Design of a Passive Incubator for Premature Infants in the Developing World

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ABSTRACT
Every year, about 1 million infants in the developing world die due to prematurity complications. These deaths are often caused due to heat loss and dehydration that can be prevented by an incubator. Unfortunately, there is a lack of low cost incubators in the developing world. Most incubators run on electricity and are rendered worthless in regions without electricity, or in those that suffer frequent power cuts. The challenge therefore has been to design a low cost incubator that will run independent of electricity. The use of phase change material as a prospective non-electric heating element is proposed within this project, in addition to the use of indigenous raw materials to build a low cost outer shell for the device. Even though the current design of this device is geared toward premature infants in war torn regions of the world, the design will have broad applicability in any geographical context where portability, cost and energy are primary concerns.

Keywords
Premature Infant, passive, sustainable, incubator

INTRODUCTION
Worldwide every year, over 4 million infants, die within a month of birth. Of this number, 3.9 million belong to the developing world. 25% of the deaths are caused due to complications of prematurity, most often heat and water loss [1]. In developing countries, not only is there limited access to modern, high-tech incubators, but the lack of electricity in many rural regions and frequent power cuts in urban areas render such devices worthless. Many of these developing regions are further burdened by war and ethnic conflict. Such conditions adversely affect the overall healthcare and nutrition of the populace, and therefore increase the occurrence of premature complications. There is thus a need for an effective, low cost incubator that runs without electricity and is portable and robust in the given terrain.

An important aspect in designing for developing communities is not only making sure that the product works, but that it is also culturally sensitive and incorporates appropriate technology. To this extent, we focused our design on the target area of the Sinhala-Tamil border in Sri Lanka.

Sri Lanka is an island off the south east coast of India. It is home to 18 million people, of which 30% live below the poverty line. Infant mortality is about 16 deaths for every 1000 live births [2]. For the past two decades, the nation has been in a state of ethnic war. Inhabitants close to the border zone that separates the two ethnic groups have been forced to live in makeshift homes provided for them by relief agencies. One such area is Mallavi, about 20 miles north of Vavuniya. In designing this incubator, we have collaborated with health professionals from Doctors Without Borders (MSF) who have been active in this region since 1986[3].

PREMATURE INFANT PHYSIOLOGY
Premature infants are babies born prior to the normal 36 or 37 weeks of gestation within the womb. As a result, their physiological systems are underdeveloped making the infant vulnerable to a number of health complications. Some common problems include jaundice caused by an immature liver, respiratory complications caused by fragile, underdeveloped lungs, and hypoglycaemia, hypoxia and even death caused by an immature response of the nervous system to cold stress[4]. This inadequate thermoregulation,

1. MSF is a private, nonprofit organization founded in 1971 that provides primary health care, performs surgery, rehabilitates hospitals and clinics, runs nutrition and sanitation programs, trains local medical personnel, and provides mental health care. MSF is an international network with sections in 18 countries. Each year, more than 2,500 volunteer doctors, nurses, other medical professionals, logistics experts, water/sanitation engineers, and administrators join 15,000 locally hired staff to provide medical aid in more than 80 countries
wherein their physiology is not able to compensate for the heat they lose [5], and the loss of water from the body are by far the leading causes of death in premature infants. Heat is lost via evaporative, conductive, convective and radiative means. Premature infants lack muscle mass, which allows adults to shiver and produce heat when necessary, as well as heat generating brown fat, which makes up about 5% of the body weight in term infants. This heat loss is enhanced by their large surface area to volume ratio (about 4 times the adult ratio). Furthermore, their immature skin allows for excessive water loss from the body causing a considerable evaporative heat loss and a potentially fatal imbalance of salts and acids in the infant’s system. In evaporative heat loss, moisture from the body first diffuses across the epidermis (general outer layer of skin). Then it evaporates off from the skin’s surface cooling the infant.

**Figure 1 Tranverse section of human skin** [6]
Premature infants have a thin, underdeveloped stratum corneum, or the rough, outer layer of the epidermis which protects the skin from external agents, that enables excess of water to diffuse out [7]. Evaporative heat losses make up a significant fraction of the total heat loss of a premature infant.

**Prior Art**
Before beginning the design process, we researched existing technologies in the field of premature infant care. One of the most pertinent examples of prior art found was the Van Hemel Incubator, a non-electric incubator built for use in developing countries. Created in 1968 in Zambia, this invention used paraffin lamps, located in a compartment below the baby, to heat the air in the incubator. This heat source created a thermally driven flow of air through the system. In addition, the hot air was passed over a water-saturated cloth, feeding off of a neighboring bowl of water, to humidify the enclosed environment [8].

Although the Van Hemel could provide infants with heat and humidity without a continuous source of electricity, it was not largely accepted by the end users. Possible reasons being that it was bulky and burned about 2 liters of paraffin a day. There was also the added concern of the paraffin lamps suffocating the infant.

**Design Constraints**
The primary design constraints for the incubator were to provide the infant with the bare necessities:
- An ambient temperature of 34°C–37°C
- A humidity greater than 70% RH
- A sterile air supply

With these in mind, our most important design elements were:
- An ideal heat source/sink to maintain the ambient temperature in the 34°C – 37°C range for as long as possible—ideally 24 hours, with minimal monitoring.
- An effective air filtration system that will remove bacteria
- An effective thermally driven air purification system that will circulate enough oxygen to the infant, while filtering harmful bacteria and particulate material from the atmosphere.
- An insulating, sound reducing container to house the infant.
- A simple incubator design that will enable easy access to the infant when needed.
- A robust, portable container that can be easily dismantled and set up while requiring and will require minimal operation capabilities.

In addition, given that this design was targeted toward use in relief camps, our overriding constraints were: portability, safety, ease of construction and use.

**Design Components**

**Incubator Case**
The basic design chosen for the incubator case is a small tent-like structure. This simple configuration enables the tent to be easily cleaned, transported and reproduced. We have chosen the simplest design for a dome tent with square base that is self-tensioning that uses the least amount of materials.

Figure 2 is a 3D model of the design, with figures 3 and 4 showing early prototypes. The square base length is 15”, large enough to easily accommodate a 1.2kg infant with enough room to allow a nurse or doctor to maneuver inside. Two semicircular arcs made of spring steel, aluminum, hot-pulled carbon fiber or even pre-tensed wooden dowels are inserted into a single, sewn piece of fabric. There are pockets at the four corners made of fabric that hold the arcs in place.
Figure 2 A 3D rendering of basic tent structure with phase change material mattress

Figure 3 shows the structure held together by string using carbon fiber rods. Guide paths made of fabric near the top of the dome cross the two arcs holding everything in place. The fabric must be a reasonably air and water tight material like sailcloth (polyester or nylon fibres) so that air flow and heat loss can be controlled. As pictured in Figure 2, there are four panels of fabric. Unlike a tent, which has poor insulation, three panels of the incubator will be double layered and filled with multiple layers of newspaper or insulation blanket to lower radiative, convective and conductive heat loss. Insulation blankets made of spun cotton or fiberglass and coated with mylar are usually available for construction projects in urban areas. If this cannot be obtained, cellulose in the form of newspapers should be readily accessible in most countries. Cellulose is non-toxic and is more energy efficient than fiberglass [9].

Figure 3 Frame structure of the tent showing the carbon fiber rods held

The fourth panel serves as an entrance to the incubator. An inexpensive reusable adhesive such as static cling vinyl attached to the perimeter of the flap serves as a good seal. Zippers and Velcro™ were not used for this purpose since they are expensive and don’t form good seals.

The bottom of the tent consists of a double-layered insulated floor. It will contain an opening to slide in the heating mattress, made of phase change material as described below. Connecting the dome panels to the mattress will be a tight mesh that will filter the air of airborne particulate matter and biological agents such as bacteria. The filter and air supply will be driven by the difference in density of the hot air at the bottom and at the top (like a fireplace) with an exit port at the top of the dome.

Figure 4 Cotton tent cover fully assembled.

This structure should be easy to take apart and re-assemble. One simply has to unhitch a rod out of its pocket and then the other three ends will easily come out. The phase change mattress can be slid in and out easily washable.

Heating Element

The heating element proposed is a passive thermoregulation system utilizing the chemical properties of phase change material. The unique self-regulatory property of PCM will enable our incubator to be relatively low maintenance. PCM and conductive foam are encased in a waterproof sack that will form a mattress for the baby to sleep on. It will thermoregulate the infant via direct conduction and minimization of convection losses. To operate, an attendant would simply need to heat the sack in a water bath. Photochromic ink in the sack would indicate when the mattress has reached a specific temperature.
**Thermodynamics of Infant Heat Transfer**

A premature infant can exchange heat with its environment through 4 main mechanisms: 1) convection 2) conduction 3) radiation and 4) evaporation. Convection describes the heat transfer between the surrounding atmosphere and the baby. Conduction is associated with the heat transfer due to the contact of one object to another object. In the case of the PCM mattress, conduction serves as the primary means of heating the baby. Radiative exchanges are caused by the energy that is emitted to or from a subject at a set temperature. Lastly, evaporative heat losses are due to the energy loss from water evaporating through a premature infant’s thin, immature skin [10].

The PCM mattress will heat the infant through conduction and heat the surrounding air, thereby minimizing the child’s convective losses. This heating element coupled with the baby’s own metabolism will combat thermal losses from convection, radiation and evaporation. These heat transfers around the infant can be modeled as follows.

\[
q_{\text{net}} + q_{\text{cond}} = q_{\text{conv}} + q_{\text{rad}} + q_{\text{evap}} \quad \text{Equation 1}[11]
\]

Each term is measured in Watts and is non-negligible in reality. The goal of an equation such as the one above would be to predict the energy budget, geometry and ventilation requirements for an energy storage material and tent that would maintain close to 37°C ambient air temperature, and provide about 6ml/kg/min [12] of fresh air for about 8-24 hours. However, there is a complex interplay between heat, airflow and humidity in a vented enclosure that prevents simple analytical calculations. Trying to solve this equation from assumptions of constant temperature or velocity will produce fallacious results whose error is on the order of the parameter to be estimated. Further complications arise due to the fact that material parameters are strong functions of temperature or humidity (such as the air conductivity as a function of humidity).

Using direct calorimetry, it was found that the average total metabolic (convective, evaporative and radiative) heat release of a premature infant was about 1.5 Watts [13]. Our own calculations have also validated those results. The surrounding environment and age of the infant will affect the heat balance as well, but the value should still be on the order of 1 Watt. While not completed for this paper, work is being done on creating a measurement apparatus and finite element simulations to begin to address these concerns.

**Phase Change Material**

When a PCM is adequately charged with energy, it is able to maintain a constant phase change temperature, whether it is at its melting point or boiling point, for a long span of time. A material reacts to the addition or subtraction of energy in different manners depending on its physical state. This change in heat can either have sensible effects, in which the input energy goes to changing the temperature of the material, or latent effects, such as when a material is in a state of phase change and the input energy goes into breaking intermolecular bonds [14]. Figure 4.0 shows this phenomenon. The same characteristics of latent and sensible heat effects also apply in the reverse process when a material gives off heat. The mechanisms that keep PCM at constant temperatures will compensate for the heat fluctuations premature infants face.

We are currently looking into a number of paraffin wax based products that, when at melting point, can maintain a baby’s temperature somewhere between 34ºC to 37ºC. Since paraffin products are available in a wide range of melting points and generally have high enthalpy (or melt enthalpy) of fusion, they make ideal PCMs. Typically, paraffin wax consists of a mixture of alkanes (CₙH₂ₙ₊₂), a type of saturated hydrocarbon. After refining, this substance is odorless and nontoxic, making it ideal for use in a baby incubator [14].

The first line of products we came across were PCM lined fabrics made by the company, Outlast. These materials, aimed at providing temperature-controlled clothing for campers and athletes, did not do well in the incubator set up. The second company we came into contact with was called Rubitherm. They offer a variety of paraffin-based waxes, granules, powders and gels that are most commonly used in household insulation and medical supplies. We are currently testing effectiveness of their products in lab. We will also look into testing other non-toxic chemicals with large phase enthalpies and heat capacities that are not commercially packaged as PCMs. One type of material is inorganic, hydrated salts, developed by Teap Energy. These materials work in the range of core body temperature and have very high latent energy storage (226 kJ/kg) [15]. Another potential type of material actually uses supercooled salts as a storage mechanism [16].
Air Purification and Ventilation System

Air Purification
Since a premature infant’s immune system is very underdeveloped, it should be kept in a sterile environment to prevent infection. Most bacteria and other air borne particles can be prevented from entering the incubator by filtering the incoming air. The use of non-woven, spunbond polypropylene fabric used in physician’s surgical masks is being looked into. Not only is this option light and hypo-allergic, but it also has 0.5micron filtration efficiency greater than 95%, while the average size of bacteria is between 1-2 microns. This component is still under study.

Ventilation System
Thermally driven air purification can be achieved by manipulating the airflow into and out of the incubator. A detailed thermodynamic model is being set up, so as to simulate the flow of air, heat and humidity within the incubator, giving a fair idea of the air supply available to the baby. There is a difficult tradeoff between providing good air purification and ventilation that needs to be considered for the final design.

ADVANTAGES OF DESIGN
From the perspective of sustainability and feasibility, this design has several advantages over its counterparts.
- It provides the relief workers with an incubator-in-a-bag that is portable
- It is a culturally sensitive design using mostly indigenous material
- It can be set up and dismantled single-handedly.
- It can be packed up to a compressed volume of 0.3 cubic feet.
- Our phase change material is cheap, non-toxic and easy to handle.
- The baby can be left unattended for 4-6 hours without concern of heat loss within the incubator.
- Unlike most incubators, this design is very low maintenance and requires minimal operational capabilities.

Our only assumption of fuel needed is a fire to heat water for the heating element. This is already available for sterilization purposes as confirmed by MSF personnel.

In regions where there is no equipment to sustain a newborn premature infant, this device will prevent the need for immediate postnatal transportation to a more well equipped location which would cause severe stress to the infant. The device serves to prevent the most common complications of prematurity: heat loss, and dehydration. In addition, if the infant is born with further complications such as respiratory problems, this incubator will serve as a transport incubator buying the infant more time until it is taken to a more equipped hospital. In the more developed county hospitals, this device could also be used as backup to the electric incubators during periods of power failure.

WORK IN PROGRESS
The design is still a work in progress. Although considerable achievements have been made, there is a large amount of work that exists to be done. Identifying the right heating element is key to this problem. This will be followed by testing and data collection to verify our design approach. Tests need to be developed in order to monitor temperature air filtration and air exchange within the incubator. We will also need to quantify the heat that is lost from the system.

When the device has passed its rigorous testing phase, we will proceed with field deployment of the device. Our hope is that we are able to successfully introduce the device to the relief workers in the targeted area. Since our primary targeted end user MSF will be involved in all stages of our device testing process, we are fairly confident that technology transfer will be smooth. Our final end user will be the local nurses and doctors, who will be introduced to the technology by MSF personnel who have already established reputable credibility within the community.

SCOPE
In designing this device, our main aim has been to engineer a simple solution to a complex problem in the developing world while keeping the user minimally dependent on Western resources for sustainability of the device. We have aimed to use materials in our product that will be locally accessible. The existence of PCM material is still under question, and for the purposes of this design, it has been assumed that this component will need to be provided in the beginning stages. However, the reusability of the PCM is encouraging. Design blueprints can easily be made available to future manufacturers of the device. All manufacturing will take place locally. The design idea is simple and very intuitive. The use of newspapers for insulation is a cheap and effective method that can be reproduced with little difficulty. The operation of the device is intuitive and limited to simple set up of the tent and heating of the PCM sack. All the materials used will also be washable and therefore reusable. The filtration system may however need to be changed for each infant to ensure sterility.

COLLABORATION
Our support network thus far has consisted of a balanced combination of experts from academia and the medical field. Dr. Kelly McQueen from Doctors Without Borders (MSF), Dr. Steven Ringer from the Brigham and Women’s Hospital in Boston, MA; and Professor Ernest Cravalho from the Mechanical Engineering Dept at MIT. Although the identification of the need for a passive incubator began in the classroom, it was strengthened by our conversations with the mentors. Our collaboration with MSF, an
organization that has first hand experience dealing with premature infant cases, has been most beneficial. In July 2002, after months of online information exchange, we were able to meet the Medical Logistics Coordinators of MSF’s project in Sri Lanka. A rough outline of our design concept and incubator model was presented. We will continue to have an open collaboration with MSF as we work toward our final product, and hope to meet with them in January 2003 again. MSF will also arrange for us to meet with local doctors in the area.

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We would like to thank the mentors, field experts and organizations we have met thus far who have contributed to this project.

Kathryn Ann Kelly McQueen M.D. is an anesthesiologist in private practice in Phoenix, Arizona. She is committed to teaching and volunteering medical expertise within the community and with many international organizations. She has taught anesthesia in East Africa, consulted on Obstetrical anesthesia in Russia, and provided anesthesia for hundreds of children requiring repair of facial deformities in China, Jordan, Brazil and Peru. When possible she also volunteers for disaster relief medical work, and in 2001 worked for Medecins Sans Frontieres/Doctors Without Borders in Sri Lanka.

Dr. Steven Ringer received his MD from Case Western Reserve University School of Medicine in 1982. He joined Brigham and Women’s Neonatology Unit in 1988 and is currently the director of the hospital’s Newborn Medicine Unit. Dr. Ringer’s interests lie in Neonatology, Antenatal Consultation and Extreme Prematurity. He is currently working with Project Vietnam in the design of low cost incubators to be used in the region.

Professor Ernest Cravalho is the Edward Hood Taplin Prof of Medical Engineering & Mechanical Engineering. He was awarded his Bachelor, Masters and Doctoral degree from the University of California, Berkeley. Professor Cravalho joined MIT as an Assistant Professor in 1966, and was promoted to Associate Dean for Academic Programs, School of Engineering in 1975. Professor Cravalho’s research interests lie in the field of Cryobiology; Biomedical Engineering Technologies for Patient Care. He currently teaches undergraduate and graduate classes in Thermodynamics and Heat Transfer.

Medecins Sans Frontieres has been in Sri Lanka since 1986, providing assistance to the civilian victims of the armed conflict, displaced persons, and others lacking adequate health care. We have been collaborating with Medical and Logistics Coordinators Lorraine Hulleman and Gianni of MSF–Project Sri Lanka.

Amy Smith is a graduate of MIT and an instructor at the Edgerton Center at MIT. Amy has worked on several low cost health technologies for developing countries, and was a pioneer in the use of phase change materials in incubators for scientific testing in the developing world. She has also worked on a low cost grain mill that won the MIT-Lemelson Award in 2000. Amy is currently spearheading several service learning initiatives within the MIT community.

Design That Matters design studio at the Media Lab at MIT, taught by the graduate student founders of the Thinkcycle Initiative.

MIT IDEAS Competition In May 2002, this design idea was awarded the 2002 MIT-Lemelson International Technology Award. The award has gone a long way in supporting our experimenting and testing phase.

CONCLUSION
Our design concept has evolved a great deal from our original, crude understanding of the problem, and continues to change as we receive feedback from field experts. Addressing these issues early on in an open collaborative environment will help us create a device that is custom made for our end user, adaptable to change, and appropriate in terms of function, culture and lifestyle. Though the device is currently geared toward a select community in a particular part of the world, this design has the potential to have a global impact.

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