Personal Statement

The need for vaccination is an important aspect in disease control, especially in developing regions. This form of preventative care combined with post infection treatment serves as an effective measure in reducing the disease burden in large populations. Furthermore, immunization services must be sustainable, since over 100 million children are born every year and need to be immunized. Despite this need, nearly 27 million children across the world were not vaccinated in 2003 (World Health Organization and UNICEF, 2006).

Indication of the success of vaccination for diseases such as Hepatitis B is evident in the United States, where the number of cases of Hepatitis B has greatly reduced since the mid-1980s. This reduction can be attributed to the availability and administration of effective vaccines to infants and high-risk populations (Sorrell et al., 2009). The system for delivering vaccines, called the cold chain, must therefore be designed efficiently enough to reach infants in especially high-risk areas, which in many countries includes rural, under developed areas.

As they are very temperature sensitive, vaccines must be kept in a very small range of temperatures. Currently, a variety of refrigeration systems are used along the cold chain to prevent overheating in ambient temperatures, including refrigerated trucks, cold rooms, containers with ice packs, and conventional standing compression refrigerators. Unfortunately, various studies have shown that these refrigerators cause significant freeze-damage to vaccines (Techathawat, Varinsathien, Rasdjarmrearnsook, & Tharmaphornpilas, 2007). This widespread freezing of vaccines can be attributed to many factors, the most prevalent of which is the lack of stable temperature in the refrigeration cell during transport and storage (Program for Appropriate Technology in Health [PATH], 2008).

In the next few years the volume of vaccines that need to be managed in the cold chain is expected to rise dramatically (PATH, 2008). Our project aims to positively impact the health care situation in developing countries by providing an alternative technology for temperature control of these vaccines throughout their transport and storage. With more precise temperature control mechanisms, vaccine wastage will be reduced.

We hope to increase the technical capacity of these systems to treat vaccine-preventable diseases by creating a more reliable refrigeration prototype that more efficiently stores vaccines, and ensures their potency. This prototype will increase efficiency in the cold chain, improve access to vaccinations, and add to existing epidemiological research.

Our group plans to research new and current storage technologies in order to finds ways that preexisting concepts can be synthesized or combined to produce a more efficient refrigeration design. As such, once we complete our model we hope that other researchers, businesses, and non-profit organizations can use our prototype to model future refrigerators built for a similar purpose in other parts of the world or in different parts of the cold chain.

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Proposal Abstract

Vaccine preventable diseases have a costly impact every year resulting in doctor's visits, hospitalizations, and premature deaths around the world. Much of the reason behind this is of inefficient transportation and storage of usable vaccines. Freezing or overheating of vaccines due to improper refrigeration renders nearly 70% of vaccines impotent before they reach their final destination. In addition to the immeasurable healthcare costs associated with failed vaccination, this results in a cost of more than $22.6 million for the vaccines. To address this problem, we propose integrating compression refrigeration and phase change material technology in order to provide a stable cooling mechanism during transport. The novel refrigeration system will be used to ensure that a higher percentage of vaccines remain potent throughout transport and storage.

Proposal Narrative

Background

Gaps in the vaccine distribution supply chain: The cold chain is a means for storing and transporting vaccines from the manufacturer to the community. Vaccines need to be stored in a temperature range of 2 to 8 °C, and any fluctuation outside this range may render vaccines unusable. In order to prevent overheating, refrigerated trucks and cold boxes are used in the cold chain (Landscape Analysis: Cool chain technologies, 2008). Seventy percent of vaccines are tossed away upon delivery, primarily due to freeze-damage (Techathawat, Varinsathien, Rasdjarmrearnsook, & Tharmaphornpilas, 2007). When a vaccine reaches 0 °C, key organic components are inactivated, rendering the vaccine impotent. Refrigerators are unable to maintain their temperatures above 0 °C, both due to inefficiencies inherent to adjustable thermostats (Wirkas et al., 2007) and from intermittent power supply characteristic of developing countries (Xinhua, 2009). Overheating the vaccine is also not ideal, because the denaturing of proteins will also render the vaccine inert. There is thus a need for more reliable refrigeration both during transport and storage (Wirkas et al., 2007; Nelson et al., 2004).

Phase change materials: We propose that the use of phase change materials (PCM) will result in a more reliable and energy efficient refrigeration system. Most matter exists in one of three states: solid, liquid and gas. When any material changes state, also called a phase, all energy entering the substance causes the phase to change, rather than increase its temperature. A phase change material has a high heat of fusion, or energy required to melt or freeze a substance, enabling it to store and release large amounts of energy. During its phase change period, the temperature is constant, since any heat that is transferred will go towards melting the PCM.

Project Objectives

To solve the problem of freezing and overheating vaccines, we propose the following objectives:

Objective 1: To select and characterize an appropriate phase change material (PCM) that will resist temperature fluctuations outside of a range of 4-8 °C, based on appropriate thermophysical properties.

Objective 2: To integrate this PCM into a compression refrigeration system, for long-term stabilization of temperatures within a range of 4-8 °C.

By meeting these objectives, we will demonstrate 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 distribution strategies.

Design Criteria and Concept

After examining two widely-used refrigeration methods, compression and sorption, we decided to use compression technology because it is more efficient and offers more reliable maintenance of temperature (Li, Wang, & Wang, 2009). We have identified several key aspects of compression refrigeration of vaccines that need improvement, most notably temperature stabilization and temperature longevity. We have chosen our target temperature range to be 6± 2 °C to ensure sufficient cooling while maintaining a buffer zone against the freezing point of the vaccines (WHO/UNICEF, 2000). To be effective in all steps of the cold chain, our solution itself must move through the cold chain. In addition, current cold boxes are designed larger than the volume of vaccines they hold (Landscape analysis: Cool chain technologies, 2008). Therefore, we plan to develop our system to fit the vaccine volume with minimal wasted space. The design must also account for intermittent power along the cold chain. Finally, we will address protection of the refrigeration system from damage due to physical shocks (e.g., transport upon unfinished roads), as well as ease and affordable maintenance throughout the cold chain, especially at local levels (UNICEF, 2004).

These design criteria lead to the concept of a smaller containment unit than the one currently used in operation. The basic premise is the use of a battery-powered, PCM-lined refrigerator that will run only to reset the PCM. The PCM will absorb heat until it has melted completely and the temperature starts to increase. The rise in temperature will turn the compression refrigerator on to remove heat from the PCM until it solidifies completely and the temperature starts to decrease. At this point, the refrigerator will switch off. This concept will operate completely independent of the cold chain, allowing the refrigerator, and thus the vaccines, to reach areas not currently accessible. Preliminary estimations show that a 30 x 30 x 30 cm cube with ~1.3 cm layer of external polyurethane insulation and a ~1.9 cm layer of lithium chlorate trihydrate as a PCM lining a 12 L storage area will provide temperature stability for ~20 hrs. A small compression system would refreeze the PCM in a half hour, and a 12V 36Ah battery would allow the refrigerator to function for 9 weeks away from grid electricity.

Plan of Experimental Work

Selection of phase change materials: We will select a phase change material that will best resist temperature fluctuations. Candidate PCMs that we will test are Lithium Chlorate Trihydrate, PropylPalmitate, Phase 5, and Tetrahydrofuran clathrate (Mehling & Cabeza, 2008). These have been selected based on desirable melting points (6± 2 °C), high heat of fusion, price, and availability. Tetrahydrofuran clathrate is of particular interest because, unlike most substances which effect freezing point depression, when tetrahydrofuran clathrate is dissolved in water at 1 to 17 mole to mole ratio, the freezing point of water rises to 4 °C.

Characterization of phase change materials: The first step is to verify the exact melting point of each PCM. To find this we will place a sample of crushed PCM within a thin glass capillary tube, and place the capillary tube on a hot plate or in a water bath. We will gradually increase the plate or bath temperature, and record the temperature with a thermocouple (ksKimball HVACR Instruments) every five seconds. The melting point will be estimated as the average temperature of the onset of the transition from solid to liquid, where liquid is just visible in the tube, and the meniscus point, where a meniscus is clearly visible in a layer of liquid above the submerged solid (cf. methodology for the OptiMelt system, Stanford Research Systems, Sunnyvale, CA). We will repeat this test 5-7 times and compare our results with predicted literature values. We will repeat this same test with ice, which has a melting point of 0°C, to serve as a control for our methodology.

We will then test the heat of fusion for each PCM in sealed tubes using a published temperature-history method (Hong, Kuk Kim, & Kim, 2004). We will suspend a test tube with liquid PCM and a reference test tube of water in the same warm water bath, until the temperature of the water bath, test tube water and PCM equilibrate. The two test tubes will be simultaneously removed from the water bath, and their temperature responses will be recorded with thermocouples and a data logger. As the test tubes cool, the PCM will solidify and the water will continue to cool as a liquid. The cooling water will remain in its sensible heat region, where its temperature decreases proportionally, based on its heat capacity, to the amount of energy leaving the test tube. Using the

known heat capacity of water, the temperature change in the water while the solidified PCM melts, the mass of the tube and water, and areas of the tubes across which convective heat transfer occurs, this known amount of energy will be related to the latent heat of fusion of the PCM.

We will verify this calculation using an analogous method. We will place a small amount of solid PCM in a beaker and place a known amount of water in another beaker. We will heat both beakers on a hot plate, and monitor the temperature of the PCM and water until the PCM has melted. Since we know the heat of fusion and mass of the water, we can calculate the heat that is transferred to the water. The heat transferred to the PCM is identical, since the heat source is the same. This then allows us to calculate the PCM's heat of fusion.

We will repeat heat of fusion experiments for 5-7 samples for statistical comparison using a student's t-test. This sample size is based on a power calculation using alpha = 0.05, beta = 0.2, and estimated variances of ~10%, based on variability in measured heats of fusion for paraffin and sodium acetate (Hong, Kuk Kim, & Kim, 2004). The optimal PCM for our system will be selected based on the best combination heat of fusion, density and cost.

Integration: Phase Change Materials often must be encapsulated in either hard or soft plastic packaging, much like an ice pack. Our prototype design involves lining the six inner walls of a cubic refrigerator with PCM. While the PCM inside will clearly melt at its melting point, it is unclear what effect this will have on the temperature of the storage area. The Edison-based company TCP Reliable makes PCM lined boxes, so we have reason to believe that PCM lining is an effective way to regulate the temperature of a space. To best integrate the PCM with a compression refrigerator, we will use a four lead thermocouple to measure the air temperature at multiple points in space inside a PCM lined box, evenly spaced from the PCM lining to the center of the refrigerator. We can use data from multiple set-ups with multiple thicknesses of PCM container, to develop a mathematical model for temperature as function of location in the box. If a PCM lined refrigerator does not keep vaccines in the center of the refrigerator cold enough, the design will change to multiple PCM lined compartments within the refrigerator to best stabilize the temperature of the vaccines.

Performance Testing: Once we decide upon on a PCM and the proper geometry to be integrated into a standard refrigerator, we will perform several tests used by the World Health Organization (WHO) to measure the efficacy of prospective refrigerators. In order to test the electricity requirements during each of these tests, we will attach an energy meter onto the electric circuit of the compressor. This will allow us to measure the voltage, energy, amperes, and kilowatt-hours used by the entire refrigeration unit during all tests (Bansal & Kruger, 1995). To test the time required for the refrigerator to cool, we will place the device in a 43 °C environment with the door open. After an equilibrium temperature is reached, we will close the door and turn the device on. Then, we will measure the time it takes for the compressor to bring the internal cell temperature of the refrigerator down to 8 °C (Ice-lined refrigerator, 2006). Next, we will determine if our refrigerator can maintain a small range of internal temperatures in different external environments over time, with and without intermittent power. Following WHO performance testing guidelines, we will place the device in 27 °C and 43 °C environments after reaching an internal temperature of 4 °C. In the absence of power, we can determine how long the device can maintain a temperature below 8 °C, thus measuring the ability of the PCM and insulation to resist temperature change (Ice-lined refrigerator, 2006). By varying the duration of and gaps between periods of intermittent power (i.e., unplugging the refrigerator), we will also determine the minimum time required to refreeze the PCM, to ensure a constant stable temperature.

Future Directions, Division of Labor, and Timeline

We anticipate the completion of PCM testing and prototype refrigerator testing within the one year of requested funding. However, we have also developed a plan for the second and final year of our program to incorporate a rechargeable battery or sustainable energy power source into the compression refrigeration system, complete vibration and durability testing, and alter refrigeration cell and/or PCM geometry to optimize temperature stability and minimize cost. Following the development of a prototype refrigeration system, we will empirically determine its cyclical durability by repeated heating and cooling within a range of temperatures from 2-43 °C. This will ensure that our PCM will be durable enough to last the life of the rest of the refrigerator's parts. Ultimately, by bringing all these parts together, we hope to create an innovative refrigerator that will meet vaccine storage needs.

Based on the two-year project timeline, for efficient division of labor, we have subdivided our team of 13 students into three teams: (i) Phase Change Material (PCM) Team, (ii) Structure and Electric (S&E) Team, and (iii) Compression Team. As the integrated system is designed and fabricated, teams will merge as necessary. Milestones for each team are provided in Table 1.

***Table 1*: Division of Labor, Milestones, and Timeline**

	Milestone/Deliverable	Spring 2010	Fall 2010	Spring 2011	Fall, 2011
PCM Team	Characterization of intrinsic properties of PCMs	X			
	Identification of concentrations, densities, etc. contributing to intrinsic properties	X			
	Selection of PCM to be used for integration		X		
	Performance Testing of PCMs in unmodified refrigerator		X		
	Calculations of PCM performance in integrated refrigeration system			X	
	Integration of PCM with structural, mechanical, and electrical components			X	X
S&E Team	Dismantle refrigerator(s) to identify insulation, inner casing, and outer housing	X			
	Determine dimensions and materials of insulation, inner casing, and outer housing	X			
	Integration of structural and electrical components with mechanical and PCM components			X	X
	Research sustainable energy sources for low-resource settings including batteries and/or plug-in	X	X		
	Construct prototype with selected energy source		X	X	
	Compare performance of selected energy source			X	
Compression Team	Establish a qualitative and quantitative understanding of the compression cycle	X			
	Develop equations to describe heat transfer, cooling capacity, and other performance indicators	X			
	Research possible alterations to compression mechanism (e.g., jet valves)	X	X		
	Research alternate refrigerants, including cost, availability, & lifetime		X		
	Determine a parts list for compression cycle components	X	X		
Entire team	Provide design drawings of integrated system (ongoing)		X	X	X
	Simulate performance based on selected components using a computer model (ongoing)		X	X	X
	Fabrication of integrated refrigeration system			X	X
	Durability and recyclability testing				X

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Itemized Budget

After compiling an estimate of the costs, the grand total for building and testing a prototype refrigerator equals $1,709.59. The total not only covers the costs for building a refrigerator, it also includes the cost for testing the prototype to determine whether or not our objectives were met. Gemstone provides us with an annual budget of $300. This will not cover the costs for our prototype design. Therefore, it is imperative that we apply for various grants.

	Quantity	Cost Per Unit	Total
Refrigeration Parts			
Water Valve and Bracket	1	$73.00	$73.00
Condenser Fan Motor	1	$30.00	$30.00
Evaporator Fan Motor	1	$36.00	$36.00
Thermostat	1	$50.00	$50.00
Tray Evaporator	1	$25.00	$25.00
Diffuser	1	$50.00	$50.00
Compressor	1	$300.00	$300.00
Pipes and Tubing	1	$75.00	$75.00
Stainless Sheet Metal (12'x12')	1	$7.73	$7.73
Miscellaneous Parts	1	$40.00	$40.00
Machine, Tool, Etc.			
Physics Lab Machine Shop Contract	5	$50.00/hr	$250.00
Energy Source			
Rechargeable 12V 36AH Battery	1	$169.23	$169.23
PCM			
Lithium Chlorate Trihydrate	5	$8.00/lb	$40.00
Phase 5 Material	18	$6.11/L	$109.98
Tetrohydrofuran Clathrate	1	$110.00/L	$110.00
Propylopalmitate	5	$30.30/100g	$151.50
Testing Supplies			
Thermocouple Thermometer		1$190.00	$192.15
Grand Total			$1,709.59

Refrigeration Parts:
To assemble a compression refrigerator, we must have all of these parts for a working refrigerator. In addition, by building a refrigerator from individual parts, we are able to understand the refrigerator better and how we can integrate the phase change material as well as the battery.

Machine, Tools, Etc:
We need the necessary tools to build a compression refrigerator and how to incorporate the many different aspects of our research, such as the PCM, and the battery. While we may have the necessary parts, we lack the instruments. It would not be cost effective to purchase all the devices we need, so we intend to borrow them from the Physics Lab Machine Shop at the University of Maryland.

Energy Source:
A rechargeable battery will help us address the concern of intermittent power supply characteristic of developing countries that may be causing refrigerators not to maintain their temperatures above 0 °C. Having a battery is one of the design criteria requirements we will fulfill.

PCM:
We need to find the most efficient and cost effective PCM to integrate within our refrigerator. To begin this process we need to purchase different PCMs and test them using our characterization of phase change materials experiment. Without having a group of phase change material to compare, it would be impossible for us to determine which would be best for integration into our refrigerator.

Testing Supplies:
The data logger with thermocouple inputs will be vital in our selection of phase change material. Without the data logger, we will not be able to able to conduct the experiments for determining heat of fusion and other experimental values in both characterization of phase change material and integration experiments as accurately as possible.