*

Objective 5: *To develop a clear and concise plan for the implementation of the aforementioned prototype into the existing cold chain.*

By meeting these objectives, we will prototype thermal innovations that may be readily incorporated both specifically into the existing vaccine distribution supply chain, and also into temperature stabilization systems in general.

Scientific Significance

Our research will combine lab bench measurements and numerical simulations towards the optimization of temperature stability for vaccines as they move through the cold chain. Characterization of several PCMs will use well-established experimental techniques in materials characterization to obtain data. This data will fill existing inhibiting gaps in these PCMs' characterization and is required for accurate simulation, prediction, and validation of temperature stability. The

greatest impact of our proposed work is the development of novel strategies for more efficient integration of PCM technology into engineering design. The majority of current strategies that incorporate PCMs into passive refrigeration systems simply use more PCM to deliver temperature stability for a longer duration. The innovation of our approach is actually quite intuitive; we hypothesize that it is not just the quantity of a PCM, but the arrangement, or configuration, of PCMs with respect to heat sources, heat sinks, and the environment that will optimize temperature stability at multiple temporal and spatial scales. Our design criteria for the proposed project are guided by the necessity to decrease freeze damage to vaccines and increase payload volume, as well as considering ease of use for operators to minimize human errors, thereby increasing efficiency of vaccine delivery. However, through comprehensive materials characterization, novel and more accurate predictive simulation approaches that build on such characterization and experimental validation of these theoretical models, fundamental principles elucidated through our work should broadly transform the engineering of passive refrigeration systems. This can lead to further innovations by allowing for a series of experiments that can develop a thermally optimized system, a unique approach to the use of modeling programs.

Significance of Findings

Our literature review of studies documenting vaccine freezing and general deficiencies in the existing cold chain provides a comprehensive summary of scientific evidence in the field. We have consolidated these studies in a visual, open-source Google Map, equipped with hyperlinks and many avenues for online

collaboration, with hope that it may be utilized by investigators in the field. Furthermore, our team translated the findings from these studies to a two-minute online motion graphics animation, which depicts the challenges in the cold chain for the viewer (See Appendix H).

The concept behind our prototype, a traveling vaccine container, offers several opportunities for preventing error in vaccine storage and handling throughout the cold chain. Since vaccines are kept in the internal storage compartment within our PCM cold box throughout the cold chain, there is no exposure to sunlight or fluorescent light for select vaccines that are susceptible to light-related damage (BCG, Measles, MR, MMR and rubella vaccines). Furthermore, healthcare workers no longer need to be trained for placing vaccines in the proper orientation within refrigerators or cold rooms to reduce risk of damage. Temperature stability of vaccines is position-independent and vaccines can simply remain in any part of the internal storage compartment. Our design utilizes existing cold chain infrastructure and accessories, including transport routes, freezers, and ice packs. There is only one scenario in which our cold box requires expert repair: if PCM panels break, the PCM cold box will be sent back to origin. By incorporating a culturally-relevant country sticker or slogan on the box, healthcare workers may handle our cold box with more care. Furthermore, the Instruction Manual (See Appendix E) includes a detailed decision-making flow chart that may be adapted to simpler language for future use in the field. All of our findings and tools are timely and relevant to the rapidly-evolving field.

Limitations

Even though our team had a structured plan for approaching the problem of vaccine freezing, we realized that there are certain factors that could have been limiting to our success. The largest limitation we faced was our lack of field experience. While our members come from diverse fields of study and have studied the cold chain extensively, there is no substitution for having experienced the cold chain in the local health centers. With the exception of one member, no one on our team has seen how vaccines are delivered in developing regions of the world. This lack of experience could have affected our ability to predict practical considerations for our cold box.

Another limitation is that we did not have the time or resources to test our cold box in a cold chain setting. Through our extensive physical experiments, we were able to confirm our predictions about our cold box's ability to stabilize temperature for a long duration; however, we were not able to send our box through the cold chain, which would be the definitive test to determine whether our concept was valid. With the aforementioned lack of field experience as well as our inability to test our cold box in the cold chain, we were limited in the real life application of our cold box.

Chapter 2: Literature Review

Background

In 2003 alone, vaccines are estimated to have prevented two million diseases and 600,000 deaths. However, at the same time, it is estimated that 27 million children and 40 million women were not vaccinated (Wolfson et al., 2008). As the public health impact of vaccines has become increasingly clear, interest in and funding for new vaccine development and improvements in the refrigerated vaccine distribution system (cold chain) has surged.

Since the World Health Organization (WHO) launched the Expanded Programme on Immunization (EPI) worldwide in the mid-1970s, most countries have been using a standard package of six vaccines—measles, tetanus, diphtheria, pertussis, tuberculosis, and polio—in their national immunization schedule. As part of the WHO's strategy to achieve "Health for All" by 2000, it set a goal in 1977 to provide universal immunization to all children by 1990. Since then, many low- and middle-income countries have modified their vaccination package to include hepatitis B (HepB) and Haemophilus influenza type b (Hib) for routine infant immunization schedules, and many are in the process of adding pneumococcal conjugate vaccine and rotavirus vaccines to their schedules. The WHO remains committed to expanding the EPI's targeted groups to include older children, adolescents, and adults, and to working in synergy with other public health initiatives (WHO, 2012).

Immunization is a proven tool for controlling and even eradicating infectious diseases, as proven by the examples of smallpox, polio, and measles. Before the 1967-1977 WHO campaign that resulted in the eradication of smallpox, the disease threatened 60% of the world's population and killed every fourth victim. Since the Global Polio Eradication Initiative in 1988, polio infections have fallen by 99% and polio is on the brink of eradication. Between 2000 and 2008, measles deaths dropped worldwide by over 78%, and some regions have since focused on eliminating the disease. Maternal and neonatal tetanus have been eliminated in 20 of the 58 high-risk countries, a feat that has saved millions of lives (WHO, 2012).

A Global Effort

As an investment in health, immunization is widely regarded as a "best buy," since it protects individuals and populations at low cost, but also provides a platform for delivering other health interventions, such as vitamin A supplementation (Stephenne, 2011). The primary responsibility for ensuring sufficient financing for immunization services rests with governments of LMICs (Low and Middle-Income Countries, as recognized by WHO); however, since national governments alone may not be able to provide all of the required funding, it is a shared responsibility of the central government, district governments, and communities to identify and mobilize the necessary resources to sustain safe and effective immunization services (USAID, 2003).

In many instances, the efforts of LMIC governments are not sufficient in providing vaccine coverage. Hence, external partners currently play a major role in

improving immunization services. International partners like USAID, PATH, UNICEF, GAVI, and WHO have recognized that campaigns conducted in a collaborative manner where each partners' strengths, resources, and networks are pooled together are more effective than campaigns directed by just one organization. WHO and PATH's Project Optimize aims to make sure that future vaccine supply chains can safely and routinely handle rapidly changing vaccine and delivery technologies while maintaining the ability to adapt to unexpected challenges, such as global pandemics (Milstien, 2002). Project Optimize continues to survey existing systems, test new processes and technologies, work with the pharmaceutical industry to innovate the presentation and packaging of vaccine products, and integrate their efforts with other health campaigns (PATH, 2009).

While these immunization campaigns are being conducted, the vaccine landscape is changing dramatically. The 2006-2015 Global Immunization Vision and Strategy (GIVS) points to a dramatic scale-up of new lifesaving vaccines for standard immunization programs (Wolfson et al., 2008). Furthermore, an extensive analysis by PATH notes that more vaccines are becoming widely available and more money is being invested in research and development of vaccines than ever before (PATH, 2009). However, the new vaccines that are being developed are much more costly than traditional vaccines. For example, there are several producers of traditional vaccines, such as measles, diptheria-tetanus-pertussis (DTP), leading to low unit cost for vaccines, often between US$0.10 and US$0.25 per dose. The cost of newer vaccines is significantly higher, typically between US$3.65 and US$15.00 per dose. Although prices are expected to drop over time, experts report that new vaccines may

never reach the low prices of traditional vaccines (PATH, 2009). Many experts and policy-makers are now investigating ways to finance the new vaccines. One way of ensuring access to vaccines in LMICs is to match the price to the level of economic development of the target country. Known as "tiered pricing," this system allows for innovative financing mechanisms such as advance market commitments or offers of long-term and high-volume contracts to vaccine producers (Stephenne, 2011).

Vaccine Delivery

Despite tremendous efforts over the past few decades to provide access to vaccines to as many people as possible, many technical, social, and programmatic obstacles remain. Vaccines are temperature-sensitive biological substances that must be carefully regulated to maintain potency (Craig, 2008). There are a wide variety of obstacles in the way of effective delivery which can depend on transportation routes and the final destination, such as a remote village with no electricity. Although it is nearly impossible to develop a specific protocol for each region, there exists a global distribution network of refrigeration equipment and procedures for maintaining vaccine quality during transport and storage (PATH, 2008). This supply network dedicated to delivering vaccines is called the cold chain.

Protecting Vaccines

Because vaccines contain temperature-sensitive biological substances, they must be kept cool from the time of production until usage to maintain efficacy and prolong shelf life (Craig, 2008). If subjected to improper refrigeration (overheating or

freezing), vaccines are rendered ineffective. DTP, TT, DT, DPT combinations, liquid Hib, HepB and any HepB combinations may have freeze damage if not properly stored (PATH, 2003a). Furthermore, not all vaccines require the same temperature range. While freezing destroys some vaccines, it extends the shelf life of others. Those that are damaged by freezing temperatures must, in general, be stored between 2-8 °C (Craig, 2008).

Literature has shown that freezing is a larger problem in the cold chain than overheating. While vaccine damage due to overheating is gradual, freeze damage is nearly instantaneous (U. PATH, 2006). Tailored packing, transportation and storage arrangements for different types of vaccines are required to provide protection from temperatures outside of specified ranges by the WHO (WHO, 1999).

In a typical cold chain, large shipments of up to 150,000 vials of vaccines are shipped or flown in refrigerated containers from the manufacturer to the national airport of the destination country (UNICEF, 2004). The vaccines are stored in a cold room at the airport until a refrigerated truck delivers them to the primary vaccine store, which is generally the country's Ministry of Health, from where vaccines are delivered periodically to regional centers, provincial health centers, local health centers, and eventually individual outreach clinics (WHO, 2002). The length of the entire delivery process depends on demand and can be as short as a month or as long as three months (UNICEF, 2004). The broad range stems from many factors that play a role in the efficacy of the cold chain in distributing viable vaccines. Though a typical cold chain routine was outlined above, customs clearance, inspection, inventory control, storage, transportation and delivery vary widely from country to

country, and even within a country between geographic and socioeconomic areas (Frost, Reich, & Harvard Center for Population and Development Studies., 2008).

Stages of the Cold Chain

The cold chain begins at the vaccine manufacturer and ends once the vaccine is administered. Along the way, the vaccines pass through international airports, vaccine stores, and local dispensaries.

When vaccines are shipped by air, the shipping cost is proportional to the weight of the package. During 1997, UNICEF and WHO reviewed actual vaccine packing practices in order to begin eliminating non-essential packing and devised a standardized vaccine arrival report, which simulates ongoing documentation and analysis on international vaccine shipments (WHO, 1999, 2005). This form also acts as a feedback mechanism for countries to correct problems in vaccine handling during international transport. The vaccine arrival report provides assurance for donors who want to track how their financial investments are being used, and for the Ministries of Health who are responsible for protecting their populations.

Vaccine manufacturers sometimes do not comply with international standards and procedures related to vaccine shipment. Documented problems include vaccines arriving without advance notification, ice packs, cold chain monitors, proper documentation/ labeling, or requested vial sizes. Furthermore, vaccines may arrive with short expiration dates without regard for black-out dates, be trans-shipped via cities lacking proper cold rooms, or be consigned to the wrong party (WHO, 1999).

For each country, the Ministry of Health and vaccine suppliers work together to specify procedures for receiving international vaccines and delegating responsibility for each step in the process of ordering, receiving, and documenting vaccine shipments. For each international shipment of vaccines, the recipient completes the vaccine arrival report and officially submits it to the supplier or, in the case of vaccines supplied through UNICEF, to UNICEF and WHO (WHO, 1999). A recent analysis suggests that the international community is pursuing improved coordination between organizations that donate and ship vaccines and the host-country officials who receive and distribute the vaccines, as well as better training for supply-chain managers (Kaufmann, Miller, & Cheyne, 2011).

After vaccines leave the international airport, they are stocked at primary vaccine stores. These stores typically contain cold rooms (insulated, refrigerated enclosures that maintain a temperature above 0 °C), freezer rooms (insulated, refrigerated enclosures that maintain temperatures below 0 °C), iced-lined refrigerators, or a packaging area ("Guidelines for Establishing or Improving Primary and Intermediate Vaccine Stores," 2002). Primary vaccine stores exist at both the provincial and district levels with the number of primary vaccine stores varying by country. Larger vaccine stores are typically found at the provincial level, while at the district level, stores usually consist of smaller storage devices such as iced lined refrigerators (ILRs). Operations within the cold stores typically involve the constant monitoring of internal temperatures of storage facilities by personnel. The principle problem that arises at this stage of the cold chain is temperature instability within cold rooms. This could be due to many problems including, but not limited to, the

improper placement of vaccines around the cold rooms and ILRs or malfunctioning, outdated or poorly maintained equipment (WHO, 1999).

From the primary store, the vaccine shipment is then taken to the next intermediate storage facility, which also uses cold rooms and freezer rooms. This stage is altogether omitted if the country delivers vaccines directly from the primary store to the health facility where vaccines will be transported. As such, every country has its own unique cold chain and associated problems from this point onward. Freezing during transport is attributed to the storage method en route, which generally consists of boxes lined with ice packs. Vaccines that come in direct contact with the ice packs will likely freeze. However, placing a buffer region in between the vaccines and ice requires larger transport containers and greater transport capacity, thus increasing costs. Furthermore, trucks carrying vaccines often struggle to transport them due to poor roads or lack of roads in remote areas (Hopkins, 1985).

A number of studies have documented freezing in the cold chain. A study of the cold chain in Papua New Guinea showed that, on average, the only steps of the cold chain that did not report freezing temperatures were storage sites at the Ministry of Health and provincial vaccine stores. During transport from the provincial vaccine stores to local health centers and subsequent outreach clinics, vaccine loads were partially

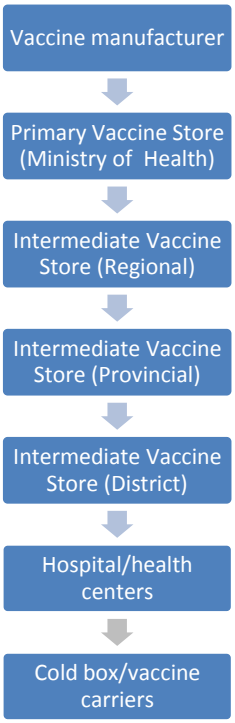


Figure 1: Path of vaccines through a standard cold chain

freeze-damaged, reaching an average temperature of -3 °C (T. Wirkas, Toikilik, S., Miller, N., Morgan, C., & Clements, C.J., 2007). In contrast, a study of vaccine freezing in the Indonesian cold chain found freezing at higher rates in storage than in transport (C. M. Nelson, Wibisono, H., Purwanto, H., Mansyur, I., Moniaga, V., & Widjaya, A., 2004). It appears that freezing is not just a problem at a single stage, but rather is manifested throughout the cold chain.

Once the vaccines reach the villages, the most basic refrigeration technology and transportation methods are used to deliver and store the vaccines. The power supply becomes increasingly intermittent and transportation becomes more difficult. This problem manifests throughout the local level of the cold chain, resulting in inefficient and unsafe delivery of vaccines. At this stage, many vaccines are kept in ice-lined boxes which can cause the vaccines to freeze, rendering them useless (T. Wirkas, Toikilik, Miller, Morgan, & Clements, 2007). Figure 1 documents the path vaccines travel in reaching their destination.

Evidence of Freezing in Vaccine Delivery

A multitude of studies have shown that vaccines in the cold chain within a wide range of countries including Thailand, India, Malaysia, Indonesia, Papua New-Guinea, Vietnam, New Zealand, Australia, Bolivia, Ethiopia, and even the United Kingdom and the United States are often exposed to freezing (<0 °C) temperatures, likely causing them to lose their potency due to the inactivation of key organic components (D. M. Matthias, Robertson, Garrison, Newland, & Nelson, 2007; C. M. Nelson, Wibisono, H., Purwanto, H., Mansyur, I., Moniaga, V., & Widjaya, A., 2004;

Techathawat, 2007; T. Wirkas, Toikilik, S., Miller, N., Morgan, C., & Clements, C.J., 2007). Such vaccine losses result in financial loss for immunization programs, as well as potential danger to the patient. One of the most prevalent factors attributed to vaccine freezing is the lack of stable temperatures in the cold boxes, which contain ice packs at 0 °C (PATH, 2008).

Unstable internal temperatures in cold boxes have made overheating and freezing the primary threats to vaccine potency. In a study of the vaccine cold chain in Thailand, 31 out of 42 routes experienced freezing temperatures for periods long enough to render the vaccines impotent. Researchers estimated that 70% of vaccines were tossed away upon delivery, mostly because they were unusable due to freeze-damage (Techathawat, 2007). Nelson et al.'s study, which observed shipment routes transporting HepB vaccines to eight health centers in Indonesia, similarly found instances of frozen vaccines in 75% of the shipments (C. M. Nelson et al., 2004).

In 2007 Matthias et al. conducted a systematic literature review on studies from January 1985 to June 2006 demonstrating vaccine freezing in the cold chain. The authors recommended that more rigorous and comprehensive studies be done to examine the exposure of vaccines to freezing temperatures through all transport and storage segments of the cold chain. The image below (Figure 2) is a snapshot of an open-source Google Map our team has created to visually demonstrate the literature on vaccine freezing in the cold chain. Each marker is accompanied by the percentage of freezing in transport/storage found and the sample size used. An abstract, citation,

and link to the article were included, if available. Placement of the marker is only accurate to the country level; the locations are not precise within each country.

Figure 2: Open-source Google Map depicting literature on vaccine freezing in the cold chain

Since 2006, more data has emerged documenting challenges and opportunities to prevent vaccine damage in the areas of improved management, monitored mechanisms, and the structure of the cold chain. If vaccines are improperly handled so that they are damaged by incorrect temperature maintenance, the tremendous effort to scale up vaccinations will be wasted. The major problem areas continue to be: improperly maintained or outdated refrigeration equipment, poor compliance with cold chain procedures, inadequate monitoring, and poor understanding of the dangers of vaccine spoiling (PATH, 2003b).

Sociopolitical Challenges in Vaccine Delivery

As Frost et al. point out in their report on increasing access to healthcare, "Just because a good health technology exists does not mean that it will be delivered, used, or achieve its potential to bring good health, especially for poor people in poor countries" (Frost et al., 2008). Technologies can be used in many ways, but can also be mishandled and misappropriated in manners that nullify their potential. Despite the immense effort and resources WHO expends on both technology and methodology of delivering health care, it cannot control what happens on the ground in LMICs whose governments are newly developed, infrastructure is young and cultures are unique (Vickers, 2005).

Some technologies are not accepted because they contradict cultural norms and are associated with negative social stigmas. In addition, in some countries, rival warfare and government instability can be a major roadblock towards vaccine delivery and healthcare in general (GAVI, 2008); therefore, WHO and other international organizations can be *inter*national regulators of health, but cannot be *intra*national overseers (WHO, 1985).

In certain areas, the local level has no power supply at all and, as such, vaccines are stored at room temperature. Local villagers run vaccine "clinics" out of their own homes, using the town's only powered mode of transportation, such as a motorbike, to replenish the supply of vaccines. In the Peruvian Amazon, it is a two-day riverboat ride to the nearest hospital where the local "clinics" in the scattered river villages are staffed by doctors assigned to work there as part of a year of service (Fraser, 2006). In Peru, vaccines are floated down river to villages, while in the

Himalayas, donkey caravans carrying vaccines are used to reach secluded Afghan tribes (GAVI, 2008).

Freezing has also been demonstrated in the cold chains of developed countries with modern technology and reliable power supplies. General practitioner vaccine providers in Australia (Wawryk, Mavromatis, & Gold, 1997) and the United Kingdom both recorded freezing temperatures in vaccine storage (Thakker Y & Woods, 1992). Similarly, physicians' offices in Georgia, United States, reported frozen vaccines 11.4% of the time (Bell, Hogue, Manning, & Kendal, 2001), and researchers in Colorado, United States, concluded that a "majority of vaccines in the community have been exposed to conditions that could reduce or destroy their potency" (Woodyard, Woodyard, & Alto, 1995).

Weaknesses in the Cold Chain

Cold Chain Equipment and Maintenance

Much of the cold chain in LMICs is outdated and in disrepair, or must be replaced due to new environmental regulations, which further complicates immunization processes (Levin, Levin, Kristensen, & Matthias, 2007).

A typical cold chain has a diverse set of equipment and provisions for staff to operate (C. M. Nelson, Wibisono, H., Purwanto, H., Mansyur, I., Moniaga, V., & Widjaya, A., 2004). These include ice-lined refrigerators, cold boxes (Error! Reference source not found.3), cold rooms, data loggers, pre-filled injection devices (Uniject), vaccine vial monitors (VVM), and freeze indicators (Freeze Watch, Error! Reference source not found.4). All of these are used to adequately store vaccines of

assured quality, defined by WHO as "one[s] that consistently meets appropriate levels of purity, potency, safety and efficacy" (Knezevic, 2009). Table 1 describes the functionality and cold chain equipment used to check for frozen vaccines.

Table 1: Some cold chain devices used to prevent vaccine freezing.

Product	Description	Use in Cold Chain
Vaccine Vial Monitor (VVM)	• Heat-sensitive label • Time and temperature cause inner square to darken • Higher temperature, faster color change	• Indicates to a health worker when a vaccine can be used/should be discarded • Either on vaccine label or cap
Shake Test	• Freeze a vaccine as the frozen control • Let frozen vaccine thaw • Shake vaccine from batch and control together vigorously 10-15 seconds • If sedimentation (formation of large particles) occurs faster in the test vaccine, it is not damaged • If sedimentation occurs equally fast in the test and control vaccines, the test one is damaged and should be discarded	• Determines whether a vaccine should be discarded or not • Should be done independently with all batches that are suspected for freezing • For use with adsorbed vaccines (DPT, DT, Td, TT, hepatitis B, Hib liquid, and combinations of these)
FreezeWatch stickers	• Placed in refrigerators to warn of freezing temperatures • Dark ink stains paper when freezing temperatures are reached	• Can signal that further freeze inspection should be done on stored vaccines

Figure 4: A typical cold chain cold box (http://apexinternational.tradeindia.com/Exporters_Suppliers/Exporter15484.361658/Cold-Box.html)

Figure 3: FreezeWatch indicator with instructions for recognizing frozen vaccines

In Nelson et al. (2004), monitoring packets were prepared by combining a data logger, a VVM on a card, and a freeze indicator in a sealed plastic bag. These packets were placed inside boxes containing 100 Uniject devices. Boxes that contained monitoring packets were marked to indicate the site for delivery. Monitoring packets were prepared immediately before the vaccines were packed into shipping containers. At each stage of the cold chain, staff from the Ministry of Health recorded the time and date of arrival and departure of the vaccine shipments, as well as the status of the vaccine vial monitor and the condition of the Freeze Watch device. Staff at each level received training on completion of forms and study procedures (C. M. Nelson et al., 2004).

The WHO mandates that all vaccines have VVMs, which will indicate heat exposure that may negatively affect vaccine potency (WHO, 1999). Oral Polio Vaccines (OPV) are considered one of the most unstable vaccines, with an ideal storage temperature of -20 °C, but can be kept between 2-8 °C for 6 months, or for

whatever duration indicated by the manufacturer. One study examined Chad's nation-wide immunization campaign in order to ascertain how long an especially sensitive vaccine would remain potent in ambient temperatures. As vaccines were exposed to maximum temperature of 47.1°C and lasted a maximum of 86.9 hours in ambient temperatures, the authors looked at the VVMs to determine potency. Laboratory testing was conducted to confirm VVM results, and the authors concluded that the VVM served as an accurate indicator of heat exposure (Zipursky et al., 2011).

In another study in India, cold chain equipment and VVMs were evaluated at 46 health centers in a rural district to see if they met WHO guidelines. Nine percent of the health centers reported VVM's in stage III had indicated that vaccines had been spoiled and should be discarded. The authors concluded that the cold chain was not adequately maintained at the primary and sub-health centers, and recommended that well-maintained ice packs and vaccine carriers be added (Samant et al., 2007).

A PEPFAR (U.S. President's Emergency Plan for AIDS Relief) evaluation of local vaccine stores in Ethiopia showed that the intermittent power supply necessitated the use of back-up power sources which are often not reliably in place. In theory, the back-up power sources are designed to safely power down the equipment when the main power supply cuts off, but improper wiring of these sources leads to unstable conditions for the vaccines. The evaluation concluded that electricity needs are not integrated in health center planning (USAID, 2008).

Data loggers present hope for detecting temperature throughout the cold chain. Kartoglu, et. al. published an article recently that discussed their invention, the Fridge-tag temperature sensor (Kartoglu, Nelaj, & Maire, 2010). This sensor records

data from various points inside a closed space and can signal to the user when the temperature has gone outside the desired 2-8 °C range. One study evaluated the use of data loggers in quantifying the cold chain failure rate within the Texas Harris County Hospital District community health center network. The researchers used Extech TH10 digital data loggers to study 54 refrigerators at 13 community health centers, and took a close look at storage of acellular pertussis vaccines, which must not be stored at less than 0 °C. Approximately 24% of the refrigerators studied exposed vaccines to considerable durations of subzero temperatures. The inadequate storage would not have been detected or quantified without the use of the digital temperature data loggers, and the authors conclude that adopting digital data loggers may be more effective than continuing the standard practice of twice-daily readings from thermometers (McColloster & Vallbona, 2011).

Health information systems may also significantly bolster cold chain management. One of the best tools utilized in the United States to ensure vaccine safety is the Vaccine Safety Datalink, which attempts to find associations between vaccines and potential health outcomes and provide signals for when a vaccine may be unsafe (Salmon, Pavia, & Gellin, 2011). In a case study on the vaccine supply chain in Ethiopia, the authors analyzed needs and offered recommendations for improving health information systems through the use of mobile and software technology. The authors noted that health centers are predominantly paper-based and includes the use of stock cards, which are both inefficient and prone to errors, specifically in transcription. This cannot forecast demand of inventory and makes it

tedious to extract useful information for decision-making at any level of the supply chain (Sabtala, Anene, Owoluganda, & Nanteza Walusimb, 2011).

The authors recommended that a pilot study be undertaken to test mobile tracking technology, such as the one provided by Logistimo, in the field. In order to evaluate this intervention, the team could measure outcomes such as (1) the number of children under five that have been immunized, (2) the quantity of consignment dispatched that has been utilized, and (3) the quality of service of a health center through prompt transfer of information. Another promising technology is CoolComply, a solar-powered wireless detection system, which monitors the doses and the temperature of the medication, relaying readings wirelessly to the local healthcare workers to track temperature and intervene when necessary. CoolComply is currently employed for drug treatment for Multiple Drug Resistant Tuberculosis (MDR-TB). Finally the authors recommended that more technology and best practices, including the use of microchips from radio-frequency identification (RFID), be strengthened (Sabtala et al., 2011).

Mismanagement of the Cold Chain

The problem of vaccine wastage is often attributed to a lack of temperature control infrastructure in LMICs; however studies have shown that vaccine packaging and administration can also cause wastage. The WHO estimates that 50% of all vaccines produced globally are not appropriately administered, and therefore wasted (Guichard & Hymbaugh, 2008). Matthias, et al., alluded to the importance of increasing training and supervision for vaccine handling throughout the cold chain

(2007). Several studies have focused on further assessing the need, and testing tailored strategies to improve cold chain management in their communities.

Using a temperature data logger, researchers in Papua New Guinea attempted to identify and locate if and where vaccines destined for use in peripheral health units were subject to freezing temperatures. Findings demonstrated that freeze damage was often a consequence of incorrect packing of vaccines in vaccine carriers for transport between stores and the field (T. Wirkas et al., 2007).

One retrospective study conducted by WHO and the Bangladashi government examined the immunization system in Bangladesh, a country that boasts an excellent record for administrating vaccines to children. The study employed a standard two-stage cluster sampling technique for assessing injection safety at the local level. Data on quantity of vaccine vials provided, distributed, used, and returned opened/unopened at the service delivery levels was collected by WHO surveyors. Vaccine receipts and distributions were recorded in the Daily Vaccine Distribution Register and the Upazila Vaccine Stock Register. Vaccination Tally Sheets were used for each immunization session. While there were many causes for wastage, the study highlighted a few key areas that require supervision or increased training for healthcare workers. For example, field workers had difficulty drawing out the necessary number of doses as indicated by the vial's label. Further, vials were often submerged in the water of the vaccine carrier, destroying their potency (Guichard & Hymbaugh, 2008).

In another recent article published by Lee et al., in 2011, the authors replaced the traditional ten dose vials with one dose vials in an effort to reduce the amount of

wasted vaccines in the Trang Province of Thailand. Healthcare workers generally had to open vials to use a few doses, but discarded remaining unused doses. This also led to risk of contamination from having repeatedly drawn vaccine doses from one ten-dose vial. However, the increased number of vials proved problematic, as it presented space issues in the refrigerators, and the doctors noticed more vials were broken as a result of mishandling (Lee et al., 2011).

In a 2004 study of the Bolivian Cold Chain, each of twelve vaccine storage centers monitored recorded temperatures below 0 °C (C. Nelson et al., 2007). Two of the health centers recorded freezing temperatures 50% of the time. Ice-lined refrigerators (ILR's) and domestic front-end refrigerators were predominantly used in all levels of storage, and all recorded freezing temperatures; freezing was even found in district level stores that housed vaccines for up to 22 days. Additionally, freezing was widespread in transport, particularly where freezer rooms are used to freeze ice packs that will line vaccine shipments in insulated boxes. The authors of this study attributed the prevalent freezing of vaccines to poor healthcare worker awareness and understanding of vaccine freezing. Only 15 out of 34 workers were able to correctly identify which vaccines are damaged through freezing, and only half could distinguish a freeze-damaged vaccine from a potent and undamaged one. Regular staff turnover led to healthcare workers who were not adequately educated regarding vaccine shipments and storage. Hence, in addition to the healthcare workers' lack of awareness mentioned above, they also frequently changed the adjustable thermostat, often times resulting in freezing temperatures (C. Nelson et al., 2007).

Similarly, in a study of the Mongolian cold chain, vaccine freezing was also attributed to the actions of healthcare workers. The once-a-month trip into the regional vaccine store takes hours of driving through the rugged countryside, and though the store personnel know a shipment is due to leave, the timing is often erratic. As a result, upon arrival, vaccines are hastily loaded onto the truck in an effort to minimize the time spent traveling, resulting in negligence of the crucial step that brings the deeply frozen ice packs up to 0 °C (Edstam, Dulmaa, Tsendjav, Dambasuren, & Densmaa, 2004).

One study collected information regarding the state of the cold chain among public, private, and community hospitals in Thailand, where there is little regulatory control over drug distribution and transportation. Each distributor is thus responsible for the quality of vaccine shipments. One notable finding was that temperature-sensitive drugs were without controlled temperature boxes to private, public and community hospitals at the rates of 46.7%, 48.3% and 72.9%, respectively. The rate of cold storage drugs (-20 °C,) i.e. polio vaccine arriving with a temperature higher than 8 °C or ice melting in the box, was 22.9%, 12.7% and 35.0% at the private, public and community hospitals, respectively. The authors recommended more regulations across all hospitals for cold chain management (Sooksriwong & Bussaparoek, 2009).

Improving Management

Delegating responsibility is critical to manage the many moving parts of the cold chain. In Chandigarh, India, an evaluation study for the Intensive Pulse Polio

Immunization (IPPI) campaign demonstrated that management of equipment was desperately needed. For example, the authors recommended ensuring an adequate number of certain equipment, such as exhaust fans and voltage stabilizers, and providing an uninterrupted power supply, since power outages reportedly occurred 2-4 hours a day. Reorientation of the training program of all health functionaries was recommended (Galhotra, Goel, Pathak, Kumar, & Swami, 2007).

Performance of trainers and training content are important parameters that can influence the effectiveness of training. One effective immunization intervention in Turkey included vaccines, national vaccination schedule, cold chain and management, planning and regulation of immunization, tracking the trends and increase in vaccination coverage, and immunization recording. Eighteen intensive immunization workshops were held between January and March 2004, lasting for about 54 weekdays in total. The intervention increased both the knowledge of primary healthcare workers and the rate of vaccination coverage in the study region (Uskun, Uskun, Uysalgenc, & Yagiz, 2008).

After conducting a baseline survey of cold chain equipment in 2008, the authors identified key areas to intervene within the Kolkata cold chain system. Using evidence-based training techniques, the research team delegated responsibility to "cold chain handlers," and reorganized the different points at which the vaccines were handled. The success achieved after intervention included significant improvement of interior condition of cold chain equipment, placement of vaccines, temperature maintenance and creation of a designated cold chain handler in each cold chain point. Persistent gaps included non-availability of cold chain equipment like voltage

stabilizers, backup generator services and separate and adequate cold chain room, which mainly depended on policy makers and funding. Preventive maintenance of cold chain equipment on a fixed day monthly, temperature maintenance on holidays and formulating a proper emergency contingency plan were also unsatisfactory (Mallik et al., 2011).

There are several programs that have been developed to strengthen training for healthcare workers responsible for different segments of the cold chain. The Centers for Disease Control and Prevention (CDC) has provided extensive materials for cold chain management, including tips on administering and timing immunization, keeping records, and maintaining general guidelines for all immunization procedures (Kroger, Atkinson, Marcuse, & Pickering, 2006) (Middleton, Zimmerman, & Mitchell, 2007). Some research teams have implemented structured methods in the field. In their 2010 article, Roger, et al., emphasized the responsibility of the US government to provide the resources needed to effectively train US cold chain employees, and the obligation of companies to ensure that employees are utilizing them once available (Rogers, Dennison, Adepoju, Dowd, & Uedoi, 2010).

Outside of the United States, countries are taking steps to improve cold chain management at several levels. In Kenya, the Merck Vaccine Network – Africa (MVA – A) is an educational program to improve the managerial and analytical skills of the mid-level managers of Kenya Expanded Programme on Immunisation (KEPI), utilizing the WHO EPI Mid-level Management Course for EPI Managers (Ayaya, Liechty, Conway, Kamau, & Esamai, 2007). This serves as an example of a targeted approach to cold chain management improvement.

Alternatives to Cold Chain

Alternative vaccines

Considering the great number of factors that contribute to improper vaccine storage and handling, thermostable vaccine products may greatly improve the safety of immunization (Levin et al., 2007).

Many areas in LMICs are plagued with unreliable power supplies, civil wars, cultural taboos, untrained workers, and rugged terrain; it is not surprising that it is thus difficult for the cold chain to successfully deliver viable vaccines. Rather than spending significant time and money on overcoming these challenges, some of which are insurmountable, the simple solution is to spend time and money developing vaccines that are durable enough to endure harsh environmental conditions, and may be easily handled by untrained workers.

Thermostable measles, DTP-hep B, BCG, and YF vaccines in single-dose presentations are potentially cost-effective interventions to reduce childhood deaths and disability in low-resource settings in Asia and Africa. These programs could save money due to reduced vaccine wastage and improved efficiency in delivery. There would also no longer be a need to invest in temperature infrastructure, such as cold rooms or refrigerators. In complex emergency situations, when the cold chain is likely to break down, the benefit is also very clear (Levin et al., 2007).

Alternatives to traditional injected liquid vaccines are being developed in the form of dry-powder and liquid that can be administered orally. Dry powder vaccines are typically freeze-dried so that vaccine proteins can be stabilized by polysaccharides. Freeze-drying vaccines formulated with Aluminum-containing

adjuvants has proven to improve the thermal stability of the vaccine compared to the liquid form (Hirschberg, van de Wijdeven, Kraan, Amorij, & Kersten, 2010). The ideal inhaled dry powder vaccine would have a small enough particle size for deep lung delivery, be able to aerosolize upon inhalation, and be simple to administer. It should also be engineered with compounds that stimulate innate immunity to improve the vaccine's immune response at a low cost with a shelf-life of 0.5-2 years without refrigeration (Sou et al., 2011). Various proteins and peptides (main antigenic biomacromolecules used in vaccines) have already been developed in the form of dry inhaled powders (Sou et al., 2011).

The best method for creating dry powder vaccines requires further investigation. Even following the identification of the appropriate method for developing dry powder vaccines, pre-clinical and clinical trials still need to be conducted (Amorij, Huckriede, Wilschut, Frijlink, & Hinrichs, 2008). The most recent developments, a dry powder vaccine for measles and tuberculosis, are not expected to undergo clinical trials for another two years in India and South Africa, respectively (Sou et al., 2011). Needle-free injection still awaits clinical testing using freeze-dried formulations of vaccine. A freeze-dried Hepatitis B vaccine recently underwent in vivo testing in mice. The objective of the testing was to observe vaccine efficacy following subcutaneous vaccine delivery through an implant made of biodegradable polymers (Sou et al., 2011).

Vaccine Transport outside the Cold Chain

Healthcare workers have also begun to take simple but creative approaches to reformulate the cold chain. The main method that researchers are investigating is the transportation and storage of vaccines out of the cold chain (OCC). According to Halm, et al., OCC transport can be defined as the absence of ice packs in the vaccine carriers during each day's vaccination activities (Halm et al., 2010). Many vaccine transportation routes already use OCC methods, especially as the vaccines get closer to the local dispensaries, quite simply because they do not have the appropriate equipment (ice boxes, vaccine carriers) to store the vaccines in. As such, OCC methods are often used out of necessity.

As OCC methods continue to be used by healthcare workers, researchers have studied the effects of ambient temperature transportation on vaccine efficacy. A comprehensive literature review carried out by PATH found that Hepatitis B, a freeze-sensitive vaccine, is serologically effective even vaccines have been stored by OCC methods prior to administration. The review covered OCC methods in China, Indonesia, and Vietnam, among other countries. The authors found no difference in the immune response between children who received vaccines stored in the cold chain and children who received vaccines stored outside the cold chain. The study concluded that allowing storage through OCC methods would permit more children to be immunized in rural areas (Villadiego, 2008).

Halm, et al. conducted a comprehensive study of the oral polio vaccine (OPV) in national immunization campaigns in Mali. This study aimed to show that storing OPV outside of the cold chain during a campaign is feasible, advantageous, and poses

no additional risk to the potency of the vaccine. The study was done in Mali during the third round of the 2009 inter-country West African National Immunization Days. Trivalent OPV, in a twenty dose vial presentation, was used to vaccinate the estimated target population of children under five years of age. All of the teams followed the same procedures by using the ice packs on two of the four days. On the remaining two days, OCC procedures were followed and ice packs were not used (Halm et al., 2010).

As expected, the vaccine vial monitors (VVM) progressed through its stages slightly faster during OCC days, in which VVMs were exposed to a higher cumulative temperature. At the time the last dose was administered, however, no VVM had surpassed the VVM stage of 60% (90% is the point at which vaccines must be discarded) despite exposure to external temperatures between 25 °C and 40 °C during vaccination activities that lasted nearly seven hours on average. The OCC procedure demonstrated that it led to no vaccine wastage, and was easily understood by all vaccination teams that participated in the National Immunization Day. A study by Wang et al. in rural China corroborated Halm et al's findings (L. Wang et al., 2007). Overall, OCC methods worked in Mali because of the availability of VVMs and well-trained healthcare workers (Halm et al., 2010).

A study by Ren, et al. investigated the effects of an inadequately trained healthcare workforce on success of OCC methods during a campaign for Hepatitis B and measles vaccines in rural Western China (Ren, Xiong, Li, Xu, & Zhu, 2009). Hepatitis B was chosen as a representative cold-sensitive vaccine, and measles as a representative heat-sensitive vaccine. They studied seven delivery routes, and found

two unsettling results: first, that consistent temperatures were not maintained, and second, that healthcare workers were uninformed about proper storage and delivery techniques. As a result, the efficacy of the vaccines was compromised.

Ren et al., found that seven routes maintained a temperature above 8 ºC 18.5 – 26.7% of time. In three of these routes, the temperature was above 8 ºC for more than 80 hours. As a result, 3 out of 48 measles vaccines showed vaccine failure. The temperature was below -0.5 ºC for 2.9 – 12.9% of the time during OCC storage. Despite these temperatures, the hepatitis-B vaccines all passed the shake test. This discrepancy could be explained by vaccines being tested before they froze overnight, or by improper execution of the shake test (Ren et al., 2009).

Using a survey to investigate the procedural knowledge of the healthcare workers, Ren et al. found that many healthcare workers at the district and local levels did not know that freezing temperatures were harmful for vaccines. The workers also had limited knowledge about the proper processes and techniques for keeping vaccines in the correct temperature range (Ren et al., 2009).

As identified by Halm et al., as the number of vaccines administered through the EPI increases, and as the relative capacity of the cold chain decreases, OCC approaches may offer a promising alternative (Halm et al., 2010); however, it is essential to note that using vaccines outside of the cold chain can only be considered with the availability of VVMs as well as adequate OCC training protocols for healthcare workers.

Another study by Nelson et al., 2004, demonstrated that an Indonesian cold chain for Uniject HepB vaccine (HB-Uniject) used OCC practices. To facilitate the

delivery of HepB vaccine to infants born at home, midwives were permitted to store HB-Unijects without refrigeration in their homes until the endpoint of the vaccine vial monitor or expiry date was reached (C. M. Nelson, Wibisono, H., Purwanto, H., Mansyur, I., Moniaga, V., & Widjaya, A., 2004). The authors found that 75% of the shipments were exposed to freezing temperatures.

The authors then led three interventions to observe the impact of taking away different aspects of the cold chain. During the first phase, "no-ice" transport was introduced in all transportation stages. HB-Unijects were transported in standard cold boxes and vaccine carriers but without any ice or ice packs. During the second phase, no-ice transport continued, and HB-Unijects were stored in air-conditioned rooms at the district level. During the third phase, in addition to no-ice transport and air-conditioned district storage, HB-Unijects were stored at ambient temperatures in the health centers. Table 2 summarizes distribution conditions, and Table 3 states the

Table 2: Interventions in Nelson, et al. 2004 study

Distribution stage	Baseline: existing cold chain	Phase I: no-ice transport	Phase II: air-conditioned storage in districts	Phase III: ambient storage in health centres
Transport to province	Cold box with ice	**Cold box without ice**[a]	**Cold box without ice**	**Cold box without ice**
Storage at province	Cold room	Cold room	Cold room	Cold room
Transport to district	Cold box with ice	**Cold box without ice**	**Cold box without ice**	**Cold box without ice**
Storage at district	Ice-lined refrigerator	Ice-lined refrigerator	**Air-conditioned room**	**Air-conditioned room**
Transport to health centre	Vaccine carrier with ice	**Vaccine carrier without ice**	**Vaccine carrier without ice**	**Vaccine carrier without ice**
Storage at health centre	Refrigerator	Refrigerator	Refrigerator	**Ambient temperature**
Midwife storage and outreach	**Ambient temperature**	**Ambient temperature**	**Ambient temperature**	**Ambient temperature**

[a] Emboldened text denotes non-standard cold-chain transport or storage condition.

Table 3: Freezing rates observed for interventions in Nelson, et al. 2004 study

Shipments	Baseline: existing cold chain	Phase I: no-ice transport	Phase II: air-conditioned storage in districts	Phase III: ambient storage in health centres
Monitored	16	15	7	8
Frozen	12 (75)[a]	10 (67)	2 (29)	0 (0)

[a] Values in parentheses are percentages.

freezing rates observed (C. M. Nelson et al., 2004).

The authors concluded that selective transport and storage of vaccines at ambient temperature would significantly reduce rates of vaccine freezing. Similar to previous studies, they also mentioned that policy changes that allow for limited storage of freeze-sensitive vaccines at temperatures outside of the 2–8 °C temperature range would enable flexible vaccine distribution strategies that could reduce overall vaccine freezing, reduce costs, and increase immunization capacity (C. M. Nelson, Wibisono, H., Purwanto, H., Mansyur, I., Moniaga, V., & Widjaya, A., 2004).

Alternative Refrigeration Technologies

There are several promising refrigeration technologies that are currently in use or have potential to be used within the cold chain. Many are specific to particularly destinations with defined levels of resources that enable users to benefit from these technologies. Overall, however, refrigeration is not practical for the main method of transport and storage of temperature-sensitive vaccines through the cold chain. Here we examine compression, adsorption, and absorption refrigeration methods.

Refrigeration: Vapor Compression Cycle

Vapor compression cycle is the most widespread method for refrigeration and air conditioning. This technology is a system in which a liquid refrigerant undergoes numerous phase changes and processes in order to cool the items stored within the refrigeration compartment (Matsuoka, 2005). As the refrigerant passes through an expansion valve, the pressure is quickly dropped. As a result, the temperature of the refrigerant drops and a small portion of the refrigerant is evaporated. The liquid-gas

mixture passes through an evaporator coil where it absorbs the heat in the air surrounding the coils. The warmed refrigerant gas then passes through a compressor in which it is bought back to a high pressure and temperature. After being compressed, the highly pressurized gas passes through a condenser where it is cooled back to its liquid form. The air in the condenser that absorbs the heat given up by the condensed liquid is discharged from the refrigerator at this stage. In an ideal system, the amount of heat energy absorbed by the system in the evaporator will equal both the amount of energy used to supply the compressor and the amount of waste heat energy discharged from the refrigerator in the condenser (Felder & Rousseau, 2005).

Adsorption Refrigeration

Adsorption refrigeration is a technology that provides active cooling of a refrigeration compartment with no mechanical or electrical energy required. This property has made adsorption a promising alternative to vapor compression refrigeration. The adsorption refrigeration cycle is similar to the common vapor compression refrigeration cycle with one key difference. Whereas the vapor compression cycle utilizes a compressor to cool the vapor refrigerant, the adsorption cycle uses the properties of adsorption/desorption (R. Z. Wang & Oliveira, 2005). The adsorbent bed, which is the main facet of any adsorption refrigerator, is composed of a solid material, such as activated carbon, which adsorbs the vapor refrigerant. Then, as an external heat source warms the adsorbent bed, desorption occurs, releasing the cooled vapor refrigerant into the condenser, where it reverts into a liquid for continual use (Yong & Wang, 2007). The external heat source can be any

available source, such as solar energy or waste heat from a nearby machine, making the adsorption refrigeration cycle attractive in situations where electricity is not readily available (R.Z. Wang, Ge, Chen, Ma, & Xiong, 2009). Furthermore, the liquids used as refrigerants are typically ammonia and water, which have zero ozone depletion potential (Yong & Wang, 2007).

Unfortunately, adsorption refrigeration is rarely used as a primary cooling source due to its disadvantages. The main drawback of this system is the adsorption/desorption time (Yong & Wang, 2007). As the adsorbent bed requires a significant amount of time to heat up, the cooling cycle of these refrigerators is often not quickly available, making it an intermittent cooling source only. Furthermore, its specific cooling power (SCP) is lower compared to other refrigeration systems. SCP is a measure of the ratio between cooling production and cycle time per unit of adsorbent weight, showing that the required adsorbent bed significantly increases the size and weight of these refrigerators, while only providing a modest refrigerated storage compartment (Yong & Wang, 2007). Adsorption refrigerators also have a low coefficient of performance (COP), which is the main indicator of cooling efficiency of any refrigeration system (Li, Wang, & Wang, 2009).

In their review of adsorption refrigeration technologies, Fan et al. (2009) note that adsorption refrigeration would be an attractive solution to current demands for less energy usage, as current compression refrigeration and air conditioning systems use about 15% of the world's energy supply each year (Fan, Luo, & Souyri, 2007). Furthermore, adsorption technology is ideal for areas in LMICs that have limited or no access to electricity (Rahmana, Akhandaa, & Sadrul Islama, 2006). Researchers

are pursuing many avenues to improve the cooling efficiency and address other disadvantages of adsorption refrigeration to meet these needs. Some areas include testing different adsorbent bed materials, using two or more adsorbent beds, and creating hybrid systems of compression and adsorption technologies (Yong & Wang, 2007).

While there are promising future directions for adsorption refrigeration, we determined that adsorption refrigeration would be impractical for transportation in the cold chain, as the adsorbent bed requires an external heat source and the SCP is relatively small.

Other Refrigeration Methods

Absorption refrigeration is very similar to adsorption refrigeration. The slight difference between these two technologies is in the conversion of the gas refrigerant back into a liquid. In absorption, the vapor refrigerant is absorbed, or dissolved into another liquid, usually a water and salt mixture (Fan et al., 2007). In adsorption, the vapor is adsorbed, meaning it does not completely dissolve in the adsorbent bed, but rather clings on to its surface. This difference means that absorption requires much more heat to release the refrigerant from the liquid. The main advantage of this type of system is that the liquid mixture is lighter and more portable than the adsorbent bed (Fan et al., 2007).

The Score project, developed at the University of Nottingham in the United Kingdom, is working on a biomass-powered generator that could make electricity for health centers using just waste products as the fuel. The key technology in this device

is a Linear Alternator, which converts sound energy into electrical energy. It uses special configurations of magnets to convert sound into electricity (Rossi, Immovilli, Bianchini, Bellini, & Serra, 2009). The researchers say that the generator is very versatile in the type of fuel that it can burn to be used as heat energy for the Linear Alternator, making it attractive in a wide variety of developing areas. Their target is to make a device that costs about $20 and weighs between 10-20 kg (Rossi et al., 2009). This generator could be an important source of electricity for health centers in LMIC regions of the world.

Another type of energy source used for powering refrigeration compressors is geothermal heat. Normally, compression refrigerators exchange heat with the surrounding air in order to remove heat from the interior compartment. However, this process is relatively inefficient, as the air changes temperature quickly and by a large amount with the seasons. In contrast, by exchanging heat with the surface of the earth, compressors can be made much more efficient, as the earth does not change temperature as quickly and stays about the same temperature all year round. The disadvantages to this system are that the refrigeration compartment cannot be transported and it must be rather large to accommodate the surface area needed for adequate heat exchange (Hepbasli & Akdemir, 2004).

PCM Technology – A Promising Alternative

A phase change material (PCM) is a very effective means of temperature regulation. It has the ability to maintain a constant temperature while absorbing

ambient heat energy, and as such has become used as a means of latent heat storage in a variety of different applications.

One of the main features of PCM is its high heat of fusion (Pasupathy, Velraj, & Seeniraj, 2008). PCM is a passive cooling method, meaning that there is no power required for it to function. Each PCM melts and becomes solid at different temperatures, either absorbing or releasing heat when switching phases from solid to liquid, or vice versa. While there are other phase changes, such as liquid to gas, the phase change from solid to liquid are of interest because it is the most practical and widely available phase change (Pasupathy et al., 2008). This effect is best demonstrated by one of the most readily available PCMs - water. When changing from ice at 0 °C to liquid at 0 °C, water is absorbing heat from its surroundings. An example is ice cooling a drink. When the ice begins to melt, it absorbs the heat from the beverage, making it cold, while still maintaining its temperature. A PCM will continue to store heat at a consistent rate until completely turning into liquid form (Pasupathy et al., 2008). This gives PCM the ability to store and release large amounts of energy and giving it many thermodynamic applications.

Since PCMs all have different melting points, a suitable PCM can be found to match a specific purpose. Thus, since most vaccines must be stored at 2-8 °C, PCMs that melt in this range would be able to keep the vaccines cool at a stable temperature. Therefore if a suitable PCM is used, the vaccines will stay in the desired temperature range, preventing them from losing potency.

Other common applications include the cooling of homes, buildings, heat and electrical engines, food, wine, and milk. PCMs can also be used in the transportation

of blood and other medical supplies, operating tables, and hot-cold therapies. PCMs are also used in many less common ways, such as the thermal storage of solar energy and in spacecraft thermal systems (Kenisarin & Mahkamov, 2007).

Many PCMs are naturally occurring, and thus readily available at a low economic cost (Kenisarin & Mahkamov, 2007). This also means that a lot of PCMs are environmentally friendly and are safe to use (Pasupathy et al., 2008).

There are a few different categories of PCM. Organic PCMs include paraffin and fatty acids. They are available in a large temperature range, melt congruently, are chemically stable, have a high heat of fusion, are safe, and are recyclable. However, they also have low thermal conductivity in their solid state and are flammable (Pasupathy et al., 2008). Inorganic PCMs are usually salt hydrates, and they are easily available at a low cost, with sharp melting points, high conductivity, high heat of fusion, and inflammability. Some disadvantages of inorganic PCMs are that their change in volume is high and that they need nucleating agents, especially after repeated use (Pasupathy et al., 2008).

A third kind of PCM called eutectics is a mixture of organic and inorganic PCMs. They have a sharp melting point and a slightly higher storage than organic. Eutectics are relatively new to the field, and thus little information is known on their performance and characteristics (Pasupathy et al., 2008).

For all the reasons listed above, we decided to use this technology in designing our innovative cold chain box.

Conclusion

As can be seen throughout the exhaustive literature review, many gaps and weaknesses are present at every stage of the cold chain such as improperly trained health workers, frequent electricity outages, and mismanaged equipment. Studies from across the field also bring to light region- and disease-specific issues, such as non-existent transportation infrastructure in the Peruvian Amazon. Despite these pitfalls, the cold chain is strengthening due to an increased focus on immunization programs and due to the diligence of public-private partnerships across the world. Should the momentum from these partnerships and programs continue, immunization rates will continue to increase.

The goal of this literature review was to provide our team with a foundation of cold chain knowledge and a focus to our multi-year research problem. As such, while problems manifest the cold chain, every issue could not be addressed by our team. As we tried to formulate responses to weaknesses in the cold chain, the issues that stood out to us the most were the prevalence of vaccine-freezing, mismanagement of current complicated equipment, and the promise of simpler technologies like PCM. As can be seen through our research objectives and methods, we used the conclusions drawn from our literature review to create the basis of our project.

Chapter 3: Methodology

Characterization of Phase Change Materials

PCMs are highly relevant solutions to vaccine storage problems with an ability to act as thermal buffers and stabilizers. Therefore, one of the goals of our methodology was to select, characterize, and implement the most applicable and high performing PCM into our prototype design. The first step in preliminary characterization was to select candidate PCMs for by examining the exact melting point and heats of fusion and costs associated with each. PCMs listed in the literature with relevant melting points are included in Table 4, along with pricing information, heat of fusion data, and densities.

Table 4: PCM names and characteristics

PCM Name	Temp (°C)	Heat of Fusion (kJ/Kg)	Density (kg/m^3)	Type	Price
Water	0	333	1000 (l), 917 (s)	N/A	N/A
Climsel C7	7	130	N/A	Eutectic	N/A
RT5	b9	205	N/A	Paraffin	$25/L
RT6	6	175	N/A	Paraffin	$25/L
Propyl Palmitate	11	186	N/A	Fatty Acid	$10/L
Paraffin C14	4.5	165	N/A	Paraffin	$25/L
Paraffin C15-16	8	153	N/A	Paraffin	$30/L
Lithium Chlorate Trihydrate	8.1	253	1720	Salt Hydrate	$17/L
Tetrohydrofuran Clathrate (Tombari et. al. 2006)	5	280	970	Clathrate	$110/L
Polyethylene Glycol MW400	8	100	N/A	Glycol	$130/L
Phase 5 ™	5	unknown	N/A	organic	
AcuTemp	unknown	unknown	N/A	organic	
PureTemp4	unknown	unknown	N/A	organic	

The variance between candidate PCMs suggested that an optimal PCM could be found based on a specific selection criteria. Of the above PCMs, the following were deemed unattainable due to manufacturing issues: Climsel 7, Lithium Chlorate Trihydrate and both RT5 and RT6 substances. These PCMs were not tested and excluded from selection. The PCMs with very high prices, such as Polyethylene Glycol, were excluded from evaluation; although their physical applicability was

strong, their economic viability was too low to consider for measurement. Beyond PCMs reported in the literature, we also evaluated several commercially available PCMs. For most of these materials, the heat of fusion was inaccessible in the scientific or company literature. One of these PCMs was Phase 5 ™ (TCP Reliable, Edison, N.J.). Its properties matched our product's desired application, prompting us to test it for melting temperature and heat of fusion. We also characterized PureTemp 4 (Entropy Solutions, Minneapolis, MN), which is a biologically produced paraffin and was therefore more economical than the paraffins in Table 4 (Rodie, 2009) and AcuTemp, another commercial PCM with minimal existing literature.

Characterization was performed using a Differential Scanning Calorimeter (DSC), and analysis was performed with the program Universal Analysis V4.7A by TA instruments for use in conjunction with a DSC. The goals of characterization and analysis were to determine the heat of fusion and melting temperature of each PCM. The heat of fusion is the energy storage capacity of the crystallized solid structure while the melting temperature can be considered the peak of energy storage. The DSC utilized was a TA instruments q100 V9.9 build 303 system certified from -80 $^{\circ}$C to 300 $^{\circ}$C (Figure 5).

Characterization involved isolating small samples of a well shaken mixture of PCM provided by the company and placing it in a small vial. Hermetically sealed alodized aluminum pans served as the nonreactive containment vessel during measurement. The mass of each pan was measured on a balance accurate to a tenth of a μg. The sample was loaded and sealed using a pneumatic press. To ensure a proper

seal, each sample was massed again and then stored in a highly ventilated fume hood for half an hour. Each sample was massed once again and the process was repeated if the sample mass changed by more than 3-4 μg. Once the sample was prepared, the instrument was turned on and allowed to reach the operating flange temperature of -80°C. The sample was placed on one of the heating sources as seen below. On the other source a comparison pan (an empty pan) was placed.

Figure 5: Image of sample containment in q100 series DSC

The instrument was instructed to seal the sampling stage and begin the inputted experimental procedure. The procedure consisted of three steps: step one was to cool to -10 °C, isothermal for two minutes to ensure the sample is frozen, followed by heating it at a specified ramp rate to room temperature. Different ramp rates will be utilized. Although more accurate measurements could have been garnered from slower ramp rates, system constraints limited the usable rates, thus a series of rate were used. Water served as a standard for these rates to determine if measures were accurate when compared to the literature value for the heat of fusion. As the system heated up, given the relative stability of the heat capacities of solid and liquids, it was reasonable to take a reading of input Watt/mass over time and construct a curve. The

curve was theoretically assumed to be linear until the melting point was reached. At the melting point, the deviation of the system from the extrapolated line represented energy input used to melt the sample at a constant temperature. The energy absorbed by the system was geared towards melting from solid to liquid, as opposed to raising the temperature of the sample. The program TA universal analysis was able to integrate the area where the limits of the deviation of the curve were inputted. The result was a series of measurements of the freezing point and heat of fusion for each sample.

CAD and FEA Theoretical Modeling

The goal of the modeling team was to simulate the heat transfer phenomenon in passively refrigerated containers in order to gain a sense of how to design an optimally shaped cold box. The starting point for any analysis of heat transfer is the heat equation, equation 1.

$$\frac{\partial T}{\partial t} + \frac{\boldsymbol{u} \cdot \nabla T}{\rho C_p} = \frac{k}{\rho C_p} \nabla^2 T + \dot{g} \qquad (1)$$

The first term of this equation is the partial derivative with respect to time. The second term represents convective heat transfer, with u representing a velocity vector which is multiplied by the temperature gradient (∇T). ρ, C_p, and k are the density, mass heat capacity and thermal conductivity of the fluid under consideration respectively. The first term on the right side of the equals sign is the conductivity term and is derived from Fourier's Law. The final term is a volumetric heat source

generation term which can represent electrical heating or heat generated from radioactive decay.

For our analysis of phase change, we ignore the convection and generation terms. (Though the temperature inside the box will probably exhibit natural convection, this requires coupling the heat equation with partial differential equations for fluid flow.)

A computer model was generated to serve as a theoretical control for our experiments using Finite Element Analysis (FEA) software. In this type of program, a geometric model may be created with defined material properties and then stressed with physical conditions, like forced loads or thermal conditions. This is done by meshing the modeled geometry, i.e., dividing the model into a grid of polygons, where the points of intersection between the polygons are called nodes. The size of the mesh regulates the node density (coarse to fine). The program solves a series of partial differential equations, dependent on what loading conditions were applied, at each node in the defined mesh. The solution is generated through iterations over a user-specified time increment and duration.

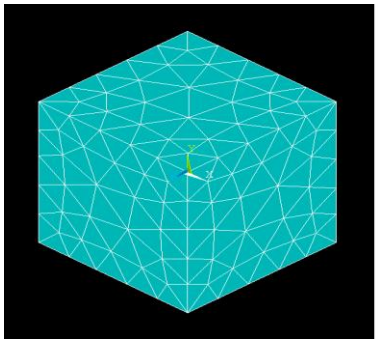


Figure 6: Example of a meshed model

Using an FEA program, simulation of any physical experiments was possible by adding thermodynamic conditions as the model physics. After running the simulation, the program may output a variety of useful information, including a time-temperature graph. This data was compared with those taken from the thermocouples in the icebox experiments to determine errors and accuracy in our findings.

At first, we were able to generate a preliminary thermal model without phase change to demonstrate the use of the FEA software COMSOL Multiphysics. We simulated a three-dimensional cubic cold box, encompassing an outside layer of insulation, a plastic-bounded layer of PCM, and an air-filled vaccine storage compartment at the core. The dimensions were arbitrarily chosen. A thermodynamic condition was placed on the boundary of the box to keep it at a constant ambient temperature. Thus, the insulation and vaccine storage compartment are initially at the ambient temperature, while the PCM begins at its freezing point.

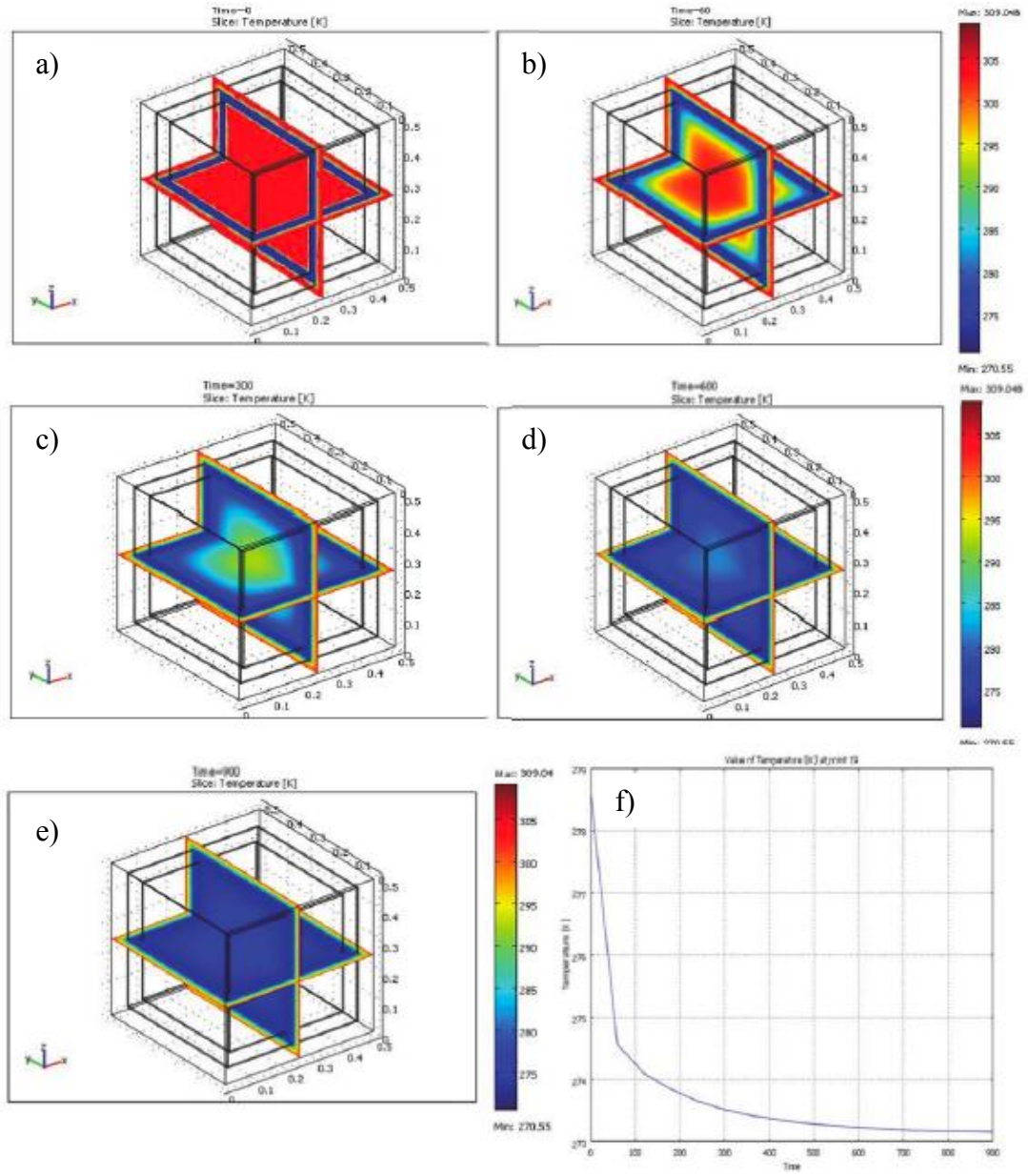


Figure 7: COMSOL model demonstrating the initial heat transfer at the onset of the melting. Output of temperature within horizontal and vertical sectional cut of model, showing the melted phase change material rising in temperature. The images are taken at times: a) 0, b) 5 hours, c) 10 hours, d) 1 day, and e) 2 days. The temperature scale is given in Kelvin, with blue signifying the freezing point and the red signifying the ambient temperature. Figure 7f displays the Time-Temperature graph at a point within the vaccine storage compartment of the model.

The model was run in two stages: the first, demonstrating the initial heat transfer at the onset of the melting period (Figure 7), and the second, demonstrating the box heating up after the melting phase (Figure 8). In this simulation, ice/water was used for the PCM, and the ambient temperature was set at 30 °C.

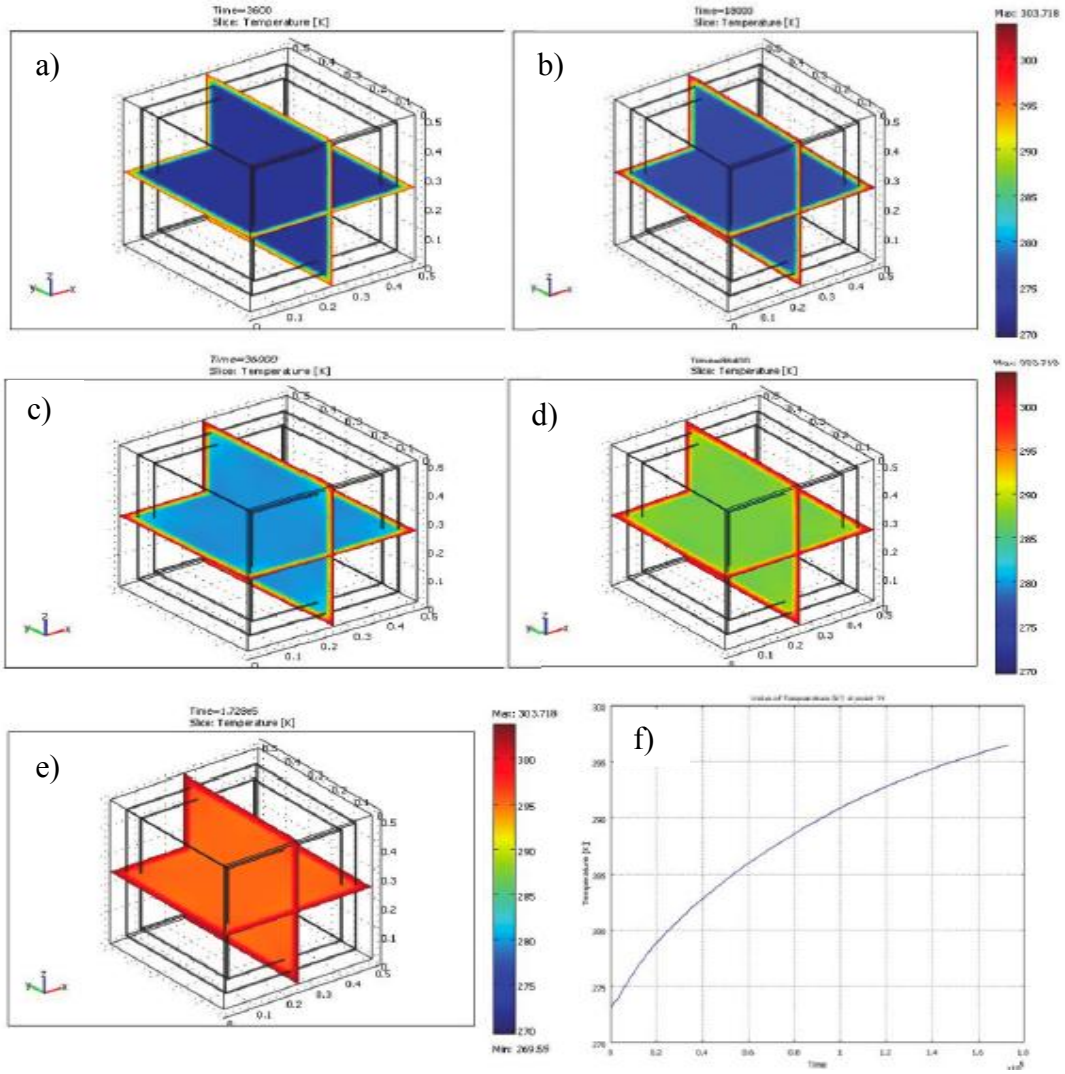


Figure 8: COMSOL model of the box heating up after the melting phase. Output of temperature within horizontal and vertical sectional cut of model, showing the melted phase change material rising in temperature. The images are taken at times: a) 0, b) 5 hours, c) 10 hours, d) 1 day, and e) 2 days. The temperature scale is given in Kelvin, with blue signifying the freezing point and the red signifying the ambient temperature. Figure 8f displays the Time-Temperature graph at a point within the vaccine storage compartment of the model.

One difficulty we experienced was that the COMSOL software (and other Finite Element Analysis programs) does not have an inherent function to address the discontinuous but natural behavior of the melting and freezing of substances. To accommodate this, we implemented the effective heat capacity method as suggested by the COMSOL documentation (Phase Change: Solved with COMSOL Multiphysics 3.5a, 2008). The program ran but gave inaccurate results. A simple implementation of the level set method also ran in 2-D axisymmetric coordinates, but was not easily adaptable to a 2-D rectangular PCM- panel geometry (Zimmerman, 2006). We also tried to implement the effective heat-capacity method in another FEM software suite, Elmer, as well as the enthalpy method using data from the DSC curves.

We finally settled upon a method of approximation for the phase change simulation. Although the real process occurs over a constant temperature, it may be approximated to occur over a very small temperature range (~0.5 °C) about the material's melting point. The energy required to change phase may then be approximated using the specific heat capacity over this small temperature range. The relation is outlined in Equations 1-3.

For a known mass (m) and material with latent heat of fusion, L, and specific heat capacity (at constant pressure), c_p, the energy (E) required to change phase is given by:

$$E = m \cdot L \qquad \text{(for constant temperature } T_{melting}\text{)} \tag{2}$$

and the energy required to cause a change in temperature (ΔT) of the material is given by:

$$E = m \cdot c_p \cdot \Delta T \tag{3}$$

Given a very small ΔT (ΔT→0), an setting the energies in equations (2) and (3) equal to each other yields the relation:

$$c_p = \frac{L}{\Delta T} \tag{4}$$

This concept of approximated phase change is graphically illustrated in Figure 9 below.

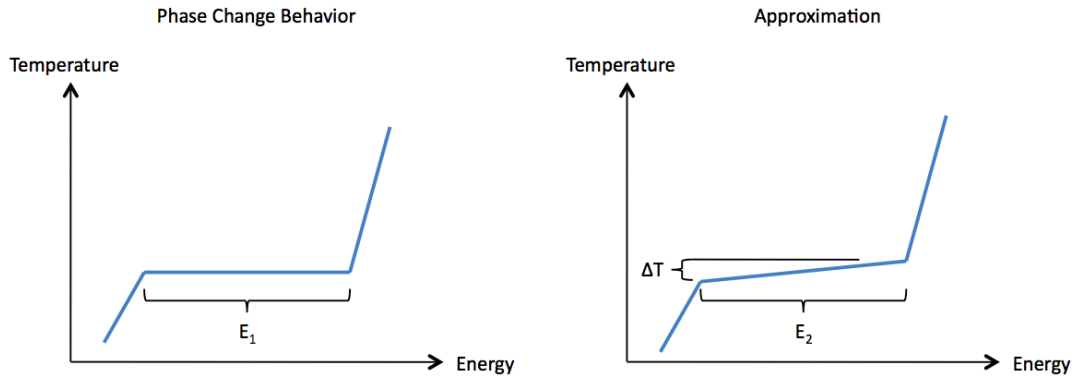


Figure 9: Graphical illustration of the approximated phase change material behavior, in taking the melting regime to occur over a very small change in temperature (slope is exaggerated for visual aid). In the true behavior, this occurs at a constant temperature for the duration of melting.

Using this relationship, we defined the specific heat coefficient of the phase change material for the melting transition ($T_{melting} \pm \Delta T/2$). Two other sets of material properties were defined: one for temperatures below the material's melting point, and one above. The model would then give an estimated simulation of the phase change process.

We began to implement this method in COMSOL Multiphysics with limited success. Many of the models resulted in failed computing executions or in questionable data, attributed to our inexperience with the program in hindsight. After

receiving formal course instruction in FEA software, we began to use the program ANSYS 13.0 to run our simulations because of its wide application and advanced capabilities.

To verify an accurate execution of the phase change simulation, we began with a simple model of a melting cube of ice (side dimensions of 10 cm). The block started at a temperature of -5 °C and was subjected to a constant boundary temperature of 40 °C to imitate an ambient environment. Conventional material values for water and ice were used, and the melting temperature range was set between -0.50 and 0.50 °C. For this range, the specific heat capacity was given to be 334000 J/K (=334 kJ / 1K). A transient analysis yielded the following results in Figure 10 below.

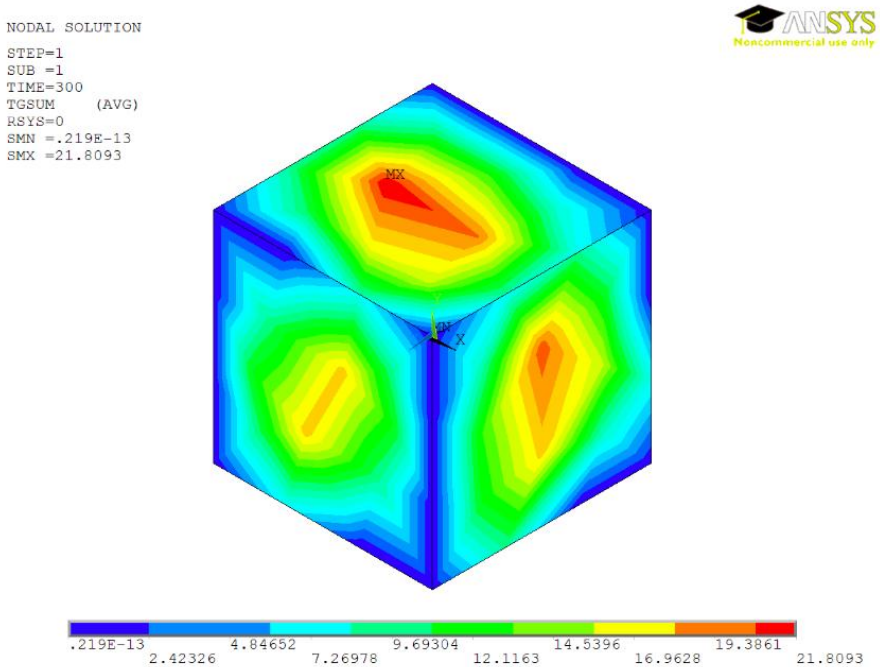


Figure 10: Contour plot of the thermal gradient vector sum at time of 300 s.

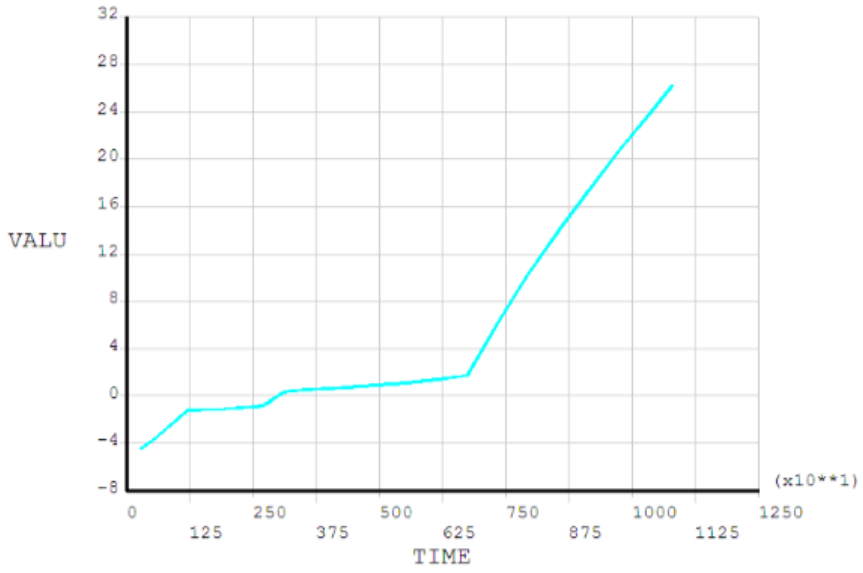


Figure 11: Time history plot of a nodal temperature within a melting ice cube. The time is given in seconds and the temperature in °C.

As demonstrated in the time-temperature graph in Figure 11, the model does exhibits phase change behavior. The temperature rises from its initial temperature for about 125 seconds until it reaches the minimum end of the melting regime (-0.5 °C). The temperature rises minimally for the melting regime, where a change in the slope is observed around 0 °C, when the material properties change from water to ice. The temperature then rises as normal for the fully melted volume, when the water absorbs heat through its natural specific heat capacity.

Given this proof of modeling concept, we then wanted to use this method to simulate the ice box experiments and other models to verify our experimental findings and to determine the optimal configuration of PCM geometry. This was also done in the ANSYS finite element analysis software.

To begin this, we created a base file to store the fundamental model settings for uniformity through all variations of the model. The model preference was set to thermal analyses, and units were accepted in the standard SI format, while specifying

Celsius temperature units. The element used was SOLID70, an 8-node element with temperature degree of freedom, given application in 3-D steady state or transient thermal conduction analyses.

Next the material properties were to be defined. The manufacturer specifications for the polystyrene insulation from the icebox experiments were translated into SI values, while a conventional value for the specific heat capacity of polystyrene was not manufacturer-defined and thus chosen from outside literature.

Given the weight and volume of the insulation product, the density was found by:

$$\rho = \frac{m}{V} = \frac{3.1\ lb}{(1\ in\ \times 96\ in\ \times 24\ in)} = 0.0013\,\frac{lb}{in^3} = 37.24\,\frac{kg}{m^3}$$

The insulating property was given at R5. This is related to the thermal conductivity property, k, by its thickness, L. The units were further converted to the SI system.

$$\frac{1}{R} = \frac{k}{L} \rightarrow k = \frac{L}{R} = \frac{1\ in}{\left(5\,\frac{°\mathrm{F}\cdot ft^2\cdot hr}{Btu}\right)} = \frac{0.0254m}{5\cdot 0.1761\left(K\cdot\frac{m^2}{W}\right)} = 0.0288\,\frac{W}{m\cdot K}$$

The materials for the PCM (ice) were defined using a piecewise functionality, where different values could be assigned to different temperatures. Specifically, two different densities and thermal conductivities were defined for ice (when the substance was at 0 °C or below), and one for water (when the substance was above 0 °C). The specific heat capacity was further defined in three segments - one for ice (less than -0.25 °C), one for the melting regime (between -2.5 and 2.5 °C), and one for water (greater than 0.25 °C). As can be inferred, the melting period was defined

through a 0.5 °C temperature change about the melting temperature of 0 °C. It was reasoned that this temperature change was small enough to ensure relative model accuracy but large enough for the program to solve the system of equations throughout the model without error or storing huge amounts of data.

It is worth noting why air was selected to fill the vaccine storage compartment at the center, instead of a denser substance like water that is comparable to actual vaccine vials or fluids. First, using an air-filled ice box was also done in our experiments, and we wanted to match the data between the physical experiment and the theoretical model. Second, the solving time would be significantly decreased, and the output data would be minimized, if the inside was filled with a negligible substance. We could thus use a coarser mesh on the air volume to reduce node density. Finally, we reasoned that using air would be the worst-case scenario for temperature distribution, in that in this case, any thermal load placed on the box would quickly affect the vaccine volume and cause a significant temperature gradient. If filled with a more dense material, the vaccine compartment would better resist a change in temperature at the onset, but would likely still eventually develop the temperature gradient observed in the air-filled case.

Although in reality air would be subject to some convective conditions within the box, it was instead treated as a conducting material for simplicity of the model. This would also coincide with the conditions for when the vaccine compartment was fully loaded, where the vials and liquids within would disrupt any form of circulation within the box and thus make any convection condition negligible or nonexistent.

Table 5: Default Material Properties for FEA ice box model

Ice/Water	Temperature (°C)					
	-100	0	0.001	100		
Density (kg/m^3)	916.2	916.2	1000	1000		
Thermal Conductivity (W/m-K)	2.22	2.22	0.58	0.58		
	-100	-0.251	-0.25	0.25	0.251	100
Specific Heat Capacity (J/°C)	2050	2050	6.68E5	6.68E5	4210	4210
	Polystyrene			Air		
Density (kg/m^3)	37.24			1.293		
Thermal Conductivity (W/m-K)	0.0288			0.0243		
Specific Heat Capacity (J/°C)	1300			1005		

Assigning these values to set material profiles completed the base settings file. A log file was then created so that input from these base settings could be read directly into any new model file, saving the effort required to set up each different model geometry. The code for this log file may be found at the end of this volume in Appendix A.

Two sets of models were then created. One set mimicked one size box of the physical experiments with outside dimensions of 9.5 in. The other set followed the larger sized box with 13-in dimensions. Each ice box experiment (ice geometry on all sides, with a horizontal shelf, and with a vertical shelf) for both sized boxes was to be executed as an FEA model. Furthermore, other geometries not physically tested were also investigated with the FEA models, as it was easier, faster, and more efficient to create a computer model, in comparison to setting up, running, and analyzing experiments. The same volume of ice was used within each set of box sizes.

The geometry for each model variation was drawn out on paper and inputted into the software. Separate volumes were created for each differing material in the icebox - the insulation layer, ice, and air at the vaccine storage compartment. Simple rectangular geometry was used to construct the model, where subtracting volumes was utilized to create each layer or unique geometry. To complete the model, all volumes were glued together to ensure that the areas between volumes were joined as one. Failing to do so resulted in no interaction between the volumes when solved, as each was considered its own entity without cross-interaction.

Each volume was then meshed using the smart size option with tetrahedral polygons. The appropriate material was assigned to each volume, and the mesh size for each volume was varied between 3 and 8 (on a scale of 1-12 [Fine to Coarse]), depending on the size constraints and maximum number of elements allowed in the model. In most instances, size 3 was considered the default value, having enough nodes to satisfy requirements and to be relatively fine without extending solving time. In some instances, volumes had to be assigned coarser meshes to cut down on the number of elements.

Following the mesh, thermal loading conditions were then applied to the model. First, a new transient analysis was created, where these loading conditions would apply. Second, the initial temperature conditions for all of the nodes were assigned. The ice layer temperature was set at an initial -10 °C to ensure proper phase change behavior prior to reaching the melting regime at -0.25 °C. All other nodes, in both the insulation and air volumes, were given an initial temperature of 22.5 °C. This was considered to be an average ambient temperature and reflected the conditions in

the ice box experiments. Instead of adding active heat loads like conduction or convection to the outside areas of the box, a temperature condition of this ambient 22.5 °C was applied on all six outside areas of the box. This was deemed a reasonable estimate of the loading condition, in considering that the box would not likely be subject to fluctuating conditions. We considered using a convection condition but decided that a constant temperature was easier to manage in the model and that it would be difficult to find the convection coefficient for the insulation used that would fit all scenarios.

Solving constraints were then defined. Data was restricted to nodal degree of freedom data, i.e., recording the temperature data from the model. A time duration of 300,000 seconds (about 3.5 days) was sufficient for most models to go through the melting phase and reach the equilibrium ambient temperature, though some required adjustment for a longer time. The time step size was set to 60 seconds, with a minimum of 0.01 seconds and maximum of 300 seconds. Temperature solutions were recorded at every three or five sub steps to cut down on the amount of data, and automatic time increments was enabled to be chosen by the program. That is, if the differential equations could not be solved at a higher time increment, then the program would try to solve for smaller time increases, and vice versa if the differential equations converged to a solution at larger time increments. Average solving time was about two to three hours for each model, depending on the element density. Sample code for this simulation log file may be found in Appendix B.

After running a few models, we began to compare the data to the ice box experiment results. Model data was pulled from nodes that mimicked the locations of

the thermal couples in the ice box experiments. In an ideal case, the time-temperature graphs from the experimental and theoretical would be near identical. In analyzing the data, we noticed similar patterns of temperature distribution. Then, to determine some quantitative analysis for duration of cold storage, we then considered the average time for the temperature probes to go from the melting state (-0.25 °C) up to the high end of the optimal vaccine temperature zone of 8 °C.

We noticed that this duration in the ice box experiments was significantly longer than the time seen in the model - the heat transfer in the model was greater than in real life. We reasoned that this might have been because of the unrealistic temperature loading condition subject to the model, where we defined the outside of the box as being subject to one constant ambient temperature. In reality, the air surrounding the box would be cooler than the ambient temperature if the box itself were colder. The box would also be subject instead to convection effects, which would lend to a slower rate of heat transfer. Another factor could have been that the experimental ice box was resting on some surface, making the bottom additionally insulated and not subject to any particular heat load. The grounding surface and the box would have come to an equilibrium temperature lower than the ambient temperature, thus having a lower heat flux. There would also be no heat loss to convection conditions along the bottom, unexposed surface.

In order to counter this disconnect between the model and the ice box experimental findings, we considered adjusting the thermal conductivity of the insulation layer to better match the model data to the experimental data. The thermal conductivity reflects a material's ability to absorb heat and change in temperature;

more specifically, a higher insulation thermal conductivity increases the rate at which heat can enter the system, where the ice is to be melted. By lowering the thermal conductivity of the insulation from its manufacturer-claimed value, we could decrease the heat flux into the box, and increase the time of the melting period. Thus we could create a more accurate model to the physical experiments, while using the same loading conditions and other material properties already defined.

To go about this, we analyzed the data from two distinctly different models. The first was the 9.5-in sided model with ice surrounding all sides of the box interior and a horizontal shelf. We then chose the 13-in sided model with ice surrounding all sides of the box interior (no shelf) as a comparative set of data. The objective was to find a value of insulation conductivity to match both sets of data to their respective counterpart data set from the physical experiments.

Initial conductivity variations for each model were calculated through a simple ratio of the measured time over the model time. The conductivity was further adjusted to attempt to pinpoint a matching conductivity. After three different variations, a mutual conductivity value of 0.0227 W/m-K was determined to be an accurate adjustment. This matched the 9.5-in side horizontal shelf model to 99.14% of the measured physical value, while the 13-in side all sides model was 100.25% of the measured physical value. Given this highly accurate correlation, we determined that this was a valid means to adjust the model. Graphical findings may be found in the later results section.

Table 6: Summary of results in finding the insulation thermal conductivity (W/m-K) for the FEA model.

	9.5-in horizontal		13-in all sides
measure	1647		3473.1
original model	1270		2624.8
% difference	77.1		132.3
k=0.0210	1856.0	k=0.0207	3816.3
% difference	88.7		91.0
k=0.0236	1584.6	k=0.0215	3673
% difference	103.9		94.6
k=0.0227	1632.9	k=0.0227	3481.778571
% difference	99.1		100.2

Given this verification of method and matched correlation between physical and theoretical data, the models were then completed using the newly found value of thermal conductivity. Models were created for both sets of box sizes, including an all sides model, a horizontal shelf model, a vertical shelf model, a top and bottom slabs model, a bottom slab only model, and an all sides model without a bottom slab (not solved for the 13-in model). In total, this became eleven different FEA models to compare and analyze.

Ice Box Experiments

In accordance with our experimental plan, we created a "cold box" to model how the PCM acts inside of a vaccine box over time. This ice box is a simplified model, constructed out of 6 sides of polystyrene, and replacing PCM with ice packs. Using an 8-lead thermocouple data logger, we obtained experimental results detailing how the internal temperature gradient shifts over time. This experimental model should be matched to a theoretical computer simulation of the same materials and geometry. If we are able to successfully match our experimental and theoretical

results, we will be able to run an optimization algorithm to determine the geometry that best matches our priorities.

In a typical cold box, there are many possible ways to distribute the same volume of ice. While panels on one or two sides are the simplest designs, it is likely that the efficacy of our box can be improved with minimal increases in complexity of panel placement. For our design, we must consider the effects of gravity, direction of heat source, the distance of the vaccines from the PCM panels, and the total volume of PCM in each panel. As ice floats, a melting ice panel will form an internal gradient with the coldest portion being the highest point. Additionally, heat rises inside of a cold box, so a good design should take advantage of these nuances created by gravitation. As the ice box travels, the sun typically will affect the top side the most and the bottom side the least. As the distance from the vaccines to the ice pack increases, there is a higher likelihood that the effective phase change temperature may be above 8 °C, especially for larger boxes. To this end, we will investigate if rearranging some of the PCM to the center of the box can counteract this effect. Finally, as rearranging the PCM distribution changes the thickness of the panels, we must investigate how much PCM is necessary to ensure the longest effective phase change time.

We predict that for same total volume of PCM, the smaller size box will be able to hold the temperature for longer, but have less storage volume than the larger box. The 6 -sided box will have the longer average time, but the center temperatures will pass 8 °C much sooner than the edges. For the geometries with shelves, the total time will have two phases: one for the panels on the edge to melt, then for the central

panel to melt. Consequently, the temperatures should be more evenly balanced throughout the total time span.

To design the experimental setup, we wanted to create a simplified model of the PCM-cold box interaction. To this end, we created polystyrene boxes of varying sizes. We used ice as a PCM due to its ubiquity and safety in case of spills and leakages during testing. We also created different configurations of PCM placement to explore possible geometries. Using an 8-lead thermocouple, we can measure various important points inside and outside of the box to monitor the temperature changes over time. The data collection mechanism in the laboratory was a thermocouple operating with the DT300 collection software, accurate to 0.1 °C (Apollo IV DT300 Multi-component Thermocouple, 2010). The locations of important leads include a lead outside of the box to monitor the ambient air temperature of the room, a lead in the center of box, a lead in the center of bottom panel, a lead in the center of the top panel, a lead in the center of top corner quadrant, a lead in the very top corner, a lead between the panel and the polystyrene, and a lead halfway between center of box and center of side panel. The placement was created to measure gradient lines extending from the center of the box to the center of the side, the center of the box to the corner, and the bottom of the box to the top of the box. We planned a total of 6 full box experiments and 1 gradient measurement experiment. Our six tests consisted of three geometries and two box sizes. We used an 8 $in.^3$ box and a 13 $in.^3$ box, with a 6 panel setup, a 6 panel and horizontal shelf setup, and a 6 panel vertical shelf setup.

To conduct the gradient measurement, we kept one panel on the bottom of the box, and equally spaced leads vertically through the box to measure the formation of a temperature gradient over time. This allows us to understand how close to the panels the vaccines can stay, as well if we can create a geometry that extends the lifetime of the most distant point from all sides (center).

All experiments were conducted in a temperature-stabilized room held at 24 ºC. For ease of matching theoretical results, there was no external heat source and no extra layers of insulation or support besides the polystyrene box. All thermocouple leads were arranged as identically as possible between trials, with obvious accommodations for trials with shelves. In order to create our ice packs, we created 6 packets with identical volumes of water and froze them flat. These were placed inside metal holders to maintain the shape of the pack once melting started. For geometries with a shelf, 7 packets were created with the same volume of water, with the total sum of individual volumes equaling the total of the six packets from the previous arrangement. The thermocouple leads were held in place with masking tape, and the lid was closed as tightly as possible. Since the presence of the thermocouple wires offset the lid slightly, additional weight was added on top of the box to ensure a tight seal with minimal air leakage.

The ice packs were taken from a freezer at -10 ºC and, correspondingly, this was the starting point of the temperature graph. After the ice box stabilized at ~0 ºC, the phase change period began, and was considered reasonable for transport until the average temperature reached 8 ºC. The box was allowed to stabilize with the ambient air temperature before the experiment was concluded.

The data strongly supports the concept that the latent heat of the PCM is the key factor in the longevity of cool temperatures within the cold box. The curves also indicate that a temperature gradient exists within the system. The internal temperature of the box settles at 0 °C for a very short duration before gradually increasing towards room temperature. In contrast, the temperature at the periphery of the box is stable for a longer time before approaching ambient temperature following the phase change. From a methodological standpoint, the consistency in the length of time each experiment took to reach two important points across all experiments (the equilibrium temperature and the point at which the ice is melted) all lend support for the repeatability of the experiment.

Prototyping and Fabrication

Prototype 1.0

In order to test our concept, the team designed a prototype using durable, inexpensive materials. The materials used for the prototype were decided upon based on their ability to insulate the cold box as best as possible. Five materials are necessary for our design. The outer shell will be constructed out of corrugated plastic. Corrugated plastic is a heavy-duty material that will provide stability and endurance to the prototype. These properties are necessary for the outer shell of the box. Corrugated plastic, although heavy-duty and stable, is actually quite light and relatively cheap. This helps the appeal to the ease of use and handling of the box, as well as the overall cost.

The next layer inside the outer shell is a one inch layer of foam insulation. There were two types of foam insulation used for this layer. Extruded polystyrene is the foam insulation that is used to cover all four walls and the top lid. It has a lower R-value than Polyisocyanurate, which is the foam insulation used for the base of the box. It was believed that the bottom of the box would be exposed to warmer temperatures than the rest of the walls, and thus demanded stronger foam insulation. As stated earlier, Polyisocyanurate was used as the insulation for the bottom panel. The bottom panel also doubles as a mount, to which the side panels and other features of the prototype are fixed. Polyisocyanurate provides the necessary insulation and thickness to serve this dual function.

Inside of the foam insulation is an inner box made of polycarbonate. We used a brand called Lexan, which is shatter resistant. The payload of vaccines rests within this box, allowing the polycarbonate to act as a thin buffer between the PCM slabs and the vaccines. The layer of polycarbonate is placed along four walls and the top lid of the box. A small gap was left between the polycarbonate and foam insulation in order for the PCM slabs to be strategically placed. The PCM slabs are the third layer of the cold box. There are five panels of PCM. A panel of PCM is used to cover each of the four walls as well as the lid of the box. These slabs are removable, and contain 2 sections: an outer panel of water, and an inner panel of our chosen PCM. This allows the cheaper, colder water to be used as a cold source, while our 5 °C PCM is used as a buffer to ensure the vaccines themselves never reach freezing temperatures. As described earlier in the methodology section, the cold box functions through the PCM melting. Once they have melted completely, and can offer no more cold storage

capability, the lid of the box is opened and the panels are removed and refrozen. The inner separate compartments for PCM and the payload allow the payload to remain in the box while the PCM slabs are recharged.

The structural integrity and thermal capacity of the box will be insured through the use of thermal adhesive. Joints between the polystyrene panels are sealed with a specialized adhesive that prevents heat from entering as well as provide structural strength. The inner polycarbonate and insulation panels will be glued in place, and then surrounded on all sides by the corrugated plastic. Figure 12 below is a CAD drawing of the prototype box, while Figure 13 demonstrates the three major structural components of the box: a) Inner Lexan layer b) middle polystyrene layer and c) outer corrugated plastic layer.

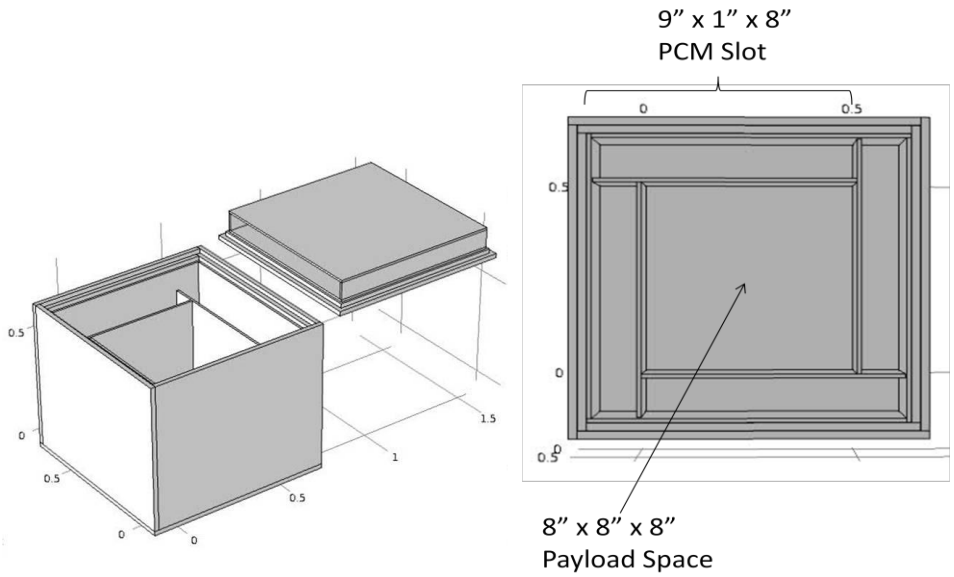


Figure 12: CAD drawing of Prototype 1.0

The end user was kept in mind during every step of the prototype’s development process. This caused the team to design a user-friendly cold box that

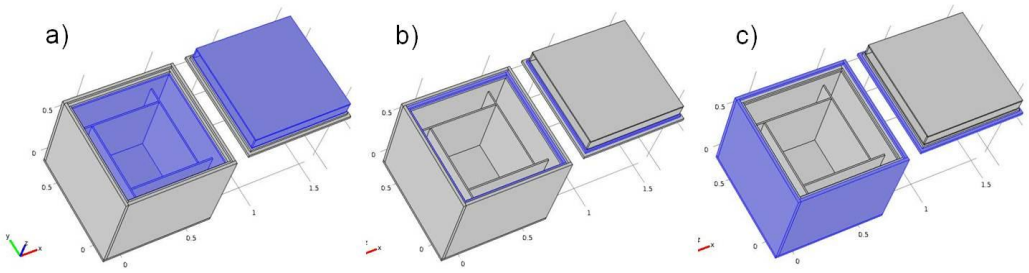


Figure 13: a) Inner Lexan b) middle polystyrene and c) outer corrugated plastic

was inexpensive, yet durable. The separated design will allow for easy operating procedures, and will prevent significant damage to the actual vaccines. Our PCM slabs will have a simple color change temperature sensor attached, which allows the user to check if the slabs are completely melted. If the PCM slabs are completely melted, the temperature will start to rise, the color will change, and the sensor will read 6 °C or higher (Figure 14). This notifies the user that the slab must be recharged in the freezer. While the PCM only requires around 6 hours to fully freeze, there is no harm if the panel is left in longer. If the PCM is removed after 24 hours, it will likely be the temperature of the freezer, which is usually around -10 °C. This is shown on the sensor, which will read temperatures below 5 °C. Since our material has a high heat of fusion, but not high heat capacity, leaving the PCM slabs in room temperature for 10 minutes will raise the temperature of the solid PCM to 5 °C, which is the phase change point. Using the sensors, the user will be able to insert the PCM

Figure 14: Color change temperature sensor

slabs are the correct temperature. Ideally, this could be 2 °C. This design will prevent any exposure to freezing temperatures as well provide simple operating instructions for the users.

Every layer used to construct the prototype was focused around the goal of maintaining a constant, cool temperature for the vaccines contained within the box. Each material used acts as some form of insulation that will reduce the rise of the internal temperature of the box, allowing for maximum use of the PCM panels before they have to be removed and refrozen. The exterior shell of corrugated plastic provides the cheap, durable material necessary for the prototype, while the remaining materials provide significant insulation for an inexpensive price. With regards to a user-friendly device, the easy removal of PCM panels and the sensors add value to this area of the prototype's goals.

Prototype 1.0 construction parameters were chosen relatively blindly. That is, the dimensions of the box, thickness of insulation and other design parameters were chose intelligently, yet ultimately arbitrarily. The methodology consisted of matching CAD and FEA results with observable results from something more complex than a simple ice box and closer to a working prototype. The compiled results of the many ice box experiments, CAD and FEA modeling, and prototype testing were then used to influence and define the design parameters of Prototype 2.0, detailed later within the RESULTS section.

Construction of Prototype 1.0

Before construction of the original prototype began, the following materials were purchased online and from the Home Depot:

Table 7: Bill of Materials for Prototype 1.0

Part Description	Cost	Qty	Total
• Polystyrene (1"x24"x96")	$9.90	2	$19.80
• Polyisocyanurate (1"x48"x96")	$29.60	1	$29.60
• Corrugated Plastic (size??)	$36.90	1	$36.90
• Lexan (Polycarbonate - .125"x18"x24")	$19.98	2	$19.98
- Lexan is shatter resistant Brand of Polycarbonate. We cut the sheets with a jigsaw, hence shatter resistance was necessary. Also, it adds resiliency to the box.			
• Construction Strength Liquid Nails	$4.97	1	$4.97
• Caulk Gun	$13.97	1	$13.97
	$115.32		*$145.20*

The construction proceeded as follows (Images of the team constructing prototype 1.0 can be seen in Appendix C at the end of this volume):

1. A corded jig-saw (Black and Decker 4.5 amp, variable speed) was used to cut the Lexan into the panels that would comprise the inner payload chamber. Panels were cut 9" wide by 8" high. A ⅛" x 4" notch was cut at the lower left of each panel, and a second ⅛" x 4" slot was cut 1" in from the top right edge of each panel. Four panels were cut as such and then fitted together by placing one panel's notch into an adjacent panels slot at right angles. As such, the four panels make an 8" x 8" x 8" cube of space to serve as the payload space.
2. A circular saw (Ryobi 12 amp, 7 ¼" dia.) was used to cut the Polyisocyanurate into an 11" x 11" square, to serve as the insulation at the base of the box.
3. The Lexan cube was then centered on the Polyisocyanurate square, and pressure was applied to cause the cube to sink into the Polyisocyanurate. The total dimensional width of the cube was 9" x 9", so that one inch remained of

Polyisocyanurate on each side of the cube. This formed the main frame of the prototype.

4. The circular saw was then used to cut the Polystyrene into four (4) 1” x 11” x 9” sheets. The sheets, each an inch in width, were then glued vertically along the one (1) inch border on the base Polyisocyanurate, to create walls.
5. At this point, all inner and outer joints of the box were sealed with a bead of glue smoothed by a finger. This created a thermal seal in each joint gap and also added structural integrity to the box.
6. The lid was created from a second similarly dimensioned piece of Polyisocyanurate. On top of that, a 1” x 9” x 9” chamber was created from Lexan. The chamber was closed on five sides; one side was left open to be able to slot PCM slabs in and out. When inverted, this lid fit snugly into the top of the box created in steps 1-4.
7. Lastly, the corrugated plastic was cut and folded to encompass the box. The plastic was glued onto the box, and held in place through a combination of butterfly clips, and mechanical clamps until dry. The finished box (lid in bottom left) can be seen below in Figure 15.

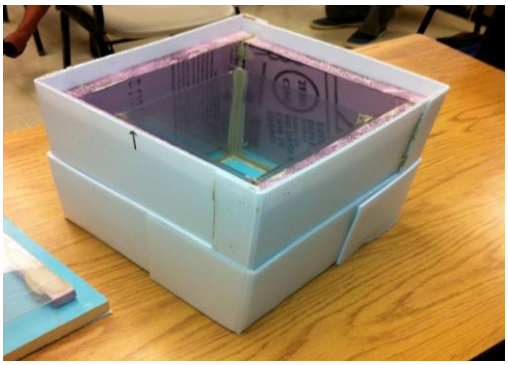


Figure 15: Finalize Prototype 1.0

Chapter 4: Results

Characterization of Phase Change Materials

The analysis was performed with high initial ramp rates on water. The high ramp rates led to large initial values of error for the measured melting temperature. To investigate the discrepancy between the literature value of 0 $^{\circ}$C and the measured values, slower ramp rates were used. A similar analysis technique was used to elucidate the melting temperature of Phase 5 ™, cited as 5 $^{\circ}$C. Data describing our characterization of Phase 5 ™ and deionized water is displayed below in Figure 16. The results indicated that the melting temperature accuracy was significantly affected by the rate at which the material was heated (ramp rate). The temperature readouts for the melting point were plotted against the ramp rate to predict the melting temperature; it appears that the regression lines fit this data (R2 values of 0.79 and 0.77 for Phase 5 ™ and water, respectively), and the y-intercepts of regression lines accurately predict the theoretical melting temperature, based on comparison with literature values of ~5 ºC for Phase 5 ™ and 0 ºC for water.

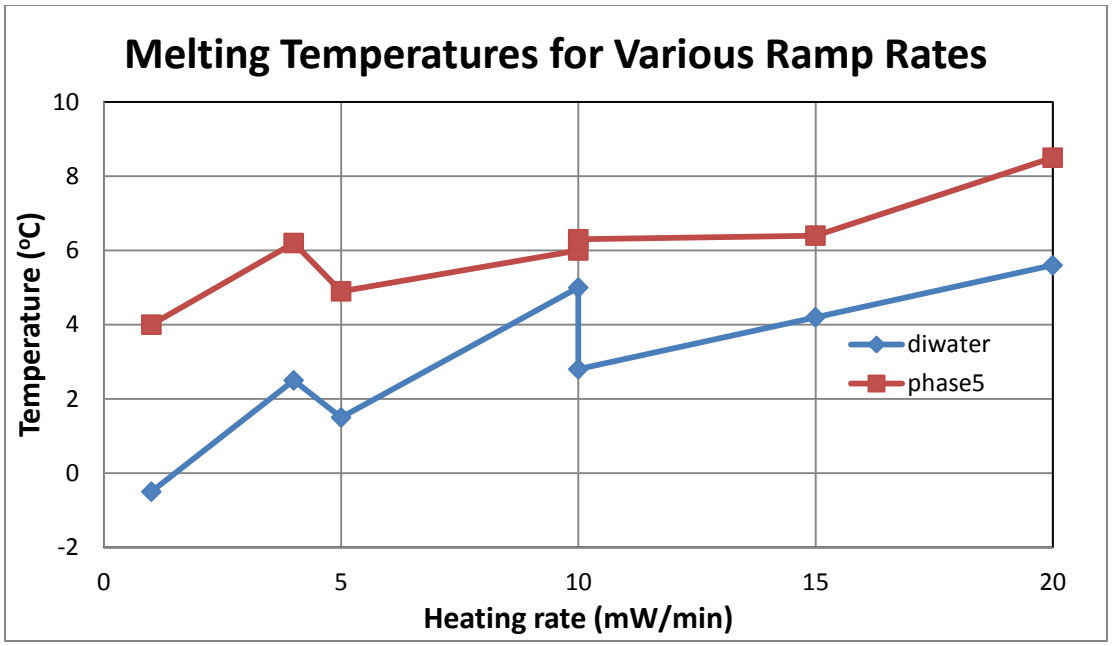


Figure 16: Characterization of water and Phase 5 ™. Melting temperatures vs. heating rate for water (blue diamonds) and Phase 5 ™ (red squares). Lower heating rates resulted in more accurate melting temperatures compared to literature values of 0 ºC and 5 ºC for water and Phase 5 ™, respectively.

The insights into the higher accuracy at lower ramp rates guided our proposed characterization of new materials. Other materials that were characterized include: Pure temp, AcuTemp and Tetrahydrofuran clathrate of various concentrations. Tetrahydrofuran clathrate showed promise in the literature as it is mixed into 1:17 molar ratio with water (Tombari, 2006). However, when prepared as prescribed in the literature, and additional solutions of 1:17.5 and 1:16.5, the resulting solution exhibited none of the predicted phase change properties observed in the literature values as evident by Figure 17 through Figure 19. The peak energy inputs were at temperatures close to zero instead of the cited 2-8 $^{\circ}$C; thus, it was disregarded as a candidate.

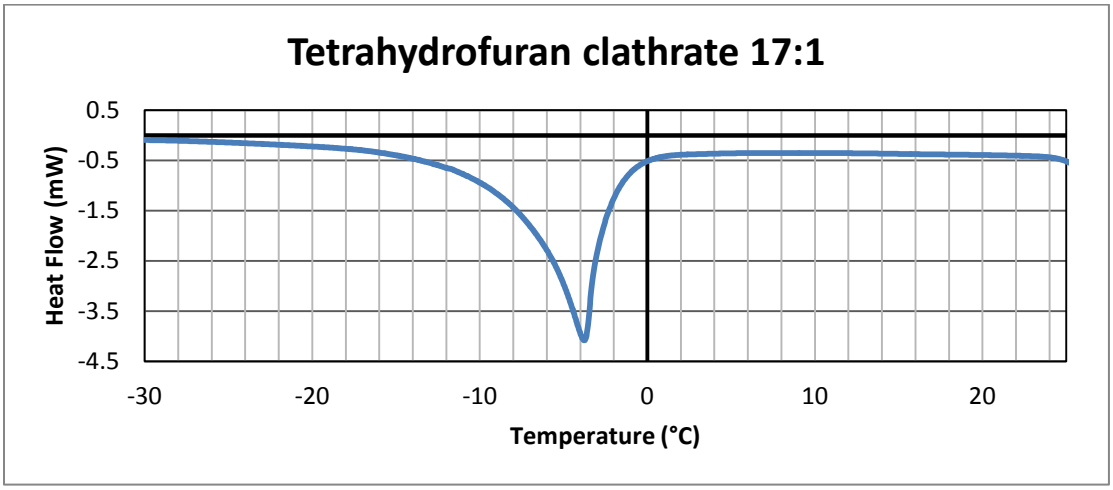


Figure 17: Tetrahydrofuran clathrate 17:1 ramp rate versus temperature

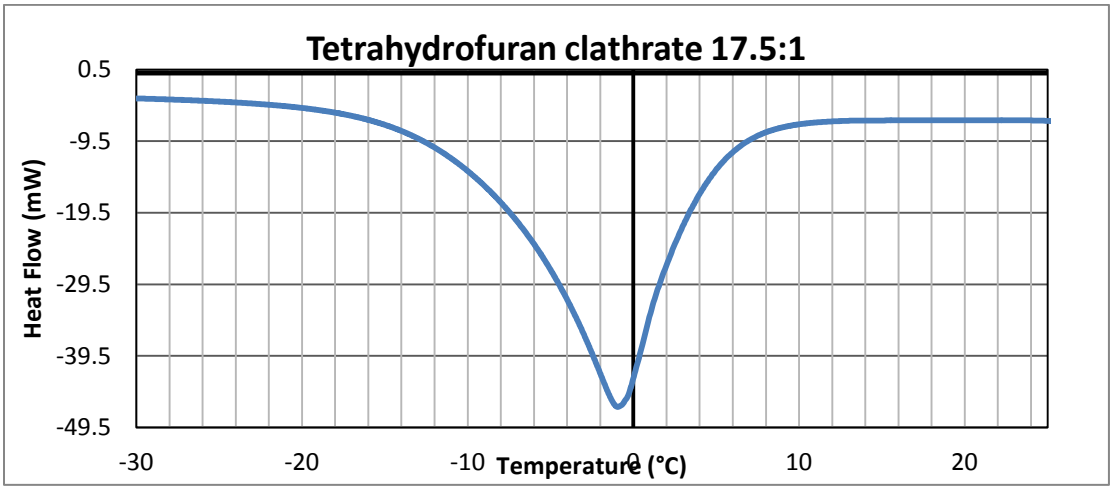


Figure 18: Tetrahydrofuran clathrate 17.5:1 ramp rate versus temperature

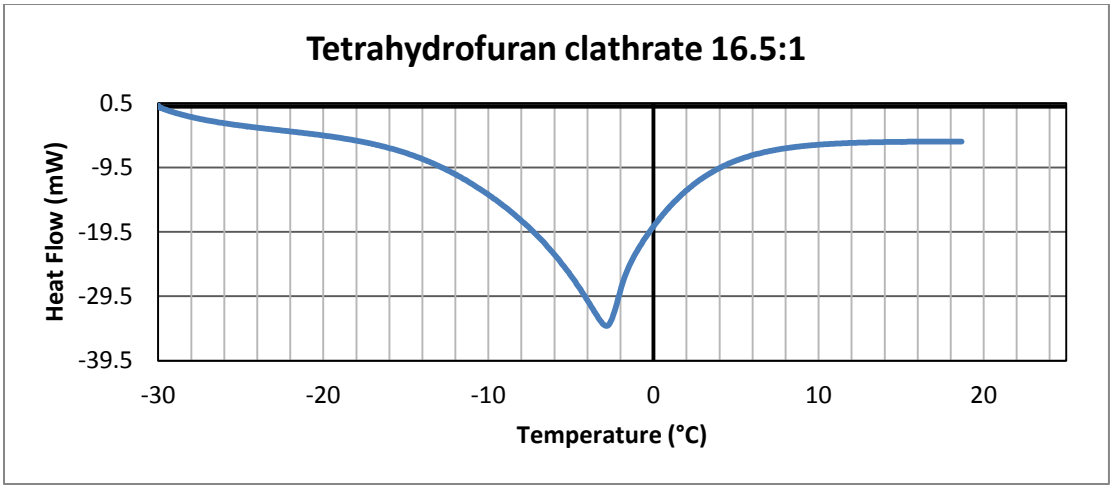


Figure 19: Tetrahydrofuran clathrate 16.5:1 ramp rate versus temperature

Heats of fusion were calculated to be 333 J/g for water and 178 J/g for Phase 5 ™ , not taking into account the incomplete 20 °C/min runs. The experimental procedure was applied to Pure temp and AcuTemp to calculate the heats of fusion as well. PureTemp was measured to be 154 J/g with a melting temperature of 2.1 °C. AcuTemp however was discovered to be a pulp substance soaked in a fluid. When the fluid was tested for thermal properties the resulting curve was detected, Figure 20. The data indicates a strange melting profile in which there is one large peak at 7 °C and two smaller shoulders at -5 °C and 9 °C.

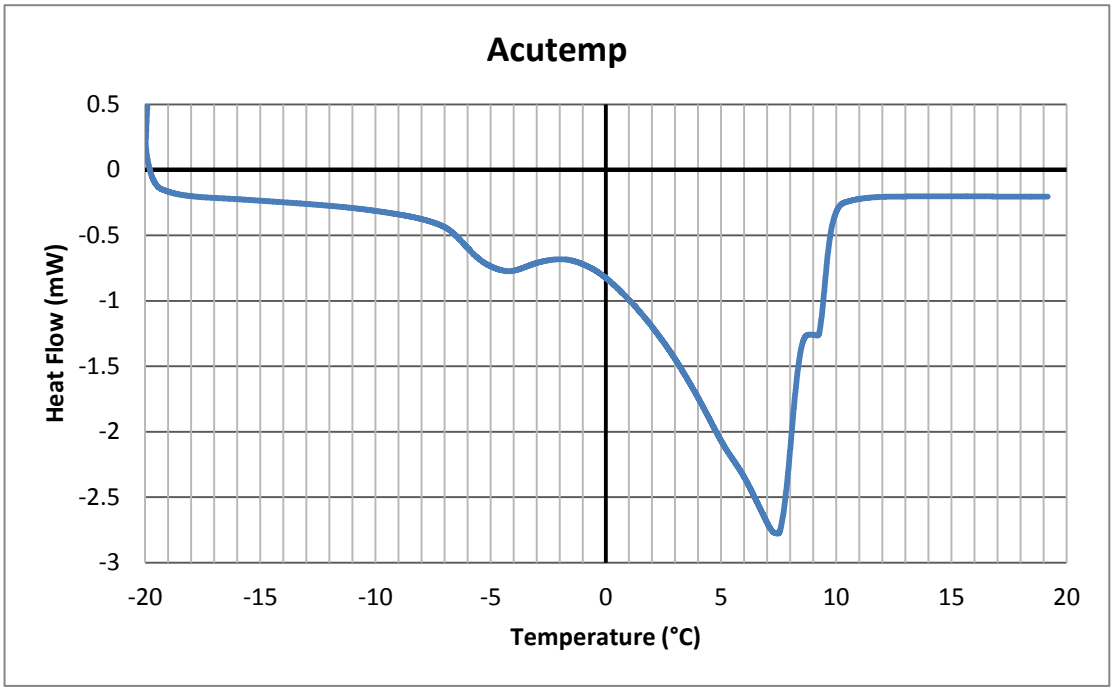


Figure 20: AcuTemp ramp rate versus temperature

The calculated latent heat for the entire melting curve was 124 J/g. Melting temperatures and heats of fusion calculated from these experiments were then input into theoretical models described below. This indicates that water as expected has the highest latent heat, followed by Phase 5 ™ then PureTemp and finally AcuTemp. The results show that Phase 5 ™ is the most desirable PCM because it has a high enough melting point 5 ºC and the highest heat of fusion of the PCMs tested as seen in Table 8.

Table 8: Table of measured PCMs

PCM measured	Latent heat (J/g)	Melting Temperature (ºC)
Tetrahydrofuran clathrate	No Result	No Result
Water	333	0
Phase 5 ™	178	5
PureTemp	154	2.1
AcuTemp	124	-2 -- 7

Ice Box Experiments

The first six sets of measurements for the ice box system are displayed in the following series of figures (

Data Set Label	*Location in Ice Box Model*
Channel 1	*Center of bottom of storage, above the ice layer (next to shelf if present)*
Channel 2	*Center of top, between the insulation and ice layers*
Channel 3	*Top corner of storage*
Channel 4	*Center of storage space (air), (on top of ice shelf if present)*
Channel 5	*Center of upper quadrant of storage*
Channel 6	*Midpoint of side along bottom of storage, above the ice layer*
Channel 7	*Center of side panel, between the insulation and ice layers*
Channel 8	*External Probe*

Figure 21 through Figure 26). The data represents two cubes sizes with side lengths of 9.5” and 13.5” with 1.4 kg and 6 kg respectively of ice as the PCM. The three experiments performed on each are the ones in which all sides are evenly covered in ice or evenly covered in ice with a PCM shelf that is either horizontal or vertical. The following diagrams illustrate the probe and PCM configurations. The figure’s coloring corresponds with the following shown in Table 9:

Table 9: Probe and PCM configurations for ice box experiments

Data Set Label	*Location in Ice Box Model*
Channel 1	*Center of bottom of storage, above the ice layer (next to shelf if present)*
Channel 2	*Center of top, between the insulation and ice layers*
Channel 3	*Top corner of storage*
Channel 4	*Center of storage space (air), (on top of ice shelf if present)*
Channel 5	*Center of upper quadrant of storage*
Channel 6	*Midpoint of side along bottom of storage, above the ice layer*
Channel 7	*Center of side panel, between the insulation and ice layers*
Channel 8	*External Probe*

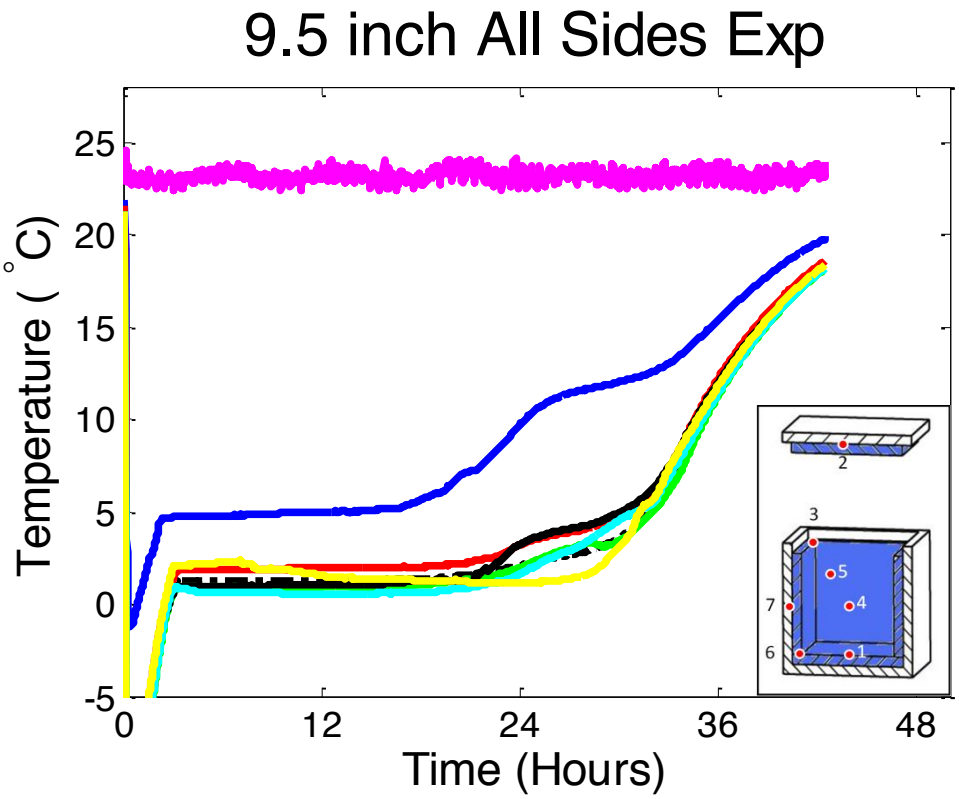


Figure 21: Ice Box Experiments – All sides with even layer of ice

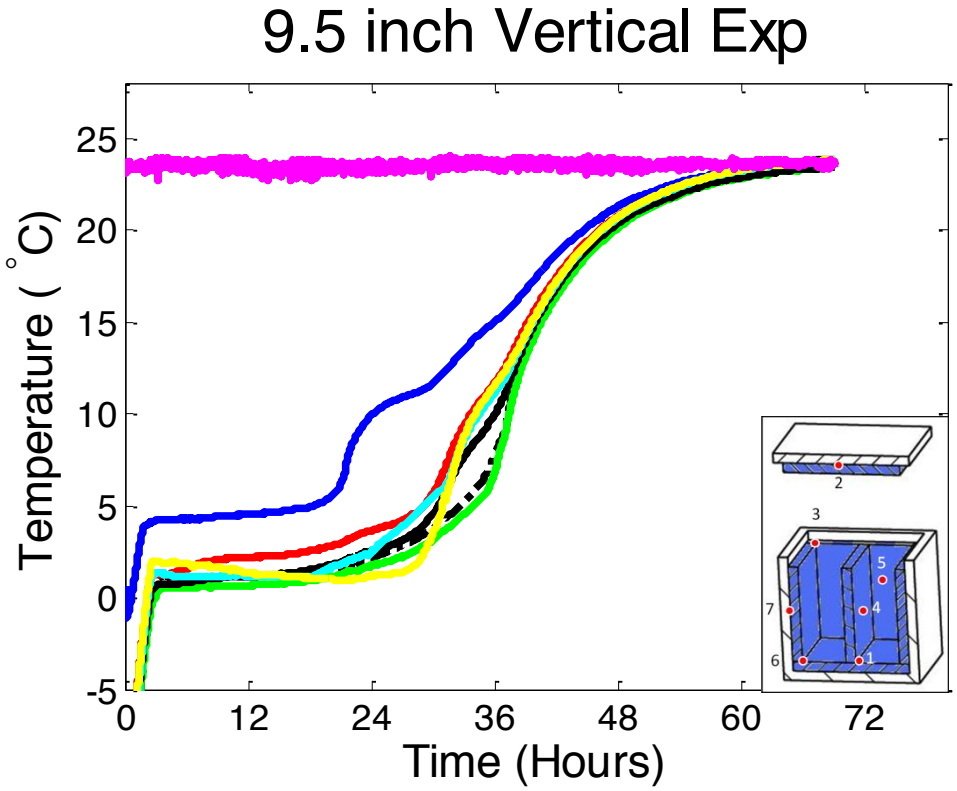


Figure 22: Ice Box Experiments - All sides with even layer of ice and vertical shelf

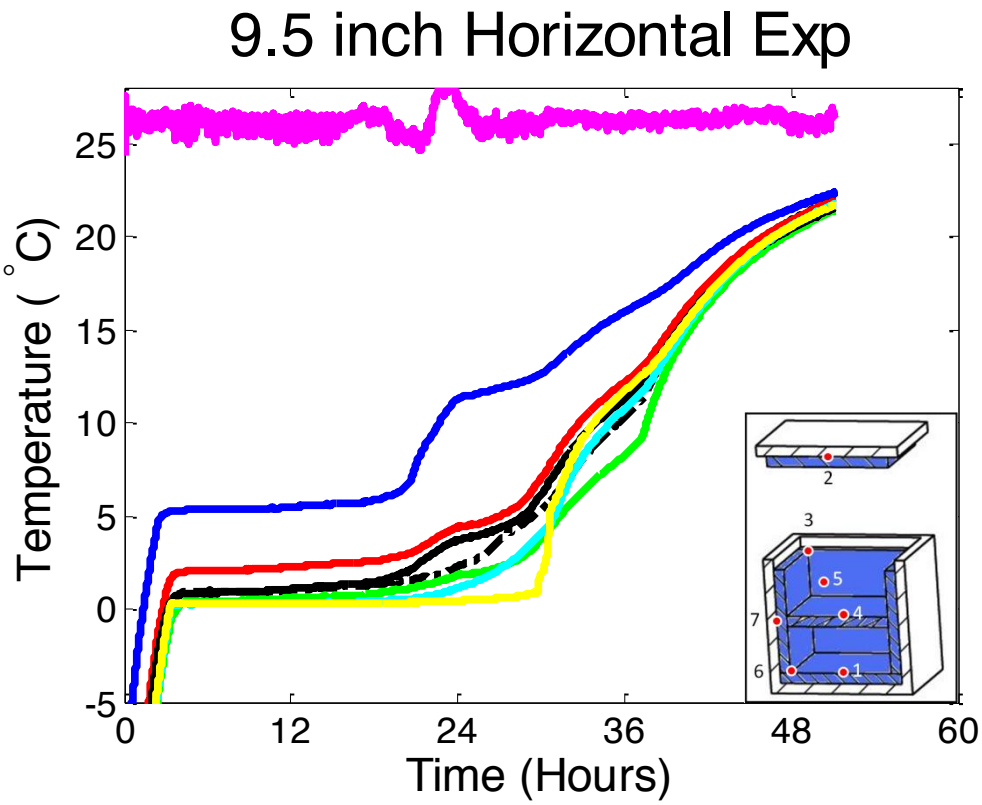


Figure 23: Ice Box Experiments - All sides with even layer of ice and horizontal shelf

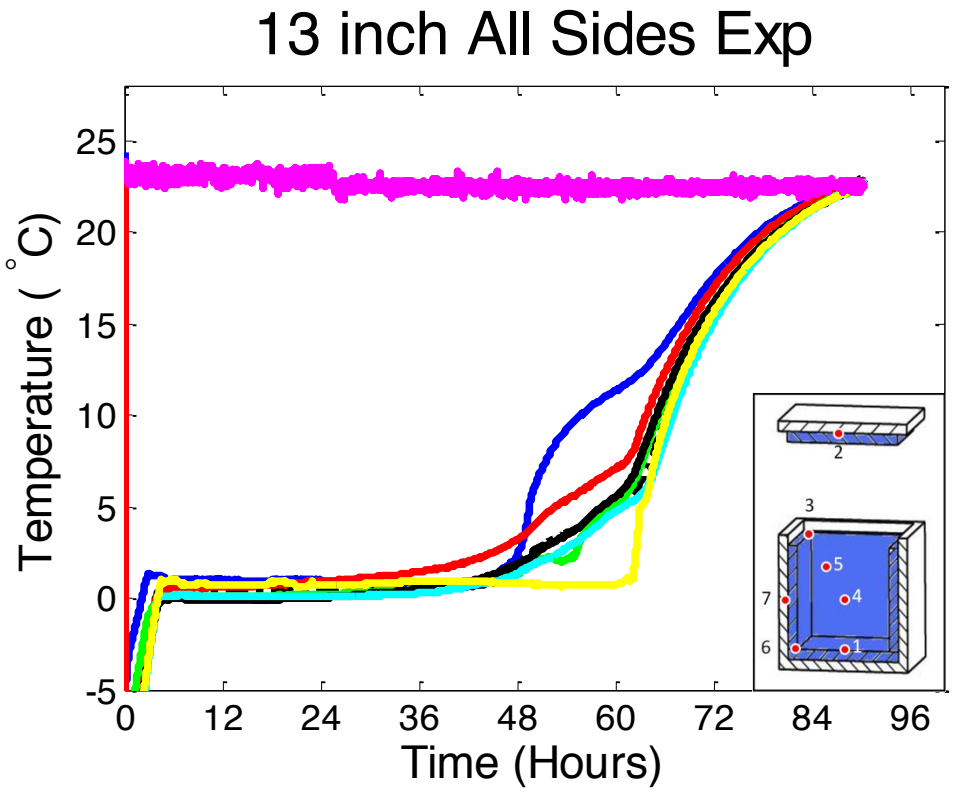


Figure 24: Ice Box Experiments - All sides with even layer of ice

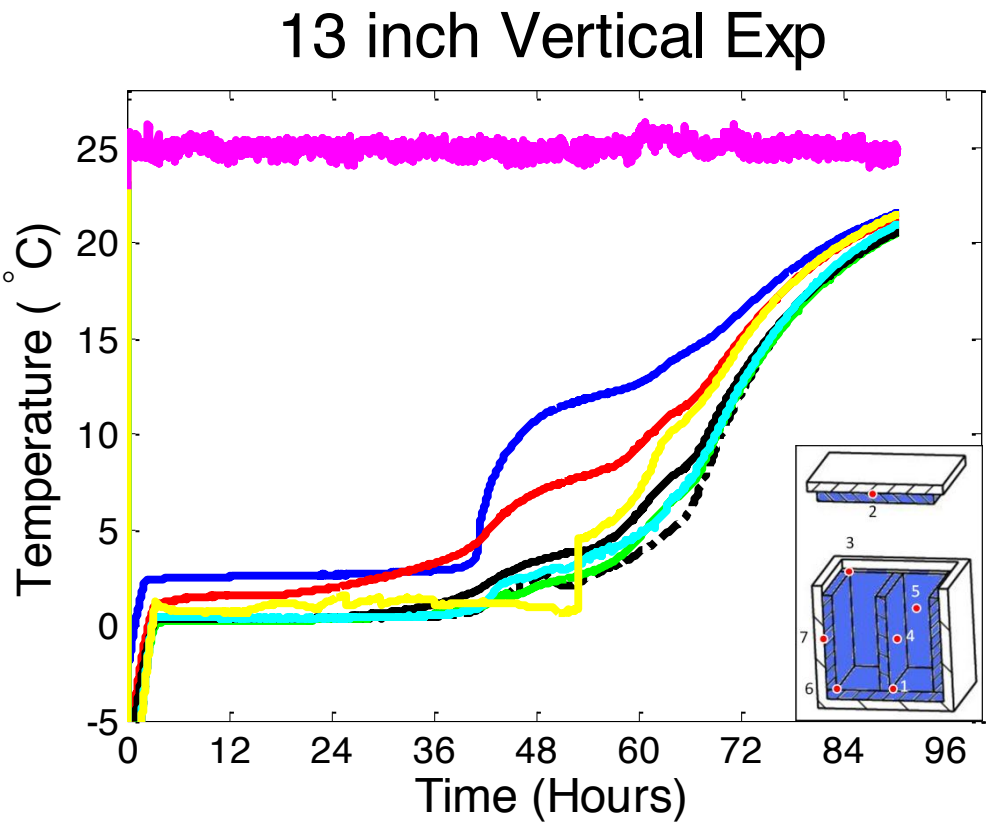


Figure 25: Ice Box Experiments - All sides with even layer of ice and vertical shelf

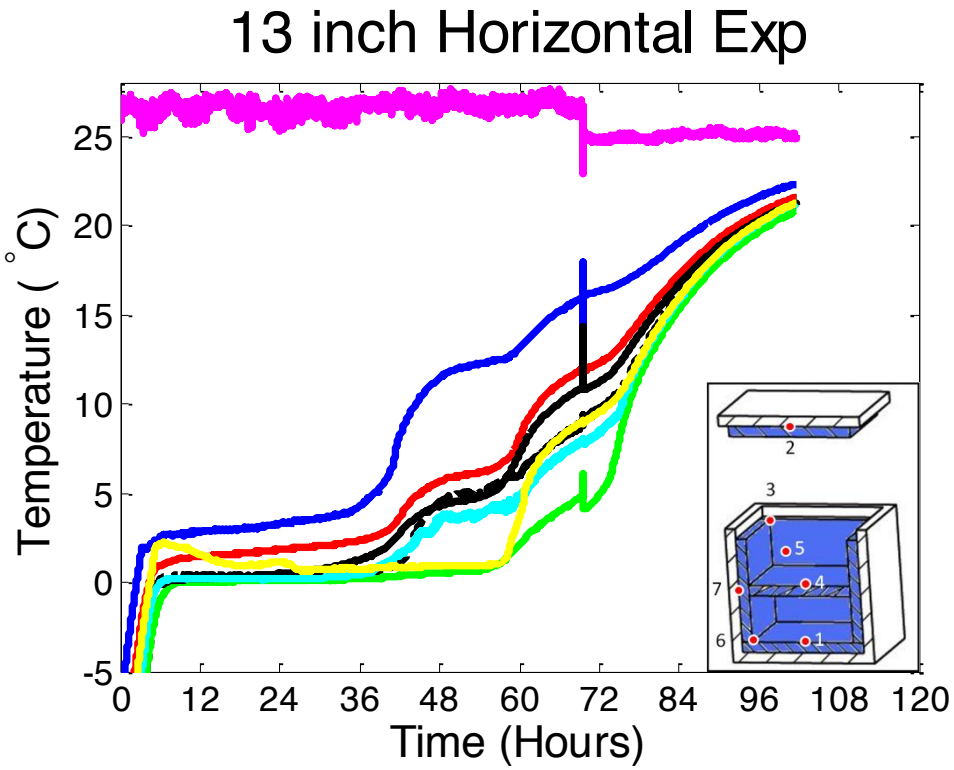


Figure 26: Ice Box Experiments - All sides with even layer of ice and vertical shelf

Although it is difficult to follow the results initially, a few key pieces of physical insight can be extracted from the data. Each graph exhibits some of the expected behaviors. The room temperature probes (Channel 8) were similar in behavior, holding steady at temperatures ranging from 24-27 °C. For all of the samples' probes within the icebox (Channels 1-7), the data recording began at a temperature below zero. Initial sampling indicates a rapid increase in temperature represented by a steep curve on the graph. Each probe then settles at a quasi-steady state value for an extended period of time. In some of the experiments, the temperature rises more quickly to reach a second quasi-steady state value. Finally, all of the internal probes rise in temperature towards the ambient value. The steepness of the approach varies, but it is flatter than the slope of the early temperature increase.

The first major feature in the graph is the rise to the initial steady state. The slope is steep and levels rapidly as evident by the graphs. This validates several theories regarding the operation of an icebox system. The steepness indicates that the driving force, the higher ambient temperature, is far away. Additionally, this signals that the physical properties which make energy storage per degree change of ice is low compared to the energy of storage for melting the same mass of ice or heating the same mass of ice once in liquid form may play a role in the rapid heating. This is illustrated with Figure 27.

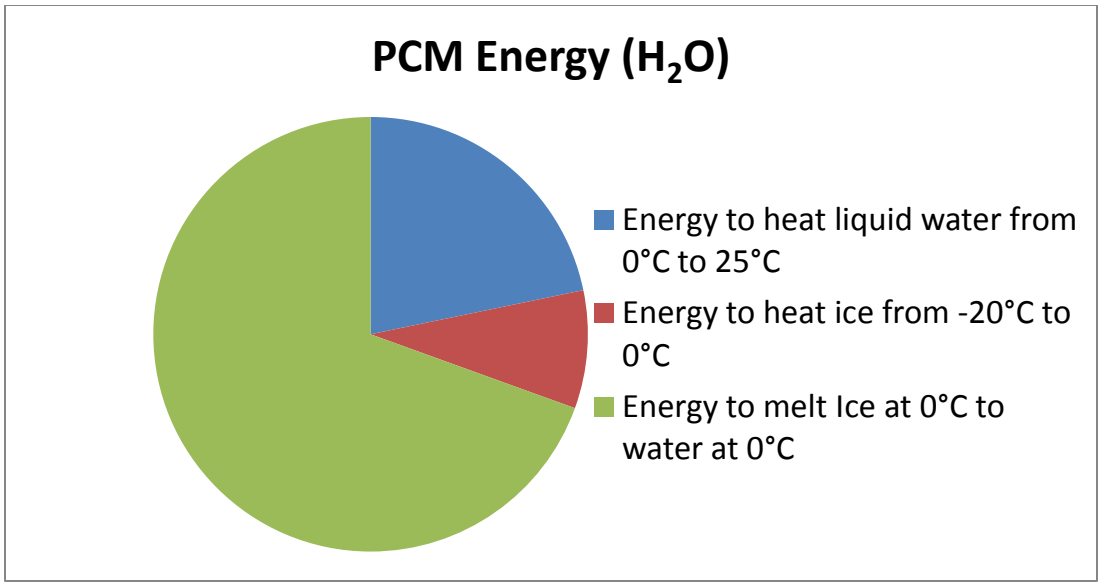


Figure 27: Energy Comparison for H_2O as PCM

It is very clear that the energy adsorption for changing similar temperatures quantities varies vastly between a sample of ice and sample of water. It takes significantly more energy to heat the water from 0 °C to 25 °C than ice from -20 °C to 0 °C. The chart shows that the temperature flattens out for a significant time period, during which we predict that the ice is melting. The energy to melt the ice is much greater than the energy to change the temperature of the system. Ice melts at a constant temperature of 0 °C, which would show up on the data as prolonged flat portions at or near 0 °C. We believe that the system is of the following pattern; initially rapid heat exchange as the inserted ice moves to its melting temperature, a melting phase during which the temperature holds near 0 °C, and finally a heating phase as the system climbs towards room temperature.

With the basic form of the probe measurements understood, an analysis between individual and group trends can be performed. The most obvious difference is in the 0.241 meter box versus 0.330 meter operating conditions. The smaller size

lasted a considerably shorter time period where approximately 2000 minutes elapsed before the system was above 8 ºC, whereas for the 0.330 meter box, nearly 4000 minutes on average elapsed before all the probes were above 8 °C. Because the systems are different sizes and different relative compositions by volume of insulation storage space and water, we cannot use relative values to compare the results. Qualitative differences are the only data that can be extracted directly. However the two box systems behave almost entirely the same with similar trends developing in each. This is likely due to the extent of the similarity between the two.

Within the sets of different geometries, overall certain trends can be observed. The external probe, channel 8, measured temperature consistently within a 0.2 °C range with few major fluctuations; this allows for a simple assumption to be made, that the driving force was relatively constant throughout experimentation. The remaining probes show typical trends throughout different geometries and box sizes. Channel 2, the probe outside of the topmost ice pack, was consistently higher in temperature than the other probes, rising more quickly during the phase transition. It mirrored the other probes' temperature profiles but was a few degrees higher in temperature. This is likely due to its placement outside the ice surrounding the storage area. Outside was only shielded by insulation, and thus at the edge of the temperature gradient developed between the ice and the air. Channel 7, the probe which was placed on a side ice pack, represents a good gauge of how quickly the side ice packs have fully melted. It should therefore be noted that the probe typically lasted longer at low temperatures than the other probes on all sides of the experiments. In the experiments with the vertical and horizontal ice pack, the probe increased in

temperature more closely to the other probes located in the storage chamber and elsewhere, indicating the center ice pack plays a role in cooling the system after the outside ice packs have fully or partially melted. The probes located in the storage chamber, channels 6, 5, 1, and 3, all exhibited similar behavior. Their temperatures were typically within a few degrees of each other, dictated by the proximity to an ice pack, and followed identical trends. It should be noted that the warmest one, channel 3, is located in the top corner of the vaccine storage chamber. The temperature separation from other similar probes was larger in the experiments with a shelf. This is most likely generated because it is the furthest probe from the shelf in either configuration and is thus the warmest of the probes once the outer shell of ice has melted.

Geometry plays a key role in creating the largest differences from prediction. These can be observed when the steady state temperature is above 0 °C and the smaller shorter quasi-steady states occurring at even higher temperatures. This can be seen in the differences between the even covering of ice and the horizontal and vertical shelf configurations. The comparison is consistent for both small and large box sizes. All sides of the experiment acted as expected. The vertical shelf, however, leaves the steady state quickly to reach a second quasi-steady state which can be observed as the large shoulder on the graph. After this short halt, the temperature begins to rise again. However, the probe corresponding to the side locations away from the vertical ice pack begins to rise in temperature faster. Probes 4 and 5 become the coolest in the system as they are closest to the center ice pack. For the horizontal setups, a similar phenomenon is observed, though the temperature difference between

the probes is less pronounced. The system experiences two quasi-steady states instead of the one observed with the vertical configuration. The result of these differences is that although the time spent from 0-8 °C on average is the same between each configuration, the average temperature experienced is much higher for the systems with shelves. This is due to the prolonged rise in temperature caused by the shoulders, which cut short the main steady state near 0 °C. These differences are key features to try to capture with the model: the similar time of steady state between configurations, the time spent from 0-8 °C, and the different rate or times at which various probes leave the steady state to rise towards room temperature.

CAD and FEA Modeling

3-Dimensial Modeling

Upon solving each FEA model, time-temperature data was generated using time-history post processing. For select nodes that corresponded to thermocouple lead locations in the ice box experiments, we could extract the degree of freedom solution and the nodal temperature, at each recorded sub step. From this, we could either graph the data directly in the FEA software, or export the data into a text file to be converted into an Excel spreadsheet and graph.

In attempting to refine the thermal conductivity (k) value for the models, Figure 28 through Figure 31 were generated from the 9.5-in sided box with horizontal ice shelf, and Figure 32 through Figure 35 were generated from the 13-in sided box with ice perimeter.

Table 10: Data set label denotation for the 9.5-in sided box with *horizontal ice shelf model*.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

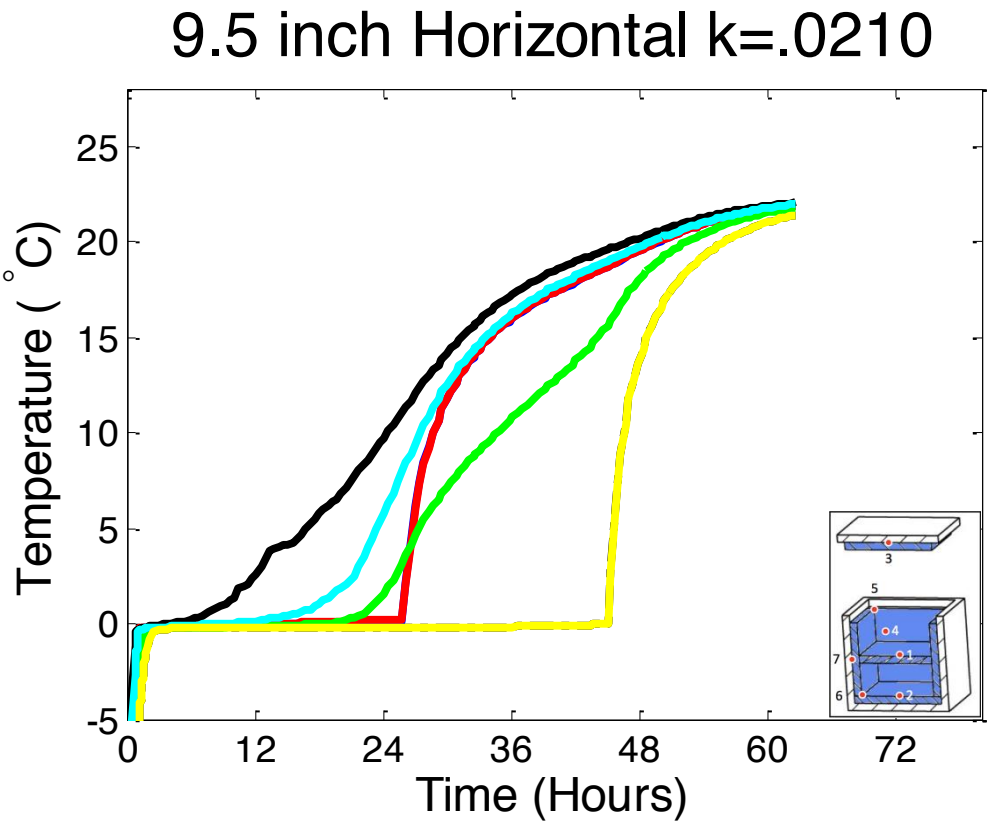


Figure 28: k-value refinement: 9.5-in sided box, horizontal ice shelf, k *= 0.0210 W/m-K*

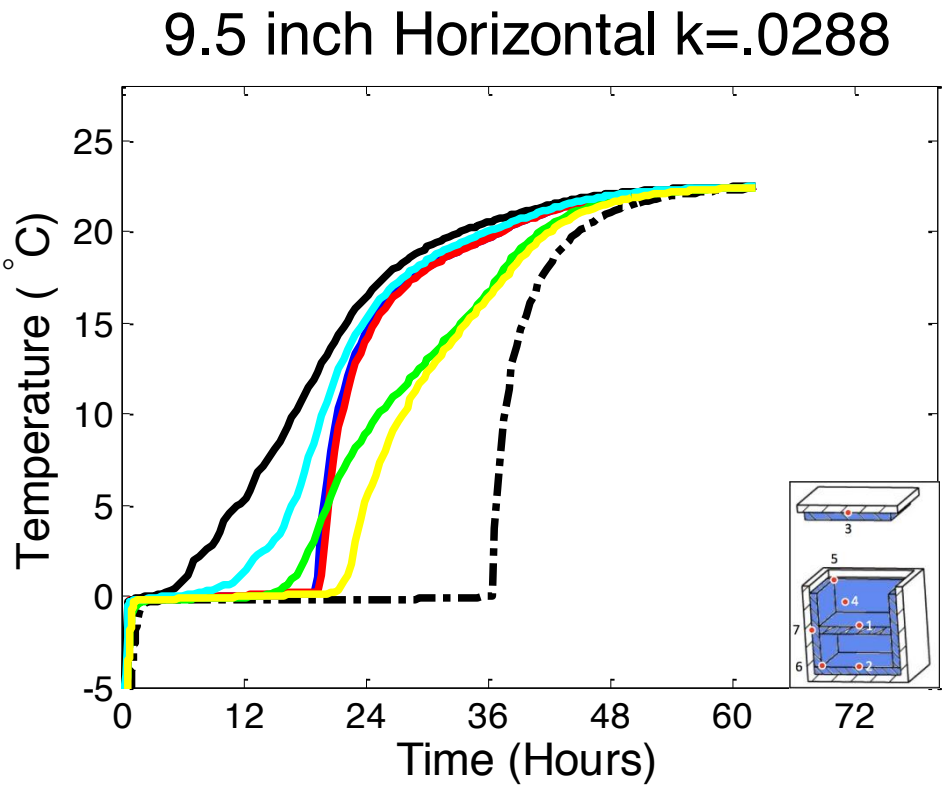


Figure 29: k-value refinement: 9.5-in sided box, horizontal ice shelf, *k = 0.0288 W/m-K*

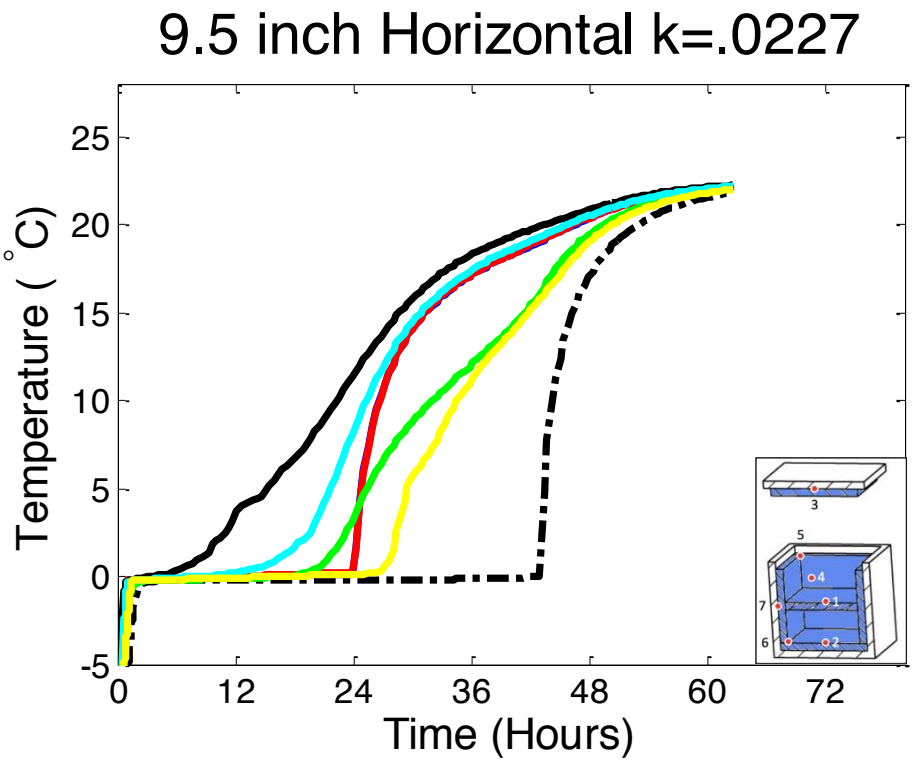


Figure 30: k-value refinement: 9.5-in sided box, horizontal ice shelf, *k = 0.0227 W/m-K*

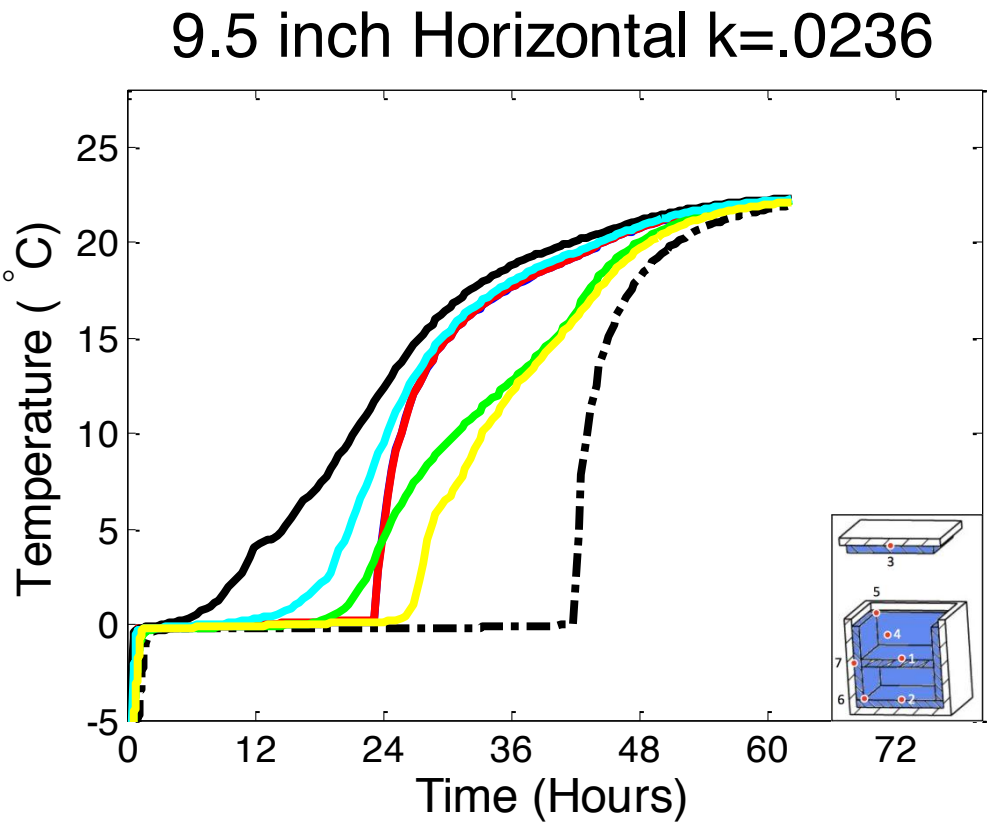


Figure 31: k-value refinement: 9.5-in sided box, horizontal ice shelf, *k = 0.0236 W/m-K*

Table 11: Data set label denotation for the 13-in sided box with ice perimeter model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

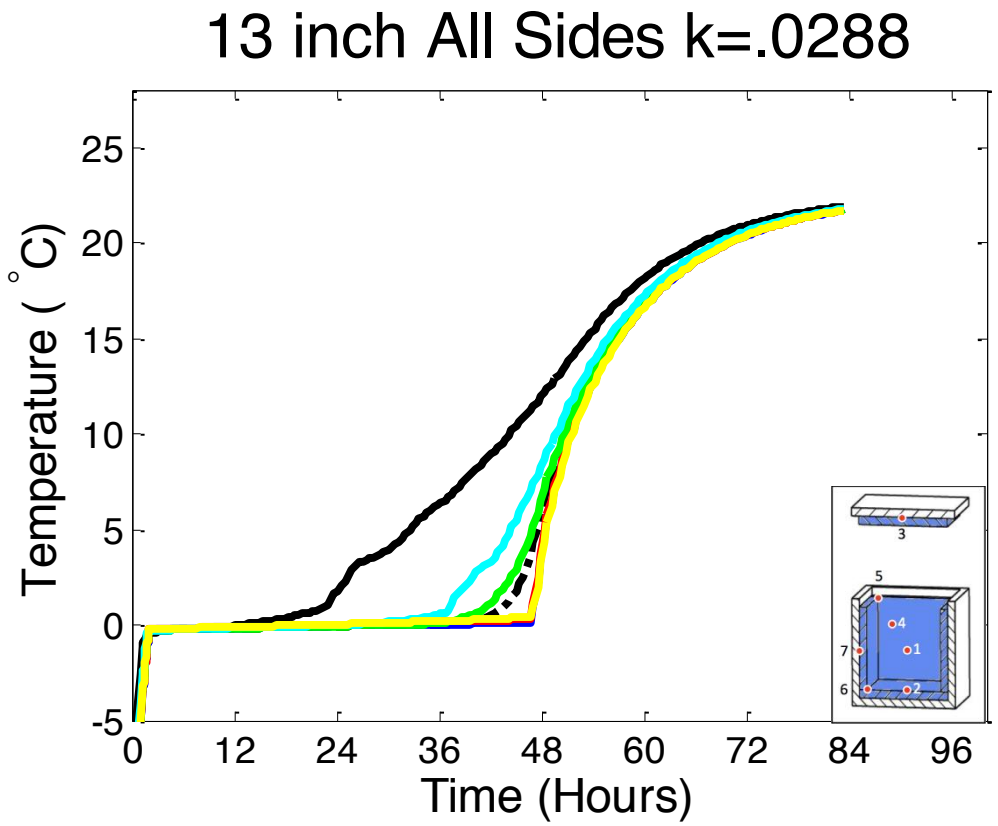


Figure 32: k-value refinement: 13-in sided box, all sides ice, *k = 0.0288 W/m-K*

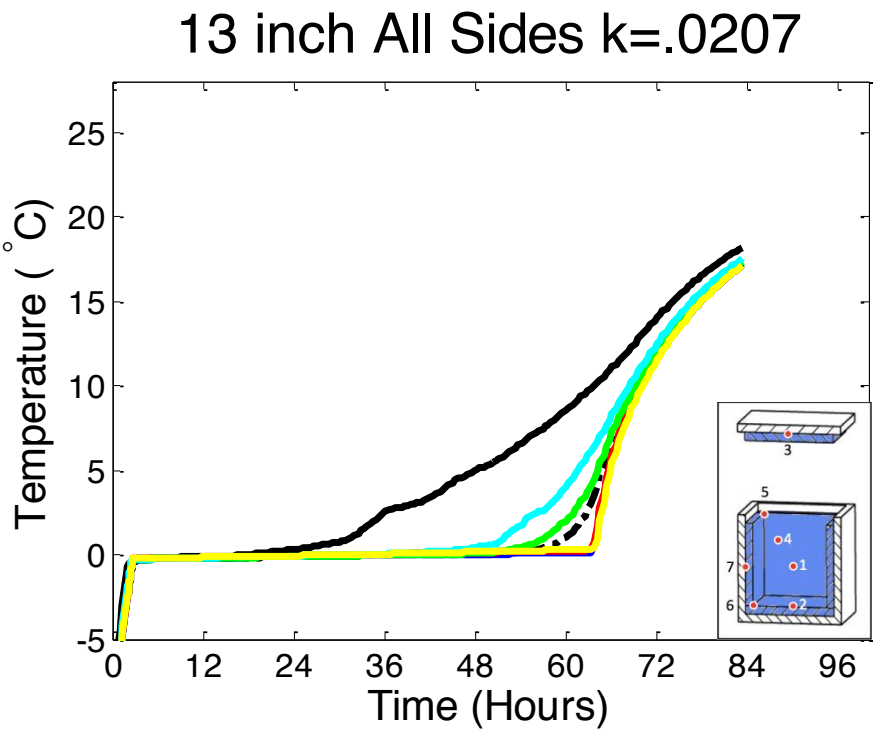


Figure 33: k-value refinement: 13-in sided box, all sides ice, k = *0.0207 W/m-K*

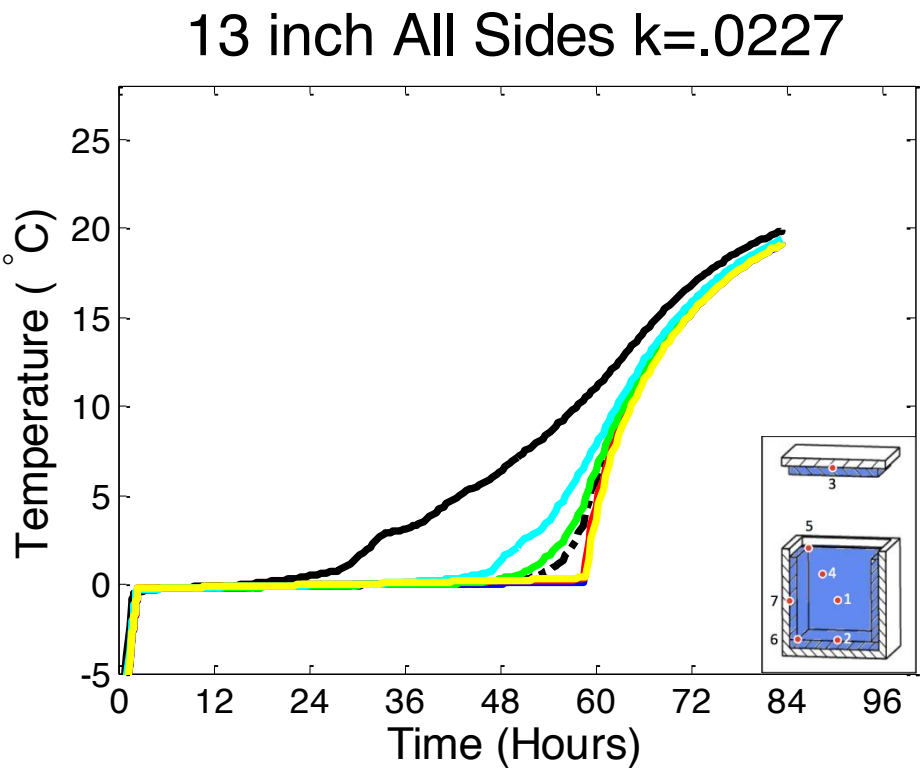


Figure 34: k-value refinement: 13-in sided box, all sides ice, *k = 0.0227 W/m-K*

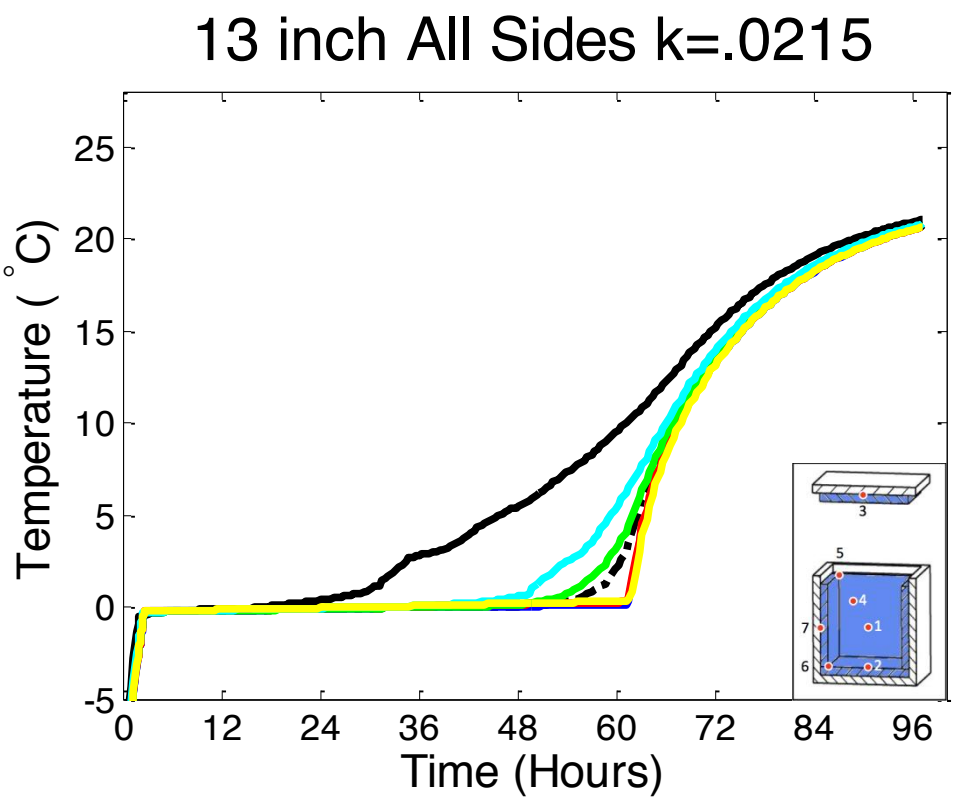


Figure 35: k-value refinement: 13-in sided box, all sides ice, *k = 0.0215 W/m-K*

As can be seen from each graph set of varying thermal conductivity, the temperature distribution through the box remains the same, but the duration of cold storage decreased as the k-value increased.

The following pages detail the results from the various PCM geometries in the 9.5-in and 13-in sided ice box models with the modified thermal conductivity, k = 0.0227 W/m-K. The volume of ice for the 9.5-in models was 85.8 in^3 (0.001406 m^3) with vaccine compartment side length of 7.5 in (0.1905 m). The volume of ice for the 13-in models was 393.4 in^3 (0.006447 m^3) with vaccine compartment side length of 11 in (0.2794 m). The cold duration of storage was defined as the average amount of time from the data sets for temperature to go from the lower bound of melting (-0.25 °C) to the upper bound of ideal vaccine storage (8 °C).

- 9.5-in Sided Model: All Sides

Table 12: Data set label denotation for the 9.5-in sided box with ice perimeter model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

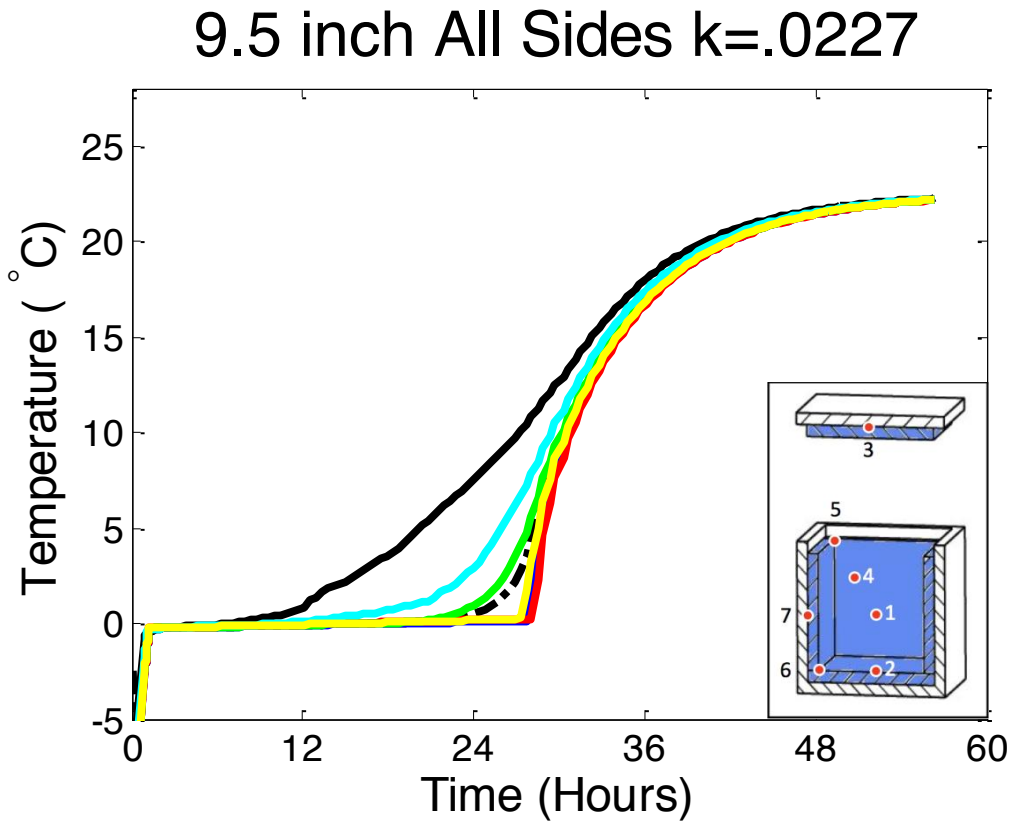


Figure 36: 9.5-in sided box, all sides ice. Inset: Cutaway of experiment (blue = ice locations)

Ice thickness:

$$0.001406m^3 = (0.1905m)^3 - (0.1905m - 2t_{ice})^3 \Rightarrow t_{ice} = 0.006950m$$

Cold duration of storage: 1640 min ≈ 27.33 hr

Analysis: This model maintained an even temperature distribution throughout the box for the duration of melting, while the box was quickly brought to thermal equilibrium after the melting. The first point to reach 8 °C was the corner probe, which was the furthest away from the center of the compartment.

- 9.5-in Sided Model: All Sides, No Bottom

Table 13: Data set label denotation for the 9.5-in sided box with all sides ice except the bottom model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

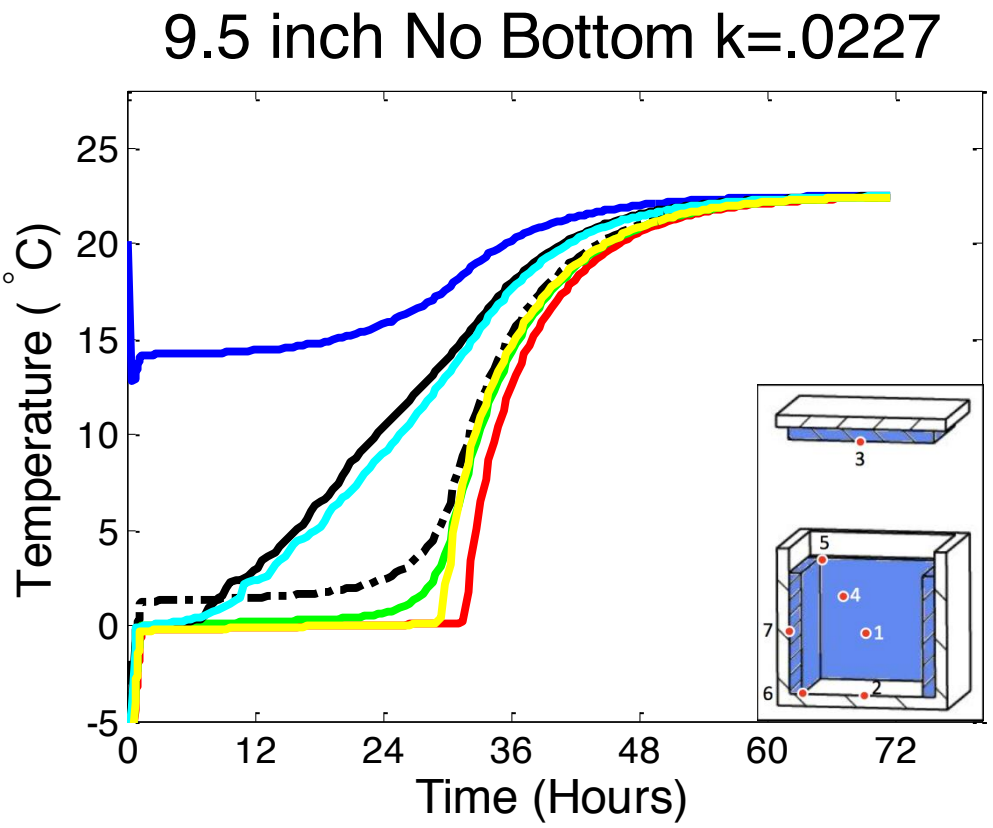


Figure 37: 9.5-in sided box, all sides ice except bottom. Inset: Cutaway of experiment (blue = ice locations)

Ice thickness:

$$0.001406m^3 = (0.1905m)^3 - (0.1905m - t_{ice})(0.1905m - 2t_{ice}) \Rightarrow t_{ice} = 0.008317m$$

Cold duration of storage: 1397 min ≈ 23.3 hr

Analysis: The points not along the bottom maintained temperature stability for the relatively same duration as the all sides model. There is a drastic difference in temperature for the points along the bottom, though this is assumed to be an extreme case given that the inner compartment is filled with a low-density substance.

- 9.5-in Sided Model: Horizontal Shelf

Table 14: Data set label denotation for the 9.5-in sided box with horizontal ice shelf model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

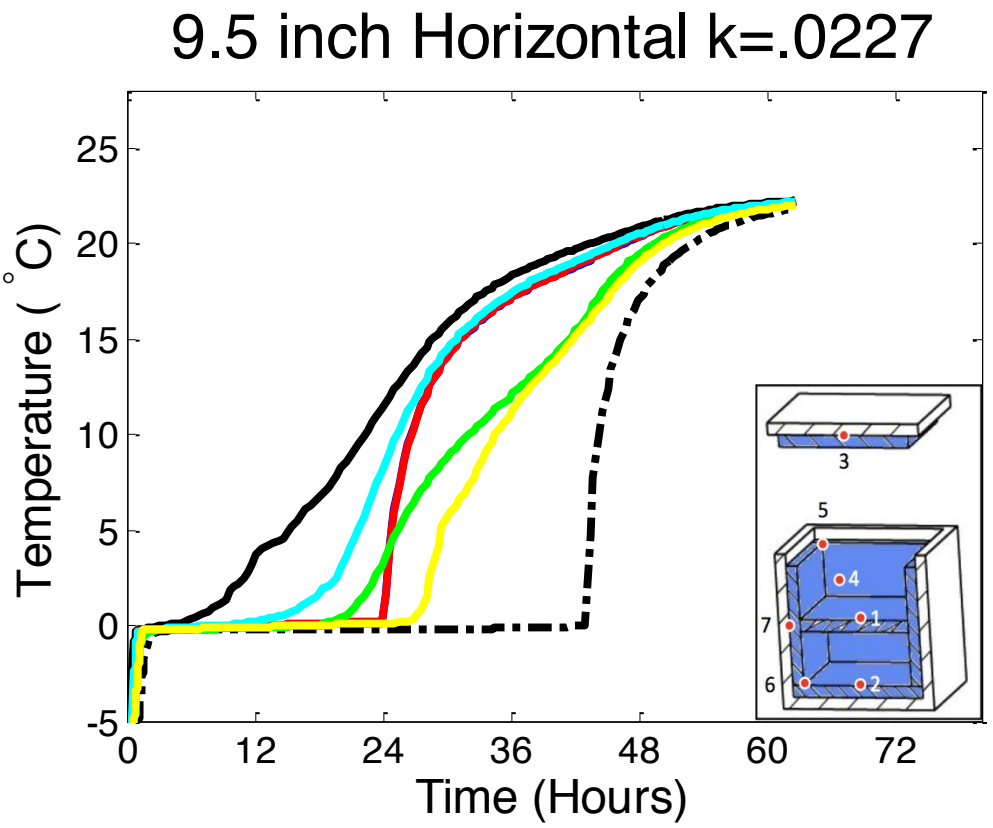


Figure 38: 9.5-in sided box, all sides ice with horizontal shelf. Inset: Cutaway of experiment (blue = ice locations)

Ice thickness:

$.001406m^3 = (0.1905m)^3 - (0.1905m - 2t_{ice})^3 + t_{ice}(0.1905m - 2t_{ice})\text{^}2 \Rightarrow t_{ice} = .005922m$

Cold duration of storage: 1633 min ≈ 27.2 hr

Analysis: An uneven duration of melting is observed in this model, where the outer ice panels melt much faster than the central shelf (skewing the cold duration to be longer). The cold duration for the outside panels is less than in the previous two models.

- 9.5-in Sided Model: Vertical Shelf

Table 15: Data set label denotation for the 9.5-in sided box with all sides and vertical ice shelf model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

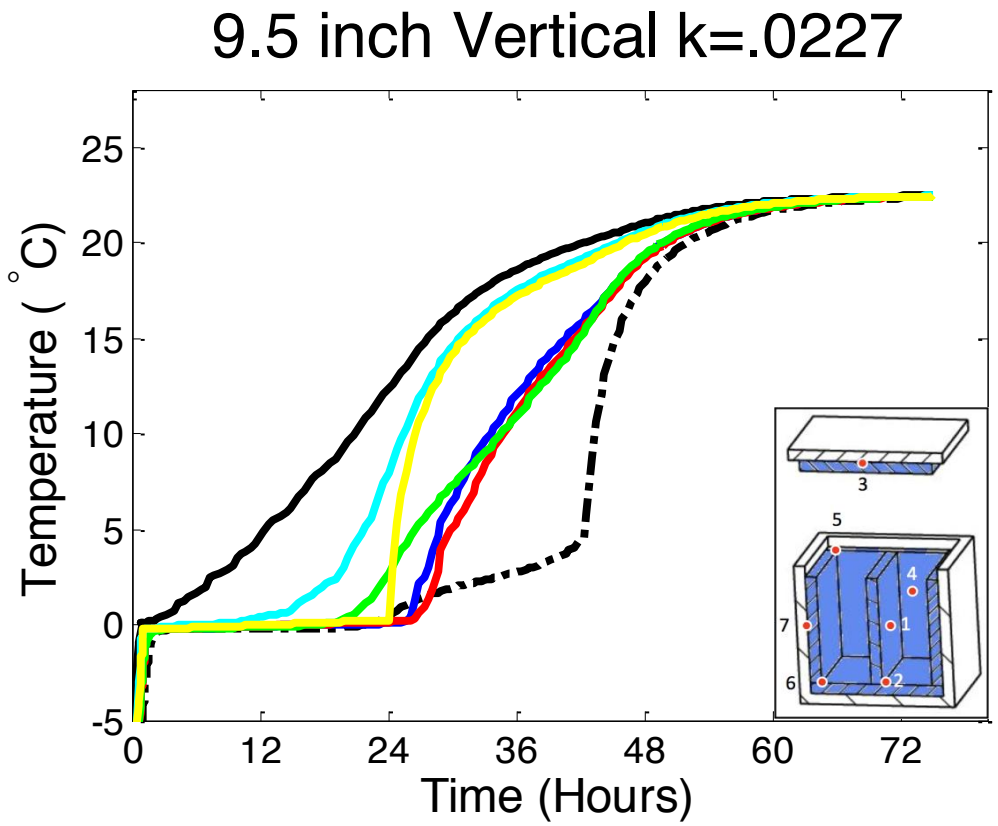


Figure 39: 9.5-in sided box, all sides ice w/ vertical shelf. Inset: Cutaway of experiment (blue = ice locations)

Ice thickness:

$$.001406m^3 = (0.1905m)^3 - (0.1905m - 2t_{ice})^3 + t_{ice}(0.1905m)\text{^}2 \Rightarrow\ t_{ice} = .005922m$$

Cold duration of storage: 1697 min ≈ 28.3 hr

Analysis: Parallels are drawn between this model and the horizontal shelf model. The same uneven duration of cold storage is observed throughout the box, with the average here being slightly longer than in the horizontal shelf model. The vertical shelf fully melts much quicker (data set T1), but it does not increase in temperature as quickly as in the horizontal shelf.

- 9.5-in Sided Model: Bottom and Top Slabs

Table 16: Data set label denotation for the 9.5-in sided box with bottom and top ice slabs model.

Data Set Label		*Location in Ice Box Model*
T1		*Center of storage space (air), on top of ice shelf*
T2		*Center of bottom of storage, above the ice layer*
T3		*Center of top, between the insulation and ice layers*
T4		*Center of upper quadrant of storage*
T5		*Top corner of storage*
T6		*Midpoint of side along bottom of storage, above the ice layer*
T7		*Center of side panel, between the insulation and ice layers*

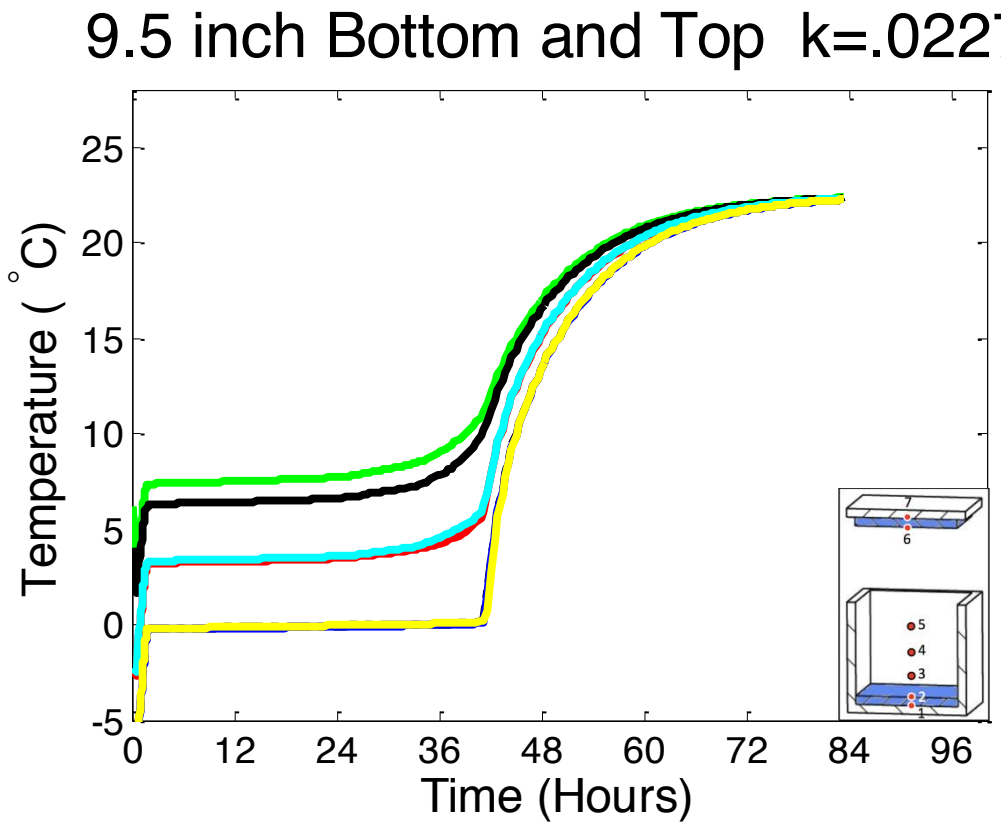


Figure 40: 9.5-in sided box, bottom and top ice slabs. Inset: Cutaway of experiment (blue = ice locations)

Ice thickness:

$.001406m^3 = 2t_{ice}(0.1905m)^2 \Rightarrow\ t_{ice} = .019372m$

Cold duration of storage: 2308 min ≈ 38.5 hr

Analysis: An obvious temperature distribution is observed in this model, though for the majority of the simulation, the temperature remains within the optimal vaccine

temperature conditions. The cold duration of storage here is by far the longest of all the models, given that the ice is concentrated into a larger block.

- 9.5-in Sided Model: Bottom Slab

Table 17: Data set label denotation for the 9.5-in sided box with bottom ice slab model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

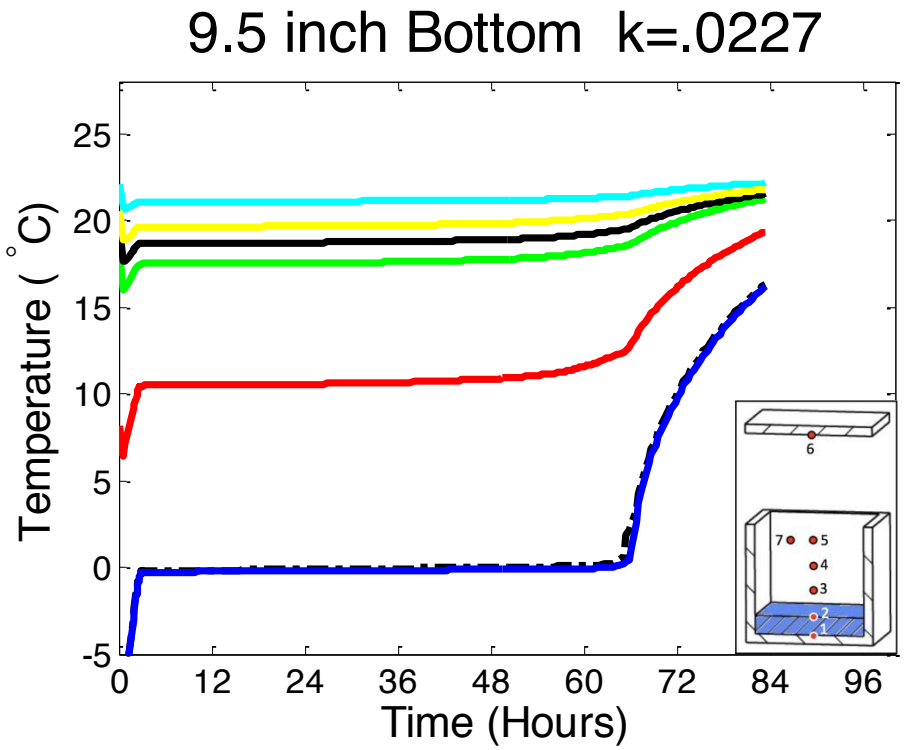


Figure 41: 9.5-in sided box, bottom ice slab

Ice thickness:

$.001406m^3 = t_{ice}(0.1905m)^2 \Rightarrow t_{ice} = .038743m$

Cold duration of storage: 1157 min ≈ 19.3 hrs

Analysis: This model demonstrated the temperature distribution in a linear sense throughout the box. The ice takes the longest to melt here (≈ 70 hrs), given that it is all concentrated in one block. However at halfway in the storage compartment, the

temperature is already above the desired mark through the whole melting duration. Above the central altitude, there is hardly any cooling in the box.

- 13-in Sided Model: All Sides

Table 18: Data set label denotation for the 13-in sided box with ice perimeter model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

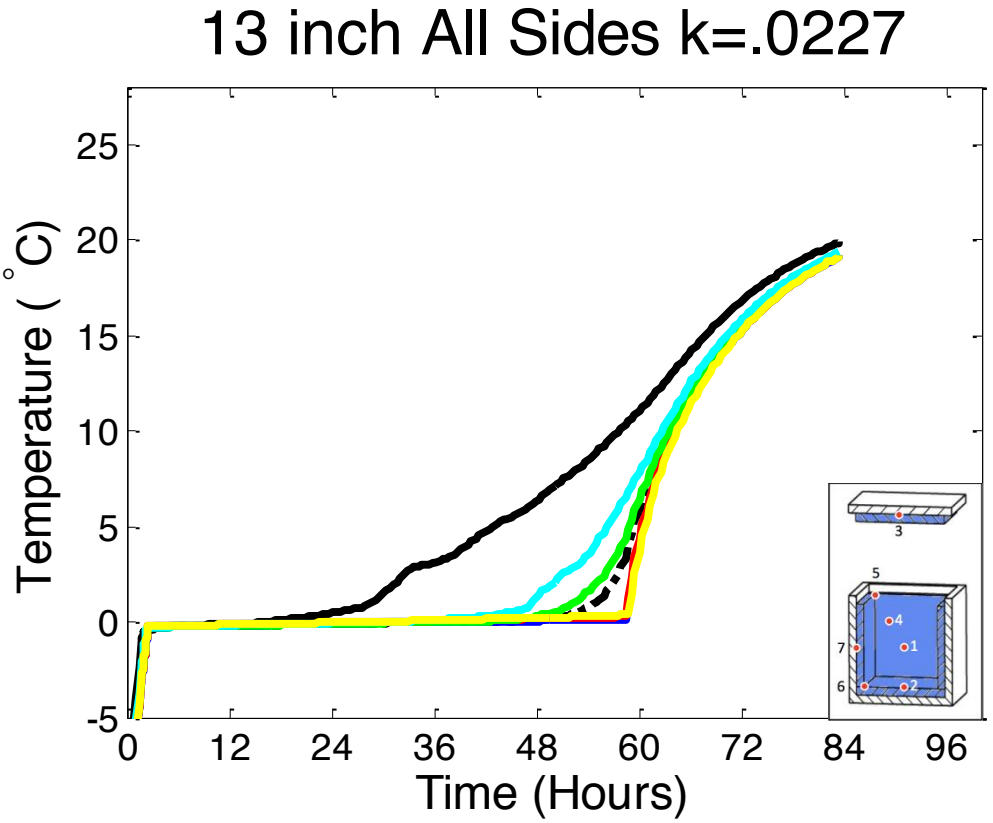


Figure 42: k-value refinement: 13-in sided box, all sides ice, k = 0.0227 W/m-K

Ice thickness:

$$.006447m^3 = (0.2794m)^3 - (0.2794m - 2t_{ice})^3 \Rightarrow t_{ice} = .012148m$$

Cold duration of storage: 3816 min ≈63.6 hr

Analysis: The temperature distribution in this model mirrors that of the 9.5-in sided model. The cold duration of storage was over twice as long as in the other model,

though the volume of ice was over four and a half times more than in the other model, verifying a nonlinear relationship between ice volume and duration of storage.

- 13-in Sided Model: Horizontal Shelf

Table 19: Data set label denotation for the 13-in sided box with all sides and horizontal ice shelf model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

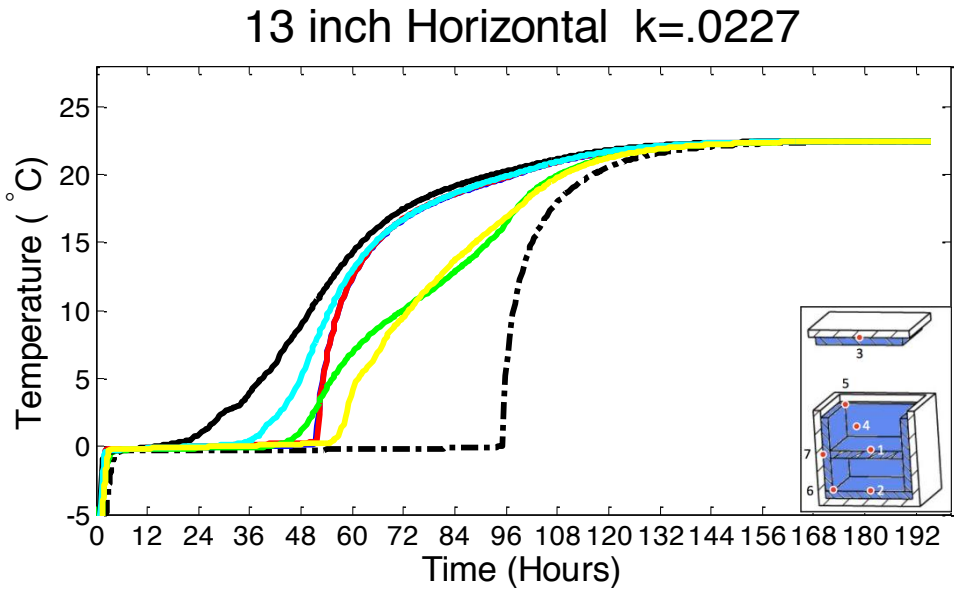


Figure 43: 13-in sided box, all sides ice with horizontal shelf

Ice thickness:

$$.006447m^3 = (0.2794m)^3 - (0.2794m - 2t_{ice})^3 + t_{ice}(0.2794m - 2t_{ice})^2 \Rightarrow t_{ice} = .014205m$$

Cold duration of storage: 3572 min ≈ 59.5 hr

Analysis: This model exhibited the same findings as in the previous model, in that the temperature distribution was mirrored from the smaller box. The duration of storage was also over twice as long.

- 13-in Sided Model: Vertical Shelf

Table 20: Data set label denotation for the 9.5-in sided box with all sides and vertical ice shelf model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

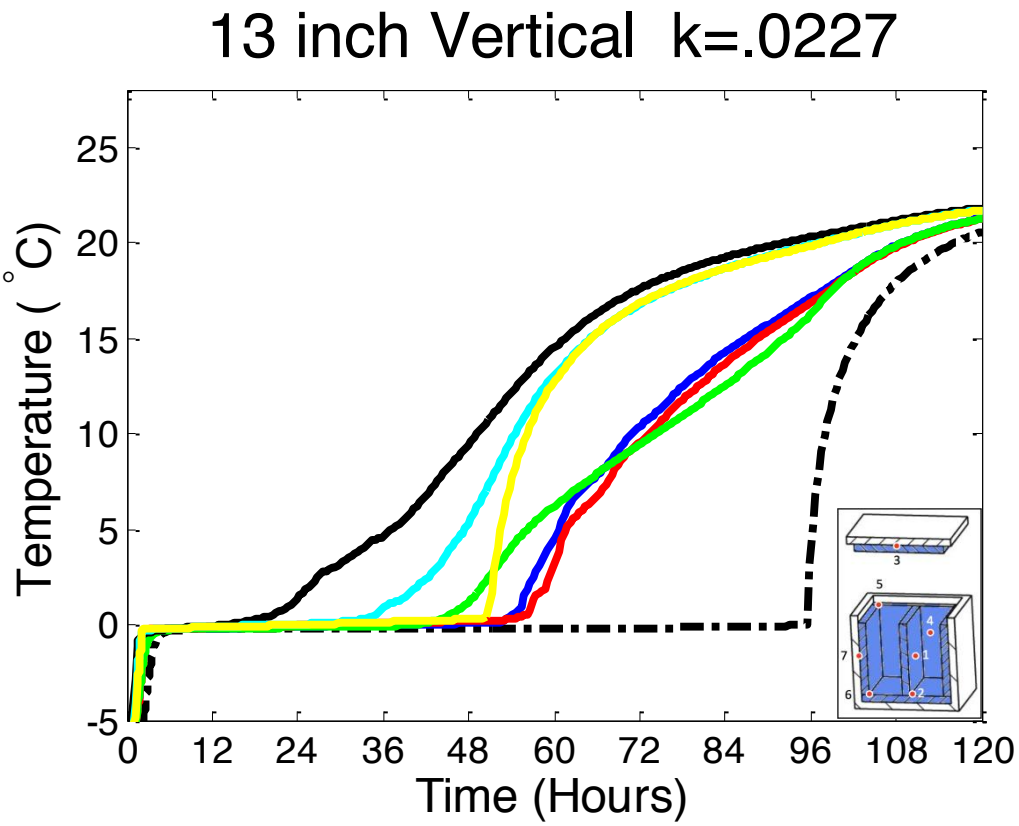


Figure 44: 13-in sided box, all sides ice with vertical shelf

Ice thickness:

$$.006447m^3 = (0.2794m)^3 - (0.2794m - 2t_{ice})^3 + t_{ice}(0.2794m - 2t_{ice})^2 \Rightarrow t_{ice} = .014205m$$

Cold duration of storage: 3852 min ≈ 64.2 hr

Analysis: This model differed from the 9-in sided counterpart in that the vertical slab exhibited an even melting regime and subsequent sharp temperature increase to

equilibrium, where previously the melted slab experienced a longer regime of cooling after melting. The overall cold duration of storage was still about twice as long, in line with the other 13-in sided models.

- 13-in Sided Model: Bottom and Top Slabs

Table 21: Data set label denotation for the 13-in sided box with bottom and top ice slabs model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

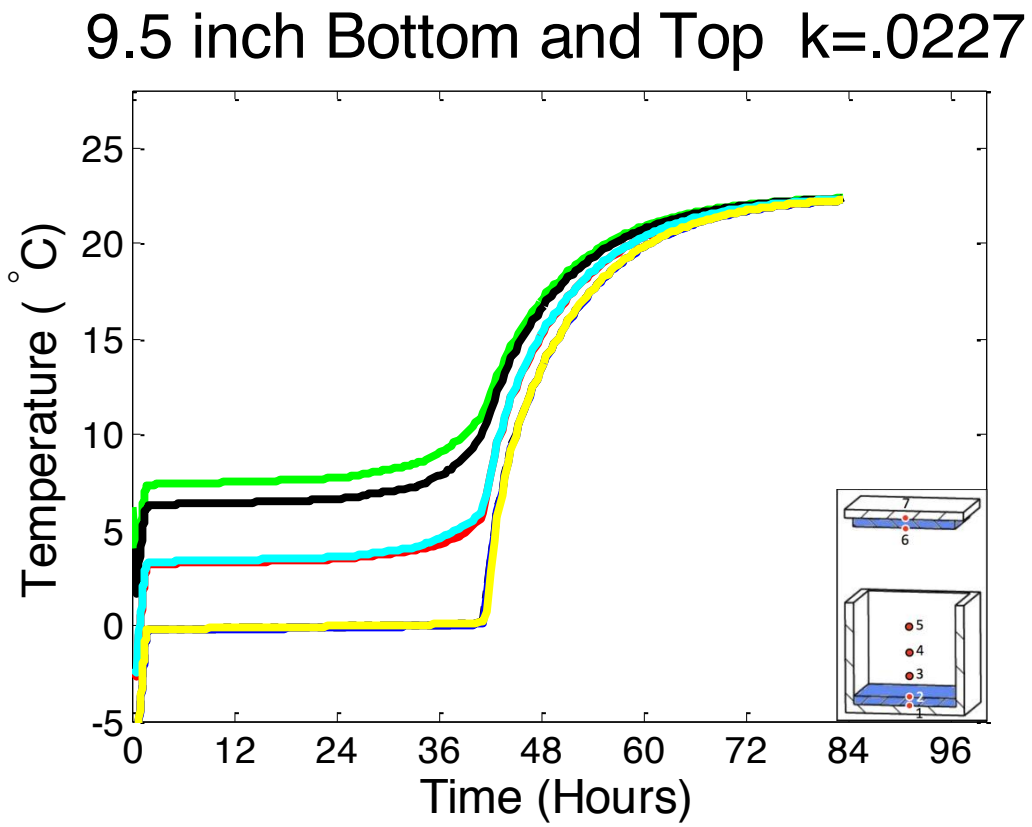


Figure 45: 13-in sided box, bottom and top ice slabs

Ice thickness:

$$.006447m^3 = 2t_{ice}(0.2794m)^2 \Rightarrow t_{ice} = .041293m$$

Cold duration of storage: 3049 min ≈ 50.8 hr

Analysis: In comparison to the 9-in sided model, this temperature distribution is almost identical, in that the relative locations in the box were stabilized at the same temperature through the melting period. The cold duration of storage here is a bit less than half of the previous model (38.5 hrs), but the time for the actual slabs to melt here (about 3.5E6 sec.) is well over twice that of the other model (about 1.5E6 sec.).

- 13-in Sided Model: Bottom Slab

Table 22: Data set label denotation for the 13-in sided box with bottom ice slab model.

Data Set Label	*Location in Ice Box Model*
T1	*Center of storage space (air), on top of ice shelf*
T2	*Center of bottom of storage, above the ice layer*
T3	*Center of top, between the insulation and ice layers*
T4	*Center of upper quadrant of storage*
T5	*Top corner of storage*
T6	*Midpoint of side along bottom of storage, above the ice layer*
T7	*Center of side panel, between the insulation and ice layers*

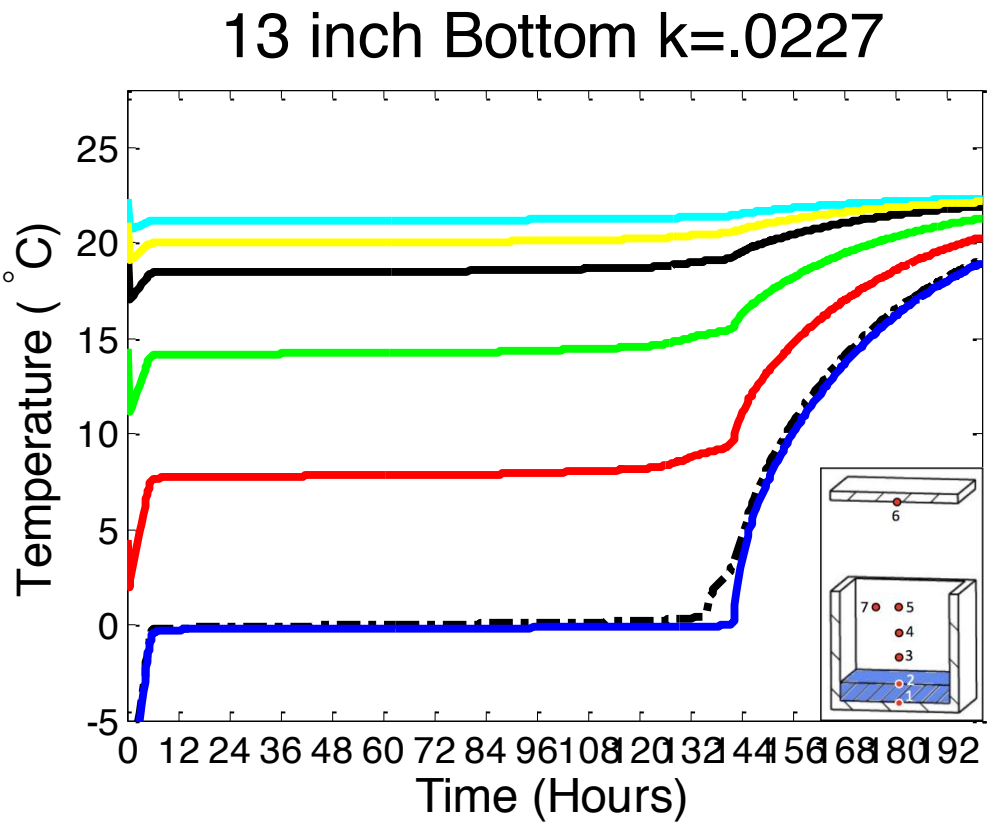


Figure 46: 13-in sided box, bottom ice slab

Ice thickness:

$.006447m^3 = 2t_{ice}(0.2794m)^2 \Rightarrow\ t_{ice} = .082586m$

Cold duration of storage: 3342 min ≈ 55.7 hrs

Analysis: The temperature distribution seen here is slightly more spread than in the 9.5-in model, but it is still far from ideal for cold storage. The time for the slab to melt here is over twice that of the smaller box model.

Each model exhibited distinctly different behavior in terms of temperature stratification and duration of melting. The all sides model had the most even temperature distribution and rate of melting in the box matching the experimental model. The five sides, no bottom model had a fairly even temperature distribution, except at the points along the bottom of the box where little cooling with prevalent. Both the horizontal and vertical shelf models exhibited longer melting times for the shelf slab, with the outer panels reaching warmer temperature much quicker. The bottom and top slab model showed an obvious temperature gradient throughout the box that mostly fell below the 8 °C mark for the melting regime, and the duration of cold storage was also the longest here, in comparison to the ice perimeter models however, the location of measurement points may not have been conducive to accurate measurement. Finally, the single bottom slab model was ruled out as a viable geometry, given the gross temperature distribution in the box, where little to no cooling was observed at the extremities away from the ice. We concluded that the FEA modeling provides a good basis for eventual prototype construction and that the different geometries, typically not considered in design, play an important role in ice box performance.

1-Dimensional Model Results

In order to identify proper thicknesses for ice, insulation, and PCM a 1-dimensional model was created in COMSOL as shown in Figure 47. This model had a run time of ~120s which allowed for rapid comparison of different combinations of ice and insulation thicknesses.

Figure 47: Comsol 1-D model

Region 1 has the material properties of insulation, Region 2 is the ice, and region 3 is the air. In all of the 1-D experiments the size of the air region was the same. The left most boundary point is held at 22.5 °C and the right most boundary point is considered symmetric, which means the heat flux is equal to 0. The initial temperatures for regions 1 and 3 were 22.5 °C and the initial value for the ice was -10 °C for all of the models.

Model Validation

The 1-D model with an insulation thickness of 1 inch and ice thickness of 0.56 inches took 76 hours to reach 8 °C, which is within 10% of both the 3-D model and the ice box experiments. The temperature profile in time of a point in the air, as

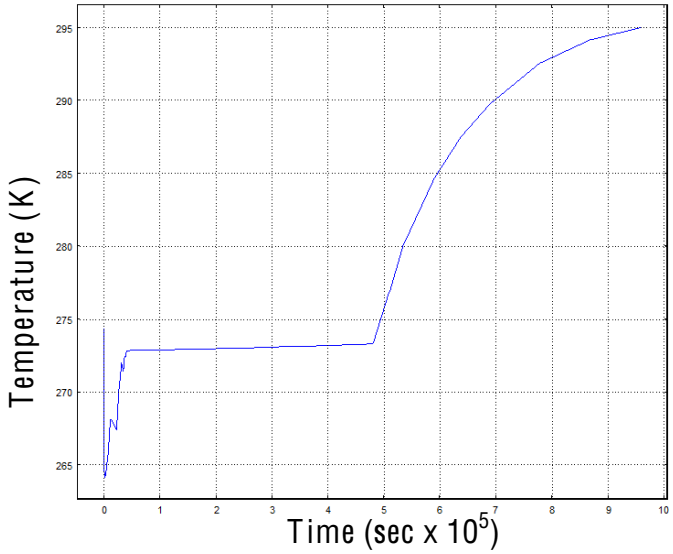


Figure 48: Dynamic temperature profile of a point in the air of the 1-D model. This profile matches qualitatively with the profiles as seen in the ice-box experiments (Fig. 22) and the 3-D model. (Fig. 29)

shown in Figure 48 had a similar shape to both of those experiments as well.

A series of experiments was run with varying thicknesses of insulation and ice in the model. The results are shown below in Figure 49 below.

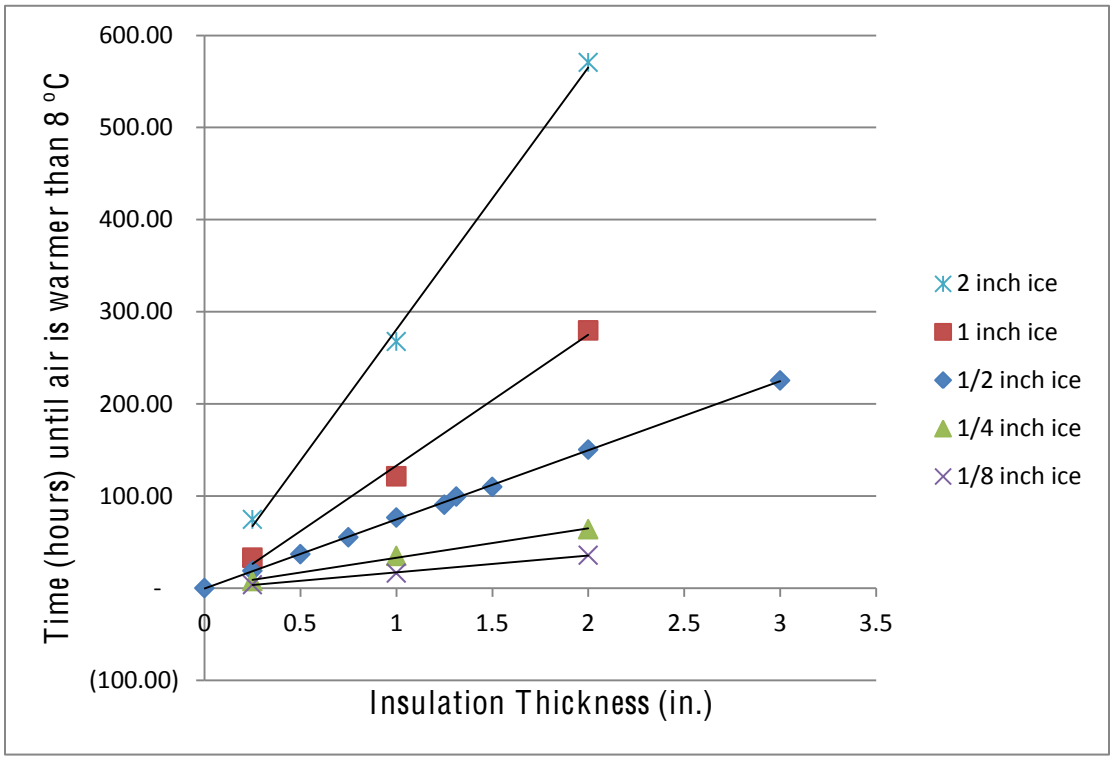


Figure 49: The time in hours that it takes the air in the 1-D model to warm up to 8 °C versus insulation thickness plotted for different series of ice thickness.

For each thickness of ice, an increase in insulation thickness directly increases the amount of time until the temperature reaches 8 °C. For each series the residual squared is above 0.99 indicating that the data is in fact linear. The slopes and intercepts of the linear regressions were plotted against the ice thickness for each series resulting in the Figure 50 below.

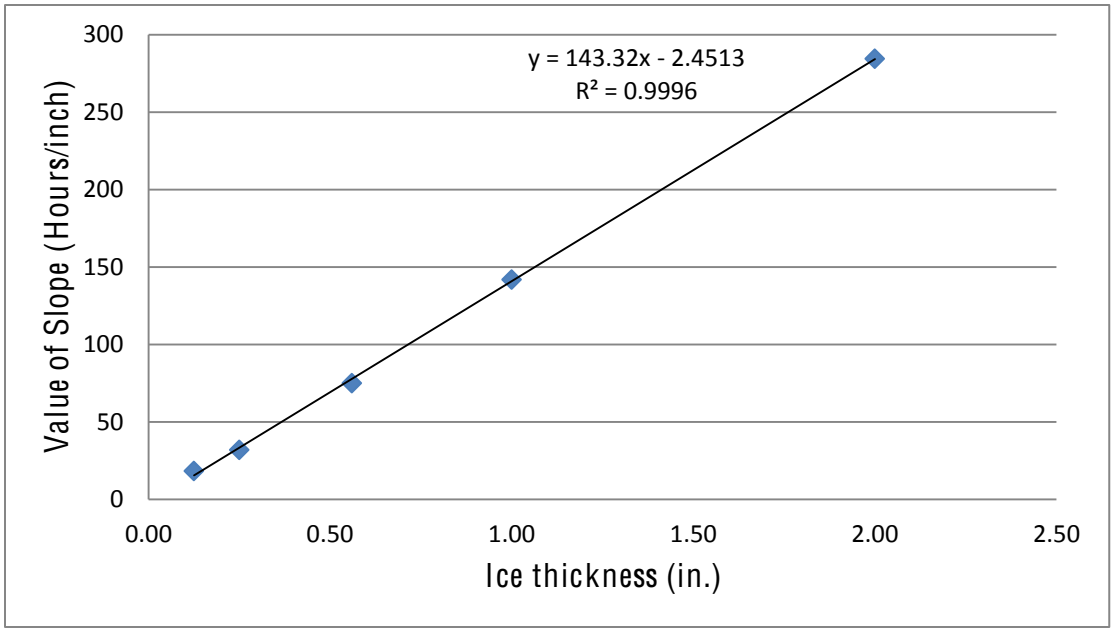


Figure 50: For each thickness of ice, the slope of the time to warm to 8 °C vs. insulation thickness graph was determined. These slopes are plotted against ice thickness, again giving a linear series.

With these correlations, the time until the box is above 8 °C can be estimated generally for any combination of ice and insulation. This is shown below in the contour plot in Figure 51.

Increasing the ice and insulation to 25 inches gives 1,900 hours of cold time, and this number increases indefinitely. The curve appears to be symmetric about the y=x line (white). This result means that if the interest is maximizing cold time while minimizing total size of the box use equal thicknesses of ice and PCM.

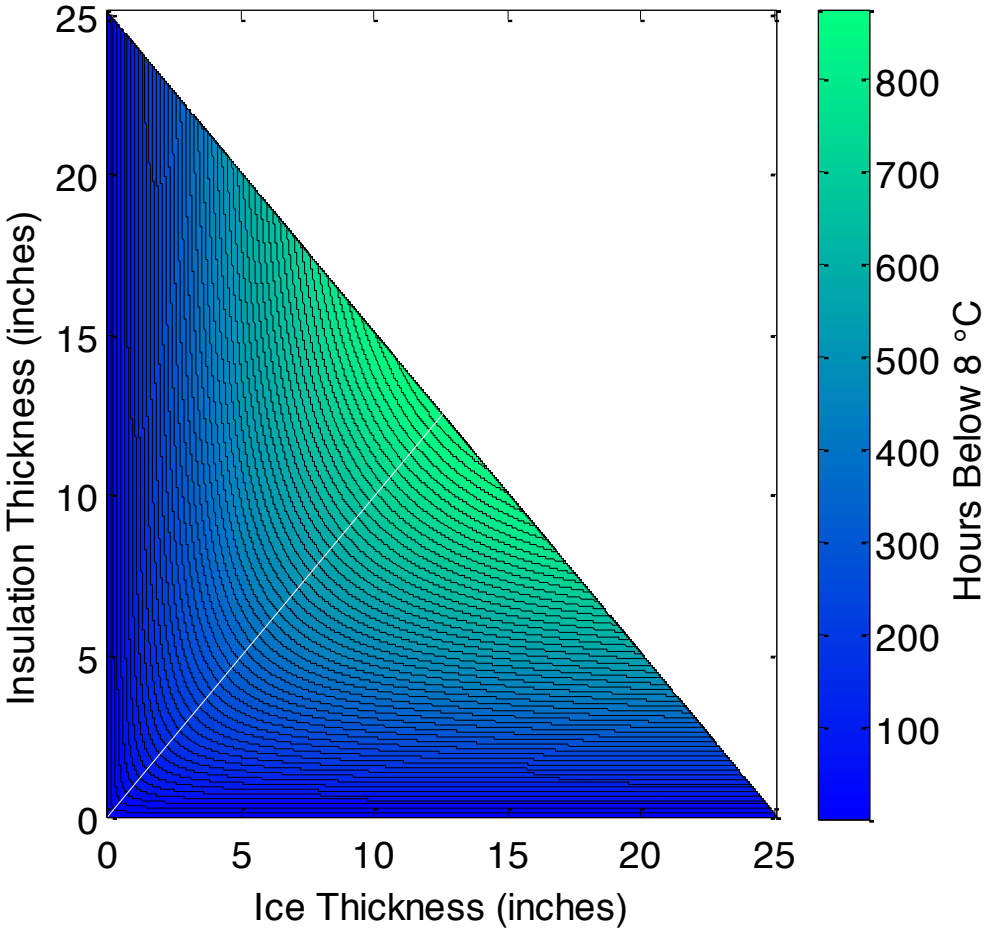


Figure 51: 2-D color contour plot of time until the air in the model is greater than 8 - °C in hours shown as a function of ice thickness vs. insulation thickness.

Cost Model

To develop an optimized cold box, the cost of materials as well as the weight of the box needed to be considered to develop an idea of the cost efficiency of the design. A previous work on optimization of an insulated shipping container for use in the U.S. developed a cost model that accounted for the cost of materials and the cost of shipping, based on typical freight rates for shipping across the continental U.S.

(East & Smale, 2008) The model requires volumetric costs for insulation and ice which were assumed to be \$900/m^3 for polystyrene insulation (East & Smale, 2008) and \$0.50/gallon for deionized water. These costs were converted to dollars per cubic inch for use in the program. To calculate shipping costs, the East and Smale's model was adapted. The equations for the costing model are shown in equations 5 through 8. This shows that the boxes with more ice are more expensive, due to the ice adding weight to the design. The full cost model can be found at the end of this volume in Appendix G.

$$C_{ice} = \frac{\$0.25}{gallon} * V_{ice} \tag{5}$$

$$C_{ins} = \frac{\$900}{m^3} = \frac{\$3.40}{gallon} * V_{ins} \tag{6}$$

$$C_{ship} = \$4.31 * lbs + \$30 \tag{7}$$

$$C_{box} = C_{ice} + C_{ins} + C_{ship} \tag{8}$$

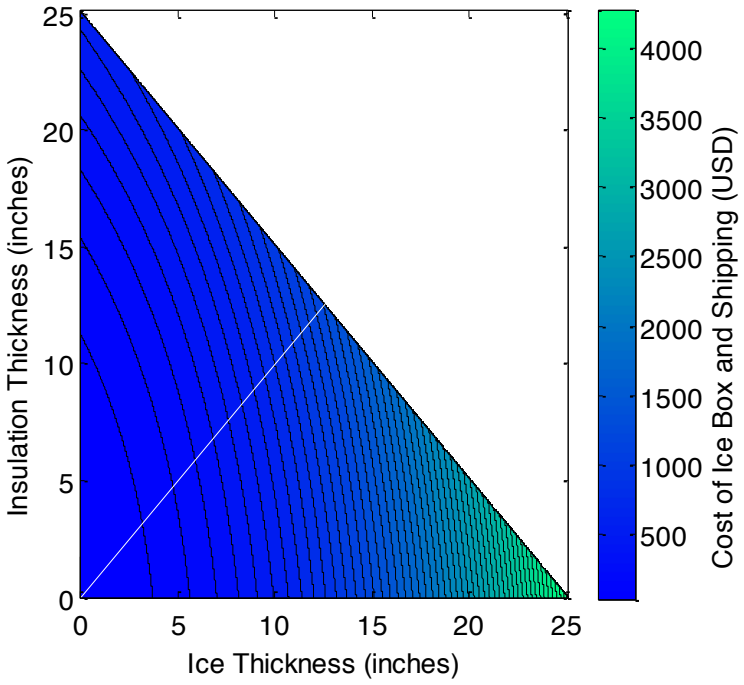


Figure 52: Cost Estimate for Ice

To optimize the design, we divided the time to melt by the cost for the box, and found a global optimum. This is shown below in Figure 53. The optimum point, the center of the green ellipse, is 6 inches of ice and 11 inches of insulation. This box is much too large for a vaccine carrier and it would cost ~$1,000 to build and ship. However for every total box size below that there is an optimum distribution of ice and insulation that lies along the white power law curve. These optimums are relatively insenstive to the price per shipping. Increasing or decreasing the price of shipping by an order of magnitude results in 30% change in the optimum insulation and ice thicknesses.

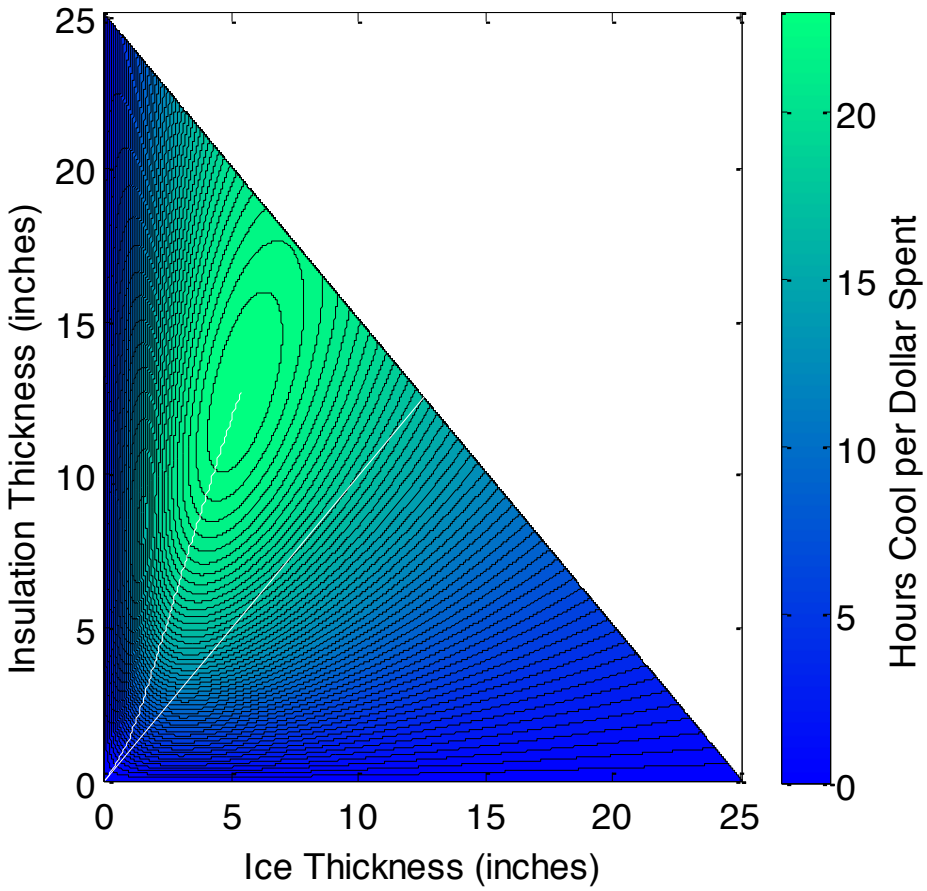


Figure 53: Optimum number of hours box is cold per dollar spent

Theoretical Integration of PCM as Buffer

The novelty of our design is in the integration of PCM as a buffer to prevent the inner storage compartment of the vaccine carrier from ever dipping below zero. The quantitative question to answer is this: what is the proper ratio of PCM to ice?

Consider the case in which there is exactly enough unfrozen phase change material inside of a shell of frozen ice such that the latent heat of the bulk PCM is exactly that of the latent heat of the ice, that is to say in 3-Dimensions:

$$\rho_{PCM} \cdot V_{PCM} \cdot \Delta H_{PCM}^{Fus} = \rho_{ice} \cdot V_{ice} \cdot \Delta H_{ice}^{Fus} \quad (9)$$

In one dimension, the cross sectional areas can cancel out on both sides out of the volumes, to give a critical thickness of PCM, x*, where the melting ice would exactly freeze the PCM slab while melting. x* can be found quite simply by arranging equation (9).

$$x^* = \frac{\rho_{ice}}{\rho_{PCM}} \cdot \frac{\Delta H_{ice}^{Fus}}{\Delta H_{PCM}^{Fus}} \cdot x_{ice} \quad (10)$$

Of course, using an x* thickness of PCM is too much buffer for the inner compartment, which never feels any of the ice's cooling in such a case. It is useful then to consider what minimum fraction of x* gives the desired temperature stability, but minimizes the total volume of PCM in the system.

Prototyping and Fabrication

A variety of experimental results and practical constraints have influenced our final prototype design. These results were drawn from physical ice box experimentation, PCM characterization, 1-D modeling and 3-D modeling of boxes in cold chain conditions. The practical constraints stemmed from data unearthed while investigating the cold chain, such as desirable storage conditions and common equipment dimensions and practical constraints for building these cold boxes.

Our research into the cold chain elucidated a variety of constraints for the design based on environmental conditions and human factors. The most obvious constraints stem from the purpose of a cold box. The goal is to keep vaccines in a temperature range of 2-8 ºC for the longest time possible; this was weighted to be the most important design parameters. Making this constraint, the priority of our design distinguishes us from previous research.

Using WHO constraints of 5-25 liters and their suggestion that vaccine vials are stored in boxes of the size of 100mm x 100mm x 50mm, we determined the inside dimension of our prototype to be 250 mm (9.84 inches). This results in a storage volume of approximately 15 L, which is mid-range for a cold box and fits the vaccine boxes with minimal wasted space.

To alleviate freezing of vaccine vials, our prototype is designed to have no contact of the ice with vaccines and additionally designed to be simple and full proof from possible misuse. This may seem an extensive measure, but ice lined refrigerators have extensive manuals that indicate that the vaccines stored within should never touch the ice, and this has been observed to be rarely abided by. The cold box design

is aimed to be mass produced for distribution across the globe, so the box needs to be both simple to construct, and easy to use. Our final prototype design does not use nonstandard material sizes, and has a simple removable lid to allow access to the vaccines.

Initial experimental investigations were into PCM characterization. The results indicate that Phase 5 ™ would be the strongest performing material for energy storage within the ice box. However the results indicate even though the melting temperature is ideal at 5 °C, the latent heat is significantly less than that of water. To store enough energy to keep the box cold during travel, much more Phase 5 ™ would be required than ice, adding volume, weight and expense to the design. There is also a possibility of the PCM's sensible heat freezing vaccines if it is placed directly in the box out of the freezer. We concluded that unfrozen PCM would best serve as a temperature stable barrier to keep vaccines at 5 ºC. External energy melts the ice at a temperature of 0 ºC, and the ice freezes the PCM at 5 ºC, which keeps the storage container at 5 ºC. When the ice is fully melted, the now frozen PCM melts at 5 °C. This design has the disadvantage of being somewhat bulkier and heavier than current cold boxes, but it is not as expensive as solely using PCM as the refrigerant and does more to prevent freezing than current cold boxes. Additionally water in the form of ice packs is highly integrated into the current cold chain maximizing accessibility.

The icebox experiments provided an excellent starting point for the eventual prototype design. The variety of designs allowed us to focus on the actual temperature profiles exhibited by different special arrangements of ice boxes. The experiments also allowed us to confirm several features cited in the literature such as the

prevalence of freezing close to ice (PATH, 2008). The two most influential features on final prototype design we found from the ice box experimentation are as follows: the internal temperature uniformity or extent of mixing within the air of the vaccine storage chamber, and the gradient formed moving away from an ice pack. The mixing of the air allows us to create a prototype without complete circulation of vaccine storage chamber in frozen materials. The gradient starting with 0 $^{\circ}$C on an ice pack confirms the research that vaccine containers need to be separated from direct contact from ice and can be shielded with a barrier such as air. Thus our final prototype was designed with a barrier of PCM between the ice and the vaccines in the vaccine storage chamber, additionally concluded that at least one side of the vaccine storage chamber does not necessarily need to be covered with ice.

FEA modeling was developed utilized on two scales, modeling of 1-D trends based on ratios of ice, PCM, vaccine storage and insulation thickness, and 3-D modeling which focus on the effects of different geometries and melting trends. The 1-D model was first used to determine the optimum ice to insulation parameters. This relationship was used to map a 2-D space between increasing ice and increasing insulation, and coupled with a costing model that found an optimum thickness for the ice and insulation that maximizes hours the box is cold per dollar spent. The most feasible dimensions were carried on for further refinement. PCM was added into the model to see the optimum ratio of PCM to ice to insulation at which the internal temperature was maintained at 5 $^{\circ}$C was performed. However no direct pattern could be observed, so only the ratio of ice to PCM could be optimized and was assumed to not significantly change the ice to insulation ratio. Because prototyping different

amounts of insulation is not easy, 1.5 inches was chosen as the insulation size for the final prototype, and the ice and PCM thicknesses were derived backwards from that using the power law derived from an updated version of the optimal costing model. The final thicknesses for the prototype box were 1.5 inches of insulation, 0.45 inches of ice, and 0.42 inches of PCM.

The 3-D modeling helped develop the final constraints setting our boxes geometry, which when combined with the data gathered from a variety of other sources served as our prototype design. The model was used to generate a variety of 3-D shapes with the hopes of finding a simple design. The geometry with five sides, everything except the bottom covered was discovered to be able to maintain low temperatures but above 0 $^{\circ}$C while providing a design that is simple to construct and refill with ice. This was translated to the final shape and structure of the box.

Construction of Prototype 2.0

The same materials used in prototype 1.0, detailed in Table 7, were used to construct prototype 2.0. Similarly, the general construction process and order of materials was similar to prototype 1.0. The exception is that in prototype 1.0 there was one inner slot along each wall for a slab of PCM. However, for reasons detailed above, we decided to incorporate a dual inner slot along each wall that would house slabs of PCM that would be sealed in a chamber and ice packs that could be easily removed. Hence in prototype 2.0 (Figure 54) the layers of the box moving from the outside to the inside are a ¼" thick corrugated plastic, a 1.5" polystyrene, a 0.45" thick layer of ice, a 0.42" thick layer of sealed PCM and finally an inner vaccine

capacity of 15.625 liters (a cube with side length 9.84 inches). The inner compartments of ice and PCM were fabricated from 3/32” Lexan sheets, a shatter resistant brand of polycarbonate (Plexiglas).

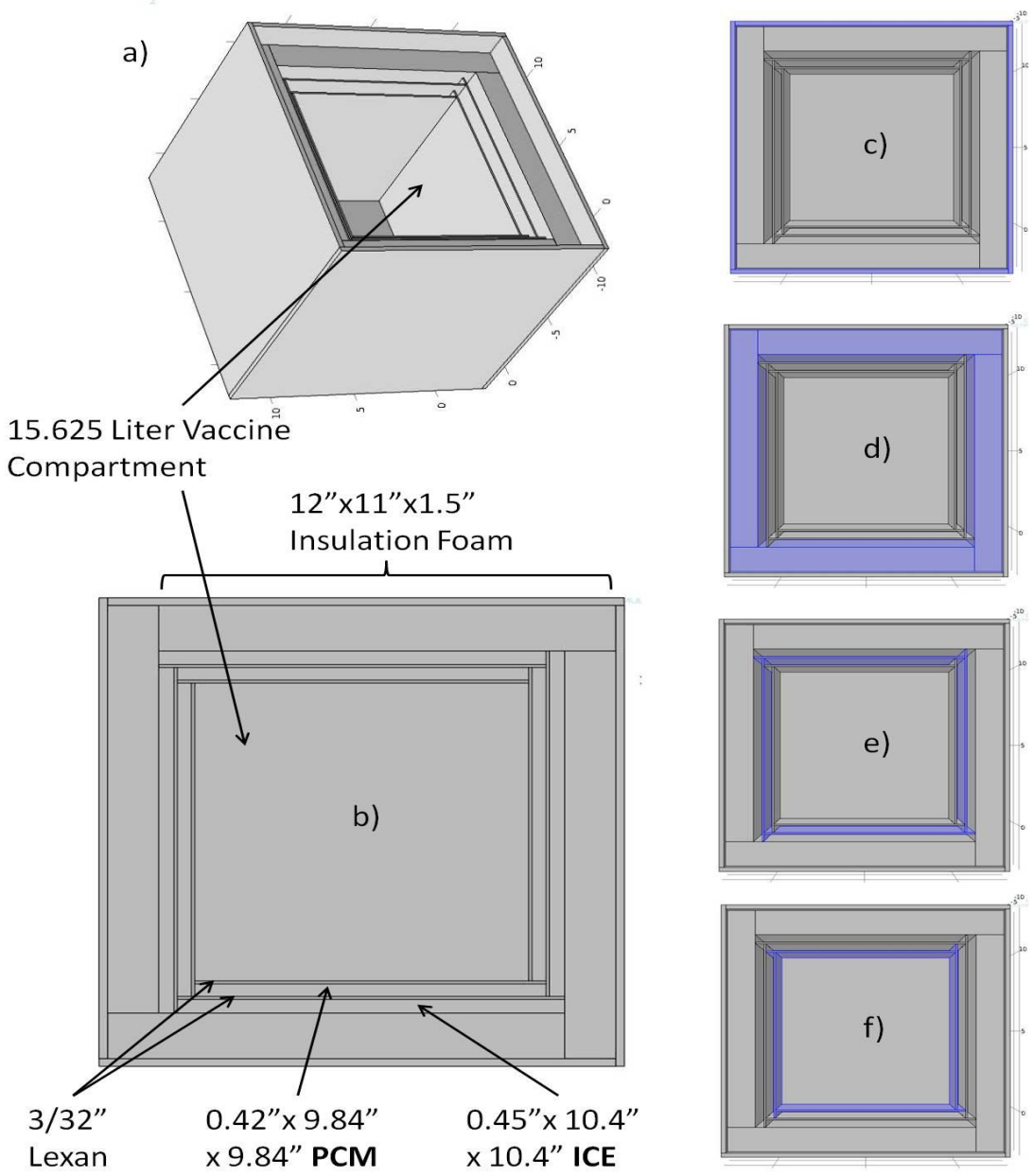


Figure 54: CAD drawings and dimensions of prototype 2.0.
a) Prototype 2.0 b) Birds-eye view with component dimensions c) ¼” corrugated plastic as outer layer d) 1.5” foam insulation e) 3/32” Lexan forming 0.45” ice pack slots f) 3/32” Lexan forming PCM slots.

The box also features a removable lid of the same layer based dimensions. Details of the dimensions and fabrication of the individual parts are given below. One of the novel features of our box is that the vaccines are packed inside initially at the beginning of transport, and are not removed until the final destination. However, the lid of the box will need to be removed in order to swap out ice packs. Therefore, we fabricated a clear plastic lid that covers the vaccine compartment even when the lid of the box is removed (Figure 55). This serves the dual purpose of allowing the healthcare worker who is changing the ice packs to view the vaccine compartment and ensure that they are all intact, while maintaining a minimal barrier between the cool vaccines and the ambient air while the ice packs are changed.

Figure 55: Clear plastic inner lid that covers vaccine payload compartment

The construction proceeded as follows (images of the construction of prototype 2.0 can be seen in Appendix D at the end of this volume):

1. A corded jig-saw (Black and Decker 4.5 amp, variable speed) was used to cut the Lexan into the panels that would comprise the inner payload chamber. Four panels were cut to form the inner walls of the vaccine payload space, and an additional four panels were cut to form the walls of the PCM and ice slots. The panels were notched (Figure 56) so that they could be fitted together by placing one panel's notch into an adjacent panels slot at a right angle. The smaller panels were fitted together to form the inner payload chamber, and the outer panels were fitted around the chamber to form the walls of the PCM and ice slots.

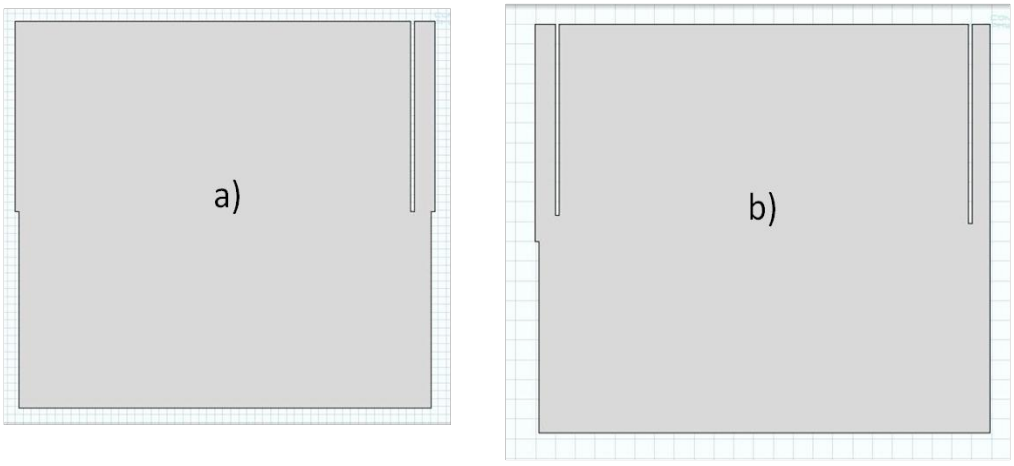


Figure 56: Lexan panels with notches and slots for assembly of a) the inner chamber and b) the PCM and ice slots.

2. The jig-saw was used to cut the Polyisocyanurate into a 15" x 15" x 1" square, to serve as the insulation at the base of the box. The Lexan frame was centered on the Polyisocyanurate.

3. The jig-saw was then used to cut the Polystyrene into four (4) 13.5” x 11” x 1.5” sheets. The sheets, each an inch and a half in thickness were then glued vertically along the border on the base Polyisocyanurate, enclosing the Lexan frame, creating sturdy walls.
4. At this point, all inner and outer joints of the box were sealed with a bead of glue smoothed by a finger. This created a thermal seal in each joint gap and also added structural integrity to the box.
5. A rectangular annulus of Lexan was fabricated to sit atop the PCM slots, allowing the slots to be sealed once the PCM is added. The center of the annulus was saved and serves as the clear plastic lid to the vaccine compartment that will remain closed even when the lid of the box is removed.
6. The lid was created from a 15” x 15” x1.5” piece of Polystyrene. On top of that, an 11.4” x 10.4” x 0.45” chamber was created from Lexan to serve as the slot for ice packs on the top of the cold box. A 10.4” x 9.84” x 0.42” chamber was fabricated from Lexan on top of the ice pack chamber to serve as the PCM chamber. When inverted, this lid fit snugly into the top of the box created in steps 1-4.
7. Lastly, the corrugated plastic was cut and folded to encompass the box. The plastic was glued onto the box, and held in place through a combination of butterfly clips, and mechanical clamps until dry.

The final prototype 2.0 can be seen below in Figure 57.

Figure 57: Prototype 2.0 fully assembled

Instructions for Using the Cold Box

In the current cold chain system, the cold box used for vaccine transport passes through country centers, regional centers, and local health centers continuously. Our box will replace the current cold box while maintaining a similar level of low-maintenance care. At the primary vaccine store, the vaccines can be placed in our PCM cold box when ready for transport. The interior section of our PCM cold box has a removable plastic lid, which covers the vaccine storage compartment. After the vaccines are stacked inside, the internal compartment is closed, and should not be opened until the shipment has reached the final destination. The ice packs should be removed from our PCM cold box and placed in the freezer until fully solid. When it is time for the shipment to leave, the frozen ice packs can be

placed in the appropriate slots and the lid closed. Our PCM cold box is now ready for deployment.

After a travel time of 48 hours, during which the PCM component of our system functions by absorbing heat from the internal environment and disposing it into the ice packs, keeping a steady temperature of 5 °C, the ice packs will have fully melted. After the trip, the cold chain worker can observe the state of the system by looking at the color temperature labels on the PCM panels. If the temperature is above 8 °C, then the system needs to be recharged by removing all the ice packs and placing them in a freezer, and reclosing the lid of the box. The box should be kept at room temperature; the insulation and the covered internal compartment will prevent high heat from destroying the vaccines. The ice packs should be in the freezer for 48 hours to ensure they freeze thoroughly, at which time they can be replaced into the PCM cold box in their respective locations without risk of freeze damage. Because there is a layer of PCM between the ice pack and the vaccine compartment, the 0 °C ice packs never touch the vaccine compartment. This process of refreezing the ice packs can occur any time when the traveling delivery truck makes a stop at a center with a freezer. Additionally, as ice packs are very cheap and simple to make and store, health centers along the way may have extra frozen ice for a quick exchange during a short stop. This way, when a shipment comes along with long distance goals, the deliverer can stop, replace the ice packs with frozen ones, and continue on his way for another 48 hours.

At the final destination, the vaccines can be removed from the PCM cold box and stored in the local health center. The cold box is reusable, and can be sent back to

the provincial center through the same distributor that brought the box. Our box will allow for less vaccine freezing along the cold chain, and create a more systematic and reproducible chain of events for shipments. The materials of our box can vary depending on the specific resources available to each country, but the general design and integration of PCM and ice packs is vital for preventing both freezing and overheating. See Appendix E for a more detailed instruction manual.

Chapter 5: Interpretation and Discussion

What the Results Mean

The main information that can be drawn from our research is as follows. A variety of PCM's were characterized and evaluated for icebox implementation with Phase 5 ™ performing the strongest. Rapid prototyping of various box geometries illustrated difference in the time until the box was warm and the temperature distribution of the box. The method of FEA modeling with the phase change as a large energy heat capacity has been observed to be an effective tool for design of iceboxes or thermal systems provided unique geometries can be generated and convection is not the dominating factor in the thermal movement. Furthermore convection plays a small but noticeable role in cold box storage. A 1-D model illustrated the economic optimum ratio of ice to insulation and was further evaluated to find the required thickness of PCM needed to maintain the air above freezing temperature in a cold box. This data can play a role in future investigations into cold box technology.

The investigation into PCM's involved an accepted technique for finding the melting temperature and latent heat of substances. Our group used a DSC to determine both. We found a variety of latent heats and melting temperatures for proprietary PCMs such as Phase 5 ™ AcuTemp and PureTemp 4. Additionally we determined that the clathrate mixture of tetrahydrofuran and water proposed in the literature is very difficult to achieve and was not repeatable. Our conclusion indicates that Phase 5 ™ is the most desirable PCM for cold box storage because it has a high

enough melting point 5 °C and the highest heat of fusion of the PCMs tested and easily attainable in the literature.

The ice box experiments performed used a variety of designs at two different box sizes, 9.5 in and 13 in and one experiment with a large ice pack on the bottom. The results gave a few different physical understandings of the melting process within a cold box which can help future investigations and guided our prototype design. It was observed that although a gradient was developed moving away from an ice pack into air or foam, the gradient was less than predicted by the model. This is attributed to the lack of convection in the computational mode.

The geometry of the ice packs affects the temperature distribution the air. For those designs with an ice pack in the middle, we observed the center icepack plays a role in cooling the system after the outside icepacks have partially melted at which point the outside packs act as secondary insulation. Furthermore the result of geometries with an icepack in the center is an average temperature of the system much higher when shelves are integrated. The higher average temperature can be used to the advantage of a cold box designer as PCM can be used as a sort of insulation by placing it inside the cooling source for the cold box, such as ice.

We were able to further study geometry using 3-D FEA models by creating a theoretical simulation that accurately exhibited phase change behavior using the approximated specific heat method. Further refinement to the model, by adjusting the thermal conductivity of the insulation, yielded results more accurate to experimental and field conditions. Using this adjusted model, we were able to investigate the pros

and cons of different ice box geometries in terms of equal temperature distribution within the cold box and duration of cold storage and a variety of other factors.

Six different geometries were simulated corresponding: all six sides of ice, five sides of ice (not the bottom), six sides of ice with a central, horizontal ice shelf, six sides of ice with a central, vertical ice shelf, two sides of ice at the top and bottom, and one side of ice at the bottom. The all sides model had the most even temperature distribution and rate of melting in the box matching the experimental model. The five sides, no bottom model had a fairly even temperature distribution, except at the points along the bottom of the box where little cooling with prevalent. Both the horizontal and vertical shelf models exhibited longer melting times for the shelf slab, with the outer panels reaching warmer temperature much quicker. The bottom and top slab model showed an obvious temperature gradient throughout the box that mostly fell below the 8 °C mark for the melting regime, and the duration of cold storage was also the longest here, in comparison to the ice perimeter models however, the location of measurement points may not have been conducive to accurate measurement. Finally, the single bottom slab model was ruled out as a viable geometry, given the gross temperature distribution in the box, where little to no cooling was observed at the extremities away from the ice. We concluded that the FEA modeling provides a good basis for eventual prototype construction and that the different geometries, typically not considered in design, play an important role in ice box performance.

We were also able to verify these results using two different size boxes - one with 9.5-in sides and one with 13-in sides. Similar temperature distributions were observed between each size of the same geometry. In most cases, the duration of cold

storage was about twice as long in the larger box models; however there was over four times the volume of ice in the larger box model. This verified that there was a nonlinear relationship between duration of cold storage and volume of PCM, and that other factors (overall size, insulation thickness, insulation quality, etc.) would need to be adjusted to find the optimal cold box and cooling conditions.

Another FEA model was created in 1-D to study the thicknesses of ice and insulation and their effect on the cold time of the box. In the model, where ice, insulation and air were changed iteratively showed the relationship between changing the ice to insulation ratio, as well as increasing the amount of either. This relationship was used to map the relationship between increasing ice or increasing insulation the result is a curve which can determine the optimal ratio of ice to insulation given a designed box size. The true optimum was outside of a realistic box size. The problem with just using ice and insulation is that the air spends a significant time at 0 ºC and this presents an opportunity for vaccines to freeze. To alleviate freezing, Phase 5 ™ PCM was included in the model between the air and the ice. It was found that PCM needs to absorb roughly half of the latent heat of the ice to maintain the temperature of the air at 5 ºC, and that this causes a reduction in the time the box spends below 8 ºC, but protects the vaccines from freezing which increases value. However, a pattern in how long the box would last was not immediately noticeable with the 1-D model with PCM. The model was still usable to find an economic optimum in the ratio of insulation to ice and PCM.

Contribution to World Vaccination

The needs presented by the cold chain studies cited above represent an opportunity for a novel icebox design that would address these issues in a cost-effective manner. There are a few possible refrigeration methods that can help minimize vaccine freezing. Vapor compression refrigeration, as is found in common household refrigerators, is the most used method of active cooling; however, it has significant drawbacks that prevent it from being practical for vaccine storage and transportation. Any active refrigeration device is energy intensive, so they may not be feasible in resource-poor areas where energy is not always reliable (Xinhua, 2009). In addition, refrigerators are heavy and relatively fragile, which precludes frequent transport in areas where conditions are less than ideal. Due to these considerations, we will deploy PCMs as a primary passive cooling source. A cold box incorporating PCM is ideal for transportation because it does not require external energy input and is relatively light and durable compared to a refrigerator ("Product Information Sheets", 2000). Furthermore, PCMs are generally less costly and have a longer lifespan than compression refrigeration systems ("Landscape Analysis: Cool Chain Technologies", 2008).

Benchmarking

In Table 23 we outline the refrigeration products that are similar to our prototype and commercially available. We characterize each product in terms of the parameters that show the product's ability to store vaccines effectively. By examining the literature available by the manufacturers for each product we were able to

successfully detail each parameter. The first parameter reviewed was whether the product used active cooling by a compressor or another method of cooling, as this was one of our primary concerns when designing our prototype. We noticed that in general the active cooling devices, such as the CSafe, Waeco CF-11, Fridge Freeze, and SunFrost refrigerators were the most costly and least durable of the products we assessed. This finding confirmed our research that showed the impracticality of using compression refrigeration in a vaccine cold box. One device, the Envirotainer storage container, uses a unique active cooling method that utilizes dry ice. This product does not have a compressor, but it is designed for long-term storage rather than transport, making it different from our box.

Next, we evaluated if the box or refrigerator could keep the inside compartment between the desired 2-8 ºC. The APEX cold box was the only product that could not maintain the desired temperature range because it uses ice packs in close proximity to the internal compartment. APEX's inability to store vaccines between 2-8 ºC also shows that ice packs are not ideal for vaccine storage.

The next parameters we looked at were the device's portability, weight, durability, and ease of repair. We determined portability by considering the exterior dimensions and durability and we determined ease of repair by considering the materials used. Generally, we also considered any product that weighed over 50 lbs to not be portable. The only two products that were not portable were the CSafe refrigerator and the Envirotainer storage container, both of which are large, heavy boxes, designed for long-term or bulk storage, rather than transportation. The lightest products considered were the Antifreeze backpack at 17.4 lbs. and the Tempak Plus

cold box at 5.5 lbs. We used these as guidelines as to how much our product should weigh.

` Then, we calculated each device's net volume to storage capacity ratio. This statistic assessed how much of the device's volume was dedicated to the actual storage compartment, which would give us an idea of how efficiently the product could store vaccines. The product with the least efficient storage capacity was the SunFrost refrigerator with the ratio of 0.070. As this is a solar-powered refrigerated box, it has many components, including the battery, solar cells, and compressor, all of which restricted the payload space available for vaccines. On the other hand, the Envirotainer had the most efficient storage capacity with the highest ratio of 0.739, primarily due to its unique cooling system that utilizes dry ice.

Next, we determined whether each product had a reasonable cost, as this is a primary concern in developing regions. Among the products for which the pricing was available, the Fridge Freeze refrigerated boxes had the highest cost at $3995, while the Antifreeze Backpack had the lowest cost at $33.78. This data represents a large variable range of prices. We hoped to keep our product's end cost as low as possible, so our aim was to match or beat the price of the Antifreeze backpack.

The penultimate parameter considered was maximum storage duration without any external energy source. The device with the shortest storage duration was the Tempak Plus box, which could keep its compartment cool for 24 hours. This shows that while its emphasis on mobility was effective, it sacrificed the ability to store vaccines for a sufficient amount of time. The product with the longest storage

duration was the CSafe refrigerator with a time of 100 hours, which was primarily achieved because it has a built in battery-powered compressor.

The final parameter we considered was if there was any user input required. All of the products assessed required some level of user involvement, usually in the form of replacing melted ice/PCM packs or setting the temperature of the interior compartment. One of our main goals was to make our cold box user friendly and easily understood in different regions of the world.

Table 23: Benchmarking of competitor products

Product	Active Cooling (compressor driven)	Temperature stable between 2-8 C	Portability/ Weight	Durability	Easily repaired	Net volume to storage capacity ratio	Reasonably cost-effective	Storage Duration	User Input
CSafe	Yes	Yes	Not mobile/ 1425 lbs.	Durable	No	0.416	No	100 hours	Downloadable temperature data
APEX	No – uses ice packs	No	Mobile/light	Yes/ can withstand WHO testing	Yes – no electricity, simple design	0.092	N/A	96 hours	Replace ice packs
Greenbox 12	No – uses PCM	Yes	Mobile/ 22.5 lbs.	Yes	No -	0.184	No – $200	72 hours	Requires refreezing PCM
Model Antifreeze Backpack 7ltd	No – 5 ice packs	Yes	Mobile/ 17.4 lbs.	Yes	Yes	0.103	Yes - $33.78	37 hours	Requires self-assembly
Envirotainer® container RAP t2	Active – dry ice based active temperature control system	Yes - ±20 C	No/ 992 lbs.	Yes	No	0.739	No – $300 per rechargeable day	72 hours	Control unit settings, chaning ice packs
Waeco CF-11	Yes	Yes	Mobile/ 19.4 lbs.	Yes	No	0.231	No – $600	N/A	Temperature control
Fridge Freeze	Yes	Yes	Mobile/ 22 lbs	Yes	No	0.207	No – $3995	N/A	Temperature control
Tempak Plus	No – uses PCM	Yes	Mobile/5.5 lbs.	No – multiple parts	Yes	0.222	N/A	24 hours	Replace gel packs
SunFrost	Yes – solar powered compressor	Yes	Semi-mobile/ 200 lbs.	No – solar panels and compressor	No	0.07	No	N/A	Temperature control, solar panel maintenance

Marketing Plan

Team FRESH has produced a cold chain box that will be used in the cold chain system as the vaccine travels from a manufacturer in developed countries to the health organizations in the less developed countries.

Although our product can be used in any places throughout the cold chain, we will be targeting the region between the intermediate vaccine storage and hospital/health centers.

Presently, our product is in the introductory stage. We first developed our product in 2011 and have made continual improvements and redesigns after conducting more research.

A complete marketing plan can be found in Appendix F.

Suggestions for Future Work

Although our cold box design was optimized to the best of our working ability, many improvements can be made to bring it closer to real utility. The overall size and dimensions of the box could be adjusted for desired use; there was a large range of vaccine storage capacity (5-25L) given for working cold boxes. We merely chose a point within the range that fit our design consideration. In addition, other commercially available phase change materials could have been considered in the design. Unfortunately, funding and availability for small scale testing limited our choices. We did not extensively investigate the overall quality of the insulation, where more optimal density or thermal conductivity could allow for a lower thickness of the necessary insulation. Lastly, design for manufacturing and assembly was not

heavily considered in our design and fabrication processes, where some procedures or further optimization would need to be applied for real world mass production.

Moreover, a working cold box would have to be approved by the World Health Organization, complying with their Performance, Quality, and Safety (PQS) performance specifications for cold boxes. This would require a number of additional features that our current design lacks, including: an approved lid seal, hinges, lid stay, catches and carrying handles. The box must also be corrosion and chemical resistant. In addition, the box should be able to optimally accommodate the four specified types of ice packs used in the cold chain, with attention given to the WHO preferred type (Type 2: 163mm x 90mm x 34mm). Each ice pack type has its own denoted size regulations, and each cold box should be dimensioned to maximize the surface area covered by the ice packs, with minimal gaps. It is important to optimize the PCM-ice ratio for different types of ice pack thickness (Type 1 is 26 mm, and Types 2-4 are 34 mm). Similarly, the vaccine storage compartment could be better dimensioned to accommodate the most vaccine packages. However, because there is no uniform secondary packaging for the vials, this was a difficult design constraint to follow. In the end, the final box should also meet the WHO testing standards for vaccine loading, cold life, and drop tests, as well as be tested under various thermal conditions and stresses that could occur in the large variable environment that is the cold chain.

Conclusion

We have developed a unique method for modeling the thermal characteristics of cold boxes, an innovation that has allowed us to conceptualize a vaccine cold box

that will keep vaccines cool but not freeze them. Our cold box employs the use ice as the cooling agent, and PCM as the stabilizing agent in an optimized geometry to maintain vaccines at 2-8 ºC for. As such, our findings can be used to build new and advanced cold chain transportation mediums that will eliminate vaccine freezing, a widespread issue in the current cold chain, ultimately saving money and lives.

A unique aspect of our cold box is that the cooling agents, the ice packs, are the only parts that are ever stored in a freezer or refrigerator. The vaccines are packed in the box initially and are not removed until they are to be used at their destination. Rather the ice packs are continuously swapped for newly frozen packs. Moreover, since the PCM separates the ice from the vaccines, the vaccines will never freeze, even if a healthcare worker places ice packs that are "too cold" into the box. Indeed, the only maintenance required of the vaccine cold box during transport is to make sure the ice packs are still frozen. As such, we have included sensors attached to the ice packs which change from green to red when the ice is no longer cold enough, indicating the need for new ice packs. In this way we provide protection from the three major causes (among others) that were mentioned above: 1) the vaccines are only packed once, not repacked numerous times, reducing the chance for error in improper packing, 2) the vaccines are never placed in any refrigerator or cold room, hence, adjustable thermostats on freezers and refrigerators are not an issue, and finally, 3) the PCM stabilizes the freezing temperature from the ice packs, and the color change sensors diminish the responsibility and room for error sue to inadequate healthcare training.

Appendices

Appendix A: Base Setup Code for ANSYS Models

The following ANSYS code contains all the basic model parameters that are constants throughout each model iteration. By maintaining this generic file called "base_settings.txt" time was save in modeling each new geometry.

```
/BATCH
! /COM,ANSYS RELEASE 13.0    UP20101012       18:47:13    02/19/2012
/input,menust,tmp,'',,,,,,,,,,,,,,,,1
! /GRA,POWER
! /GST,ON
! /PLO,INFO,3
! /GRO,CURL,ON
! /CPLANE,1
! /REPLOT,RESIZE
WPSTYLE,,,,,,,,0
/PREP7
!*
/NOPR
KEYW,PR_SET,1
KEYW,PR_STRUC,0
KEYW,PR_THERM,1
KEYW,PR_FLUID,0
KEYW,PR_ELMAG,0
KEYW,MAGNOD,0
KEYW,MAGEDG,0
KEYW,MAGHFE,0
KEYW,MAGELC,0
KEYW,PR_MULTI,0
KEYW,PR_CFD,0
/GO
!*
! /COM,
! /COM,Preferences for GUI filtering have been set to display:
! /COM,  Thermal
!*
!*
ET,1,SOLID70
!*
TOFFST,273
!*
MPTEMP,,,,,,,,
MPTEMP,1,-100
MPTEMP,2,0
MPTEMP,3,0.001
MPTEMP,4,100
MPDATA,DENS,1,,916.2
MPDATA,DENS,1,,916.2
```

```
MPDATA,DENS,1,,1000
MPDATA,DENS,1,,1000
MPTEMP,,,,,,,,
MPTEMP,1,-100
MPTEMP,2,0
MPTEMP,3,0.001
MPTEMP,4,100
MPDATA,KXX,1,,2.22
MPDATA,KXX,1,,2.22
MPDATA,KXX,1,,.58
MPDATA,KXX,1,,.58
MPTEMP,,,,,,,,
MPTEMP,1,-100
MPTEMP,2,-.251
MPTEMP,3,-.25
MPTEMP,4,.25
MPTEMP,5,.251
MPTEMP,6,100
MPDATA,C,1,,2050
MPDATA,C,1,,2050
MPDATA,C,1,,668000
MPDATA,C,1,,668000
MPDATA,C,1,,4210
MPDATA,C,1,,4210
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,2,,37.24
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,2,,1300
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,2,,0.0227
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,3,,1.293
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,3,,1005
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,3,,0.0243
! LGWRITE,'base_settings','lgw','H:\Desktop\GEMS\',COMMENT
```

Appendix B: Sample Code for one of the geometry models in ANSYS

```
 /BATCH
! /COM,ANSYS RELEASE 13.0    UP20101012       16:29:02    01/29/2012
/input,menust,tmp,'',,,,,,,,,,,,,,,,1
! /GRA,POWER
! /GST,ON
! /PLO,INFO,3
! /GRO,CURL,ON
! /CPLANE,1
! /REPLOT,RESIZE
WPSTYLE,,,,,,,,0
! /REPLOT,RESIZE
/INPUT,'base','lgw','H:\Desktop\GEMS\Prototype_1\',, 0
!*
MPDE,ALL,2
TBDE,ALL,2
MPTEMP,,,,,,,
MPDE,ALL,4
TBDE,ALL,4
MPTEMP,,,,,,,
MPTEMP,,,,,,,,
MPTEMP,1,-100
MPTEMP,2,-.251
MPTEMP,3,-.25
MPTEMP,4,.25
MPTEMP,5,.251
MPTEMP,6,100
MPDE,C,1
MPDATA,C,1,,2050
MPDATA,C,1,,2050
MPDATA,C,1,,668000
MPDATA,C,1,,668000
MPDATA,C,1,,4210
MPDATA,C,1,,4210
! LGWRITE,'base','lgw','H:\Desktop\GEMS\',COMMENT
BLOCK,0,.3302,0,.3302,0,.3302,
BLOCK,.0254,.3048,.0254,.3048,0.0254,.3048,
BLOCK,0.0254,0.3048,0.0254,0.3048,0.0254,0.3048,
BLOCK,.039605,.290595,.039605,.290595,.039605,.290595,
BLOCK,0.039605,0.290595,0.039605,0.290595,0.039605,0.290595,
! vlist, all
VSBV,      1,      2
! vlist, all
! VPLOT
VSBV,      3,      4
! vlist, all
FLST,2,3,6,ORDE,3
FITEM,2,1
FITEM,2,5
FITEM,2,-6
VGLUE,P51X
! /VIEW,1,1,2,3
! /ANG,1
! /REP,FAST
```

```
! /VIEW,1,,,1
! /ANG,1
! /REP,FAST
WPSTYLE,,,,,,,,0
WPSTYLE,,,,,,,,0
! LGWRITE,'geom','lgw','H:\Desktop\GEMS\13-IN~3W\ALL_S~5W\',COMMENT
! vlist, all
SMRT,6
SMRT,7
SMRT,8
SMRT,7
SMRT,6
CM,_Y,VOLU
VSEL, , , ,      1
CM,_Y1,VOLU
CMSEL,S,_Y
!*
CMSEL,S,_Y1
VATT,      1, ,   1,      0
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
!*
MSHAPE,1,3-D
MSHKEY,0
!*
CM,_Y,VOLU
VSEL, , , ,      1
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
!*
VMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
! NLIST,ALL, , , ,NODE,NODE,NODE
! vlist, all
! VPLOT
WPSTYLE,,,,,,,,0
WPSTYLE,,,,,,,,0
CM,_Y,VOLU
VSEL, , , ,      2
CM,_Y1,VOLU
CMSEL,S,_Y
!*
CMSEL,S,_Y1
VATT,      5, ,   1,      0
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
!*
CM,_Y,VOLU
```

```
VSEL, , , ,      2
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
!*
VMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
! VPLOT
WPSTYLE,,,,,,,,0
WPSTYLE,,,,,,,,0
CM,_Y,VOLU
VSEL, , , ,      3
CM,_Y1,VOLU
CMSEL,S,_Y
!*
CMSEL,S,_Y1
VATT,      3, ,   1,      0
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
!*
CM,_Y,VOLU
VSEL, , , ,      3
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
!*
VMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
! LGWRITE,'meshed','lgw','H:\Desktop\GEMS\13-IN~3W\ALL_S~5W\',COMMENT
!*
ANTYPE,4
!*
TRNOPT,FULL
LUMPM,0
!*
/UI,MESH,OFF
! VPLOT
WPSTYLE,,,,,,,,0
WPSTYLE,,,,,,,,0
! /VIEW,1,1,1,1
! /ANG,1
! /REP,FAST
FLST,2,948,1,ORDE,2
FITEM,2,1
FITEM,2,-948
IC,P51X,TEMP,-10,
```

```
FLST,2,3,1,ORDE,3
FITEM,2,1
FITEM,2,949
FITEM,2,1418
IC,P51X,TEMP,22.5,
FLST,2,6,5,ORDE,2
FITEM,2,1
FITEM,2,-6
!*
/GO
DA,P51X,TEMP,22.5
FINISH
/SOL
DELTIM,60,0.01,300
OUTRES,ERASE
OUTRES,NSOL,5
TIME,300000
! LGWRITE,'ready','lgw','H:\Desktop\GEMS\13-IN~3W\ALL_S~5W\',COMMENT
```

Appendix C: Images of Construction of Prototype 1.0

Figure 58: Cutting a sheet of Lexan using the Black and Deck jigsaw

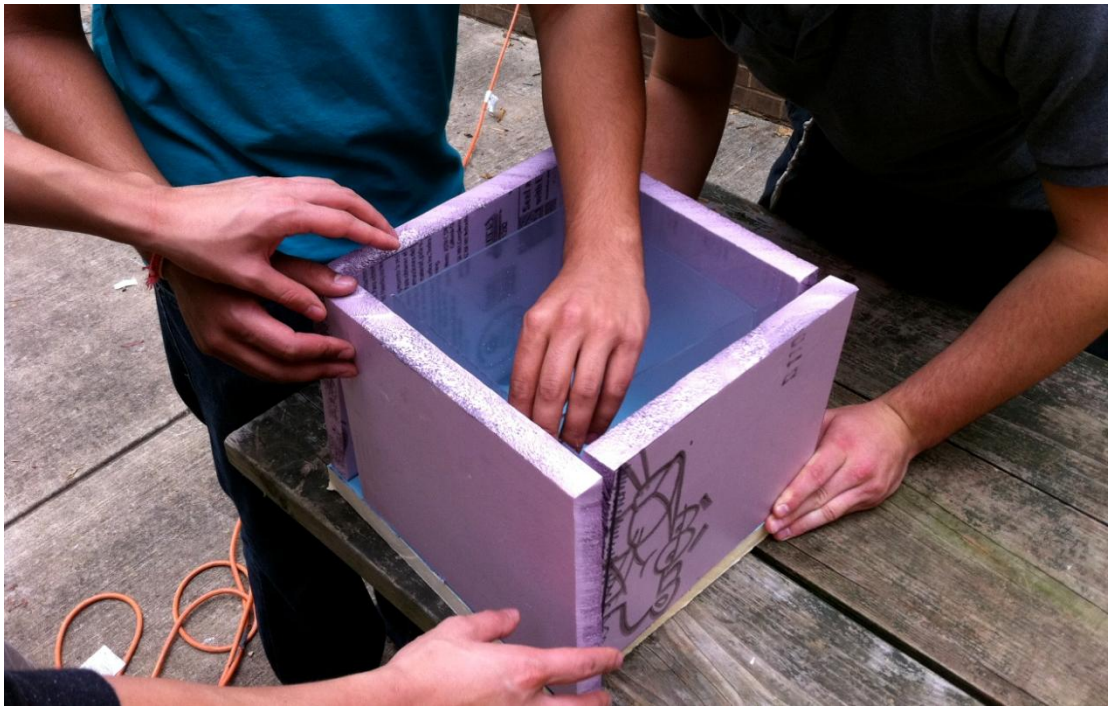


Figure 59: Assembling foam insulation around inner Lexan frame

Figure 60: Using glue to seal gaps between Lexan and Polyisocyanurate base

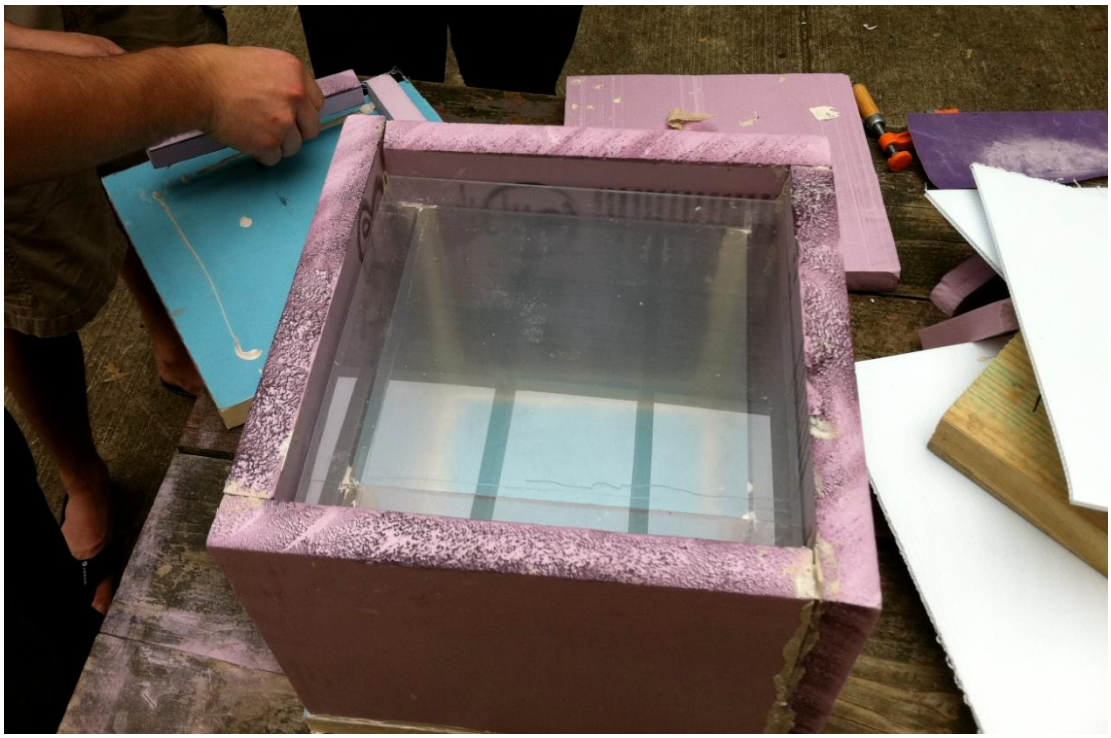


Figure 61: Foreground - assembled box, background - construction of box cover

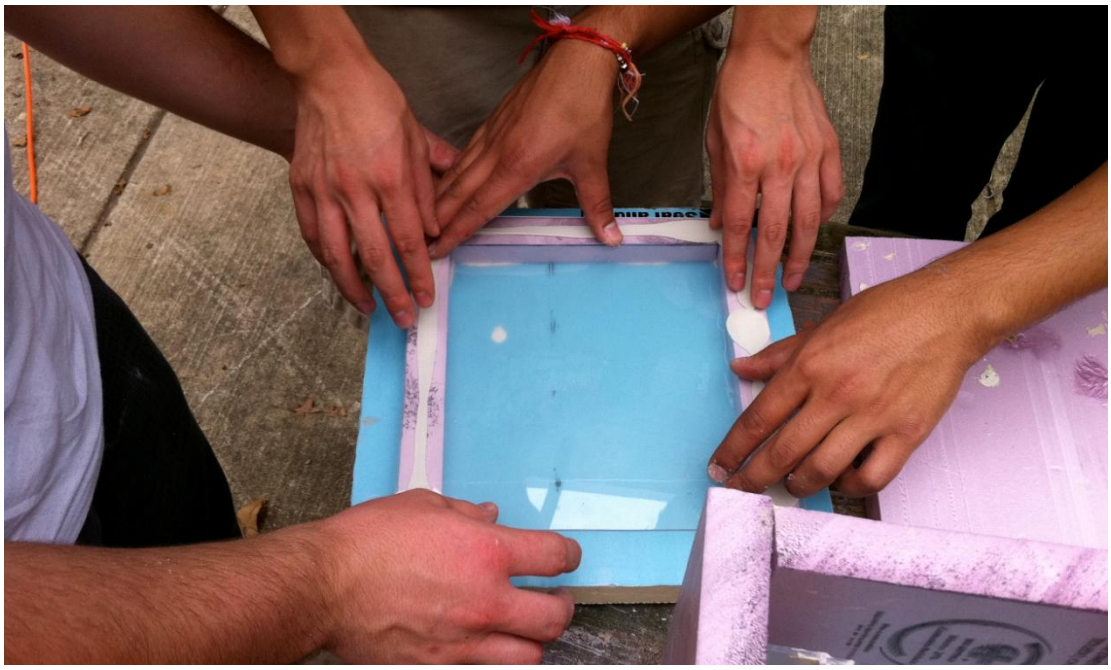


Figure 62: Team effort in assembling PCM slot on underside of box cover

Figure 63: Finished PCM slot on underside of box cover

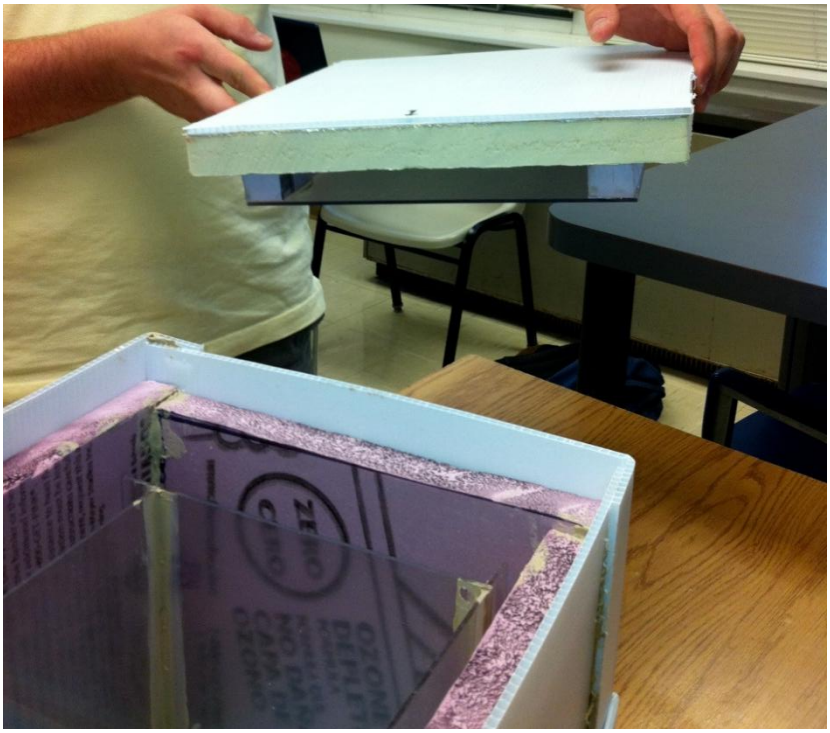


Figure 64: Box cover being placed on box

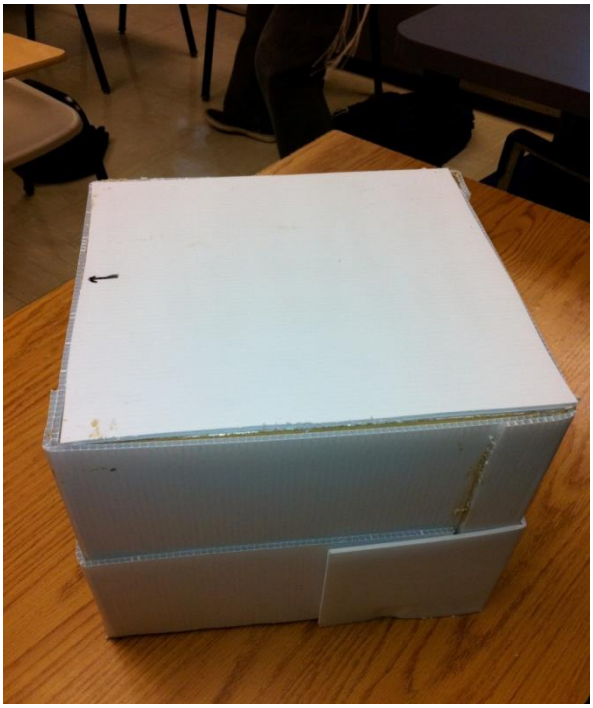


Figure 65: Prototype 1.0

Appendix D: Images from Construction of Prototype 2.0

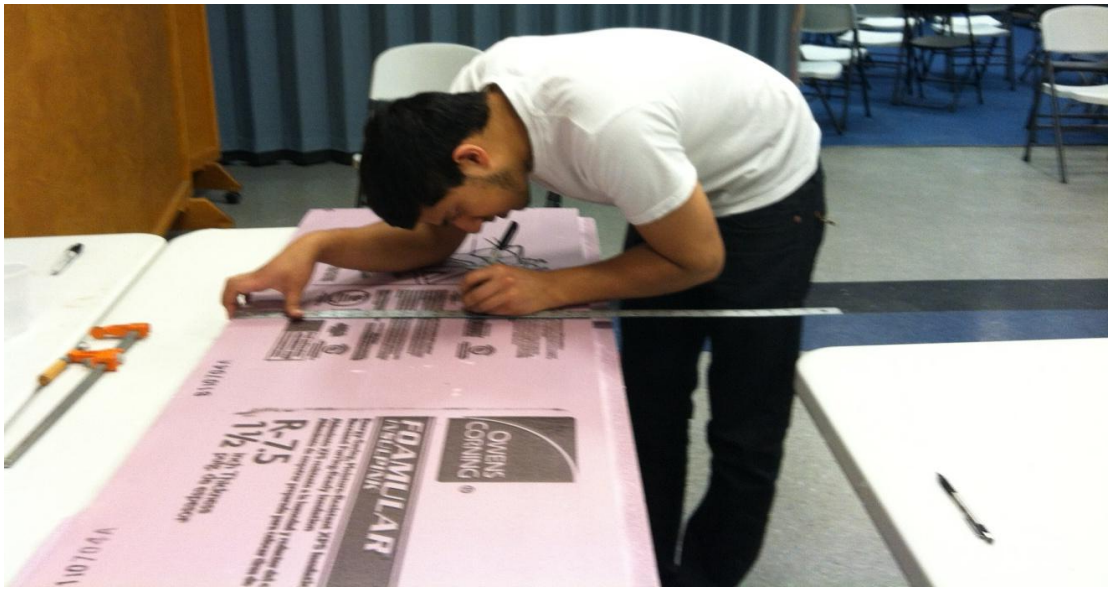


Figure 66: Sahil Shah measuring the Polystyrene sheet for cutting

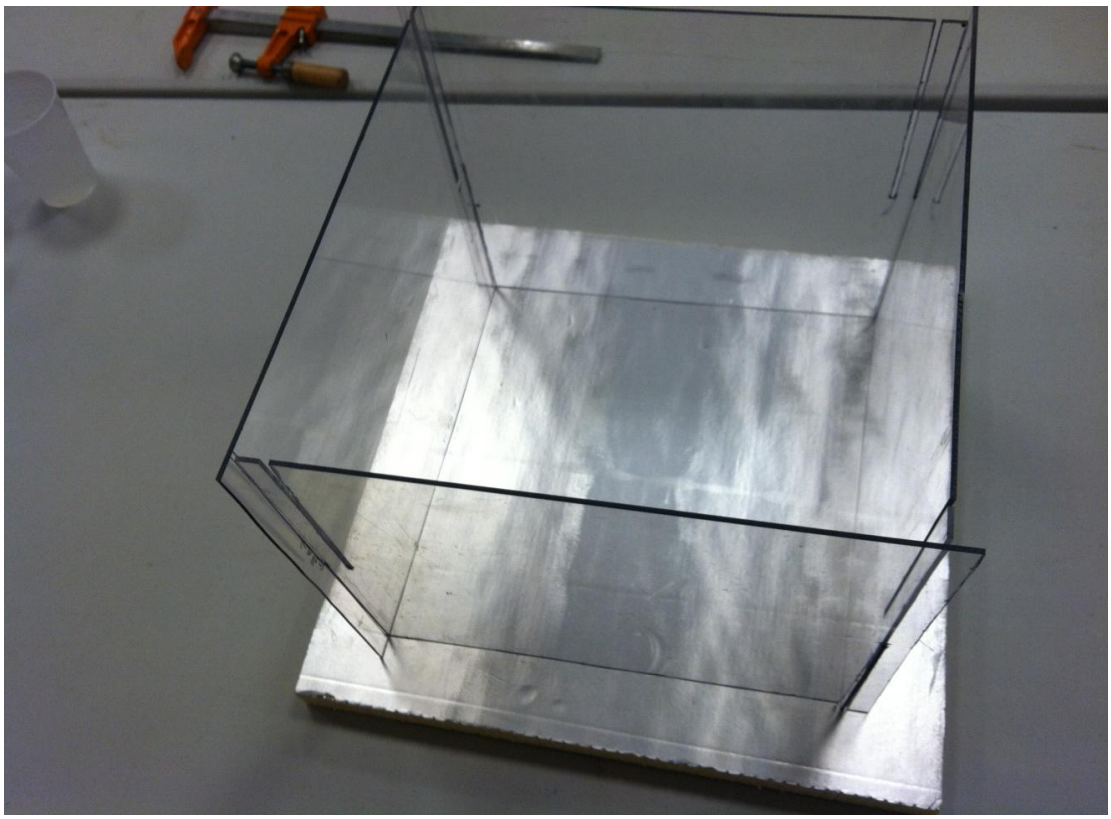


Figure 67: Assembled outer Lexan frame atop the Polyisocyanurate base

Figure 68: Assembled Lexan frame comprising inner and outer panels atop the Polyisocyanurate base

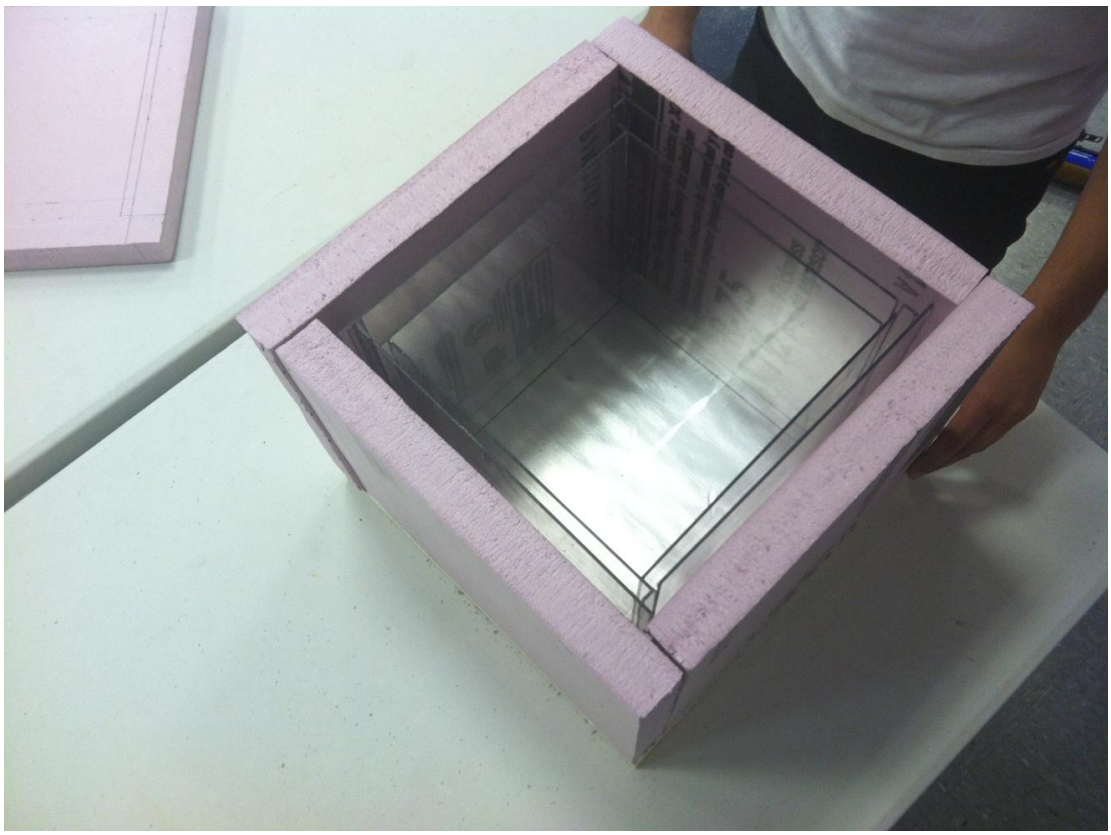


Figure 69: Inner Lexan frame surrounded by 1.5" thick insulation foam

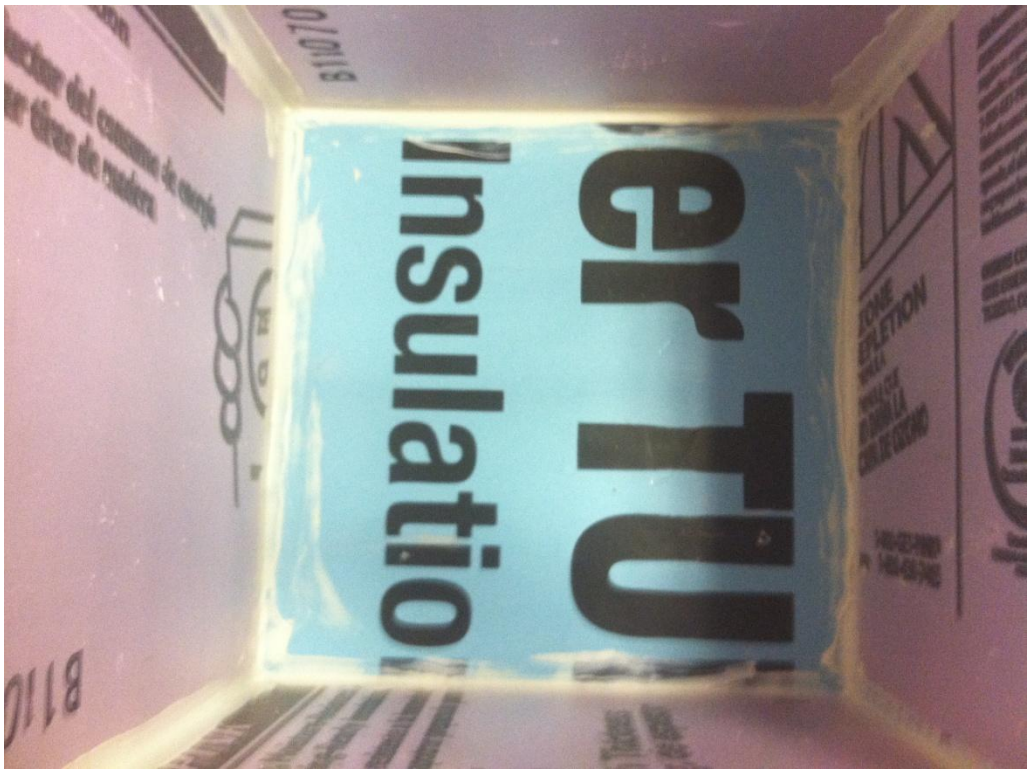


Figure 70: Inside of foam box (with Lexan frame removed) while glue dries in the gaps

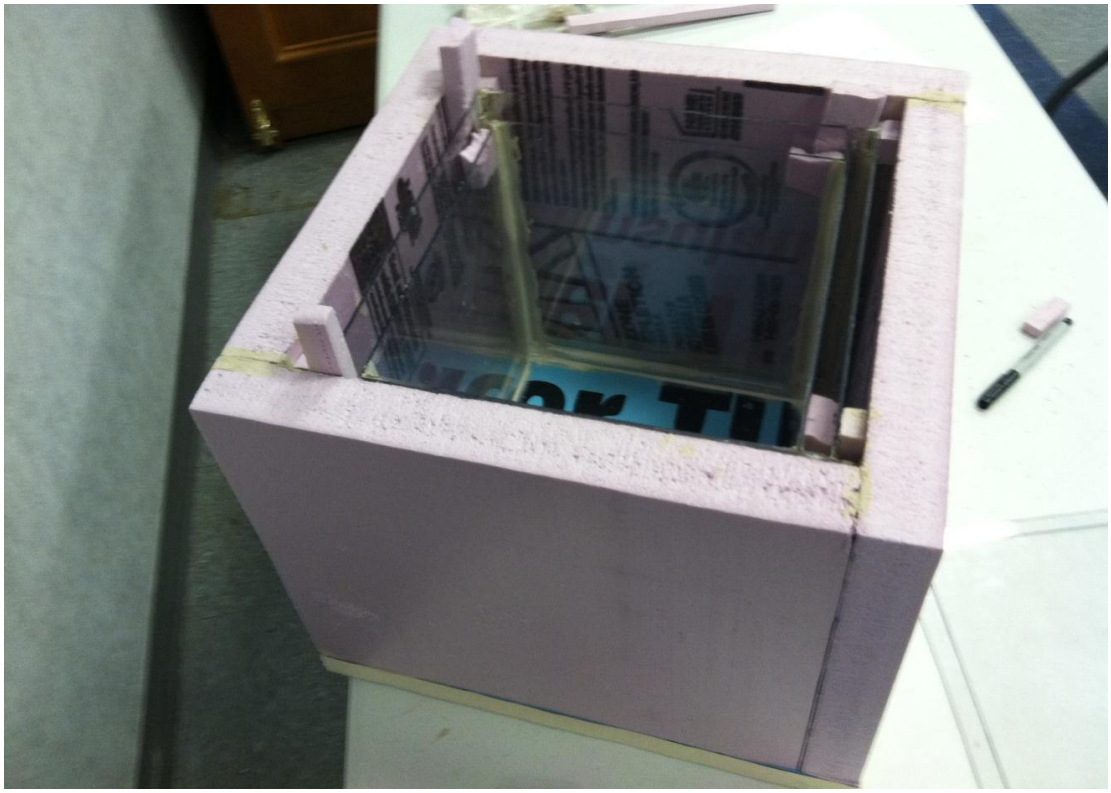


Figure 71: Lexan frame inside polystyrene frame. Spacers are used to ensure frame dries correctly

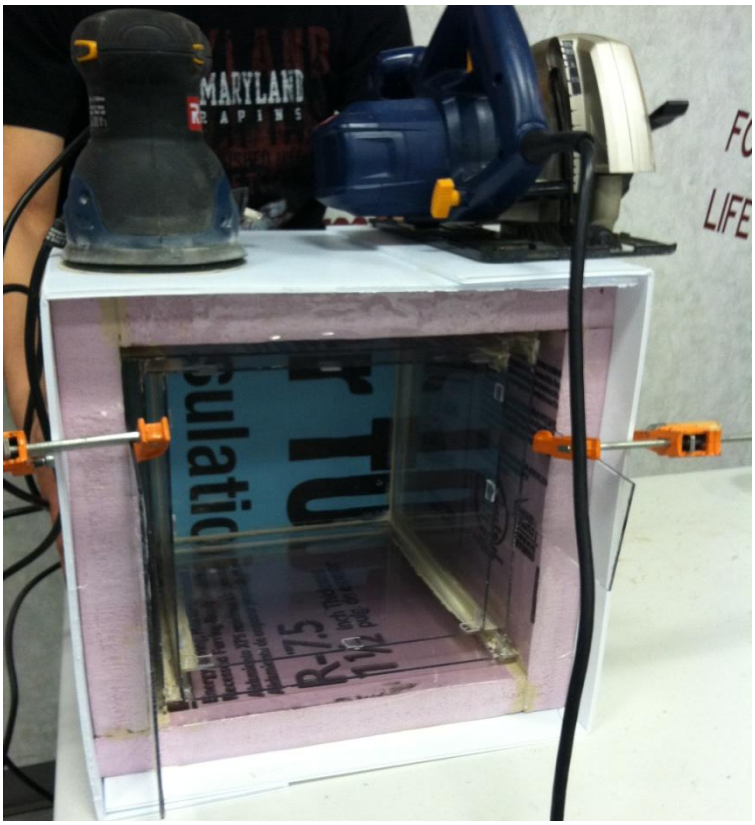


Figure 72: Corrugated plastic (white border) drying around box.
Weights (power sander and circular saw) and C-clamps were used to apply pressure while drying.

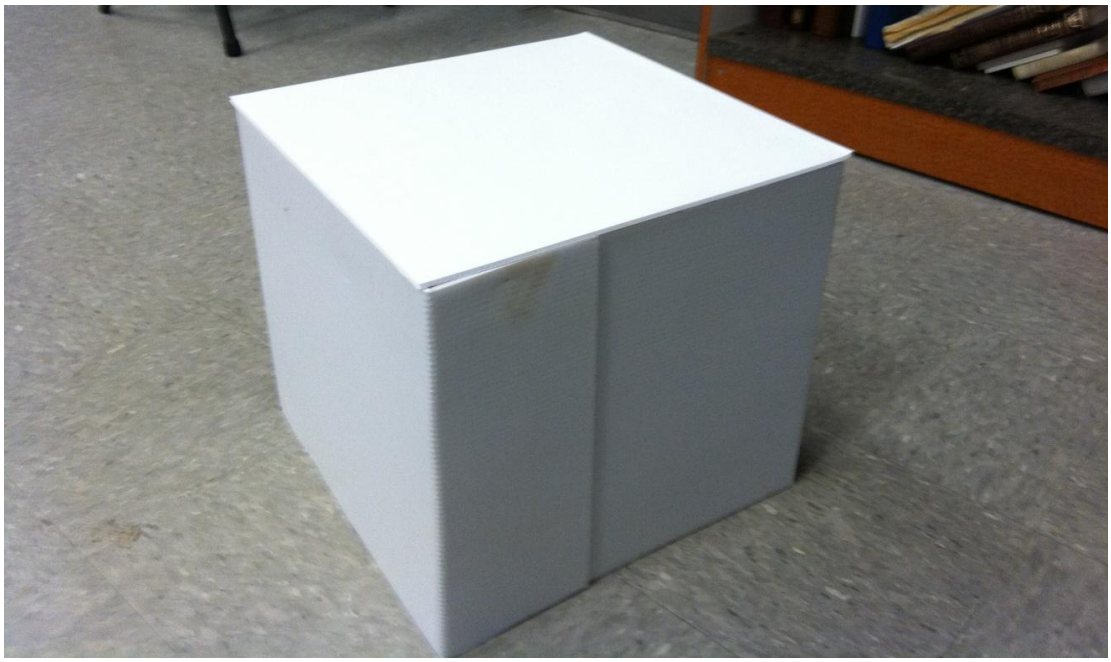


Figure 73: Prototype 2.0

Appendix E: Instruction Manual

INSTRUCTIONS: Traveling Container

Precautions

- Take care when handling the PCM cold box.
- Always make sure that the lid is tightly secured onto the PCM cold box.
- Minimize time of exposure of inside of PCM cold box to external environment.
- After leaving the central level, do not place the PCM cold box in a cold room or freezer. Only place ice packs in freezer.

Emergency Scenarios

- In the event of an emergency, adhere to the contingency plan prepared by responsible health officers at respective health centers.
- Do not leave a cold box or vaccine carrier in a vehicle that is standing in the sun. Take it out of the vehicle and put it in the shade.
- If there is no shade for PCM cold box when left outside, drape a material that reflects light over it. The ideal material is light-colored (preferably white) cloth or paper.
- In case of power failure, place unfrozen ice packs in the bottom of a refrigerator to keep it cool, as indicated below.

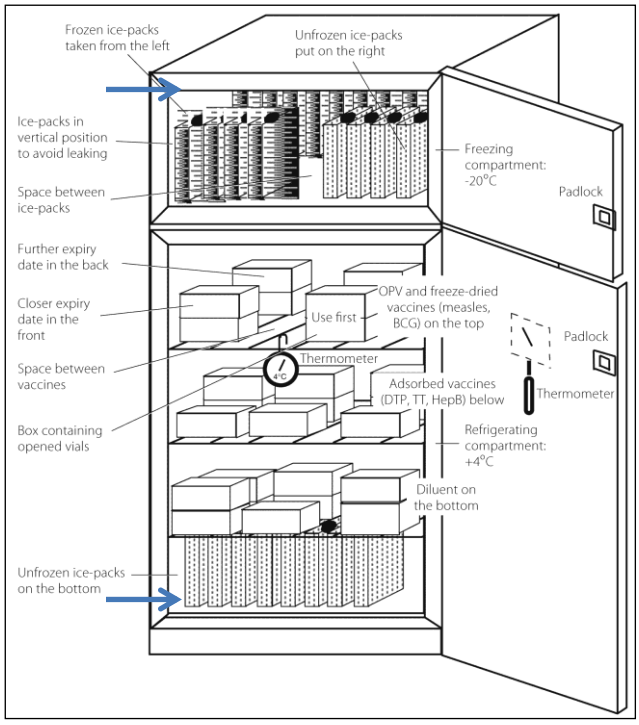


Figure 74: Standard refrigerator with freezer compartment.

Unfrozen ice packs should be stored in freezer compartment (top) unless there is a power failure, at which point unfrozen ice packs should be stored in the bottom of the refrigerator.

- If constrained for time to refreeze ice packs, and pre-frozen ice packs are not available at health center, freeze the ice pack as long as possible and place it back in the PCM cold box. In transport, keep the PCM cold box in the shade, and make another stop as soon as possible to fully freeze ice packs.
- In the following situations, the condition of the PCM cold box is compromised. Vaccines must immediately be taken out of the PCM cold box, and placed back into the existing cold chain transportation/storage infrastructure. The PCM cold box should then be sent back to origin, where the container will be repaired and working parts will be recycled.
    a. PCM breaks or leaks. If PCM does not fill approximately 90% of its packaging, this means that it has been compromised.
    b. Corrugated plastic gets punctured

Responsibility

- In order to successfully execute this plan, every transporter and at least one responsible officer at each respective health center (as identified by the head of the MOH or institution) should follow this flow chart.
- There is never a situation in which the PCM cold box will require expertise to repair; please see "Emergency Scenarios" section for situations in which there are easy repairs; otherwise send the PCM cold box back to distributor.
- Over time, integrate the time sheet into tailored checklists that healthcare workers currently use when transporting/storing vaccines throughout the cold chain.
- Over time, responsible health officers must strive towards these goals (adapted from PATH, USA)
    - Create awareness of the problem among staff. Always explain global evidence and dangers of freezing certain vaccines to healthcare workers involved in the vaccine supply chain.
    - Establish routine surveillance as a practice. Establish practices of continual monitoring, evaluating, and adapting programs to the local environment. Conduct local cold chain freezing studies regularly.
    - Push policy change. Establish new guidelines and procedures for preventing accidental freezing in the cold chain. Network with advocacy groups for targeted local action.
    - Promote public awareness of immunization. Retrain, supervise, and provide materials such as posters and stickers.

Optional Design Additions

- Include sticker of the target country's flag and slogan on PCM cold box to further protect from mishandling. Collaborate with PCM cold box distribution site to acquire stickers or labels.

- In collaboration with PCM cold box distribution site, ensure that all time sheets and instruction manuals are appropriately translated to local languages en route of cold chain.

Note about Flow Chart

- Always start with the first problem shown in the problem-solving flow chart.
- Make sure that a problem does not exist before moving on to the next step. Note all irregularities in ***"TIME SHEET: Traveling Container."*** This sheet will be protected in a plastic sleeve attached to the outside of the PCM cold box.
- Record all time/date values as indicated in ***"TIME SHEET: Traveling Container."***

Assumptions

- Vaccines have already undergone the usual procedures for checking potency under supervision at the central level before being placed for the first time into PCM cold box.
- Traveling containers will be distributed from the central level.
- Responsibility has been given to responsible officers at every point of the cold chain for adhering to this flow chart.
- Upon delivery of the vaccines to the target community, standard procedures regarding testing vaccine potency (VVM, Shake Test) will be followed.
- Traveling containers will be returned to the central level by whatever means appropriate in the target community. Traveling container will be handled with care.

Instructions

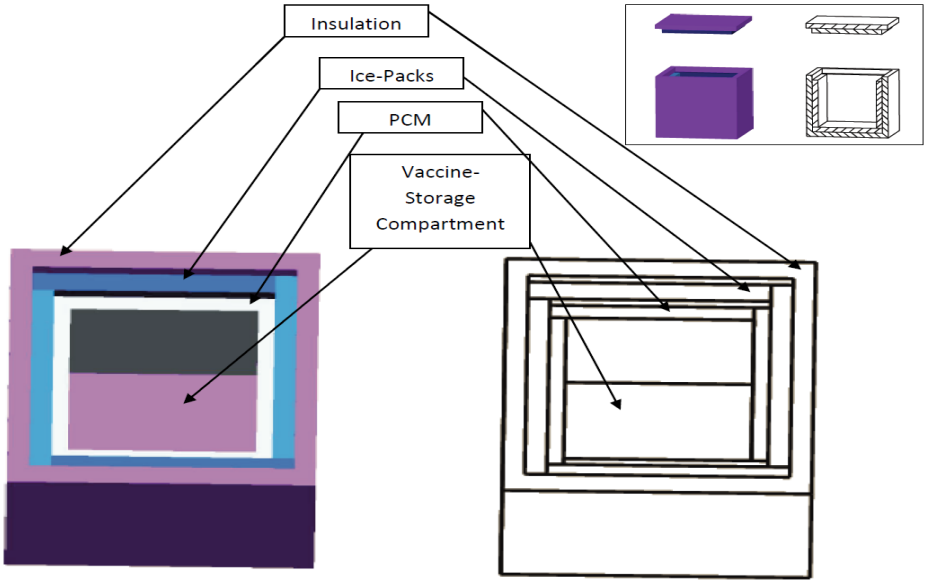


Figure 75: Cross-section of PCM cold box

Figure 76: Color sensor on PCM panels in PCM cold box

- Is the PCM cold box in working condition (No broken PCM panels, no visible leaks inside/outside the container, PCM panels look 90% full)?
    - IF NO, send back to PCM cold box distribution site.
    - IF YES, continue to next step.
- Place vaccines in internal compartment. Is the internal compartment fully closed (plastic lid is fully pressed down to make a tight fit)? NOTE: Do not open this compartment until shipment reaches end of chain.
    - IF NO, close it completely, so that the plastic lid makes a tight fit.
    - IF YES, continue to next step.
- Is PCM cold box in the cold room?
    - IF NO, place in cold room.
    - IF YES, continue to next step.
- Are WHO PQS pre-qualified ice packs available?
    - IF NO, acquire ice packs by asking head of health center.
    - IF YES, continue to next step.
- Observe ice packs. Are WHO PQS pre-qualified ice packs completely frozen (no liquid inside the rigid pack; shake to make sure you can't hear any liquid splashing; make sure that the center is frozen as well as the outside)?
    - IF NO, keep the ice packs in the freezer compartment of refrigerator/cold room to freeze thoroughly. Check if completely frozen before proceeding to next step.
    - IF YES, continue to next step.

- Insert the ice packs into the vaccine carrier. Have ice packs been properly oriented within PCM cold box (Figure 75)?
    - IF NO, use Figure 75 as a guide to ensure proper orientation.
    - IF YES, continue to next step.
- Has the current local time/date/location been written in the TOP BOX on the "*TIME SHEET: Traveling Container*?" NOTE: Irregularities in the journey (emergencies as noted above, changed time schedule) will be **noted in the last column of "*TIME SHEET"***
    - IF NO, record the local time/date/location on the ***"TIME SHEET:*** *Traveling Container*."
    - IF YES, continue to next step.
- In BOLD letters, Mark time (48 hours later) that ice pack must be refrozen based on projected transport route. Write in the FIRST COLUMN on ***"TIME SHEET: Traveling Container."*** Has projected time/date been recorded in appropriate time zone/language for the next stop?
    - IF NO, record the projected local time/date/location on the ***"TIME SHEET: Traveling Container."***
    - IF YES, continue to next step.
- Traveling container is ready to be transported. Has the PCM cold box been placed on a level surface?
    - IF NO, try to ensure the most level surface possible so that the PCM cold box may stay tightly closed for the duration of transport.
    - IF YES, continue to next step.
- Upon reaching the next stop-over (within 48 hours of loading ice packs), has the responsible health officer been contacted?
    - IF NO, contact the responsible officer immediately.
    - IF YES, continue to next step.
- Have there been any irregularities in the journey?
    - IF NO, check the "Emergency Scenarios" section above in INSTRUCTIONS, and make sure there have been no irregularities. Then proceed to next step.
    - IF YES, indicate these to the responsible health officer using the ***"TIME SHEET: Traveling Container."*** Answer any questions, and ensure that the health officer knows that he/she must continue filling the ***"TIME SHEET: Traveling Container"*** for the next leg of the journey. Proceed to next step.
- (Next health officer) Is the PCM cold box in working condition (No broken PCM panels, no visible leaks inside/outside the container, PCM panels are 90% full)?
    - IF NO, send back to PCM cold box distribution site.
    - IF YES, continue to next step.
- Bring the PCM cold box to an area at room-temperature. Quickly open the container, and check the color sensor on the PCM panels (Figure 76). Is the sensor red?
    - IF NO, quickly take out ice packs, and place them in the freezer compartment of refrigerator/cold room to refreeze.

    - IF YES, quickly take out ice packs, and place them in the freezer compartment of refrigerator/cold room to refreeze.
- Has the current local time/date/location been written for SECOND COLUMN on the "*TIME SHEET: Traveling Container*?"
    - IF NO, record the local time/date/location on the ***"TIME SHEET: Traveling Container***."
    - IF YES, continue to next step.
- Has the PCM cold box been placed in a safe location where it will not be touched by others?
    - IF NO, secure a safe location so that the PCM cold box remains in optimal condition for the remainder of the journey.
    - IF YES, continue to next step.

**If there are completely frozen WHO PQS ice packs available in the health center, you may swap those into the PCM cold box directly before the shipment leaves for transport. The same ice packs from the beginning of the journey do not need to be used.

- Are ice packs completely frozen (no liquid inside the rigid pack; shake to make sure you can't hear any liquid splashing; make sure that the center is frozen as well as the outside)?
    - IF NO, keep the ice packs in the freezer compartment of refrigerator/cold room to refreeze. Check if completely frozen before proceeding to next step.
    - IF YES, continue to next step.
- Insert the ice packs into the vaccine carrier. Have ice packs been properly oriented within PCM cold box (Figure 75)?
    - IF NO, use Figure 75 as a guide to ensure proper orientation.
    - IF YES, continue to next step.
- Has the current local time/date/location been written in the THIRD COLUMN of the "*TIME SHEET: Traveling Container*?" NOTE: Irregularities in the journey (emergencies as noted above, changed time **schedule) will be noted in the last column of "*TIME SHEET"***
    - IF NO, record the local time/date/location on the ***"TIME SHEET: Traveling Container***."
    - IF YES, continue to next step.
- In BOLD letters, Mark time (48 hours later) that ice pack must be refrozen based on projected transport route. Write in the FIRST COLUMN, SECOND ROW, on ***"TIME SHEET: Traveling Container."*** Has projected time/date been recorded in appropriate time zone/language for the next stop?
    - IF NO, record the projected local time/date/location on the ***"TIME SHEET: Traveling Container."***
    - IF YES, continue to next step.
- Traveling container is ready to be transported. Has the PCM cold box been placed on a level surface?
    - IF NO, try to ensure the most level surface possible so that the PCM cold box may stay tightly closed for the duration of transport.
    - IF YES, continue to next step.

Repeat above steps to load and refreeze ice packs, while recording indicated time points in the next row of *"TIME SHEET: Traveling Container"*** until you arrive at the target community.

- Upon reaching the target community, has the responsible officer been notified?
    - IF NO, immediately notify the point health officer. If there is difficulty, inform health professionals on site, and suggest contacting the Ministry of Health.
    - IF YES, continue to next step.
- (Next health officer) Is the PCM cold box in working condition (No broken PCM panels, no visible leaks inside/outside the container, PCM panels look 90% full)?
    - IF NO, send back to PCM cold box distribution site.
    - IF YES, continue to next step.
- Open internal storage compartment within PCM cold box, and take out vaccines in a safe, stable, and shaded area if possible. Defer to check vaccine potency by WHO procedures (Shake Test, VVM). Have vaccines been unloaded and passed on to health staff?
    - IF NO, unload the vaccines and notify responsible health officer. Then close PCM cold box, and send it back to central level distribution site.
    - IF YES, close PCM cold box and send it back to central level distribution site.

TIME SHEET: Traveling Container

Time/date/location ice packs initially loaded into traveling container:

Estimated time/date/location for refreezing ice packs	Time/date/location ice packs are placed into freezer	Time/date/location ice packs are reloaded into PCM cold box	Additional Comments (Note any irregularities here)

Appendix F: Marketing Plan

EXECUTIVE SUMMARY

Mission

Our company's mission is to develop a vaccine cold box that prevents vaccine freezing and can be used throughout the cold chain.

Company

Team FRESH was founded in 2009 and we are an innovator in the vaccine storage marketplace. We aspire to develop and deliver to our customers a cheaper and more efficient product to be used in the cold chain system.

Business

We are a service provider that is seeking to sell its prototype design to a manufacturer that will be able to mass-produce our product. Our company is at the seed stage of business, having just developed an initial prototype. We will conduct more field-testing, experimentations and lab testing to develop a better-designed prototype.

Currently, our company has continued to perform more research to determine the optimal dimensions for our second prototype. We have sufficient funding to start the initial research and development; however, we need more funds to conduct field-testing that will help better emulate the conditions of our marketplace.

Product or Service

Team FRESH will produce a vaccine cold box design that will be used in the cold chain system as the vaccine travels from a manufacturer in developed countries to the health organizations in the LMICs.

Our product is unique because it has a larger vaccine storage capacity and is more cost effective than the current products in the market.

The Market

The organizations that oversee the cold chain in LMICs are the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), which are both part of the GAVI alliance, an initiative started to coordinate and collaborate between Non-Governmental Organizations (NGOs) and target countries. These organizations are the main buyers of vaccine cold boxes such as ours, and they have stringent requirements that every refrigerator and cold box must meet before it can be considered for implementation in the cold chain. Therefore, our primary concern during testing is to prove that our concept can meet these requirements.

Competition

We outlined the commercially available refrigeration and cold boxes that are similar to our prototype, and we characterized each product in terms of the parameters that show its ability to store vaccines effectively by examining the literature available by the manufacturers. The parameters examined were: Active cooling, temperature stability between 2-8 °C, portability/weight, durability, ease of reparability, storage capacity to net volume ratio, cost-effectiveness, storage duration and user input.

Risk/ Opportunity

The greatest risks we face are limited field experience, not meeting WHO standards, production, and competition. We know that we can overcome these risks by connecting with experts, completing proper testing, outsourcing our production,

and completing a thorough benchmarking of the competition and emerging technologies. The latter we have already completed.

We have an exciting and promising future, with many substantial opportunities ahead of us. We have the opportunity to become the primary vaccine cold box in the cold chain for LMICs, if we can overcome the risks we have outlined.

Management Team

Our team is composed of 13 undergraduate students who come from diverse backgrounds and academic pursuits. We have five women and eight men whose disciplines vary from business, Spanish, Arabic, engineering, government and politics to biology.

Capital Requirements

We seek additional funds that will enable us to conduct more testing. This is a necessary step as we hope to address the demands and requirements of the World Health Organizations and the health centers in the less developed countries.

MISSION

Mission Statement

Our goal is to develop a vaccine cold box that prevents vaccine freezing and can be used throughout the cold chain. We aspire to carry a reputation in the marketplace for developing and delivering a cheaper, more efficient product that is sold at an affordable price for the primary use in the vaccine storage market. We will achieve this through extensive research into the product design and specifications, as well as our thorough understanding of the marketplace and its demands.

To accomplish our goal, Team Fixing Refrigeration Efficiency to Sustain Health (FRESH) needs capital to continue improving our research and development, as well as expand our field-testing procedures to create an optimal prototype.

In pursuit of our goal, we will treat customers and the community with the best customer service, answering any questions and concerns that they may have. The foundation of our relationship begins with a quality product; after developing a sound initial connection with the stakeholders, through first-class service, we hope to continue to work with our partners into the future.

THE COMPANY

Team FRESH was founded in 2009 under the Gemstone program, a unique multidisciplinary four-year research program for selected undergraduate honors students at the University of Maryland. Our company addresses the current need in the vaccine distribution market, called the "cold chain."

In addition to the effects on public health due to vaccine wastage, there is a significant loss of capital. We hope to design a cold box that will prevent freezing and reduce wasted capacity in vaccine carriers. We will develop a prototype that we can outsource to another company for mass-production.

Strategic Alliances

Team FRESH has developed important and profitable strategic alliance with the Centers for Disease Control (CDC). CDC is an organization under the Department of Health and Human Services whose mission is to "create the expertise, information, and tools that people and communities need to protect their health – through health

promotion, prevention of disease, injury and disability, and preparedness for new health threats" (Control, 2010). Through our partnership, we are able to receive current feedback about our findings concerning the cold chain. This partnership helps us understand what the optimal strategy is concerning our prototype design.

THE BUSINESS

Team FRESH is a service provider that seeks to sell its prototype to a manufacturer mass-production. Our company is at the seed stage of business, having just developed an initial prototype. We will conduct more field-testing, experimentations and lab testing to develop a better-designed prototype.

Product or Service

Team FRESH will produce a cold box that will be used in the cold chain system as the vaccine travels from a manufacturer in developed countries to the health organizations in the less developed countries (Figure 77). Although our product can be used at any stage throughout the cold chain, we will be targeting the region between the intermediate vaccine storage and hospital/health centers, as it is here where most of the deficiencies in vaccine transportation occur.

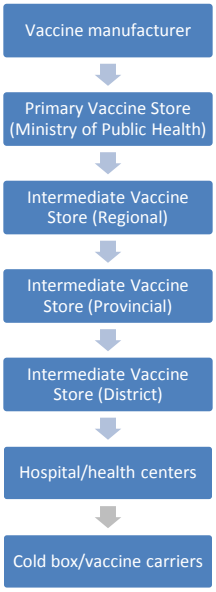


Figure 77: The cold chain

Presently, our product is in the introductory stage. We first developed our product in 2011 and have made continual improvements and redesigns after conducting more research.

Unique Features or Proprietary Aspects of Product

Although there are similar products that address the same market, we are able to differentiate ourselves because of two specific reasons: affordability and vaccine storage capacity. We believe that the prices for similar products in the current marketplace are too high. By selecting optimal materials and design, we believe we have created a better cold box than those currently in existence. In addition, most of the current cold boxes have a relatively low vaccine storage capacity compared to their external dimensions. We have addressed that issue and have a greater effective storage capacity than other products.

Research and Development

Our research will combine lab bench measurements and numerical simulations towards the optimization of temperature stability for vaccines as they move through the cold chain. Characterization of several phase change materials (PCMs) will use well-established experimental techniques in materials characterization to obtain data. This data will fill existing inhibiting gaps in these PCMs' characterization and is required for accurate simulation, prediction, and validation of temperature stability. The greatest impact of our proposed work is the development of novel strategies for more efficient integration of PCM technology into engineering design. The majority of current strategies that incorporate PCMs into passive refrigeration systems simply use more PCM to deliver temperature stability for a longer duration. The novelty of our approach is that we consider the arrangement of PCMs with respect to heat sources, heat sinks, and the environment that will optimize temperature stability at multiple temporal and spatial scales in

addition to the quantity of PCM used. Our design criteria for the proposed project are guided by the necessity to decrease freeze damage to vaccines, increase payload volume, and maximize ease of use for operators in order to minimize human errors, thereby increasing efficiency of vaccine delivery. Through comprehensive materials characterization, novel and more accurate predictive simulation approaches, and experimental validation of these theoretical models, our work should broadly transform the engineering of passive refrigeration systems. This will lead to further innovations by allowing for a series of experiments that can develop a thermally optimized system, which is a unique approach to the use of modeling programs.

New and Follow-up Products

There are many alternative uses for our product. In addition to vaccines, our box can be adapted to be used in various other markets, such as blood, organs, food, insulin, and other pharmaceuticals.

Production

Our product will be subcontracted in order to mass-produce our prototype. We do not possess the resources necessary to produce a cold box in large quantities.

Uniqueness

Our product is unique because we will have an advantage in the marketplace through our patent and partnerships with various organizations.

THE MARKET

Market Definition

Since vaccines contain temperature-sensitive biological substances, they must be kept between 2-8 °C from the time of production until usage to maintain efficacy and prolong shelf life (Craig, 2008). If subjected to improper refrigeration (overheating or freezing), vaccines are rendered ineffective. Conditions conducive to vaccine storage are achieved through the cold chain, which is the temperature-regulated supply network for vaccine transport and storage. The cold chain equipment that keeps vaccines cool consists of various cooling systems including refrigerated vehicles, vaccine carriers, cold storage rooms, freezers, refrigerators, and cold boxes. In a typical cold chain, large shipments of up to 150,000 vials of vaccines are shipped or flown in refrigerated containers or compartments from the manufacturer to the national airport of the destination country (UNICEF, 2004). The vaccines are stored in a cold room at the airport until a refrigerated truck delivers them to the primary vaccine store, which is generally the country's Ministry of Health, from where vaccines are delivered periodically to regional centers, provincial health centers, local health centers, and eventually individual outreach clinics (Figure 77) ("Guidelin for Establishing or Improving Primary and Intermediate Vaccine Stores," 2002).

The entire delivery process, depending on demand, can be as short as a month or as long as three months (UNICEF, 2004). Various studies have shown that vaccines in the cold chain within a wide range of countries including Thailand, India, Malaysia, Indonesia, Papua New-Guinea, Vietnam, New Zealand, Australia, Bolivia, Ethiopia, and even the United Kingdom and the United States are often exposed to

freezing (<0 °C) temperatures, likely rendering them impotent due to the inactivation of key organic components (D. M. Matthias, Robertson, J., Garrison, M. M., Newland, S., Nelson, C., 2007; C. M. Nelson, Wibisono, H., Purwanto, H., Mansyur, I., Moniaga, V., & Widjaya, A., 2004; Techathawat, 2007; T. Wirkas, Toikilik, S., Miller, N., Morgan, C., & Clements, C.J., 2007). Such vaccine losses result in great financial loss for immunization programs, as well as potential danger to patients.

One of the most prevalent factors attributed to vaccine freezing is the lack of a stable temperatures in the cold boxes, which contain ice packs that freeze at 0 °C ("Landscape Analysis: Cool Chain Technologies", 2008). In one study, a staggering 70% of vaccines were discarded upon delivery, mostly due to freeze-damage (Techathawat, 2007). The widespread freezing of vaccines can be attributed to many factors, the most prevalent of which is the lack of stable temperatures in the refrigeration cell during transport and storage. A study of the cold chain in Papua New Guinea showed that during transport from the provincial vaccine stores (PVS) to local health centers and outreach clinics, vaccine loads were partially freeze-damaged, reaching an average temperature of -3 °C (T. Wirkas, Toikilik, S., Miller, N., Morgan, C., & Clements, C.J., 2007).

Freezing during transport is ascribed to the storage method en route, which generally consists of boxes lined with ice packs. Vaccines that come in direct contact with the ice packs will likely freeze; however, placing a buffer region in between the vaccines and ice requires larger transport containers and greater transport capacity, thus increasing costs and decreasing efficiency. There is also no regulation of temperature within the cold boxes ("Landscape Analysis: Cool Chain Technologies",

2008). In addition, trucks carrying vaccines often struggle to transport vaccines due to poor roads or lack of roads in remote areas (Hopkins, 1985).

Once the vaccines reach the villages, the most basic refrigeration technology and transportation methods are used to deliver and store the vaccines. The power supply becomes increasingly intermittent and transportation becomes more difficult. These problems manifest themselves throughout the local level of the cold chain, resulting in inefficient and unsafe delivery of vaccines. In terms of refrigeration, it is at this stage that many vaccines are kept in ice-lined boxes, which can cause the vaccines to freeze, rendering them useless (WHO, 1999). A PEPFAR (U.S. President's Emergency Plan for AIDS Relief) evaluation of local vaccine stores in Ethiopia showed that the intermittent power supply there necessitated the use of back-up power sources that are often not reliably in place. In theory, the back-up power sources are designed to safely power down the equipment when the main power supply cuts off, but improper wiring of these sources leads to unstable conditions for the vaccines. The evaluation concluded that electricity needs are not integrated in health center planning (USAID, 2008). Furthermore, in many regions of South East Asia, particularly in Indonesia, local midwives are the intermediaries administering the vaccines. They often have to store vaccine vials in their households for the entire village. Standard refrigerators are cumbersome in size and energy demands (C. M. Nelson, Wibisono, H., Purwanto, H., Mansyur, I., Moniaga, V., & Widjaya, A., 2004).

Other recent studies have also shown similar issues in relation to regional cold chains. Malik, et al. conducted a survey in Kolkata, India, through which they

identified issues such as cold chain maintenance, placement of vaccines, and availability of some equipment. The authors were able to address some of these problems, but the issue of long-term storage persisted (Dasgupta S, 2010). In another recent article published by Lee et al. in 2011, the authors replaced the traditional ten dose vials with one dose vials in an effort to reduce the amount of wasted vaccines. The increased number of vials proved problematic, however, as it presented space issues in the refrigerators, and the doctors noticed more broken vials as a result of mishandling (Lee et al., 2011). These studies show the importance of strengthening the cold chain infrastructure.

In 2008, the WHO released an analysis of the current cold chain landscape and the main challenges and necessities for the future. The analysis notes that there will be a eight-fold increase in the number of vaccines distributed in the next few years, necessitating an increase in storage capacity. The landscape analysis also underscored the importance of developing passive cooling technologies and improved temperature monitoring devices ("Landscape Analysis: Cool Chain Technologies", 2008).

The needs presented by these studies represent an opportunity for a novel icebox design that would address these issues in a cost-effective manner. There are a number of possible refrigeration methods that can help minimize vaccine freezing. Compression refrigeration, as is used in common household refrigerators, is the most used method of active cooling, but it has significant drawbacks that prevent it from being practical for vaccine storage and transportation. Any active refrigeration device is energy intensive, so they may not be feasible in resource-poor areas where energy

is not always reliably available (Xinhua, 2009). In addition, refrigerators are heavy and relatively fragile, which precludes frequent transport in areas where conditions are less than ideal.

Due to these considerations, we will deploy PCMs as a primary passive cooling source. A cold box incorporating PCM is ideal for transportation because it does not require external energy input and is relatively light and durable compared to a refrigerator ("Product Information Sheets", 2000). Furthermore, PCMs are generally less costly and have a longer lifespan than compression refrigeration systems ("Landscape Analysis: Cool Chain Technologies", 2008).

Market Segment

The organizations that oversee the cold chain in LMICs are the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), which are both part of the GAVI alliance, an initiative started to coordinate and collaborate between these NGOs and the target countries. These organizations are the main buyers of vaccine cold boxes such as ours, and they have stringent requirements that every refrigerator and cold box must meet before it can be considered for implementation in the cold chain. Therefore, our primary concern during testing is to prove that our concept can meet these requirements. The main standards have been compiled in the Performance and Quality Standards (PQS) published by the WHO. The different points relevant to our long-range vaccine cold box concept are summarized in the following table:

Table 24: WHO requirements ("PQS Performance Specification: Vaccine Cold Box", 2008)

Category	Requirement	Prototype Comments
Performance		
Vaccine Storage Capacity	5.0 – 25.0 Liters	8.4 L
Cold Life	96 hours	96 hour cold life
Shape	Square or rectangular	Square shaped payload
Stacking	Multiple units must be stackable	Flat top, bottom, and sides
Robustness	Withstand a one meter drop on all sides/angles	Testing pending
Environmental Considerations		
Ambient Temperatures	Usable in temperatures from -30 °C - +50 °C	Testing Pending
Physical Characteristics		
Weight	Max: 50 kg.	Weight:
Interface Compatibility		
Ice Packs	Must accommodate different types of approved ice packs	PCM slots can accommodate ice packs
Vaccine Packaging	Must accommodate different vaccine packaging	Versatile cube for vaccine payload space
Transportation Mode	Must fit in any transport vehicle used	Small, rectangular package
Materials		
Casing	Resistant to UV degradations and must be water proof	Corrugated plastic is rugged material
Disposal	All materials must be environment-friendly	All materials can be disposed of safely

Our final prototype has been designed specifically to follow the PQS requirements, and we have tested some properties to verify that they meet the standards. Our prototype still needs to be tested in the field in an actual cold chain setting in order for us to confirm its practical versatility, usability, and durability. After testing our cold box in a LMIC's cold chain, we can show the WHO and

UNICEF that our concept can lead to an improved cold box design that can help decrease vaccine wastage by preventing freezing during transport.

Marketing

Our marketing plan is unorthodox in the sense that we hope to prove our concept so that we may contract our prototype to be mass-produced by a third party. If WHO approves our design, we will be able to distribute our product design. We hope to become the leading product in the cold chain system market.

Position

We will be position our product design as an exceptional product at an affordable cost. We have increased the vaccine storage capacity in our product, a characteristic that was not answered as best as possible by other products.

Pricing

Our pricing strategy is to price our prototype as a cheap, yet quality product. We want to have the highest market share in the marketplace. We are focused on becoming a market share leader because we believe our product will answer the problems in the cold chain the most efficiently.

Distribution Channels

Our distribution channel is the third-party that we contract to mass-produce our prototype. This makes sense because the manufacturers have more resources to distribute the products.

COMPETITION

In Table 23 in the text (also reproduced below), we outlined the refrigeration products similar to our prototype that are commercially available. We characterized

each product in terms of the parameters that show the product's ability to store vaccines effectively by examining the literature available from the manufacturers. The first parameter reviewed was if the product used active cooling by a compressor, as this was one of our primary concerns when designing our prototype. We noticed that in general, the active cooling devices, such as the CSafe, Waeco CF-11, Fridge Freeze, and SunFrost refrigerators were the most costly and least durable of the products we assessed. This finding confirmed our research that showed the impracticality of using compression refrigeration in a traveling vaccine cold box. One device, the Envirotainer uses a unique active cooling method that utilizes dry ice. This product does not have a compressor, but it is designed for long-term storage, rather than transport.

Next, we evaluated if the box or refrigerator could keep the inside compartment between the desired 2-8 °C. The APEX cold box was the only product that cannot maintain the desired temperature range because it uses ice packs in close proximity to the internal compartment. This lack of ability to store vaccines between 2-8 °C also shows that ice packs are not ideal for vaccine storage.

The next parameters we looked at were the device's portability, weight, durability, and ease of repair. We determined portability by considering the exterior dimensions, and durability and ease of repair by considering the materials used. Generally, we also considered any product that weighed over 50 lbs to be not portable. The only two products that were not portable were the CSafe refrigerator and the Envirotainer storage container, both of which are large, heavy boxes, designed for long-term or bulk storage, rather than transportation. The lightest

products considered were the Antifreeze backpack at 17.4 lbs. and the Tempak Plus cold box at 5.5 lbs. We used these as guidelines as to how much our product should weigh.

Then, we calculated each device's storage capacity to net volume ratio. This statistic assessed how much of the device's volume is dedicated to the actual storage compartment, which would give us an idea of how efficiently the product stores vaccines. The product with the least efficient storage capacity was the SunFrost refrigerator with the lowest ratio of 0.070. As this is a solar-powered refrigerated box, it has many components, including the battery, solar cells, and compressor, all of which restrict the payload space available for vaccines. On the other hand, the Envirotainer had the most efficient storage capacity with the highest ratio of 0.739, primarily due to its unique cooling system that utilizes dry ice.

Next, we determined whether each product had a reasonable cost, as this is a primary concern in developing regions. Among the products for which the pricing was available, the Fridge Freeze refrigerated boxes had the highest cost of $3995.00, while the Antifreeze Backpack had the lowest cost of $33.78. This data represents a large variable range of prices. We hope to keep our product's end cost as low as possible, so our aim was to match or beat the price of the Antifreeze backpack.

The penultimate parameter considered was maximum storage duration without any external energy source. The device with the shortest storage duration was the Tempak Plus box, which could keep its compartment cool for 24 hours. This shows that while its emphasis on mobility was effective, it sacrificed the ability to store vaccines for a sufficient amount of time. The product with the longest storage

duration was the CSafe refrigerator with a time of 100 hours, which was primarily achieved because it has a built-in battery-powered compressor.

The final parameter we considered was if there was any user input required. All of the products assessed required some level of user involvement, usually in the form of replacing melted ice/PCM packs or setting the temperature of the interior compartment. One of our main goals was to make our cold box user friendly and easily understood in different regions of the world.

Description of Competitors

Table 25: Benchmarking of competitor products

Product	Active Cooling (compressor driven)	Temperature stable between 2-8 C	Portability/ Weight	Durability	Easily repaired	Net volume to storage capacity ratio	Reasonably cost-effective	Storage Duration	User Input
CSafe	Yes	Yes	Not mobile/ 1425 lbs.	Durable	No	0.416	No	100 hours	Downloadable temperature data
APEX	No – uses ice packs	No	Mobile/light	Yes/ can withstand WHO testing	Yes – no electricity, simple design	0.092	N/A	96 hours	Replace ice packs
Greenbox 12	No – uses PCM	Yes	Mobile/ 22.5 lbs.	Yes	No -	0.184	No – $200	72 hours	Requires refreezing PCM
Model Antifreeze Backpack 7ltd	No – 5 ice packs	Yes	Mobile/ 17.4 lbs.	Yes	Yes	0.103	Yes - $33.78	37 hours	Requires self-assembly
Envirotainer® container RAP t2	Active – dry ice based active temperature control system	Yes - ±20 C	No/ 992 lbs.	Yes	No	0.739	No – $300 per rechargeable day	72 hours	Control unit settings, chaning ice packs
Waeco CF-11	Yes	Yes	Mobile/ 19.4 lbs.	Yes	No	0.231	No – $600	N/A	Temperature control
Fridge Freeze	Yes	Yes	Mobile/ 22 lbs	Yes	No	0.207	No – $3995	N/A	Temperature control
Tempak Plus	No – uses PCM	Yes	Mobile/5.5 lbs.	No – multiple parts	Yes	0.222	N/A	24 hours	Replace gel packs
SunFrost	Yes – solar powered compressor	Yes	Semi-mobile/ 200 lbs.	No – solar panels and compressor	No	0.07	No	N/A	Temperature control, solar panel maintenance

CSafe is an active cooling refrigerator that utilizes a compressor. Having a compressor makes this product heavy with many moving parts. While having the

compressor allows CSafe to effectively regulate temperature, it also restricts its portability. CSafe is too fragile and heavy to be used as a reasonable carrier for vaccines in the cold chain.

APEX is a vaccine carrier box that uses ice packs to keep vaccines cool. This small box makes for a lightweight, portable box. However, as it is so small, its storage capacity to net volume ratio is very poor. Therefore, while it is portable, it does not provide an efficient means of transportation. Also, since it uses ice packs, the box does not keep vaccines between the desired range of 2-8 $^{\circ}$C. APEX is a product that has the advantage of having already passed the WHO testing protocols.

Greenbox is another vaccine carrier that uses passive cooling. Instead of ice packs, however, it uses PCM. Greenbox is mobile and has a long storage duration time. Furthermore, its storage capacity to net volume ratio is relatively high. The downsides to Greenbox are that it is expensive and more focused on a developed market.

The Model Antifreeze Backpack is another product that has passed WHO testing. Similar to APEX, the backpack uses ice packs, however the goal with this carrier is to use proper insulation to prevent the ice packs from freezing the vaccines. This allows for a more stable temperature. Yet, while it is more reliable, the vaccines are not entirely protected from freezing since ice packs are used. The Model Antifreeze Backpack has a short storage duration and small storage to capacity ratio. It is cost effective, however, as it is a product already used by the WHO.

Envirotainer uses dry ice-based refrigeration. This provides a stable temperature for vaccines. This technology also allows for a large payload, and so is

very efficient in keeping vaccines at the proper temperature and for transporting a large quantity of vaccines. Envirotainer is very heavy and not feasible for mobile transport of vaccines. A container like this is more suited for the large-scale shipment of vaccines, rather than for use as a vaccine carrier. Envirotainer is also very expensive with a cost of $300 for every day it is recharged.

Waeco is a mobile vaccine carrier that also applies active cooling technologies. Since it uses a compressor, the Waeco cooler provides a very safe and stable environment for vaccines. It also has a very high payload space, relative to other coolers. Waeco has a high price tag, and is not intended for use in the cold chain of LMICs. The main issue with compression-based cooling, refrigerators and cold boxes are not easily repaired, especially in a developing region.

Fridge Freeze is a product similar to Waeco; however, it is designed more specifically for the transport of medical supplies, such as vaccines and organs. This product is targeted to developed countries, and its exorbitant cost is too high for use in the cold chain.

Tempak Plus is another vaccine carrier that, similar to Greenbox, uses PCM. Tempak Plus is small and lightweight, with a greater payload space ratio than Greenbox. The only negative is that it is designed for short transport and can only carry a limited quantity of vaccines.

SunFrost is a different solution, as it uses solar energy to power its compressor. This provides a system that is not only temperature stable but also environmentally friendly. With this type of compressor vaccine carrier, a power source is not always necessary. However, solar power also has its drawbacks in that

the carrier is heavy and only semi-portable. With the solar panels and compressor, the system is also fragile and not easily repaired. It also has a very poor storage capacity to net volume ratio.

When designing our own vaccine carrier we took into account all of the information we learned from our competitors. Our box uses PCM, so temperature remains at a stable and safe range. We designed our box to be lightweight and portable, while still being durable and able to pass WHO guidelines. The vaccine cold box we have designed has optimized geometries and the storage capacity to net volume is higher than our direct competitors. Our carrier also has the ability to last for long periods of time and still maintain vaccines safely. Finally, it is our goal to produce and sell this product at a low cost, thereby making it readily available to the cold chain market in LMICs.

RISK

When starting any new business there are many different risks. As we are just starting in this industry, there are many problems we will face as newcomers. Many times when businesses fail it is because they do not make themselves aware of the risks their business faced. It is important to not shy away from risk but rather to define it as clearly as possible.

We have limited field experience, so what we do know is based solely off of our extensive research. We do not know how things are in the actual cold chain, as we have not seen it or experienced it ourselves. When it comes to being around the problem first hand, our team lacks experience.

Another risk is that in order for a product to be used in the cold chain, it must pass certain tests defined by WHO in their Product, Quality, and Safety (PQS) guidelines. Therefore, we need to meet these PQS standards in order to be placed on the "prequalified" products list by WHO so that our product can be available to cold chain suppliers. There is a risk that if we do not get on this list that our product will not be available to cold chains in LMICs and we will not meet our goal.

Also, as a new, small project, the production of our project is a significant risk. Even if we have the best product, being able to produce enough of our product to meet demand is a real concern.

A final risk involved with our business is that there are always new, innovative technologies being developed. The field of medicine is an ever-changing landscape, and there are vaccines currently being developed that are temperature stable, which would obviate the need for a temperature stable cold box.

While these are some of the risks we face as a new entity, it is imperative that we not only understand these risks, but also have a plan for overcoming them. Defining our risks is one of the first steps on our road to success.

OPPORTUNITY

We are very excited about our idea, and there are many different opportunities that we look forward to taking advantage of in the future. While our team does have very little field experience, this will not stop us from being successful. We have done the research to paint an accurate picture of what the cold chain currently looks like. We also have contact with experts who work in the field, so we will be able to receive

feedback on our product. Also, WHO clearly defines what a vaccine carrier should be able to do and what tests it must pass in the PQS document. If our carrier passes these tests, it will be competitive in the field.

However, it is another concern of ours that we must pass these PQS guidelines. In order to pass PQS guidelines we must perform all of the testing outlined by WHO. Once we meet the PQS, it is our hope that we will be able to outsource the assembly of our vaccine carrier.

As for the future of our product and the industry in general, the future is always hard to predict. During our research on the industry we learned of new temperature stable vaccines. While we are aware and do acknowledge that these other products do exist, we also know that these technologies are years away from the market, ensuring that our cold box will have a place in the cold chain at least for the near future.

If our business can overcome the obstacles we face, we have the opportunity to be the primary vaccine cold box utilized in the cold chain. Our product has the chance to revolutionize the industry and save many lives. We will bring the most effective technologies to the developing world. Our product improves performance over what is in the field now and is the best choice in safe vaccine transportation.

The following SWOT analysis summarizes our team's approach:

Table 26: SWOT Analysis

STRENGTHS	WEAKNESSES
• Cost-effective • Tailored geometry allowing optimal storage capacity • Capable of holding vaccines for entire duration of cold chain • No risk of exposure to sunlight or fluorescent light • Employs the same directions for the orientation of all vaccines in the box • Rarely requires expert repair • May be integrated into existing cold chain • Includes culturally relevant flag/logo to reduce risk of mishandling • Will be supplemented with time sheet and translated instructions to promote uniformity in use	• Does not currently meet WHO PQS standards • Requires more product development • Requires field testing • Management team has little field experience
OPPORTUNITIES	**THREATS**
• Increasing vaccine production/distribution • Alternative markets (food, pharmaceuticals, blood) • Contacts with existing organizations	• Competing products from established cold chain technology businesses • Switch to OCC (Out-of-cold-chain) practices • Substitution of temperature-sensitive vaccines with thermostable alternatives

MANAGEMENT TEAM

Our team is composed of thirteen undergraduate students that come from diverse backgrounds and academic pursuits. We have five women and eight men whose disciplines include business, Spanish, Arabic, engineering, government and politics, and biology. In addition, we have a mentor who is a bioengineering professor at the University of California, San Diego.

Teammate	Major(s)
Amanda Pereira	Spanish/Pre-Med
Amina Goheer	Government and Politics/Arabic
Andrew Foo	Mechanical Engineering
Anthony Mazzella	Operations Management
Divya Raghavachari	Neurobiology and Physiology/Spanish
George Peabody V	Chemical Engineering
Jason Felder	Mechanical Engineering
Kelly Daniluk	Mechanical Engineering
Matt Conway	Chemical Engineering
Ravi Vaswani	Neurobiology and Physiology/Spanish
Sahil Shah	Neuroscience
Veena Katikineni	Biology
Young Park	Accounting and Finance

Capital Requirements

We seek additional funding for our research and development. The initial stage of funding will be used to conduct more testing on our prototype so we can improve the dimensions. Here is a breakdown of how the funds will be spent:

Complete development
Purchase equipment
Fund working capital

Appendix G: Costing Model MATLAB Code

Cost Optimizing without PCM

```
%% Insulation vs. Ice Thickness Color Plot

%% Assumptions
% We wanted a 20 liter box that fit a real number of 50 mm boxes
% 250 mm square is the storage area side length. This is 9.84
inches.
% we are considering half of a box so:
s = 9.84/2; % storage side length

% The maximum possible width for the box is 30 inches. Then it
starts not
% to fit through doorways.

maxL =30/2;

L = maxL - s;

%% Costing parameters

ice.rho = 62.4 ; % lb/ft^3
ice.rho = ice.rho*(1/12^3); % lb/in^3
ice.cost = 5*0.25/231; % 25 c/gal -> dollars/cubic inch

ins.rho =  0.00134548874; % 37.24300 (kg / (m^3)) = 0.00134548874
pound / (in^3)
ins.cost = 900*(1/ 39.3700787^3); % dollars/in^3 (East & Smale)

weightcost =@(mass) 2*4.75*mass/2.2 + 30; % heavy packages ship on
weight cost
volumecost =@(mass) 800*(1/ 39.3700787^3)*mass + 30; % small
packages ship on volume cost

%% Define feasible space

% We could have no ice, all insulation; all ice, no insulation; or
no ice,
% no insulation. This forms a right triangle.

%       |\
%       | \
```

```
%        |   \
%        |    \
%        |     \
%th_ins   |      \
%        |       \
%        |        \
%        |         \
%        |__________\
%           th_ice

n = 1000; % number of subdivisions

Z = zeros(n,n);
C = zeros(n,n);
X = zeros(n,1);
Y = zeros(n,1);
T = zeros(n,n);
for i = 1:n
    x = L/(n-1)*(i-1);
    X(i) = x;
    Y(i) = x;
    m = 142.4*x+0.0016;
    for j = 1:n
        y = L*(j-1)/(n-1);
        T(j,i) = x+y;
        Z(j,i) = m*y;
%         if x+y > L;
%             Z(j,i) = NaN;
%         end
    end
end
figure

colormap(winter)
contourf(X,Y,Z./T,50)
hold on
plot([0 10.08],[0 10.08],'w');
title('Time in hours until 8 degrees');
xlabel('Ice Thickness (inches)')
ylabel('Insulation Thickness (inches)')
axis square


for i = 1:n
    x = L/(n-1)*(i-1);
    X(i) = x;
    Y(i) = x;
    m = 142.4*x+0.0016;
    v_ice = (x+s)^3-s^3;
    C_ice = v_ice*ice.cost ;

    for j = 1:n
        y = L*(j-1)/(n-1);
        v_ins = (x+s+y)^3 - (x+s)^3;
        C_ins = v_ins*ins.cost ;
```

```
        if
(v_ice*ice.rho+v_ins*ins.rho)>160/(2.2*39.3700787^3)*(v_ice+v_ins)+.
2/2.2 % if mass box > some factor times volume of box
            C_ship = weightcost(v_ice*ice.rho+v_ins*ins.rho);
            %disp('costed by weight')
        else
            C_ship = volumecost(v_ice*ice.rho+v_ins*ins.rho);
         %   disp('costed by volume')
        end
        C(j,i) = C_ice + C_ins + C_ship;
        Z(j,i) = m*y;
%         if x+y > L;
%             C(j,i) = NaN;
%         end
    end
end
figure

colormap(winter)
contourf(X,Y,C,50)
hold on
plot([0 10.08],[0 10.08],'w');
title('Cost estimate for ice and insulation');
xlabel('Ice Thickness (inches)')
ylabel('Insulation Thickness (inches)')
axis square

figure
%% optimize time/$
H = Z./C;
colormap(winter)
[ch,ch] = contourf(X,Y,H,50);
%[ch,ch] = contourf(H,50);
 set(ch,'edgecolor','none');
hold on
title('Find an optimum please?');
plot([0 10.08],[0 10.08],'w');
xlabel('Ice Thickness (inches)')
ylabel('Insulation Thickness (inches)')
axis square

%% Regress left-lower value of every contour

H = flipdim(H,1);
Y = flipdim(Y,1);
IND=find(H==max(max(H)));
[I,J] = ind2sub(size(H),IND);
% Xs(1) = X(I); %x values corresponding to the points where Z is
maximum
% Ys(1) = Y(J); %y values corresponding to the points where Z is
maximum

kinit = whichdiag(H,IND);
siz = size(H);
param = abs(abs(kinit) - (siz(1)-1)) ;
```

```
clear Xs Ys

for i=1:param;
    k = kinit-(i-1);
    Hd = tril(H,k);

    IND=find(Hd==max(max(Hd)));
    [Jd,Id] = ind2sub(size(Hd),IND);
    if length(Id) > 1
        Id = mean(Id);
    end
    if length(Jd) > 1
        Jd = mean(Jd);
    end
    Xs(i) = Id; %x values corresponding to the points where Z is
maximum
    Ys(i) = n-Jd+1; %y values corresponding to the points where Z is
maximum
end

Xs = max(X)*Xs./(n);
Ys = max(Y)*Ys./(n);

plot(Xs,Ys,'w');

%% Log rules
figure

logx=log(Xs);
logy=log(Ys);
p=polyfit(logx,logy,1);
plot(logx,logy,'bo');
axis equal square
grid
xlabel('log(x)');
ylabel('log(y)');
k=p(1);
loga=p(2);
a=exp(loga);
hold on; plot(logx,k*logx+loga,'g')
legend('Data',sprintf('y=%.3f{}log(x)+log(%.3f)',k,a));
figure
plot(Xs,Ys,'bo');
xlabel('x');
ylabel('y');
axis equal square
grid
hold on; plot(Xs,a*Xs.^k,'g')
legend('Data',sprintf('y=%.3f{}x^{%.3f}',a,k));
```

Cost optimizing with the PCM

```
%% Insulation vs. Ice w/ PCM Thickness Color Plot
```

```
%% Assumptions
% We wanted a 20 liter box that fit a real number of 50 mm boxes
% 250 mm square is the storage area side length. This is 9.84
inches.
% we are considering half of a box so:
s = 9.84/2; % storage side length

maxL =(9.84+6.4)/2;

L = maxL - s;

%% Costing parameters

ice.rho = 62.4 ; % lb/ft^3
ice.rho = ice.rho*(1/12^3); % lb/in^3
ice.cost = 5*0.25/231; % 25 c/gal -> dollars/cubic inch

ins.rho =  0.00134548874; % 37.24300 (kg / (m^3)) = 0.00134548874
pound / (in^3)
ins.cost = 900*(1/ 39.3700787^3); % dollars/in^3 (East & Smale)

pcm.rho = .9*62.4 ; % lb/ft^3
pcm.cost = 0.0944510035  ; % $/in^3 % From Mark Barakat's Email
dated 16 Feb 12.

weightcost =@(mass) 4.75*mass/2.2 + 30; % heavy packages ship on
weight cost
volumecost =@(mass) 800*(1/ 39.3700787^3)*mass + 30; % small
packages ship on volume cost

%% Define feasible space

% We could have no ice, all insulation; all ice, no insulation; or
no ice,
% no insulation. This forms a right triangle.

%       |\
%       | \
%       |  \
%       |   \
%       |    \
%th_ins |     \
%       |      \
%       |       \
%       |        \
%       |_________\
%          th_ice

n = 1000; % number of subdivisions

Z = zeros(n,n);
```

```
C = zeros(n,n);
X = zeros(n,1);
Y = zeros(n,1);
T = zeros(n,n);
for i = 1:n
    x = L/(n-1)*(i-1);
    X(i) = x;
    Y(i) = x;
    m = 142.4*x+0.0016;
    for j = 1:n
        y = L*(j-1)/(n-1);
        T(j,i) = x+y;
        Z(j,i) = m*y;
        if x+y > L;
            Z(j,i) = NaN;
        end
    end
end
figure

colormap(winter)
contourf(X,Y,Z./T,50)
hold on
plot([0 10.08],[0 10.08],'w');
title('Time in hours until 8 degrees');
xlabel('Ice Thickness (inches)')
ylabel('Insulation Thickness (inches)')
axis square


for i = 1:n
    x = L/(n-1)*(i-1);
    X(i) = x;
    Y(i) = x;
    p = x*334/178*1/2;  % pcm thickness (must be at least half of
the length where PCM and ice would have equal latent heats)
    m = 142.4*x+0.0016;
    v_pcm = (s+p)^3 - s^3;
    v_ice = (x+s+p)^3-(s+p)^3;
    C_ice = v_ice*ice.cost ;
    C_pcm = v_pcm*pcm.cost ;
    for j = 1:n
        y = L*(j-1)/(n-1);
        v_ins = (x+s+y+p)^3 - (x+s+p)^3;
        C_ins = v_ins*ins.cost ;
        if
((v_ice+v_pcm)*ice.rho+v_ins*ins.rho)>160/(2.2*39.3700787^3)*(v_ice+
v_ins+v_pcm)+.2/2.2 % if mass box > some factor times volume of box
            C_ship =
weightcost((v_ice+v_pcm)*ice.rho+v_ins*ins.rho);
            %disp('costed by weight')
        else
            C_ship =
volumecost((v_ice+v_pcm)*ice.rho+v_ins*ins.rho);
         %   disp('costed by volume')
        end
```

```
        C(j,i) = C_ice + C_ins + C_pcm + C_ship;
        Z(j,i) = m*y;
        if x+y > L;
            C(j,i) = NaN;
        end
    end
end
figure

colormap(winter)
contourf(X,Y,C,50)
hold on
plot([0 10.08],[0 10.08],'w');
title('Cost estimate for ice and insulation');
xlabel('Ice Thickness (inches)')
ylabel('Insulation Thickness (inches)')
axis square

figure
%% optimize time/$
H = Z./C;
colormap(winter)
[ch,ch] = contourf(X,Y,H,50);
%[ch,ch] = contourf(H,50);
 set(ch,'edgecolor','none');
hold on
title('Find an optimum please?');
plot([0 10.08],[0 10.08],'w');
xlabel('Ice Thickness (inches)')
ylabel('Insulation Thickness (inches)')
axis square

%% Regress left-lower value of every contour

H = flipdim(H,1);
Y = flipdim(Y,1);
IND=find(H==max(max(H)));
[I,J] = ind2sub(size(H),IND);
% Xs(1) = X(I); %x values corresponding to the points where Z is
maximum
% Ys(1) = Y(J); %y values corresponding to the points where Z is
maximum

kinit = whichdiag(H,IND);
siz = size(H);
param = abs(abs(kinit) - (siz(1)-1)) ;
clear Xs Ys

for i=1:param;
    k = kinit-(i-1);
    Hd = tril(H,k);

    IND=find(Hd==max(max(Hd)));
    [Jd,Id] = ind2sub(size(Hd),IND);
    if length(Id) > 1
```

```
        Id = mean(Id);
    end
    if length(Jd) > 1
        Jd = mean(Jd);
    end
    Xs(i) = Id; %x values corresponding to the points where Z is
maximum
    Ys(i) = n-Jd+1; %y values corresponding to the points where Z is
maximum
end

Xs = max(X)*Xs./(n);
Ys = max(Y)*Ys./(n);

plot(Xs,Ys,'w');

%% Log rules
figure

logx=log(Xs);
logy=log(Ys);
p=polyfit(logx,logy,1);
plot(logx,logy,'bo');
axis equal square
grid
xlabel('log(x)');
ylabel('log(y)');
k=p(1);
loga=p(2);
a=exp(loga);
hold on; plot(logx,k*logx+loga,'g')
legend('Data',sprintf('y=%.3f{}log(x)+log(%.3f)',k,a));
figure
plot(Xs,Ys,'bo');
xlabel('x');
ylabel('y');
axis equal square
grid
hold on; plot(Xs,a*Xs.^k,'g')
legend('Data',sprintf('y=%.3f{}x^{%.3f}',a,k));
```

whichdiag.m

```
function [ k ] = whichdiag( X, IND )
% Find which diaganol of matrix an index is on
%   Input a matrix, and the index of an element either as a linear
indices
%   (IND)
%   or coordinates [I,J]

% Convert coordinates to linear indices
if length(IND) > 1
```

```
    IND = sub2ind(size(X), IND(2), IND(1));
end

% Recreate matrix of size X where every value is it's linear indices
s = size(X);
l = s(1);
w = s(2);
n = numel(X);
for i = 1:n
    X(i) = i;
end

% Find total number of diagonals
nd = l + w -1;
% X has w-1 superdiaganol diags, l-1 sub diaganol diags, and 1
diagonal
%
% Create a matrix where the diagonals of the X index matrix are the
columns

% preallocate based on biggest diagonal
h = length(diag(X,0));
S = zeros(h,nd);
j = 1;
for i = (1-l):(w-1)
    v = diag(X,i);
    S(1:length(v),j) = v;
    j=j+1;
end

% Search for which column of S has the desired index
q = find(IND==S);

[x,y] = ind2sub(size(S),q);

% convert index to k=0 being the diagonal.
k = y-l;

end
```

Appendix H: Animation: A Journey Through the Cold Chain

In collaboration with Vishnu Priya Ganti, Motion Graphics Designer and student at the Maryland Institute College of Art, Team FRESH developed an animation illustrating the journey of a typical vaccine shipment through the cold chain. Vishnu Priya Ganti is a Bachelor in Fine Arts: Graphic Design candidate (May 2012). She is pursuing a concentration in Animation, and she is also completing a minor in Culture and Politics (Literature).

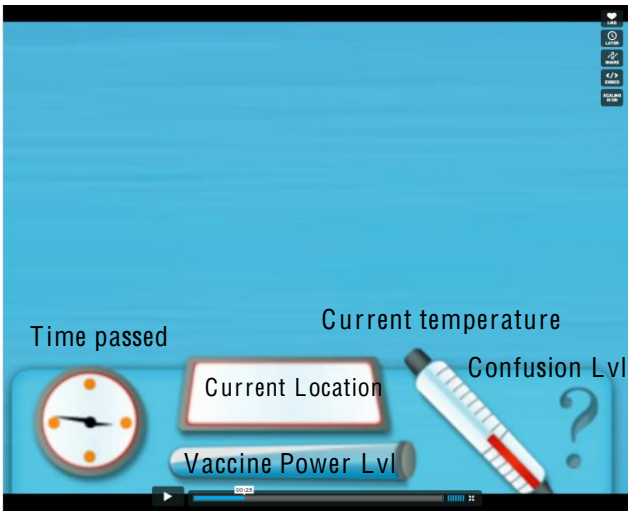
Below is the introductory excerpt, story-line, and screen-shots for the animation. The full two-minute animation is available on Vishnu Priya Ganti's Vimeo page, which can be found at the following URL: http://vimeo.com/16537015. By linking this animation to our open-source Google Map, blog, as well as external sites such as the Vimeo page, Team FRESH hopes viewers will be able to better understand the nature of the cold chain. Equipped with this understanding, our viewer base of students, professionals, and others may join the effort towards reaching the goal of universal immunization.

Introduction

Vaccines have earned a place among the best public health technologies and investments in the human history. They are currently estimated to prevent 2.5 million deaths per year. There are 28 vaccine-preventable diseases, which contribute to 1.76 million deaths per year. In line with the Millennium Development Goals, the international community has devoted heavy resources and programming towards improving vaccine efficacy, ease of administration, and most recently, the infrastructure behind vaccine transport and distribution, otherwise known as the cold chain. Most vaccines require a 2-8 °C temperature range to remain potent. The cold chain strives to ensure these conditions but the current system falls short.

Story-line

Now we'll follow a vaccine shipment through a typical route that lasts anywhere from 3-8 weeks. Please keep an eye on the dashboard below showing important parameters: the amount of time that has passed, current location, the vaccine potency or "power level," the temperature of the shipment, and the level of confusion among healthcare workers.



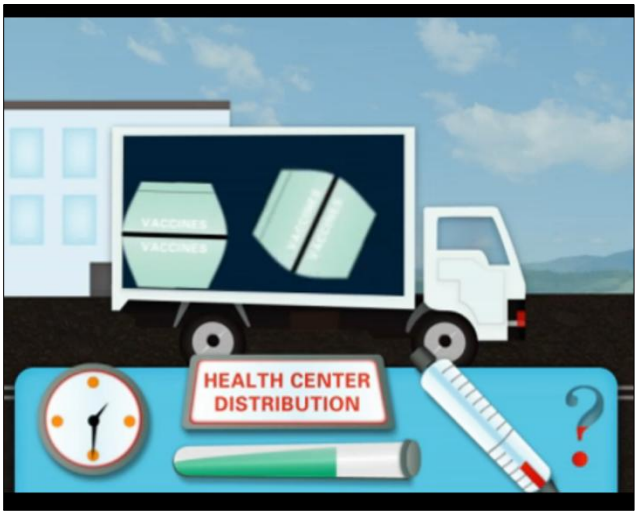
We start in the United States, and the vaccine shipment boards international air freight; here the crate moves around and are sometimes exposed to slight heating. They're still in good condition.

Upon reaching the destination country, vaccines are often placed outside, where they are exposed to high temperatures. Vaccines may be neglected by staff that is unaware of the requirements for vaccine handling.

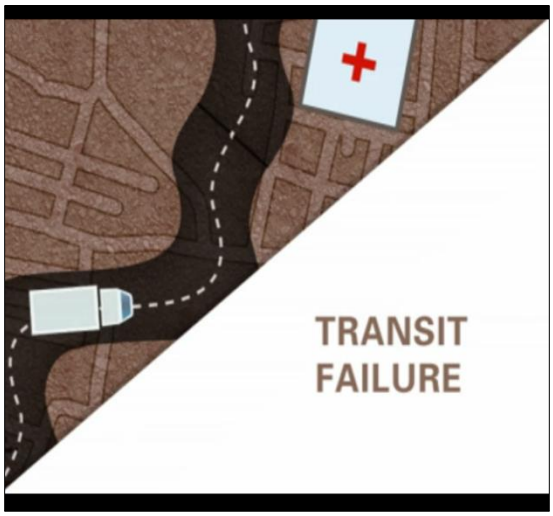
In Customs, literature has demonstrated that vaccines may be stalled for as much as 2-3 weeks due to confusion among staff or changing delivery schedules. They are again exposed to hot temperatures, and vaccine potency is waning.

At the central level, often a government-run institution, there are warehouses with freezer rooms set to extremely low temperatures, often around -20 °C, resulting in freezing of vaccines if left unprotected. Since we are at the central level, and there are more trained personnel than at any other stage of the cold chain, improper storage or handling is unlikely. Still these locations are subject to electricity fluctuations, which create an unstable environment for vaccines. Precautions may not be systematically or uniformly taken to protect vaccines from freezing or overheating.

In transport to the health centers, vaccines are stored in Ice-lined Refrigerators or cold boxes, which are equipped with ice packs. The bulky refrigerators often bump into each other, and vaccine vials may break if packaging has not been properly installed.



Other issues in transport include unscheduled stopovers that strand vaccines for indefinite period of time, as well as poor road conditions. The drivers and staff are often unaware of the careful conditions that vaccines require, or they may not have the time or delegated responsibility to ensure the appropriate precautions are taken.

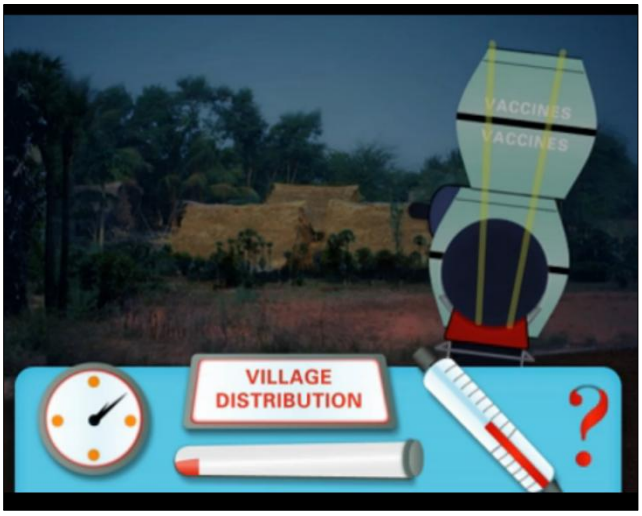


At the provincial vaccine store, we see an ice-line refrigerator holding vaccines. They are filled in an organized fashion, and the position of each vaccine often corresponds to the sensitivity to temperature. For example, some are more susceptible to freezing or light exposure than others.

Just like the freezer rooms, however, refrigerators may be plugged in, and therefore vulnerable to electricity fluctuations. This not only creates an unstable temperature environment for vaccines, but also can lead to damage to the equipment itself, which may halt temperature-controlled vaccine storage altogether. When equipment breaks, there is lag-time for a trained technical expert to help repair it; significant time, money, and effort are expended.

Finally, these same shipments that are no longer useful are delivered by bus, scooter/motorcycle, foot, or sometimes with the help of domesticated animals, to the target community. Although there are color-ink sensors (Vaccine Vial Monitors) that indicate diminished potency of the vaccines, many staff in small health clinics are not trained to discard vaccines systematically due to the demand for vaccinations from

the public, who are desperate for protection from disease, as well as campaigns who seek to complete the work for which they have been funded. People are checked off as immunized by larger eradication campaigns when they are not always protected from disease. Furthermore, the spoiled vaccines can have adverse effects on the recipient. These realities lead to harsh consequences for meeting the greater goal of universal immunization. Failure of immunization reduces the trust of the public in vaccination, and fuels resistance against health campaigns. Some return to clinics and seek repeat vaccinations, which may not be available to them, while others revert to traditional healing methods.



Learn more about reaching universal immunization at the GAVI Alliance web site (http://www.gavialliance.org/).

Glossary

Absorption refrigeration: A refrigerator that uses an external heat source as the driving force for refrigeration.

Adjuvant: An additive to a vaccine that can change its effect or potency.

Adsorption refrigeration: A refrigerator that uses an external heat source as the driving force for refrigeration; the heat source releases an adsorbed fluid from an adsorbent bed, which replaces the conventional compressor.

ANSYS: Finite Element Analysis software.

CAD: Computer aided design; 3-D modeling software used for the visualization of concepts and in the process of designing prototypes.

Convective heat transfer: Heat transfer through movement, similar to a fan.

Cold Box: A portable storage container that utilizes a passive cooling system to store and transport vaccines.

Cold chain: The distribution system of temperature-sensitive products, such as vaccines, from the manufacturer to the end user.

Compression refrigeration: A refrigerator that operates on the compression and expansion of a substance, the same as a typical household refrigerator.

COMSOL: Multiphysics Finite Element Analysis software.

Data Logger: A device that can record temperature at a specified location.

Differential scanning calorimetry: A data collection method in which the heat input to change the temperature of a substance over time is recorded.

EPI - Extended Program on Immunization; a WHO initiative started in the 1970s to expand vaccinations to children worldwide.

Eutectic mixture: A mixture with a composition of materials that provides the lowest melting temperature, and for which upon cooling, no phase separation occurs.

FEA: Finite Element Analysis. Creation of a geometric model with defined material properties that is then stressed with physical conditions, like forced loads or thermal conditions.

Freeze Indicator: A device that can indicate whether a vaccine has frozen, usually through utilization of temperature-sensitive ink.

GAVI Alliance – Global Alliance for Vaccines and Immunisation; a partnership between the WHO, UNICEF, Bill and Melinda Gates Foundation, World Bank, and other public and private organizations dedicated to increasing immunizations rates in developing countries.

Heat of Fusion-Latent Heat-Latent Heat of Fusion: The energy per mass or mole that is needed to convert a substance from a solid to a liquid.

Hermetic seal: A vacuum seal.

Ice-lined refrigerators: Refrigerators equipped with large amounts of ice lining the walls to help keep vaccines cool. They typically require the ice to be separated from the vaccines in order to prevent freezing.

Immunization: The act of inoculating a patient with a vaccine.

Impotent vaccines: Vaccines that will no longer provide immunity due to denatured proteins. Some of the causes of impotency include freezing, overheating, or extended duration of storage.

Isothermal: A process in which the temperature of the system does not change.

Lead (thermocouple): The location at which a thermocouple measures the temperature.

Local health center: A small distribution center that is or is one step away from the actual inoculation stage.

Mass heat capacity-Specific heat capacity: Energy to raise a unit mass of a substance one degree.

Mesh: A series of locations at which a FEA program will solve the input data.

Nucleating agents: Substances that trigger nucleation, typically in the form of crystallization.

Outreach clinic: A clinic that provides health care free of charge.

Passive refrigeration: Refrigeration that does not involve any electrical or mechanical movement of heat.

PATH - Founded in 1977 by family planning researchers, PATH is an international non-profit organization dedicated to resolving public health issues such as immunization programs; PATH often works in conjunction with the WHO and UNICEF.

PEPFAR - President's Emergency Plan for AIDS Relief – Started by President George W. Bush in 2008, PEPFAR consists of a $50 million commitment to combat worldwide diseases, such as AIDS, malaria, and tuberculosis.

Phase change materials: Materials with a high latent heat, otherwise known as materials requiring a large amount of energy to change from solid to liquid.

PQS specifications: Performance, Quality, and Safety standards established by WHO. All products must meet them before they can be used in the cold chain.

Ramp rate (PCM testing): The rate at which temperature is changed by the DSC, a slower rate has higher accuracy.

Refrigerant: A substance that can be used in a refrigerator as the cycling liquid.

Regional center: A larger national distribution center that stores various resources ready for distribution.

Steady state: The state at which a system is non-changing.

Thermal conductivity: The relative ability of a substance to transfer heat through itself.

Thermal equilibrium: The time at which a system is at a uniform temperature.

Thermochromic ink: An ink that changes color based on the temperature. It is a technology utilized in various devices that monitor freezing.

Thermocouple: A device with multiple leads that can be used to measure temperature in different locations inside a cold box.

Transient analysis: A solution that occurs over time.

Vaccine Vial Monitor: A heat sensitive label that changes color according to changes in temperature and time. It can indicate to a healthcare worker if a vaccine has been exposed to freezing temperatures.

Vaccine: a preparation of killed microorganisms, living attenuated organisms, or living fully virulent organisms that is administered to produce or artificially increase immunity to a particular disease.

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